ENVELOPE DESIGN FOR THERMAL COMFORT AND REDUCED ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS

BY

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عمادة الدراسات العليا
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بسم الله الرحمن الرحيم

DEDICATED

TO MY MOTHER, WIFE AND MY KIDS ZAIZAFOON, NASSAR AND MOHAMMAD AND TO MY BROTHERS AND SISTERS

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All praise and thanks are due to my Lord: ALLAH SUBHAN WA TAALA for giving me the health, knowledge and patience to complete this work. I acknowledge the financial supports given by KFUPM, Architectural Engineering Department, at the early stage of my Master study. I appreciate the computer facilities and the energy simulation program VisualDOE provided by Architectural Engineering Department for this research study.

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THESIS ABSTRACT

NAME: SALEH AL-SAADI
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Residential buildings are characterized by being envelope-load dominated buildings, hence are greatly influenced by the outside climatic conditions. Due to the harsh climate of Saudi Arabia, residential buildings on average, consume more than half of the total consumed energy. The bulk of this energy is consumed by the air-conditioning system which is required to remove substantial amount of gained heat due to poor thermal envelope performance. Implementing proper envelope thermal and air leakage characteristics for residential buildings can significantly reduce energy consumption.

The objectives of this research are to evaluate the thermal characteristics of building envelope and consequently define those that enhance the indoor thermal conditions and improve the energy efficiency of residential buildings. In order to achieve these objectives, a typical base case residential building was developed by conducting a questionnaire survey in Dhahran and Riyadh. Envelope design practices were defined and eight designs were selected to represent the wide variation of thermal characteristics.

Energy simulation program; VisualDOE 4.1 was used to evaluate the impact of thermal performance of the selected envelope designs and air leakage characteristics in the residential building when no air-conditioning is used. Parametric analysis was performed in Dhahran and consequently ventilation strategies were developed for the eight envelope designs at various windows to wall ratio (WWR). The thermal comfort has significantly improved when outside cool air is introduced. The base case was also simulated under the climatic conditions of Riyadh and Dhahran when air-conditioning (cooling and heating) is utilized. A sensitivity analysis was performed for wall and roof designs, combination of wall and roof designs, glazing types, window to wall ratio (WWR), orientation and various air infiltrations. The most effective strategies were selected and simulated for the eight envelope designs. The total energy consumption of residential buildings in Dhahran and Riyadh was reduced by 20% when compared to International Energy Conservation Code (IECC) proposed design. The Dhahran case was further improved by incorporating combined ventilation and air-conditioning strategies. Finally, envelope thermal design guidelines were developed for residential buildings in hot climates of Saudi Arabia.

MASTER OF SCIENCE DEGREE

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS
DHAHRAN, SAUDI ARABIA

ملخص الرسالة

الاســــــــم: صالح ناصر الساعدي

عنوان الرسالة: تصميم الغلاف الخارجي لتحقيق الراحة الحرارية وتقليل استهلاك الطاقة في المباني السكنية

التخصـــــص: قسم الهندسة المعمارية

تاريخ التخـرج: مايو 2006 م

تتميز المباني السكنية بمواصفات تصميمية وتشغيلية تجعلها تتأثر بتغيُر البيئة المناخية المحيطة. وفي المملكة العربية السعودية ونتيجة لوجود مناخ قاسي (حار- جاف في المناطق الداخلية وحار- رطب في المناطق الساحلية) فإن المباني السكنية لوحدها تستهلك أكثر من نصف الطاقة الكهربائية المستهلكة. ونظراً لوجود قصور تصميمي في الخصائص الحرارية للغلاف الخارجي للمباني وتسرب الهواء من وإلى الأجواء الداخلية فإن معظم الطاقة الكهربائية تستهلكها أنظمة تكييف الهواء لعلاج هذا القصور. لذلك فإن اختيار وتصميم الغلاف الخارجي من حيث خصائصه الحرارية والسيطرة على تسرب الهواء يساهم بفاعلية في تقليل استهلاك الطاقة الكهربائية دون التأثير السلبي على الراحة الحرارية لمستخدمي المباني.

وفي هذه الدراسة كان الهدف تقييم الخصائص الحرارية للغلاف الخارجي للمباني وبالتالي الوصول إلى تلك التي تُحسن الحالة الحرارية الداخلية ورفع كفاءة استهلاك الطاقة الكهربائية في المباني. ولتحقيق هذا الهدف تم عمل مسح استبياني للوقوف على أهم الممارسات في تصميم الغلاف الخارجي للمباني في المنطقة الشرقية (الدمام والخبر والظهران) والرياض , وبالتالي عمل نموذج مبنى سكني لدراسته دراسة تحليلية دقيقه. حيث تم اختيار ثمانية تصاميم للغلاف الخارجي تغطي الخصائص الحرارية المحتملة وبالتالي دراسة شريحة واسعة ومختلفة من التصاميم.

وقد تم في هذه الدراسة استخدام برنامج محاكاة لحساب الطاقة الكهربائية في المباني: Visual DOE لدراسة الكفاءة الحرارية لأنظمة الغلاف المختارة وتأثير الهواء الخارجي عند دخوله المباني السكنية في حالة عدم وجود أنظمة التكييف. وقد شملت الدراسة تحليل دقيق لتأثير الهواء الخارجي على البيئة الداخلية بوجود الأنظمة المختارة و نسب متفاوتة من مساحة الزجاج الخارجي في منطقة الظهران. وقد وُجد أن استخدام الهواء الخارجي البارد يرفع درجة الراحة الحرارية لمستخدمي المباني في أوقات معينة من السنة. كما تم دراسة كفاءة استهلاك الطاقة الكهربائية للنموذج السكني عند استخدام أنظمة التكييف طوال السنة تحت تأثير مناخ الرياض والظهران وقد اشتملت على دراسة دقيقة لتأثير التصاميم المختلفة لأنظمة الجدران والأسقف وأنواع ونسب مختلفة من الزجاج وجهات مختلفة للمبنى تحت تأثير نسب متفاوتة من الهواء الخارجي. وبناءاً على هذه الدراسة تم اختيار انسب تصميم والذي ساهم في تقليل استهلاك الطاقة الكهربائية بنسبة تصل إلى 20% مقارنةً بالتصميم المقترح في الكود العالمي لترشيد الطاقة في المباني. كما تم تقليل استهلاك الطاقة الكهربائية في منطقة الظهران باستخدام التهوية الطبيعية وأنظمة التكييف الميكانيكية. وفي النهاية تم الوصول إلى استراتيجيات مقترحة لنظام الأغلفة الخارجية في المباني السكنية تحت الظروف المناخية الحارة للمملكة العربية السعودية.

درجة الماجستير في العلوم

جامعة الملك فهد البترول و المعادن

الظهران - 31261

المملكة العربية السعودية

CHAPTER ONE

INTRODUCTION

1.1 Background

In traditional buildings of Saudi Arabia, climatic thermal design of exterior building envelope was predominantly utilized to manipulate the indoor air temperature to achieve thermal comfort. Climatic thermal design such as thermal characteristics of building envelope and air leakage characteristics greatly influences the room air temperature and subsequently the energy consumption. Thermal characteristics are the principle properties of building materials such as heat transmission, heat storage, solar heat gain and air infiltration **(Fazio et al., 1997)**. Givoni has identified these characteristics as thermo-physical properties of building envelope which include thermal conductivity and subsequently thermal resistance, heat capacity, transparency to radiation of different wavelengths, surface convective coefficient, and surface radiation properties: absorptivity, reflectivity, and emmisivity **(Givoni, 1976)**. To utilize the potential of the thermal performance of building envelope, these characteristics should be identified and properly considered at an early design stage to reduce the energy consumption required to achieve thermal comfort. The rapid development and prosperity of construction industry in the Kingdom of Saudi Arabia has contributed in introducing new building materials that are incompatible to the local harsh climate. On the other hand and in the Saudi design practices, materials for building envelope are seldom selected with proper considerations to thermal performance **(Al-Hammad and Hassanain, 1996)**. New building's designs are developed to meet the client's requirements without much concern to the climate and with no objective to conserve energy. This has undoubtedly disregarded the climate as a design determinant in building envelope design process. As a result, these have contributed to an overall poor thermal performance of residential buildings which became more dependent on artificial means to provide comfortable thermal environment at high energy consumption.

Residential buildings in Saudi Arabia consumed 51% of the total energy use in the year 2002 as shown in **Figure 1.1**. Majority of the consumed energy is used for heating and cooling purposes to provide thermal comfort. The poor thermal performance of exterior building envelope is responsible for large portion of total cooling load which determines the energy consumption in hot climates. Harsh climatic conditions could increase the contribution of the building envelope to 77% of the total cooling load **(Al-Mofeez, 2002)**.

Air leakage characteristics on the other hand play major role in either enhancing or deteriorating the indoor thermal environment. The impact of air leakage on the indoor environment is dependent on the severity of outside climatic conditions. The poor construction practices including the workmanship, construction methods and lack of testing procedures for locally made building components and the incompatibility of imported building materials to the harsh climate in Saudi Arabia have presumably resulted in buildings with high air leakage rates.

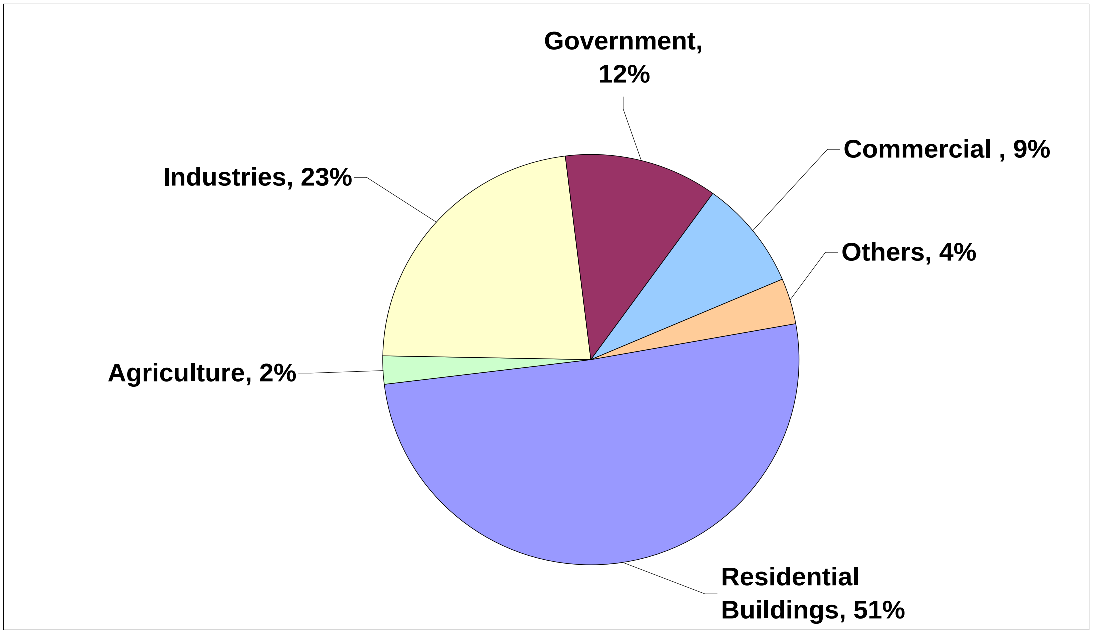


Figure 1.1 Distribution of Sold Energy for All over the Kingdom in Year 2002 **(SEC, 2002)**

While the air leakage is advantageous in improving the indoor thermal environment when the outdoor temperature is within the thermal comfort limits, it can negatively impact the indoor thermal environment in hot-dry and hot-humid days. The severity of air leakage on indoor thermal environment may be more pronounced in hot-humid climate where humidity is the major cause of discomfort.

Thermal performance of residential buildings under Saudi climate needs careful attention due to the diversity of the climatic conditions. This is particularly true for buildings in hot-humid climate where passive design concepts such as building thermal design, orientation, planning, material selection, window treatments, natural ventilation, including proper facility planning and management are difficult to accomplish but imperative in improving the indoor thermal environment **(Sreshthaputra, 2003)**. Considering these design concepts at the early design stage, it is strongly believed that an acceptable indoor thermal environment could be achieved with low energy consumption in developing countries where codes are not available. This is particularly important when thermal design concepts are intended to accomplish thermal comfort at low energy consumption. Although the potential of saving energy at national level in Saudi Arabia is still not quantifiable at this stage but some estimates show that the energy use in the future buildings could be reduced by as much as 20% compared to the existing available designs if proper code is implemented **(Ishteeaque, 2002)**. Many efforts are currently under way to develop the first national Saudi Building Code.

1.2 Statement of the Problem

As envelope-load dominated buildings, residential buildings are greatly influenced by the climatic conditions. In Saudi Arabia, the thermal load of building envelope (i.e. walls, roof and windows) is responsible for more than 70% of the total thermal load in a single-family house in Dhahran **(Said and Abdelrahman 1989, Abdelrahman and Ahmed 1991, Ahmed and Elhadidy 2002)**. Residential buildings on average consume more than 51% of total consumed energy in Saudi Arabia in year 2002 with an annual growth rate of 8.1% **(SEC, 2002)**. The majority of this consumption, measured to be more than 76% in hot-dry climate of Saudi Arabia **(Al-Arfag, 2002)** and more than 62% in hot-humid climate **(Al-Najem, 2002)**, is used by mechanical cooling and heating systems to provide thermal comfort. In addition, air leakage is an important parameter that influences the behavior of indoor air temperature. While the air leakage is advantageous in improving the indoor thermal environment when its temperature falls within the comfortable limit zones, it is unfavorable for cooling load in hot-dry and hot-humid days at which the infiltrated air temperature is out of the comfortable limit zones. Studies in hot-humid climate of Saudi Arabia, using DOE2 have shown that the peak cooling load in a single-family house is very sensitive to air infiltration which represents 22% of the peak cooling load **(Said and Abdelrahman 1989, Abdelrahman and Ahmed 1991, and Ahmed and Elhadidy 2002)**. The thermal load can significantly be reduced by considering climatic thermal design strategies. It might not be possible to completely avoid using mechanical systems in harsh climates of Saudi Arabia but the dependence on artificial means to provide a constant thermal comfort can be minimized.

Despite the general awareness about the importance and relevance of envelope thermal design, practical guidelines on envelope thermal design and optimal utilization or mitigation of air leakage characteristics are not always available especially for a country such as Saudi Arabia that has variations on climatic conditions. Owners can also contribute to high energy consumption due their lack of awareness on the impact of outside air on their level of comfort. For example in hot-humid climate, as a first step to achieve thermal comfort, occupants tend to fully open windows and doors for quite long time. Consequently, hot-humid air is introduced to the environment which could cause thermal discomfort. To remove this excessive heat, high cooling energy is required to bring the space back to a comfortable level.

1.3 Significance of the Study

In Saudi Arabia, the bulk of electrical energy in residential buildings is used by mechanical system to achieve thermal comfort. The high energy consumption is mostly related to poor thermal performance of building envelope. Therefore, the study of investigating the thermal performance of building envelope under hot-dry and hot-humid climates in Saudi Arabia will identify the most important thermal design parameters that could be implemented to reduce the dependence on mechanical means and achieve thermal comfort with reduced energy consumption. This study is beneficial to those who design residential buildings as well as those who approve them such as municipality engineers. The study will provide general requirements on the proper thermal characteristics of the exterior building envelope that are necessary to achieve thermal comfort at low energy consumption. Therefore, it will contribute to the current efforts of developing the first Saudi Building Code by providing general design guidelines that can be implemented to reduce energy consumption. The study will also be important to home owners who will use the results of this study to better utilize the natural outside air.

1.4 Objectives of the Study

The objectives of the study are:

1. To investigate the impact of the thermal characteristics of exterior building envelope and air leakage characteristics on the indoor air temperature of a typical residential building in Saudi Arabia.

2. To define the suitable thermal design parameters for exterior building envelope and air leakage characteristics that enhance the indoor air temperature and consequently improve the energy efficiency of the residential building in Saudi Arabia.

3. To develop design guidelines for envelope thermal design and air leakage characteristics that enhances the indoor air temperature and consequently improves the energy efficiency of a typical residential building in Saudi Arabia.

1.5 Scope and Limitation

The scope of the study will be limited to:

1. A single family residential building (i.e. Villa) with its walls, windows and roofing systems that are in common use in Saudi residential construction environment. The size and number of occupancy with their activities will be defined for this building.

2. Two Saudi climates: hot-dry climate represented by Riyadh city and hot-humid climate represented by Dhahran city.
3. A rectangular two-floor villa (i.e. ground and 1st floor) with two basic orientations: South-North and East-West major axis.
4. The building under two cases:
    - 4.1 Unconditioned case to investigate the influence of thermal characteristics of building envelope including the air leakage characteristics on the indoor air temperature behavior.
    - 4.2 A conditioned case for the identified thermal design parameters to quantify the amount of energy required to achieve thermal comfort.

1.6 Research Methodology

Many important inputs are required to run the simulation program utilized in this study. Therefore, four main phases are found necessary and is carried out as follows as shown in **Figure 1.2**:

1. Conducting a literature review and reviewing the related case studies:
    - 1.1. Thermal characteristics of building’s exterior envelope and its impact on dynamic behavior of indoor thermal environment and energy consumption under hot-dry and hot-humid climates.

1.2. Influence of air leakage characteristics on dynamic behavior of indoor thermal environment and energy consumption.

1.3. The international standard requirements for Human thermal comfort.

1.4. Available simulation programs and the sources and types of weather data.

2. Identifying practices of building envelope design:

2.1. Developing and conducting a designer questionnaire to identify envelope thermal design parameters in Saudi construction environment and formulating a base case scenario for residential buildings.

3. Conducting the simulation analysis utilizing the VisualDOE program:

3.1. Simulating the base case scenario.

3.2. A parametric study on unconditioned building using the indoor air temperature as a performance indicator.

3.3. Identifying the effective envelope thermal designs that enhance the indoor air temperature.

3.4. Simulating a conditioned building with the identified parameters to quantify the energy consumption.

4. Preparing the envelope design guidelines, Conclusion and Recommendations:

4.1. Formulating the envelope thermal design guidelines.

4.2. Conclusions & Recommendations.

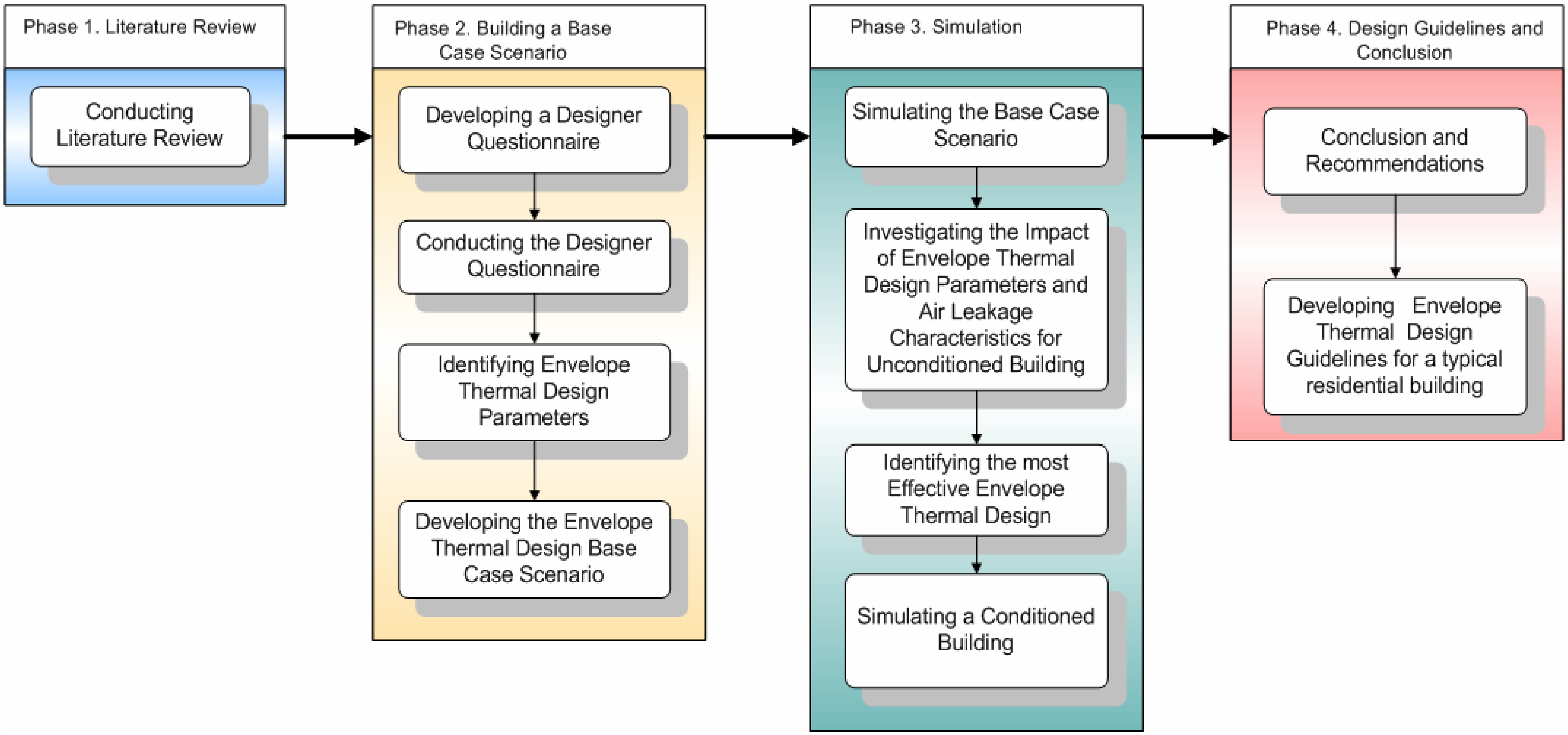


Figure 1.2 Flow Chart of Research Methodology

CHAPTER TWO

LITERATURE REVIEW

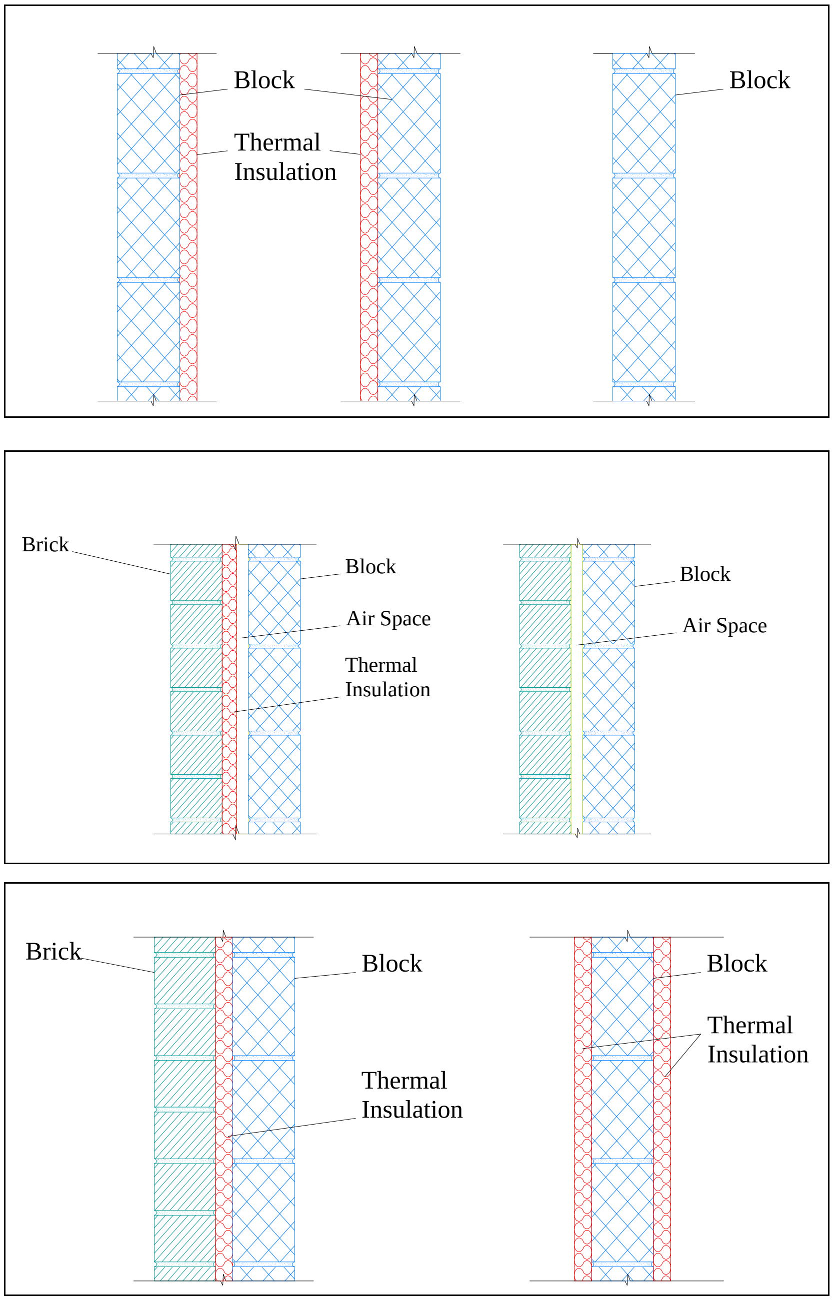
2.1 Building Envelope System and Components Configuration

Building is composed of many systems that are categorized as either simple or sophisticated in their structure depends on the function and complexity of the building. These systems could be functionally categorized as passive or active systems. Passive systems are those that perform their intended function by utilizing their components properties whether these properties are natural or artificial made. On the other hand, active systems are those associated with using mechanical, electrical and electronic equipment to perform their intended function.

Building enclosure or "building envelope" is a primary passive system that has many principal requirements such as control air flow, water vapor flow, rain penetration, and light, control solar and other radiation, noise, and fire, provide strength and rigidity, be durable, be aesthetically pleasing, be economical **(Hutcheo, 1968)**. It influences the indoor air temperature and consequently the occupants comfort. It is defined as a physical means that selectively separates the interior of the building from the exterior. The building enclosure system consists of a group of individual systems such as walls, roof, foundation, floors, windows, and doors. These elements help to regulate the indoor environment. The integration of all enclosure systems and their components is critical in controlling the inside environment at comfortable conditions during the winter and summer seasons. The building envelope system can be further categorized as: opaque and transparent envelope system. Opaque envelope system includes walls, roof, and floors while transparent envelope system includes windows, skylights and glass doors.

The wall and roof systems use a number of materials that are carefully located to achieve certain aesthetic, structural, and thermal purposes. Many building materials include wood, glass, steel, concrete; clay and thermal insulation are used to structure walling and roofing systems. In developing countries, the basic building materials such as wood, concrete and clay are widely used in the construction of residential buildings. It is a common practice that these materials are combined to achieve specific function. Building materials can be assembled in many ways to form different types of building envelope. For walls, the materials can be arranged to create single-leaf solid walls with or with-out insulation. Insulation material is either located inside or outside relevant to the principle material. Other arrangements are also possible such as cavity walls with full air space or partially filled with an insulated material or with reflective material such as aluminum paper, and a sandwich or composite wall panel as shown in **Figure 2.1 (a), (b)** and **(c)**.

Roof system is the most important element of the exterior envelope. It can be flat or sloped (pitched). Flat roofs are widely used in hot climates where rain and water accumulation is not significant. Similar to walling systems, many roof types can be generated with different arrangement of building materials.



(a)

(b)

(c)

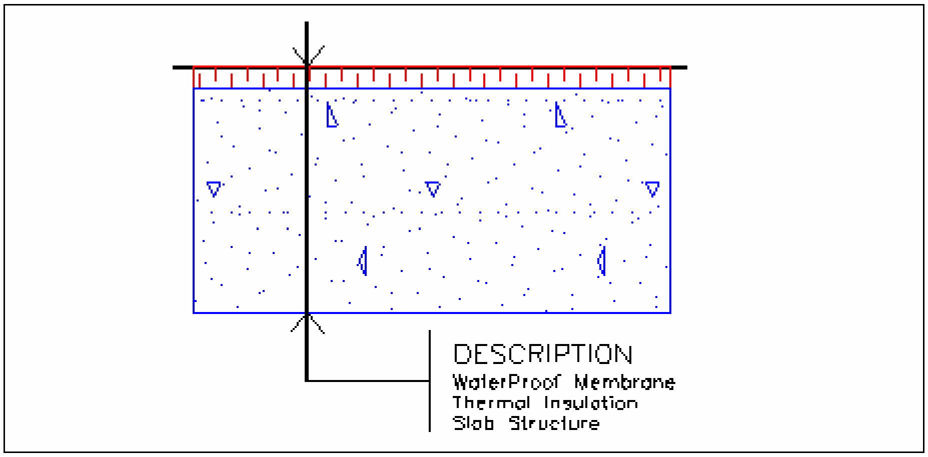
Figure 2.1 Basic Wall Systems in Residential Buildings, **(a)** Single-Leaf Solid Wall, **(b)** Cavity Walls and **(c)** Sandwich Walls

In many countries where no building codes are in place, traditional roofs without insulation are general practice in construction industry. In countries where energy codes are mandatory, roof systems can be classified into conventional warm roofs, inverted (protected membrane) warm roofs and cold roofs. These types are categorized relative to the positions of the thermal insulation and the waterproof membrane as shown in **Figure 2.2 (a), (b)** and **(c)**. In conventional warm roofs, insulation is placed on top of all roof materials except the waterproofing membrane. In inverted roofs, the waterproofing membrane is located under the insulation but still the insulation is above all. For cold roofs, the insulation material is placed at the bottom of all roof materials.

Many factors are influencing the selection of specific roof systems **(Fishburn, 1989)**. These factors include:

- The code requirements such as structural loads, wind loads, drainage, fire protection, health and safety.
- Design considerations such as thermal considerations, vapor and air barrier protection, slope and drainage, building expansion and contraction, service temperature parameters, compatibility, deck type and ease of attachment, suitability of existing surfaces, surface contaminants, building use, interior considerations, aesthetics.
- Construction considerations: the availability of materials and labor, construction schedule and protection during construction, building location, building height and shape, roof size and number of projections.

(a)



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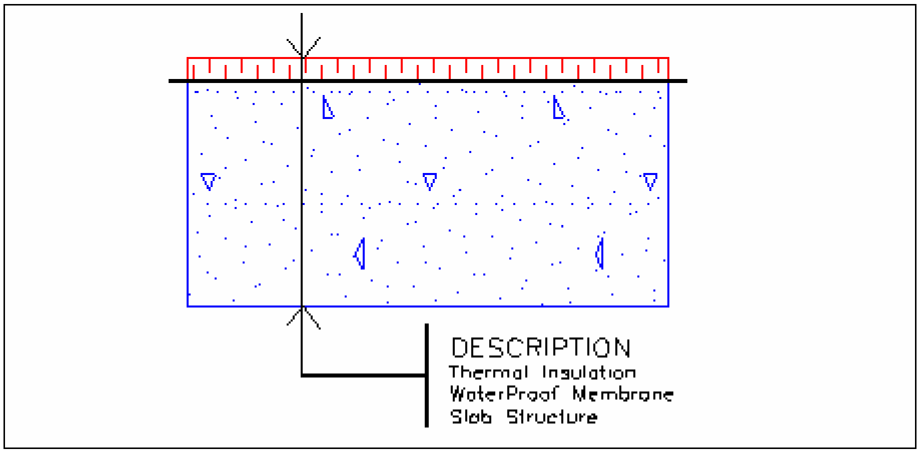

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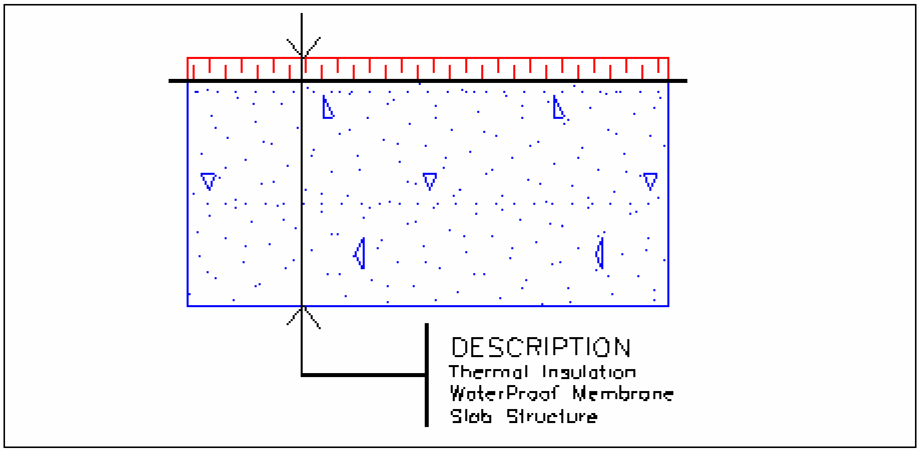


Figure 2.2 Basic Roof Systems in Residential Buildings, **(a)** Conventional Warm Roof, **(b)** Inverted Warm Roof and **(c)** Cold Roofs

- Maintenance considerations: owner's preference and experience, susceptibility to damage and accessibility for inspection, life expectancy.
- Cost considerations: initial cost, life cycle cost.
- Other considerations: technical literature and support, warranty provisions, experience of designers.

2.2 Thermal Characteristics of Opaque Building Envelope

The continuous exchange of heat between the building envelope and its outdoor and/or indoor environment is much dependent on the thermal characteristics of the building envelope. The principal thermal characteristics that influence the indoor air temperature and subsequently the energy consumption include the heat transmission, heat storage, solar heat gain and infiltration rates **(Fazio et al., 1997)**. **Givoni, (1976)** has identified many properties of building envelope that affect the rate of heat transfer in and out of the building and consequently influencing the indoor thermal conditions and comfort of the occupants. The properties of opaque building envelope include the thermal conductivity, thermal resistance, and heat capacity, transparency to radiation of different wavelengths, surface convective coefficient, and surface radiation characteristics such as absorptivity, reflectivity, and emmisivity.

The thermal performance of a building envelope depends largely on how the thermal characteristics and material thicknesses are selected and arranged within the envelope.

The proper design of these parameters determine the thermal behavior of the building envelope with regards to its surface heat exchange mechanism with outdoor and indoor environments as well as the heat transfer mechanisms within the envelope. Opaque building envelope manages the heat exchange and heat flows by three important mechanisms: conduction, convection and radiation as shown in **Figure 2.3**. Normally, the three modes of heat transfer occur simultaneously. Thermal conduction is the transfer of heat energy between two objects at different temperature that are in contact. In thermal convection, heat is transferred by the movement of fluid from one region to another. The fluid motion could be driven by natural means such as wind force or buoyancy forces that are set up by temperature differences and is called natural or free convection. If the fluid motion is caused by some other mechanism, such as a fan or pump, it is called forced convection **(Stephenson, 1964)**. Radiation is the transfer of heat between two surfaces by electro-magnetic waves. For most common building materials used in building envelope, all heat exchange and transfer mechanisms simultaneously occur. However, the degree of dominance of one mechanism over other differs from one material to another based on many factors such as the surface properties, thermal characteristics and the airflow characteristics.

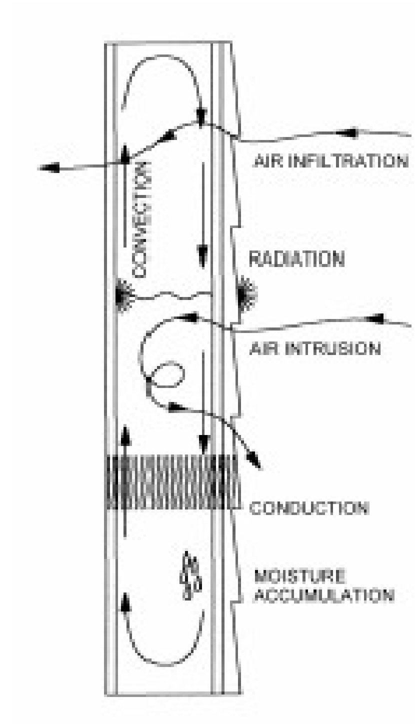


Figure 2.3 Mechanisms of Heat Transfer in Exterior Opaque Building Envelope **(NCFI, 1995)**

2.2.1 Surface Characteristics of Opaque Building Envelope

From a thermal point of view, the main function of the building envelope is to mitigate the outside climate variables as well as those of the indoor environment to help accomplishing a comfortable environment for occupants to perform their day to day activities. The building envelope is dynamically responding to the fluctuation of climate variables particularly to the solar radiation and temperature variation. While both walling and roof systems are responding to the climate variables, roof systems are more sensitive to solar radiation due to longer exposure time to the sun. The surface properties of both walling and roof systems can be used to reduce the effect of climatic conditions.

At the exterior surface of opaque building envelope as shown in **Figure 2.4**, convection and radiation heat transfer mechanisms are predominant. Generally for the building envelope, the convection heat transfer is a function of wind speed and details of the surface roughness but for roof systems additional parameters such as the height of the roof above ground level and how the roof is exposed to the wind are also important **(Berdahl and Bertz, 1997)**.

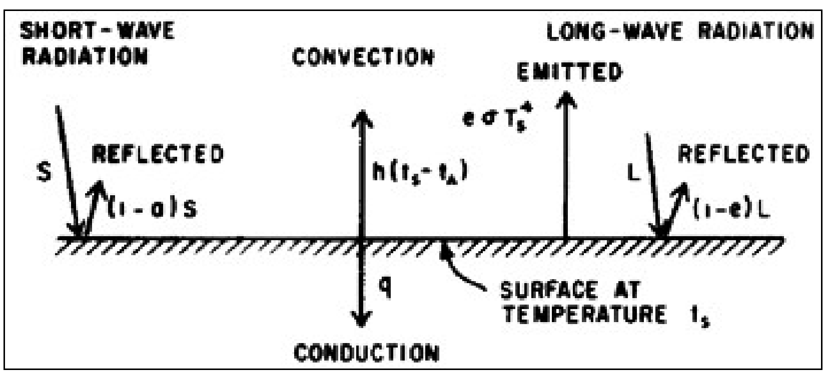


Figure 2.4 Components of Heat Balance at an Opaque Surface **(Stephenson, 1963)**

Surface roughness contributes to the effectiveness of convection heat transfer. Higher roughness increases the contact between the air and the surface and consequently increases the surface convective coefficients **(Givoni, 1976)**. The surface convective coefficient determines the rate of heat exchange between the surface and the surrounding air. The higher the convective heat coefficient the closer is the surface temperature to ambient temperature. The surface roughness of the building material can be classified into six categories **(Ely, 2001)**:

- Very Rough. e.g. stucco walls, wood shingle roofs, or built-up roof with stones
- Rough. e.g. brick or plaster.
- Textured. e.g. poured concrete walls, or asphalt shingle roofs.
- Flat. e.g. painted wood siding.
- Smooth. e.g. unpolished marble, smooth plaster, or metal.
- Polished. e.g. glass, polished marble, or chrome finished metal.

The convective heat transfer at roof systems can also be affected by some special architectural features such as parapet. Parapet is very common roof feature in buildings of Middle East and in some cases can be more than 1.70 m for privacy purposes. This can reduce the air flow near the roof surfaces which reduces the convective heat exchange rate and consequently increases the roof temperature **(Berdahl and Bertz, 1997)**.

On the other hand, solar radiation heat exchange between the exterior surfaces and the environment is governed by three important properties of the building material: absorptivity, reflectivity and emmissivity **(Givoni, 1976)**. These properties determine the thermal performance of exterior building envelope with respect to both shortwave and long-wave radiant heat exchanges. The absorptivity (α) can be described as the ratio of the absorbed radiant flux to the incident radiant flux at a certain wavelength. The reflectivity (ρ) is the ratio of the reflected radiant flux at a certain wavelength to the incident radiant flux. The emmisivity (ε) is the relative power of a material to emit radiant energy **(Givoni, 1976)**. It can be defined as ratio of radiative flux emitted at a certain wavelength and temperature to that emitted by a black body under the same conditions. Opaque building materials absorb some radiant heat and reflect the remainder, hence the relationship between the absorptivity and the reflectivity can be described by the following equation: reflectivity (ρ) =1- absorptivity (α). The emmisivity and absorptivity are numerically equal at the same wavelength and temperature as is stated by “Kirchhoff”s Law”.

At the exterior surface, solar radiation is selectively absorbed based on its wavelength **(Givoni, 1976)**. Solar radiation (wave length: 0.1 – 100 microns) can be divided according to its wavelength into: shortwave radiation or near-infrared (0.1 to 2.6 microns) and long-wave radiation or far-infrared (3 – 100 microns). The shortwave radiations are received from the direct sun, sky radiations or reflected solar radiation from adjacent surfaces. The long-wave radiation is received from the nearby emitted surfaces. It is important to note that the shortwave solar absorptance is different from one building material to another but long-wave solar absorptance is similar for many building materials. Typical values of shortwave absorptivity and long-wave emissivity for various surface types and colors are listed in **Table 2.1**. It is noticed that the color (or visual appearance) is an indicator of the surface behavior with respect to shortwave radiation but it is not for long-wave radiation. For example, a white oil paint and a black color can absorb 20% and 85% of the near-infrared radiation respectively but both colors have the same long-wave absorptivity for far-infrared radiation. This alludes to a fact that both colors will behave differently during the day but will have a similar behavior at night when only long-wave radiation exists.

The absorbed heat increases the exterior surface temperature of the envelope. The magnitude of exterior surface temperature is a function of the outdoor air temperature, the received solar radiation and the surface radiant properties. This temperature is represented by an imaginary temperature which is referred to as “Sol-air Temperature”.

Table 2.1 Absorptivity and Emissivity of Various Surfaces **(Givoni, 1976)**

Material or Color	**Shortwave Absorptivity**	**Long-wave Emissivity (Long-wave Absorptivity)**
Aluminum Foil, bright	0.05	0.05
Aluminum Foil, oxidized	0.15	0.12
Galvanized steel, bright	0.25	0.25
Aluminum paint	0.50	0.50
Whitewash, new	0.12	0.90
White Oil paint	0.20	0.90
Grey color, light	0.40	0.90
Grey color, dark	0.70	0.90
Green color, light	0.40	0.90
Green color, dark	0.70	0.90
Ordinary black color	0.85	0.90

It can be mathematically represented by: te = to+$\frac{\alpha It}{ho}-\frac{\varepsilon R}{ho}$, Where; to: ambient air temperature, α= solar absorption, It=incident solar radiation, ho: surface conductance

=17 W/m^2.°C (convective coefficient(hc)+radiation coefficient(hr)) , $\frac{\varepsilon R}{ho}$ =correction factor $\begin{cases} 0 & \text{for vertical surfaces} \\ -4 & \text{for horizontal surface.} \end{cases}$

From this relationship, the peak surface temperature is directly proportional to absorptivity (α) and is inversely proportional to the total surface conductance (hr+hc). Therefore, the exterior surface temperature can significantly be reduced by lowering the shortwave solar absorptance (i.e. increasing reflectivity). It can also be lowered by increasing the long-wave solar emissivity which increases the radiative cooling. Low sol-air temperature (exterior surface temperature) influences the temperature gradient across the envelope by reducing the heat flows and consequently reducing the internal surface temperature which is the main cause of thermal discomfort.

Studies have been conducted to measure the surface properties of building materials. **Reagan and Acklam (1979)** have studied the solar reflectivity of many opaque building materials that were available in USA. The study has recommended a color-reflectivity classification for opaque building material as shown in **Table 2.2**. Many data for solar reflectance (albedo) of building materials has been collected and presented by **(Taha et al., 1992)** with results from field measurements. Spectral information on many building materials have been presented by **(Parker et al., 1993)** and **(Touloukain et al., 1972)**. Yellott has presented the solar reflectance and the emmittence of many building materials in an indicative diagram as shown in **Figure 2.5**.

Table 2.2 Color-Reflectivity Classification for Opaque Building Materials **(Reagan and Acklam, 1979)**

Color Code	**Solar Reflectivity**	**Solar Absorptivity**
Very Light	0.75	0.25
Light	0.65	0.35
Medium	0.45	0.55
Dark	0.25	0.75
Very Dark	0.10	0.9

Very Light:	Smooth building material surfaces covered with a fresh or clean stark white paint or coating
Light:	Masonry, textured, rough wood, or gravel roof surfaces covered with a white paint or coating
Medium:	Off-white, cream, buff or other light colored brick, concrete block, or painted surfaces and white-chip marble covered roofs
Dark:	Brown, red or other dark colored brick, concrete block, painted or natural wood walls and roofs with gravel, red tile, stone, or tan to brown shingles
Very Dark:	Dark brown, dark green or other very dark color pained, coated or shingled surfaces

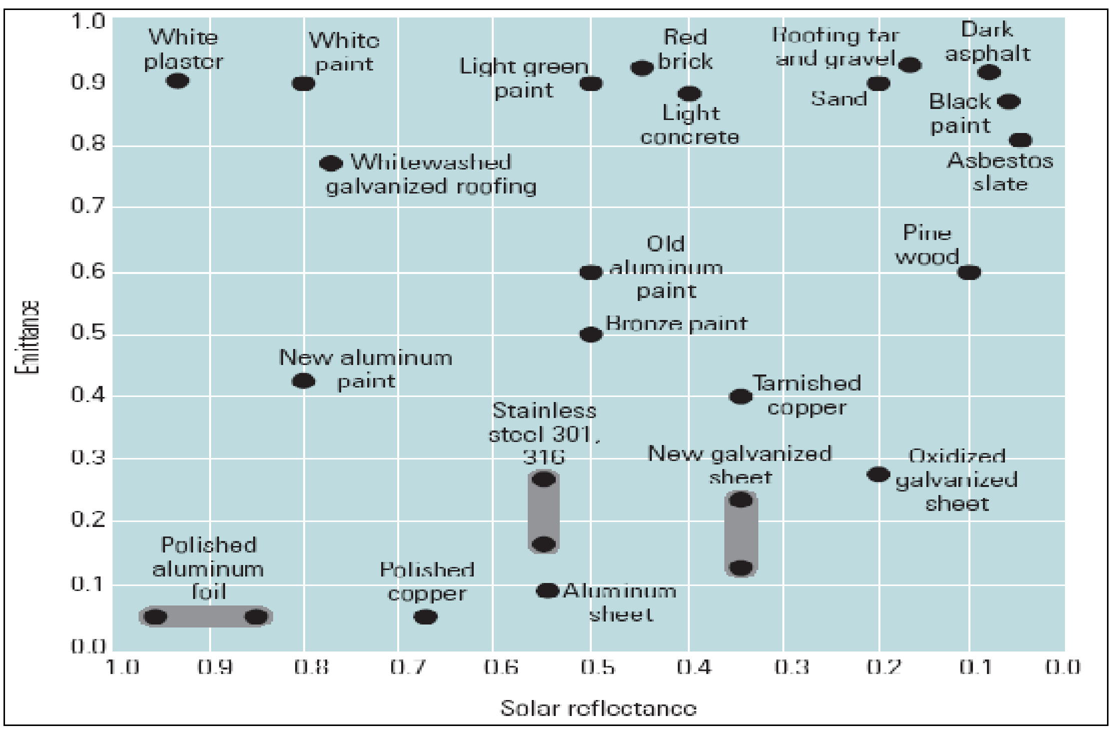


Figure 2.5 Solar Properties of Typical Building Materials **(Yellot,1966)**

Another study has characterized the solar reflectance of a number of roofing materials with spectral reflectance measurements **(Berdahl and Bertz, 1997)**. The study has highlighted the importance of material selection, its surface roughness and the presence of impurities on effectiveness of the solar reflectance. The high surface roughness promotes multiple reflections of solar radiation on the surface which increases the probability of absorption.

The surface characteristics of enclosed surfaces in a cavity of building envelope are as important as the characteristics of the exterior surfaces. The heat transfer mechanism in a cavity under specific condition (i.e. specific thickness and still air) is dominated by long-wave radiation. The long-wave radiation relies on the effective emissivity of the enclosed building materials. Most common building materials, including glass and paints of all colors, have high emissivity which is near 0.9 as listed in **Table 2.1**. These materials absorb significant amount of far-infrared radiation and therefore have high capability of transferring the long-wave radiation energy **(Fairey, 1994)**. Raidative materials are characterized by their low emissivity and high reflectivity and therefore have low capability to transfer long-wave radiation. Reflective materials can be utilized to create radiant barriers or act as reflective insulations **(Swinton, 1991)**. A radiant barrier is a single sheet of reflective materials positioned on one side or both sides of a cavity.

2.2.2 Thermal Insulation Materials and Their Properties

Thermal insulation is the most effective passive technique that is used to reduce heat flow and consequently reduce the energy consumption in buildings. Thermal insulation is functionally defined as a material or assembly of materials used to provide resistance to heat transmission. Many types of thermal insulation are available and broadly classified as capacitive, resistive and reflective. The capacitive insulation materials are characterized by their wide thickness and high capacity to store heat and restrict its flow. Capacitive insulation materials were primarily used in traditional buildings. Building materials such as stones and adobe are examples of capacitive insulation. Resistive insulations constitute of high porous and low density materials which reduce the conductive heat transfer due to the availability of air holes or gaps which have good heat resistance. The most important character of this type is the high thermal performance (i.e. R-value) it provides for thin layers of material compared to capacitive insulation.

In modern buildings, insulated materials are commonly combined with normal building material to achieve high thermal performance. Insulation materials are available in different types according to their compositions as illustrated in **Figure 2.6**.

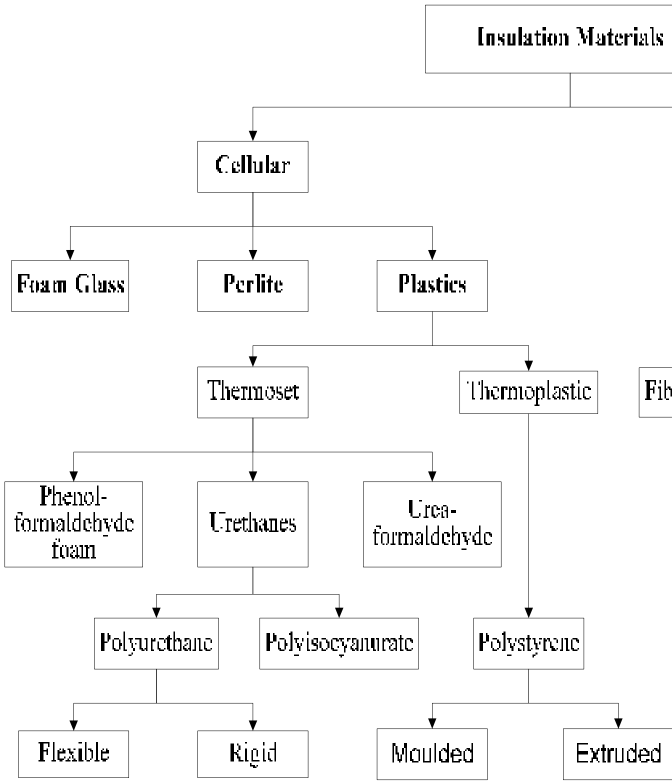


Figure 2.6 Generic Types of Insulation Materials **(Barnatt, 1981)**

Insulation materials can take many forms such as batt-type, loose fill, rigid foam panels, and spray-type. Some insulation materials are specifically used in certain types of building envelope as depicted in **Table 2.3**.

Additionally, insulated materials can be combined with the basic building materials to improve their thermal properties. For example, the insulation materials can be inserted in the cores of concrete masonry units (CMU) or brick units to improve their thermal performance and reduce the mass weight for structural purposes.

Table 2.3 Typical Application of Different Insulation Materials **(DOE, 2002)**

Form	Where Applicable
Blankets, Batts or Rolls: Fiber glass Rock wool	All unfinished walls, floors and ceilings
Loose-Fill (poured in): Vermiculite or Perlite	Enclosed existing wall cavities or open new wall cavities
Loose-Fill (blown-in): Rock wool Fiber glass Cellulose Spray-applied Polyurethane foam	Unfinished attic floors and hard to reach places
Rigid Insulation: Extruded polystyrene foam (XPS) Expanded polystyrene foam (EPS or beadboard) Polyurethane foam Polyisocyanurate foam	Basement walls Exterior walls under finishing (Some foam boards include a foil facing which will act as a vapor retarder Un-vented low slope roofs
Reflective Systems: Foil-faced paper Foil-faced polyethylene bubbles Foil-faced plastic film Foil-faced cardboard	Unfinished ceilings, walls, and floors In walls, ceiling cavities.

The chemical compositions of concrete masonry units (CMU) can be altered with the addition of insulation materials during the manufacturing process. Some other techniques are also available to improve the thermal properties of aggregate block concrete units by intentionally increasing the air gaps with the addition of special types of foams or agents. Precast autoclaved concrete masonry units are examples of these types and include autoclaved aerated concrete (AAC) which uses high-silica sand as an agent for increasing air gaps, and autoclaved cellular concrete (ACC) which uses fly ash as an agent for increasing air gaps. Some agents such as powdered aluminum are added to the concrete mixture which generates small bubbles of hydrogen that fills the gaps and act as a thermal resistance in the concrete blocks **(Hampshire, 1981)**.

Air space can also be considered as an insulation medium which is used in cavity walls to reduce the conductive heat transfer. In order to increase its thermal performance, high reflective materials such as aluminum paper are used on envelope surfaces to reduce the effect of long wave radiation. They don't have a thermal resistance; but must be positioned to face an air-space. Reflective insulations are composed of a system of reflective sheets that divides air spaces in to layers. The utilization of reflective foil insulation can help to reduce the radiative heat transmission by about two-thirds **(Griffin, 1974)**.

The thermal performance of the insulation material is rated in terms of its thermal resistance, known as R-value or its metric equivalent RSI-values, which indicates the resistance to heat flow. The higher the R-value or RSI-value for a material, the more is its resistance to the heat flows. The reciprocal of the R-value is the U-value, which describes the rate of heat transmission. The thermal resistance (R= L/k, m^2.K/W) of a material depends largely on its thickness (L) and thermal conductivity (k). The thermal conductivity (k, W/m.K) is defined as the heat flow in watts across a thickness of 1 m when there is a temperature difference of 1°C. It is measured in the laboratory under steady state and at constant climatic conditions (constant temperature and humidity).

Thermal properties of many building materials are listed in Chapter 28 of ASHRAE Fundamental Handbook **(ASHRAE, 1997)**.

2.2.3 Thermal Dynamic Behavior of Massive Envelope

Thermal mass is a characteristic of building material that describes its ability to absorb, store and release heat depending on the surrounding climatic conditions. Traditional housings were built with heavy weight, massive constructions to reduce the extremes in temperature experienced in summer days. Massive constructions or thermal mass can significantly improve thermal comfort by moderating the average indoor air temperature in buildings. The massive materials in building envelope absorb and store heat and subsequently delaying or dampening the effect of peak exterior wall temperature. As a result, the peak interior wall temperature is reduced and delayed as shown in **Figure 2.7**. The flattened temperature curve shifts the peak cooling load (i.e. delayed and reduced) to times where either the energy demand cost is low or the outside air temperature is cool. This mechanism helps in achieving a thermally comfortable environment at a low energy cost. From **Figure 2.7**, two important characteristics of massive building envelope that determine its dynamic behavior can be defined: a decrement factor and a time lag (h). The decrement factor is the ratio between the maximum indoor and outdoor temperature. The time lag is the time between the occurrence of maximum outdoor and indoor temperature.

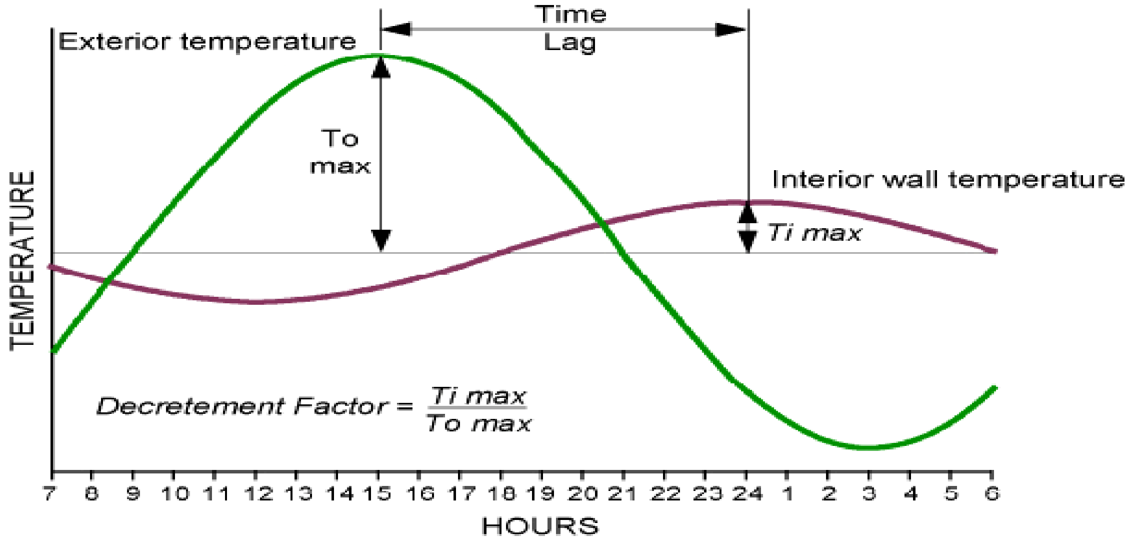


Figure 2.7 Influence of Thermal Mass on Diurnal Temperature

The impact of the thermal mass on indoor air temperature has been investigated in South Africa **(Richards, 1959)**. A serious of measurements on a warm day was carried out in a number of test houses in Pretoria, South Africa. The results indicated that heavy-weight construction have a great influence in reducing the daily indoor temperature variations than light-weight construction as shown in **Figure 2.8**.

An experimental study has been carried out in Iraq during July to investigate the thermal behavior of light-weight timber structure having a 2-hours time lag and heave-weight brick structure (229 mm) having a 10 hours time lag, keeping the same overall heat transmission coefficient (U-value) **(Olgayay , 1963)**. The study showed that although the total daily heat transmission is the same for the two structures, the amplitude and the period of transmission is different as indicated in **Figure 2.9**.

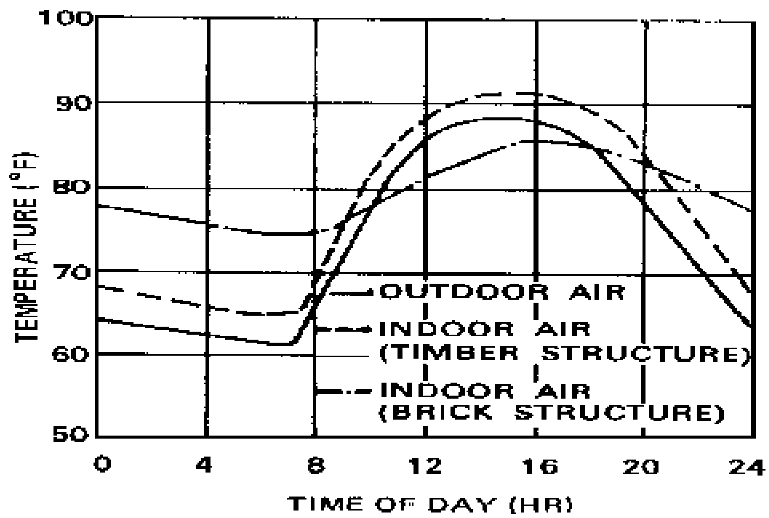


Figure 2.8 Influence of Thermal Mass on Indoor Air Temperature **(Richards, 1959)**

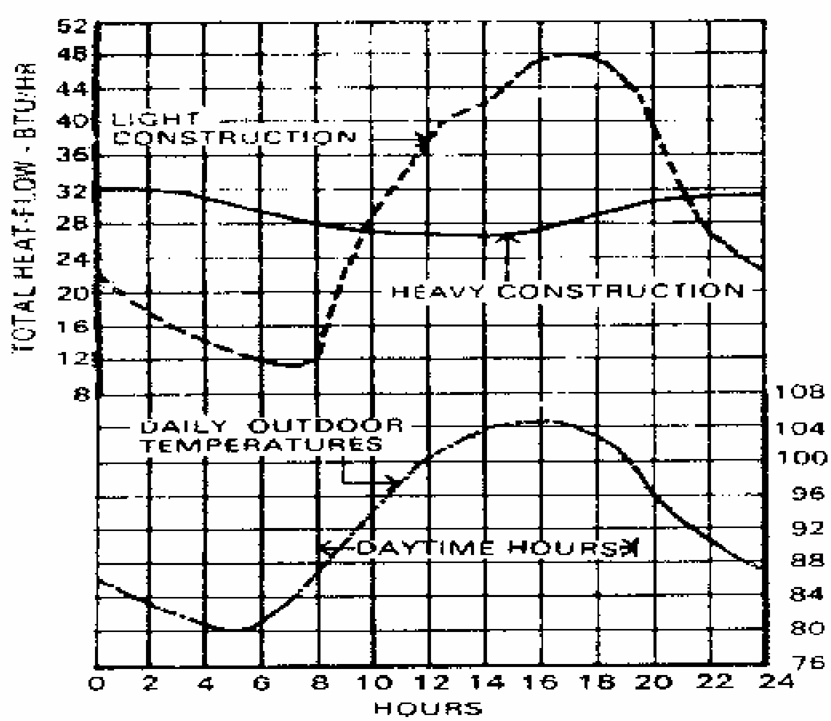


Figure 2.9 Dynamic Thermal Behavior of Heavy and Light Construction in Iraq **(Olgayay, 1963)**

The heat flow during daytime (from 7 a.m. to 7 p.m.) in heavy-weight structure is 26% lesser than that of the light-weight structure as shown in the figure. It has been concluded that in hot climates where the outdoor temperature is above that of the indoor during the full day cycle, the thermal mass is only delaying the peak cooling load rather than reducing the total amount of heat transmission.

Roof is the most important elements of the exterior building envelope because it is exposed to the solar radiation for large portion of the time in a day. In buildings, roof is a major source of heat gain and therefore need to be heavy enough with long time lag. Traditionally in the Middle East, roof is covered with a layer of soil with a considerable capacity of heat storage. A mud layer of 102 mm on top of 102 mm of thick concrete slab can reduce ceiling temperature by as much as 10° C **(Saini, 1980)**. However, this conclusion might be applicable when the soil layer is added on top of low massive roofs. An experimental study on a room of 3.45 m x 3.45 m x 3 m in Saudi Arabia has shown that an addition of 350 mm of dry natural soil on top of 225 mm roof (25 mm white cement tiles + 25 mm cement plaster + 50 mm sand+10 mm water proofing + 120 mm concrete slab+ 25 mm cement plaster) has a minor effect on indoor air temperature **(Al-Hemiddi, 1995)**. The indoor temperature drop between that of the control room (no sand) and that of the tested room (with sand) is only 0.6 ° C. However, the improvement is up to 4.6° C if some treatments are made to the soil layer such as increasing the moisture content, or adding a layer of gravel and/or applying shading. Another study in Saudi Arabia has investigated the influence of adding a layer of gravel on top of a roof **(Al-**

Turki et al., 1997). The study has been conducted on six concrete tiles of dimensions 20 x 20 x 3 cm by using different gravel sizes and different gravel mass distribution. The gravel has delayed the effect of solar radiation by 3 hours. The study has concluded that the thickness of the gravel layer is more effective than the size of the gravel.

A number of parameters and conditions, such as building material properties, building orientation and its effect on thermal mass location and distribution, thermal insulation, ventilation, climatic conditions and use of auxiliary cooling systems and occupancy patterns, are all parameters that determine the dynamic thermal behavior of massive construction **(Balaras, 1996)**.

Thermo-physical properties of building materials determine the effectiveness of thermal mass in influencing the indoor thermal environment. The combined effect of the basic thermo-physical properties: specific heat or heat capacity: C (J/kg.K), density: ρ (kg/m^3) and conductivity: k (W/m.K) as well as the thickness (m) of building material define the characteristic magnitude of time lag and decrement factor **(Ulgen, 2002)**. In literature, other properties are also used to theoretically compute the decrement factor and time lag. For example, thermal diffusivity (α, m^2/h), which is the ratio between the thermal conductivity (W/m.K) and volumetric heat capacity (specific heat x density) (J/K. m^2), is mainly used in theoretical computation of decrement factor and time lag (i.e. heat flow and temperature patterns) under periodic conditions **(Givoni, 1976)**. Building materials with high value of thermal diffusivity (α) rapidly modify their temperature to that of surroundings, because they conduct heat quickly in comparison to their volumetric heat capacity. In contrary, materials with small thermal diffusivity values have large volumetric heat capacity which in turns affect the decrement factor and increase the time lag. This consequently has a positive impact on the interior thermal conditions **(Ulgen, 2002)**. There is no specific material that gives all thermal properties needed; therefore, building envelope system is normally assembled with several materials to achieve certain thermal purposes.

The effect of thermal diffusivity on interior wall temperature, the relationship between the thermal diffusivity and the decrement factor and the time lag has been studied in detail by **(Asan and Sancaktar, 1998)** using computational code. The study has shown that if the thermal diffusivity decreases (due to increases in volumetric heat capacity); the wall inner surface temperature goes to a constant value. As the thermal diffusivity approaches its lowest value (maximum heat capacity), the time lag exponentially goes to infinity and the decrement factor converges to zero (inverse exponential relationship). The same relationship has been found between the wall thickness (at constant diffusivity), the time lag and decrement factor. In contrary, if the thermal diffusivity goes to infinity (zero heat capacity) time lag converges to zero and decrement factor takes constant value.

The study has quantified the limit values of the thermo-physical properties that affect both the time lag and decrement factor. For thermal conductivity of k=0.05 W/m.K, time lag takes the value of 24h. For smaller values of thermal conductivity < 0.01 W/m.K, thermal lag is very high while decrement factor is zero. Thermal lag gets smaller with increasing value of thermal conductivity until a value of k>100 W/m.K where time lag takes a constant value of 2h. The decrement factor increases with increasing value of thermal conductivity until k>10 W/m.K where the increase is slow. Decrement factor, time lag of 42 roof assemblies and 41 walling assemblies are described in Chapter 28, Table 14 and Table 19 of ASHRAE Fundamental Handbook **(ASHRAE, 1997)**.

Thermal mass in building envelope interacts with the outdoor conditions as well as those of the indoor. The location of the thermal mass (i.e. interior or exterior) and its distribution around the building (south, north, east and west) must be properly considered based on the space usage/function and the desirable time lag **(Balaras, 1996)**. Therefore, the heat gain should be characterized for all sides of the building envelope which is mostly related to outside climatic conditions. While the interaction of outdoor air temperature with buildings is independent of the building envelope orientation (i.e. similar for all four sides of the building), the effect of solar radiation varies from one side of the building to another and from one season to another. During summer, east and west sides receive higher solar radiation compared to other sides, with more solar heat received on west side from mid-to-late summer afternoon **(Andersson et al., 1985)**. In contrary, the south side receives higher solar energy during winter in comparison with other sides. The impact of solar radiation on north side of the building are minimal in both summer and winter seasons. Therefore, the west and south sides of the building envelope should be considered for a thermal mass with at least 8 hrs time lag while the other sides should be designed with low thermal mass **(Balaras, 1996)**. For south wall in winter, thermal mass is used for heating while it is to delay the peak summer cooling load for the west wall. High thermal mass in east wall could have adverse effect on indoor conditions as the solar heat gain in the morning is stored, delayed and released at hottest afternoon hours which consequently cause thermal discomfort **(Andersson et al., 1985)**. A desirable time lag using proper level of thermal mass should be considered for the space usage. For example, in rooms that are occupied during the day, a time lag of 8-10 hrs is required but for a night-time living areas the time lag should be short **(Saini , 1980)**.

The placement of the thermal mass within the envelope relative to the thermal insulation is important in the overall thermal performance of the building, yet highly dependence on the building operation strategy. Several studies have investigated the influence of both the thermal mass and thermal insulation placement within the building envelope. For a three-layered building envelope, a study using a computer program “BRE-ADMIT” has investigated the influence of layer distribution of insulation and masonry on the thermal behavior under different mode of building operation **(Bojic and Loveday, 1997)**. The distributions of two layers were investigated: masonry/insulation/masonry and insulation/masonry/insulation. The study has concluded that for intermittent heating, the insulation/masonry/insulation structure performs better, but for intermittent cooling, the masonry/insulation/masonry structure is better. For a continuous cooling, the distribution doesn't influence the energy consumption but influences the daily maximum cooling power demand. Using whole-building dynamic modeling DOE 2.1E, a study for a continuously used residential building in six USA climates has shown that walls containing massive internal layers are more preferable than those with internal insulation with regard to energy savings **(Kossecka and Kosny, 2002)**.

In Saudi Arabia, a study has investigated the effect of insulation location relative to thermal mass on the heat transfer characteristics of building wall elements for different wall orientations under initial transient conditions **(Al-Sanea and Zedan, 2001)**. Using the climatic data of Riyadh, the results showed that the insulation layer location relative to thermal mass had significant effect on the instantaneous and daily mean loads. It was recommended that for spaces where the air-conditioning system is switched on and off intermittently, the insulation should be placed on the inside. Comparing the thermal performance of different roofs under climatic conditions of Riyadh, **Al-Sanea, (2003)** has found that a slightly better thermal performance is achieved by locating the insulation closer to the inside surface of the roof. A study in hot-humid climate of Dhahran using 10 roofs and 14 walls assemblies have indicated that placing the insulation on the inside of the building envelope results in higher reduction of heat flow than placing it on the outside **(Said et al., 1997)**.

The significance of thermal mass is more pronounced in climates with a large diurnal temperature range and intense solar radiation. Poor thermal mass considerations at the early design stage could cause thermal discomfort during the occupation which will result in high energy consumption. Careful attention should be given when considering thermal mass for the purpose of reducing energy consumption. As a rule of thumb, diurnal ranges of less than 6°C are insufficient; 7°C to 10°C can be useful depending on climate; high mass construction is attractive when diurnal ranges exceed 10°C **(Reardon et al., 2004)**.

The high thermal mass is of great advantage in hot-arid climate but unsuitable in regions of hot-humid climate **(Givoni, 1976)**. The study conducted by **(Kossecka and Kosny, 2002)** to evaluate the dynamic benefits of thermal mass in wall assemblies of residential buildings for six USA climates found that the most favorable climate for application of the massive wall systems is in hot-dry climate of Phoenix. In hot-humid climate of Miami, although the steady state R-value for both walls is the same and insulation material is kept on the interior side of the wall, light weight walls performed better compared to massive walls. In warm humid climate of Sri Lanka, a simulation study utilizing TRANSYS was conducted to investigate the influence of many passive design concepts to achieve thermal comfort in residential buildings **(Ratnaweera and Hestnes, 1996)**. Thermal mass in walls was found insignificant in improving thermal comfort. In hot humid climate of Saudi Arabia, Dhahran, a light walling system (i.e. insulated 100 mm steel stud frame) had a better thermal performance compared to a thermally massive wall (i.e. 200 mm hollow core concrete masonry unit) **(Said et al., 1997)**.

2.3 Air Leakage Characteristics in Buildings

Air leakage influences many building performance indicators such as thermal performance, hygro-thermal performance, indoor air quality, smoke control and fire propagation, , HVAC design, thermal comfort and consequently energy consumption. It is often overlooked at the design stage when many aspects of building performance are determined. The exchange of air between the outdoor and indoor environment through building envelope can be divided into two broad classifications based on air flow driven mechanisms: ventilation and infiltration **(ASHRAE, 1997)**. The air exchange rate is the sum of infiltration, natural ventilation (open windows), and mechanical ventilation. Ventilation is a controlled introduction of outside air into a building through designed openings (i.e. windows and doors) in the building envelope or by mechanical equipment. Infiltration is an uncontrolled flow of outdoor air into a building through cracks in walls, floors, and ceilings, and around windows and doors and other unintentional openings and through the normal use of exterior doors for entrance and egress. The air leakage area and air infiltration rate are two confusing terms that are often used interchangeably. The air leakage area is a measure of building airtightness which describes the physical property of a building that is determined by its design, its construction, and its deterioration over time **(ASHRAE, 1997)**. It is one parameter that is necessary to calculate the air infiltration rate. In addition to airtightness, air infiltration rate is influenced by other factors such as weather conditions including wind forces, thermal forces, site landscaping and occupants use patterns.

2.3.1 Mechanisms of Air Leakage in Buildings

Air leakage is a complex mechanism that is induced by a pressure difference across the building envelope (i.e. between indoor and outdoor environment). Many parameters such as extreme weather conditions, poor workmanship, and building age, its operation strategies, and occupants activity patterns can influence the magnitude of air leakage. Air leakage is driven by three important mechanisms: wind forces, thermal forces (i.e. stack effect or buoyancy) and operation of appliances **(ASHRAE, 1997)**.

Wind forces act over and around buildings which causes variations in surface pressure. The pressure distribution around the building varies and depends on wind speed and direction, height and shape of the building, and surrounding terrain. Generally, positive pressure acts on windward side causing air infiltration into the building. On leeward, negative pressure (suction) is created which drives air out of the building (i.e. ex-filtration). Wind force causes negative (uplift) pressure on flat roofs while positive pressures on windward and negative (suction) pressures on leeward is produced on pitched roofs as shown in **Figure 2.10**. The severity of wind forces on a building is influenced by the local terrain, the immediate shielding, and height of the building, location and flow resistance characteristics of envelope openings.

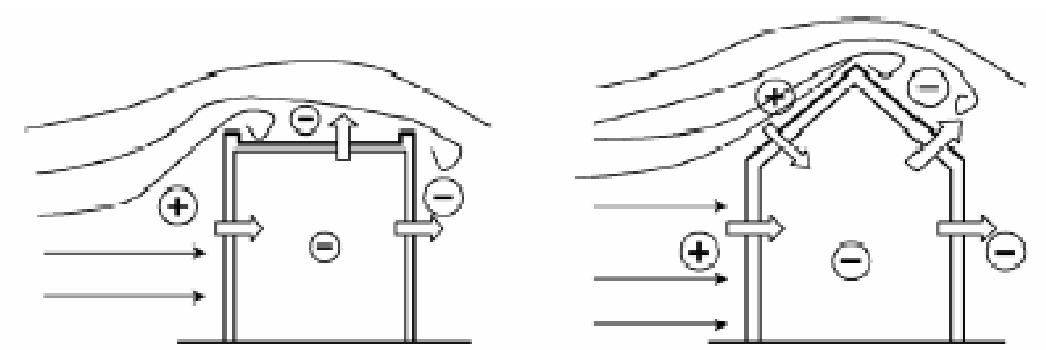


Figure 2.10 Effects of Wind Forces on Building Envelope **(Straube, 2001)**

Under the thermal forces (i.e. stack effect), the difference between the indoor air temperature and outdoor temperature causes air leakage due to density differentials that promotes pressure differences. The mechanism of air leakage in a building depends on seasonal variations. In winter when outside air temperature is below that of the indoor as depicted in **Figure 2.11 (a)**, the warmer indoor air becomes less dense and rise towards ceiling where it ex-filtrates to the outside. This upwards movement produces negative indoor pressure at lower floor which causes the outside colder air to infiltrates near the base or floor. In summer, the process is reversed as illustrated in **Figure 2.11 (b)**.

Stack effect is influenced by many variables such as temperatures difference, internal separation of floors (i.e. internal resistance to vertical airflow), level of air-tightness, and imbalance supply or exhaust of air by mechanical equipment. The pressure differences created by wind forces and stack effect across the building can be modified by the operation of mechanical equipment either to assist or counteract the air leakage. Mechanical equipment provides specific amount of air to compensate the lost air. It applies internal pressure that balances the wind and stack induced pressure and consequently reduces the air leakage.

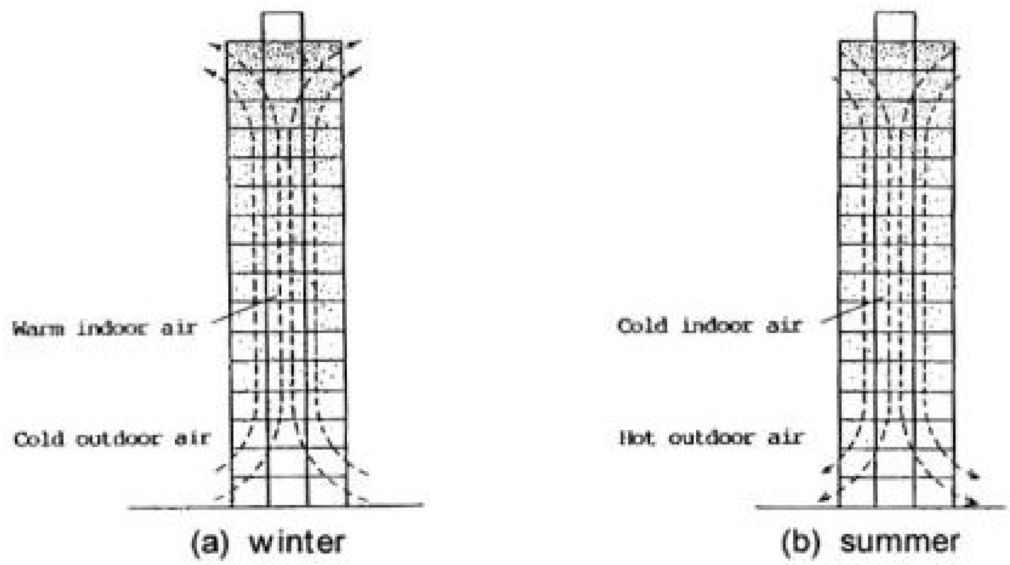


Figure 2.11 Effects of Thermal Forces (Stack Effect) on Building

2.3.2 Prediction Techniques of Air Leakage in Buildings

Air leakage through channel flow is characterized by an indirect path from one side of the opening to another. This type normally occurs through electrical outlet, wiring holes and many other leakage paths in a building. The complexity of the air leakage makes it difficult to find or diagnose unless specific measurements are performed. However, theoretical models as well as some measurement techniques are used to predict the air infiltration rate of residential building as shown in **Figure 2.12**. The air infiltration's magnitude depends on the air leakage characteristics (i.e. airtightness) of a building, magnitude of stack and wind forces, mechanical appliances induced pressure differences and occupant's activities. The airthightness of a building is one input parameter that is used in mathematical models to calculate the air infiltration. It depends on the leakage size, sources of leakage, building age, and workmanship.

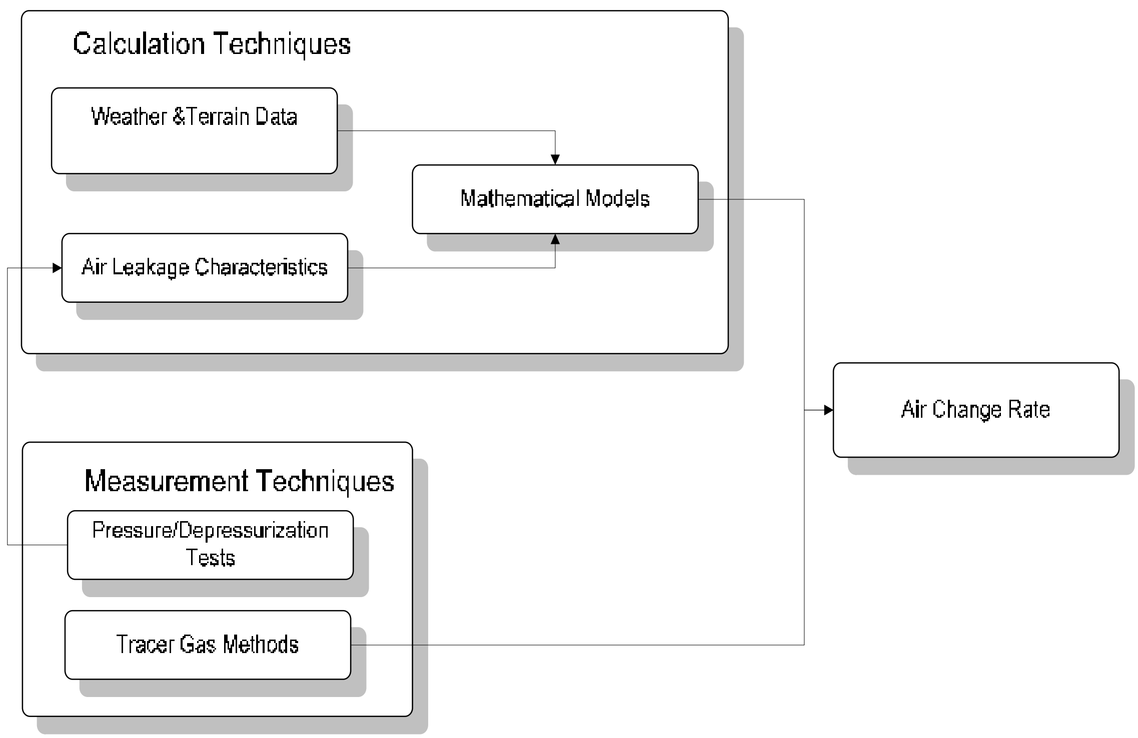


Figure 2.12 Alternative Methods for the Estimation of Air Change Rates **(Liddament, 1986)**

2.3.2.1 Theoretical Modeling of Air Leakage in Buildings

Many research studies have been conducted to predict air infiltration in buildings. The studies range from a simple assumption on infiltration rate to very sophisticated theoretical models. Models include empirical, single zone and multi-zone infiltration models. The selection of a specific model to estimate air infiltration varies according to the required level of accuracy, data availability and building type **(Tuomaala, 2002)**.

Infiltration rate can be estimated using simplified methods that are empirically derived such as Air Change Method and Crack Method. Air Change Method is based on an assumed number of air changes per hour based on experience. The number of air changes per hour (ACH) in a building is assumed according to building type and use patterns. Air change of 0.5/h can be assumed to be very low whereas 2.0 ACH is assumed to be very high **(McQuiston and Parker, 1994)**.

ACH can also be predicted using the residential method. Under this single zone method, the air change per hour (ACH) is defined in terms of wind speed, zone temperature T , and dry-bulb outdoor temperature T **(DOE-2, 1982)**: ACH= a + b. ΔT + c. V, Where: a, b, and c are default coefficients (equals to 0.1, 0.011 and 0.009 for tight construction, and 0.1, 0.22 and 0.018 for loosely constructed houses) **(Hutcheon and Handegord, 1983)**, V: wind speed in Km/h, ΔT: absolute indoor to outdoor temperature in °K. Then, the air infiltration rate (m^3/h) can be calculated by multiplying ACH and space volume.

Crack Method is based on the characteristics of windows, walls, and doors and the pressure difference between inside and outside. All cracks in the building can be represented by an effective leakage area which can be used to calculate the air infiltration using the power law relationship: $Q = A.C.\Delta P^n$ **(McQuiston and Parker, 1994)**. The crack method can also be utilized by using a single zone empirical model **(DOE-2, 1982)**. Under this method, the wind-generated pressure (PW), and the stack-generated pressure (PST), are added, and used in the pressure-flow relationship:

$Q= C \times (PW+PST)^n \times A$

Where;

PW = abs [a x V2 x cosθ], θ is the wind incidence angle,

PST = d x P x [1/To -1/Ti] x ZHT, where ZHT is the vertical distance measured from the neutral plan, n=0.8 for delayed walls, n=0.66 for windows.

LBL (Lawrence Berkeley Laboratory) model is a single zone model that predicts either hour-by-hour or long-term average infiltration **(Sherman and Grimsrud, 1980)**. It has been adopted by ASHREA to estimate infiltration for residential buildings **(ASHRAE, 1997)**. Many data inputs such as the amount and distribution of leakage in the structure, building height, local terrain and shielding characteristics is required to estimate the airflow due to the stack and wind effect. It can be simplified according to the following equation:

$Q = ELA\ (C_1 * \Delta T + C_2 * V^2)^{1/2}$

Where;

ELA = Effective leakage area of the building at 4 Pa pressure differences, cm^2

ΔT = Absolute value of the inside - outside temperature difference for the time interval of the calculation, °C

V = Average wind speed for the time interval of the interest, m/s

C_1 = Stack coefficient, $(L/s)^2/cm^4/°C$

C_2 = Wind coefficient, $(L/s)^2/cm^4/(m/s)^2$

The model parameters can either be empirically derived or found by conducting tests. The stack and wind coefficients for one, two and three stories residential building can be found in ASHRAE Handbook-Fundamentals **(ASHRAE, 1997)**. The ELA can either be found by conducting blower door tests for whole house measurements or estimated by adding the individual building components leakage using tables of ELA values **(ASHRAE 1997, Colliver et al. 1994)**.

Sophisticated models such as Nodal Network Models (Multi-zone models) are also used to predict air flow (ventilation + infiltration) through leak paths connecting internal spaces and distribution networks in HVAC **(Clarke, 2001)**. A set of detailed data is required to use the model including the characteristics of each individual opening. Air flow simulation programs such as COMIS, Clim2000, CONTAM and House-II/ASHRAE SP43 use the Nodal Network model to estimate a complex air flow distribution in buildings **(Zmeureanu, 1997)**.

2.3.2.2 Measurements Techniques of Air Leakage in Buildings

Many measurement techniques have been developed over years to quantify the air leakage in buildings for many purposes such as indoor air quality and energy consumption. The application of measurement techniques vary according to the objective, accuracy, complexity and the type of building under examination. The measurement techniques currently available are tracer gas, fan pressurization, AC pressurization, infrasonic impedance, acoustic techniques, and quantified thermography **(McWilliams, 2002)**.

Tracer gas techniques have been widely used to diagnose specific issues such as indoor air quality and air flow characteristics, energy consumption in single zone such as houses. Tracer gas can be either in transient or steady-state behavior. Transient methods include Tracer Decay while steady-state methods include Pulse, Constant Injection, Long-Term Integral Method and Constant Concentration **(Sherman, 1998a)**. Tracer gas is a reliable method to measure the air infiltration because of its capability to consider weather conditions such as wind and stack forces. The tracer gas combined with conservation laws allows determination of the tracer transport mechanism (i.e. air flow mechanism) **(Sherman, 1998a)**. The high cost detection equipment of tracer gas makes this technique less common in determining the air leakage.

Pressurization technique (pressurizing or depressurizing) using Fan or Blower Door is a widely used measurement technique. It is intended to measure airtightness which is the main parameter in determining the leakage through building envelope. A single point test at 50 Pa is carried out to measure the air leakage. The air leakage rate at this pressure can be divided by the building volume where ACH_{50} is determined. As a rule of thumb **(Sherman, 1998b)** which relates Blower-Door data to seasonal air change data, the ACH_{50} can be divided by a factor of 20 to determine the natural air infiltration rate (ACH_{Nat}). A multiple point test can also be conducted using this technique where a curve of power law $Q = C.\Delta P^n$ can be drawn and properly fit. Using this fit, the parameters C and n are characterized for a particular building.

While the single zone techniques measure the air leakage for the whole building, other leakage test techniques are used to identify the components contribution to air leakage in a building. A method using a balanced fan approach for measuring component leakage area is proposed by **(Reardon et al., 1987)**. The building is divided into segments or components and the air leakage for every component is separately measured.

2.3.2.3 Measurement Indices for Air Leakage in Buildings

Air leakage in buildings has been reported in many formats depending on whether it is reported for the whole building or specific building components. The data format has been dictated by the measurement methods or/and prediction models used to quantify the air leakage. The total air leakage rate (Q) of a building can be obtained from a fan blower pressurization test at a reference envelope pressure difference normally at 50 Pa. In order to utilize this total rate for comparison between different buildings or with an air leakage standard, it is generally normalized with one of the three quantities: building volume, envelope area, and floor area **(Sherman, 2004)**. When total air leakage rate (Q_{50}) measured at 50 Pa is normalized to building volume, the air leakage rate is converted to units of air changes per hour ACH_{50}. This air leakage rate doesn't consider other factors that influence the natural air infiltration such as wind, stack forces and geographical location. However, it is the most widely used indicator of air leakage in buildings.

Air leakage characteristics can also be expressed in one of the following formats **(Edwards, 1999)**:

- Constants for the fit of the data to pressure versus flow power law equations (flow coefficient C and flow exponent n): $Q = C(\Delta P)^n$. Fan pressurization tests can be conducted at multiple pressure points where corresponding air leakage rate are drawn. The flow coefficient "C" and flow exponent "n" are derived from the relationship for that particular house. Then, the air leakage rate is mathematically correlated to the pressure differentials across the envelope using the power law. Rate of flow at a given differential pressure across the component or between the interior and exterior of the building: examples include the air leakage rate across doors, windows and other leakage paths or components.

- Equivalent Leakage Area (ELA) of the opening, typically at a reference pressure of 10 Pa with a discharge coefficient (Cd) of 0.611 (ELA10).

  Note: ELA10 is most commonly used for reporting leakage characteristics in Canada and the Netherlands.

- Effective Leakage Area (ELA) of the component, typically at a reference pressure of 4 Pa with a discharge coefficient (Cd) of 1.0 (ELA4).

  Note: ELA4 is most commonly used for reporting leakage characteristics in the United States.

- Equivalent or effective leakage area is normalized to:
  - the area of the component (for example leakage area of interior partitions per m^2 of partition area),
  - the length of the component or crack between components (for example leakage area of windows per crack length)
  - the floor area of the suite or whole building
- Contribution of leakage of a particular component as a percentage of total leakage of the suite or whole building such as those reported in Chapter 25 **(ASHRAE, 1997)**.
- Effective Leakage Area is normalized with the building floor area and a correction factor for the building height in to a factor called "normalized leakage (NL)" **(Chan, 2003)** as per the following relationship:

$$NL = 1000 \cdot \frac{ELA}{Af} \cdot \left(\frac{H}{2.5m} \right)^{0.3},$$

NL can also be correlated to ACH at natural conditions by using a Factor “F”:

$ACH = 48 . \left(\frac{2.5m}{H} \right)^{0.3} . \frac{NL}{H.F}$, F (LBL) is a factor used to relate typical air exchanges per hour with the air exchange rate at 50 Pa ($ACH = \frac{ACH_{50}}{F}$). It is a factor that varies from 10 to 30 for as per USA Zones **(Sherman, 1987 and Energy Star, 2001).**

2.3.3 Typical Air Leakage Rates for Residential Buildings

Air leakage in buildings is an important indicator of building performance. By using the available techniques, air leakage can be estimated and proper control measures can accordingly be applied. Many studies in developed countries have been carried out to evaluate the building performance in terms of its air leakage or airtightness. Studies in North America have indicated that an average rate of 0.2 ACH and 2 ACH for a tightly and loosely constructed housing respectively can be experienced **(ASHRAE, 1997)**. Some other studies in North America have concluded that the air infiltration rates of 0.5 ACH can be expected in new, energy-efficient houses while 0.9 ACH in low-income housing **(Grimsrud et al. 1982 , Grot and Clark 1979)**. Air leakage rates in terms of Effective Area Leakage (EAL) for building components in North America have been reported by **(Colliver et al. 1994)**.

A recent report summarizes the state of the art literature on building air tightness **(Sherman, 2004)**. This report has concluded that dwellings in severe climates such as Sweden, Norway, and Canada are known to be more air tight than those located in milder climate such as the US and the UK. In UK, a large database of air leakage measurements was analyzed by BRE **(Stephen, 1998)**. The study has reported a mean air leakage rate value (Q_{50}/envelope area) of 11.5 (m^3/h per m^2) for 384 dwellings. The Canadian houses showed an airtightness of 2 ACH under a test pressure difference of 50 Pa **(Steel, 1982)**. Another study in Canada has been performed to evaluate air leakage of 35 windows **(Henry and Patenaude, 1998)**. It was concluded that the majority of windows met or exceeded the highest levels of air leakage performance of Canadian window standards at normal temperatures.

Studies in Sweden have shown that the ACH_{50} varies between 0.44 and 3.08 /h **(Pettersen, 1994)**. The air tightness of 6 low energy houses in Belgium was studied and found that the values of pressurized air infiltration ranged from 3.8 to 4.9 ACH_{50} **(Pittomvils et al., 1996)**. The natural air infiltration rate for 28 Denmark homes was quantified by **(Kvisgaard and Collet, 1990)**. The measured air change rates for 17 naturally ventilated houses, with all windows and doors closed, were found to be 0.1 to 0.4 /h. In Australia, a field study of nine houses in Perth indicated that the air infiltration rates are in the range of 0.05 to 0.41 ACH **(Harrison, 1985)**. Natural infiltration rates of unoccupied houses in Melbourne were found to be 0.33 ACH **(Biggs et al., 1987)**. In 41 Sydney dwellings, a study demonstrated that air exchange rates ranged from 0.2 to 2.3

ACH **(Ferrari, 1991)**. An international comparison of airtightness with Australian houses (Air leakage rates at 50 Pa (ACH_{50})) was conducted as shown in **Table 2.4 (Biggs et al., 1987)**.

In Japan, the air infiltration of 8 dwellings in a housing complex with closed doors and windows have been investigated using Tracer gas method and showed that the ACH value varies from 0.8 to 3.1 ACH **(Iwashita and Askasak, 1997)**. If doors and windows are opened, incremental increase of air change rates varies from 5.2-43.8 ACH.

Table 2.4 Pressurized Infiltration rates (ACH_{50}) in International houses

Country	Number of houses	Mean ACH_{50}
Australia (sample 1)	10	26.3
Australia (sample 2)	12	12.2
New Zealand	10	11.0
Netherlands	130	12.0
United Kingdom	19	13.9
Canada	60	4.4
Sweden	205	3.7

The air leakage characteristics are sensitive to many factors such as climatic conditions, building age, level of construction and building components manufacturing workmanship. Despite the fact that many studies have been conducted to evaluate the air leakage characteristics in developed countries, few studies have been carried out in developing hot countries. In Kuwait, ten residential buildings with different volumes, configurations and occupant activities were tested using a tracer gas method to determine their air leakage characteristics **(Bouhamra et al., 1998)**. The tests were conducted both in winter and summer and under different modes of operation. For naturally ventilated buildings during winter, the air leakage ranged from 0.60 ACH to 1.35 ACH. For controlled buildings (i.e. under heating in winter or cooling in summer), the air leakage ranged from 0.25 ACH to 0.601 ACH. Another experimental study was also conducted in Kuwait to evaluate the influence of aluminum window characteristics on the air infiltration **(Daoud et al., 1991)**. The study showed that aluminum windows have a mean infiltration rate of 13.48 m^3/h/m at 75 Pa, which is about 3.4 times higher than the ANSI/AAMA maximum limit. Many windows types such as horizontal double slider, vertical single slider, vertically hinged single slider and double leaf, horizontally hinged single and double leaf, tilt-and-turn and fixed were examined in this study. The infiltration rate for openable windows exceeded the ANSI/AAMA limit, whereas fixed windows meet the standard. Among the openable windows, horizontally hinged single window and vertically hinged double leaf slider window were the highest. Tilt-and-turn and double sliders were close to the standard limit and other windows fall in between the two categories. In conclusion, the natural air leakage rates can be categorized in terms of ACH as illustrated in **Table 2.5**.

Table 2.5 Categories of Air Leakage Rates

Category of Air Leakage	Proposed Value (ACH)
Extremely Low	0.1
Low	0.5
Normal	1
High	2
Extremely High	3

2.4 Impact of Envelope Thermal Design on Energy Consumption

2.4.1 Influence of Surface Properties on Energy Consumption

The application of surface treatments such as light coatings, light color tiles on exterior surface of building envelope and low-emissive sheets on exterior/interior surfaces have significantly improved the overall thermal performance of buildings in hot climates. In air conditioned buildings, the surface treatment determine the cooling load while in unconditioned buildings, it determines the interior surface temperature which consequently influence the occupants thermal comfort **(Givoni, 1976)**. Many experimental and numerical research studies have been conducted in USA, South Africa, Israel, and India and in some tropical warm and humid climates to investigate the impact of surface treatments on thermal performance of building envelope.

An experimental field study investigating the thermal effects of black versus white membranes on an insulated roof was conducted in eastern Tennessee, USA **(Griggs and Shipp, 1988)**. The study indicated that the peak summer surface temperature of the black roof was 10°C more than the white roof. Many studies in USA have been mainly carried out in hot climates especially in Florida and California to reduce the energy consumption of residential and small commercial buildings. In hot-humid climate of Florida, a study has investigated the impact of white tiles and black wood shingle on the summer attic thermal performance of six roof construction types **(Parker and Sherwin, 1998)**. It was found that white tile roof performed better in controlling attic heat gain than black shingle tile roof. White tile roof reduced the heat gain through the attic by 75% compared to black shingle tile roof. In another study in Florida, an average reduction of 19% in energy consumption (averaged over 9 monitored homes) was reported for 9 monitored homes when their roof solar reflectances were increased **(Parker et al., 1995)**. The large reduction in energy consumption is more pronounced in poorly insulated roof assemblies. This conclusion was previously approved by field monitoring experiments that were conducted for two houses (one with insulated ceiling (R-11) and the other with un-insulated flat roof) in Cocoa Beach, Florida. Substantial reductions in space-cooling energy use were achieved for the two houses, 25% for insulated roof and 43% for un-insulated **(Parker et al., 1994)**. For school buildings in Florida, a reduction of 10% in cooling energy has been realized when its roof reflectance increased from 0.23 to 0.67 **(Parker et al., 1998)**. The energy savings in California was found more pronounced than Florida. When a cool roof was applied to a house in Sacramento CA, the energy consumption was reduced by 80% (**Akbari et al., 1997)**. In another study of non-residential buildings in Sacramento CA, an energy saving of 17%- 39% was reported when cool roofs were used **(Hildebrandt et al., 1998)**.

A simulation study utilizing a transient model “RESHEAT” was conducted to study the thermal performance of a highly reflective paint applied to exterior insulated walls and roof of a residence in a hot and arid region of Las Vegas, Navada **(Moujaes and Brickma, 2003)**. The study has shown a reduction of 33.3% in energy consumption when both walls and roof are coated with highly reflective paint. On the other hand, cooling load was reduced by 41% when both walls and roof were painted, while it was reduced by 17% when the roof was painted. In an attempt to quantify the trade-off that the high roof reflectivity can offer to keep the annual energy use for a dark-colored roof at a constant level, a single residential one-storey building was simulated for 32 USA climate regions utilizing DOE-2 **(Akbari et al., 2000)**. The roof reflectivity was increased from 20% to 60% and the results indicated that the targeted annual energy-use can be achieved with half insulation thickness of that required by the base case.

The potential benefits of using cool roofs on Federal buildings and facilities around the US states have been investigated using DOE-2 simulation program **(Taha and Akbari, 2003)**. The study has covered many building types, diversified USA climates and different scenarios but with a fixed insulated roof (R-11). For a moderate and a high solar reflectance, the energy savings were reported to be 3.8% and 7.5% of the base case scenario, respectively but with an increase in winter heating energy use.

Thermal Analysis Research Program (TARP) was used to analyze the roof solar reflectance on annual and peak cooling/heating load, and exterior roof temperature of six climates that represent extreme to moderate climate conditions in USA **(Zarr, 1998)**. It was found that there is linear decrease of cooling load requirements with increasing roof solar reflectance especially for buildings with an un-insulated ceiling. In hot climates, the exterior roof temperature was significantly reduced, by 27°C and 32°C in Miami, FL and Phoenix, AZ respectively when the roof reflectance increased from 0.10 to 0.8.

The outside surface temperature of a galvanized steel roof with different colors was measured in an experimental study in South Africa **(Van Straaten, 1964)**. The roof surface temperature was reduced by 16 °C when painted with white color and increased by 10 °C when painted with black color. Studying lightweight horizontal panels with grey and whitewashed color in hot climate of Haifa, it was found that the exterior surface temperature of grey panel was 32 °C higher than the maximum air temperature while that of the whitewashed panel is only 1 °C higher than the maximum air temperature **(Givoni and Hoffman, 1965)**. The indoor air temperature measured at 0.1 m from the ceiling of the white roof was found 3 °C lower than the grey roof.

In hot dry climate of India, a study found that external surface color of a building envelope had a significant impact on the indoor air temperature in summer as well as in winter seasons even at high ventilation rates of 3 ACH **(Bansal et al., 1992)**. In summer, the indoor air temperature of a white painted room was recorded to be 6°C lower than that of a black painted room. In winter, the temperature difference was found to be 4°C. In a similar climate of India, a test room was painted with white cement and showed that the indoor air temperature dropped by 5.4°C compared to unpainted reinforced concrete roof **(Nahar et al., 2003)**.

In warm humid climate of Sri Lanka, a simulation study using DEROP-LTH showed that a rise of 1°C in a room air temperature is resulted when a dark color roof is used compared to a light color roof **(Jayasinghe et al., 2002)**. The indoor air temperature of a poorly passive designed house reached 33°C when the building envelope was painted with dark color. However, the impact of the color of building envelope on indoor air temperature was found insignificant when the house is designed with desirable passive features such optimum orientation, windows in north or south, shading devices for windows and balcony for roof. The indoor air temperature of light color house was kept within 29°C which is assumed to consume very low energy for thermal comfort in Sri Lanka. Another simulation study in Sri Lanka has shown that the light color roof of a single house maintains the indoor air temperature within 29°C compared to 31°C for the dark color roof **(Jayasinghe et al., 2003)**.

In hot humid climate, a free running Thai Buddhist temple was simulated using a coupled DOE-2/HEATX(CFD) simulation program to investigate possible design and operation strategies for thermal comfort without mechanical equipment **(Sreshthaputra et al., 2004)**. The study has indicated that the low-absorption roof option performed better than R-30 ceiling insulation in terms of average indoor temperature, yet the peak indoor temperature for the two options were similar. The merit of utilizing the surface treatments have been found sensitive to thermal characteristics of building envelope such as thermal mass, thermal insulation (**Givoni, 1976)**, rate of ventilation or infiltration and the direct solar radiation gain in buildings **(Bansal et al., 1992)**.

2.4.2 Energy Performance of Insulated Building Envelope

Thermal insulation offers many benefits to home owners such as improving thermal comfort, reducing the capacity of mechanical equipment, reducing the operation cost and lowering utility bills, and improving the resale value especially in regions where energy cost is high. Many studies have been conducted to evaluate the benefits of thermal insulation. The studies address the benefits of insulation materials in different performance measures such as: annual or peak heating and cooling loads, exterior surface temperature, economic cost benefits, annual energy consumption, and indoor air temperature.

In harsh climates, heat transmission through building envelope is high, and therefore, thermal insulation is an important design concept to reduce heat flows and consequently reduce energy consumption. Several experimental and numerical studies have shown that thermal insulation in roof and walls can reduce the heat transmission and energy consumption. In hot-humid climate of Dhahran, Saudi Arabia, an experimental study using 10 roof and 14 wall assemblies have been carried out to investigate the impact of varying insulation and construction approaches on the annual net heat flow **(Said et al., 1997)**. The study has demonstrated that using 75 mm of extruded polystyrene in roof slab reduces the net heat flow by more than 80%. In wall assemblies, the reduction in net heat flow using 50 mm of thermal insulation ranges from 64-84% depending on the type of insulation and its placement within the building envelope. Annual energy consumption for three 2-story villas, one w/o insulation and others with different insulation materials, has been monitored in hot-dry climate of Madina, Saudi Arabia **(Al-Maimani, 2002)**. The study has shown that insulation in both walls and roof contributed to actual savings of 48-80% in annual energy consumption.

Many simulation studies utilizing detailed energy simulation programs have been conducted to quantify the energy consumption as a result of using insulation in residential buildings. A parametric simulation analysis using DOE 2.1A for a single floor house in Dhahran has indicated that using thermal insulation for both roof and walls would contribute a reduction of 12.6% of the total annual energy consumption **(Said and Abdelrahman, 1989)**. For the same climate, a similar study for a two-story detached single family house has shown that a reduction of 42% in total energy consumption can be utilized if walls and roof are insulated **(Ahmed and Elhadidy, 2002)**. Utilizing PC-DOE program, **(AL-Maziad, 1999)** has investigated the impact of many building envelope design parameters in eastern province of Saudi Arabia, Dammam. He found that with insulated walls, electrical consumption for cooling purposes could be reduced by 23% compared to buildings without insulation.

Al-Homoud has investigated the impact of different level and types of thermal insulation on thermal performance of residential and office buildings in hot-dry climate of Riyadh and hot-humid climate of Dhahran in Saudi Arabia by utilizing the hourly building energy simulation program “EnerWin” **(Al-Homoud, 2004)**. Thermal insulation materials used in this study are: Fiberglass insulation; Rock Wool; Expanded Polystyrene; Extruded Polystyrene; Polyethylene; Polyurethane; Siporex; and Low-e Air Space (e=0.03, air space=90 mm). The study has indicated that residential buildings are more sensitive to the level of thermal insulation in reducing the energy consumption. For the residential buildings in Riyadh, the reductions in the annual energy consumption due to the use of walls and roof thermal insulation ranges from 23.69% to 45.51%, while in the climate of Dhahran, the reductions are more and ranging from 25.29% to 50.24%. Seeking an optimum thermal design of building envelope for a small two story residential building, it has been found that savings of as much as 37% and 28% in annual energy consumption can be achieved in hot-dry and hot-humid climates of Saudi Arabia, respectively **(Al-Homoud, 1997)**.

Al-Sanea has developed a numerical model under Riyadh climate and it was applied for six variants of a typical roof structure used in the construction of buildings in Saudi Arabia **(Al-Sanea, 2002)**. In this study, he found that using 50 mm of insulation layer of molded polystyrene, extruded polystyrene and polyurethane in a roof can result into a heat transfer load of 32%, 27%, and 22% of the reference daily average heat transfer load, respectively.

In order to point out the potential of ceiling insulation in achieving thermal comfort in summer of South Africa, a field study has been conducted using eight different houses in Pretoria **(Taylor et al., 2000)**. The controlled houses without ceiling insulation showed that indoor and outdoor temperatures are close to each other. On the other hand, the maximum indoor temperature in the insulated houses was found to be lower than that of the outdoor. The improvements in the temperature difference between the outdoors and indoors was found in the range of 1.9-4.5 K with an average of 3.1 K. Different thicknesses of fiberglass insulation (5,7 and 10 cm) was investigated. It was concluded that the thickness of insulation doesn't have a significant influence on the comfort improvements.

2.4.3 Impact of Air Leakage on Energy Consumption

The exchange of air between the outdoor and indoor has equal benefits and drawbacks. In some climates, outside air is utilized for natural ventilation to accomplish thermal comfort and hence reduce energy consumption. Outside air is also used to dilute indoor generated pollutants and make buildings healthy. This amount has been specified at 0.35 ACH by ASHRAE standard 62-1999 for controlling Indoor Air Quality. However, uncontrolled air leakage into buildings could have an adverse effect on energy consumption. In hot climates, air infiltration introduces excessive amount of heat that has to be removed by mechanical equipment. In hot-humid climate, this is more critical because hot humid air is the main cause of thermal discomfort. Therefore, uncontrolled air leakage rates should be kept at minimum for better control of indoor environment.

Few studies have been conducted to investigate the impact of air infiltration on the energy consumption of buildings. Considering the building stock of 13 countries, the total annual loss of delivered heating energy due to air change (assumed at 0.75 ACH) is estimated to be 53% of delivered space heating energy **(Orme, 2001)**. If ACH is reduced to meet the minimum requirement of IAQ, a reduction of 30% in the heating air change energy loss can be achieved. In office buildings of USA, the impact of infiltration rates on energy use has been investigated using simplified infiltration assumptions and a simplified bin method for energy consumption **(VanBronkhorst et al., 1995)**. The initial estimate has shown that infiltration is responsible for 18% of the total heating energy use and 2% of the total cooling energy use. While this study used a simplified infiltration assumption, another follow-up study has been conducted with improved estimating method of infiltration rates using multi-zone airflow modeling **(Emmerich and Persily, 1998)**. The study has shown that the infiltration is on average responsible for 13% and 25% of the total heating load in old and new office buildings respectively while it is responsible for 3% and 4% of the total cooling load. It has also been shown that if the building envelope air leakage is reduced by 25-50%, an average energy saving of 26% in heating load and 15% in cooling load is realized.

In hot-humid climate of Dhahran, Saudi Arabia, a simulation study using DOE 2.1A for a single floor house has assumed an infiltration rate close to 0.5 ACH (based on residential method) and indicated that the infiltration is responsible for 22.5 % of the peak cooling load **(Said and Abdelrahman, 1989)**. A parametric evaluation of air infiltration was made, varying the infiltration rate from 0.25 ACH to 1 ACH. When a lower level of 0.25 ACH is assumed, the total energy consumption was reduced by 8.5% compared to the base case of 0.5 ACH. The total energy consumption was increased by 10% when air infiltration rate of 1 ACH is assumed. It was noticed that impact of air infiltration is more severe in heating season than in the cooling season. This observation was also supported by **(Al-Homoud, 1997)** in his optimization study when the optimum infiltration rates were found to the lower end of the specified boundary (0.5 ACH). He concluded that the infiltration loss (ex-filtration) is more sensitive in cold climates followed by temperate climate.

The energy use in residential buildings due to infiltration has received little attention. On contrary, many studies have been devoted to energy saving credits of utilizing the outside air change rates due to both natural ventilation and infiltration. Although, these studies are not directly related to this research but they indirectly show the negative or positive impact of utilizing outside air when the outdoor conditions are at specific conditions.

A simulation study using TRANSYS in Cyprus has indicated that introducing the outdoor air during winter when the outdoor temperature is above that of the indoor is insignificant because of low duration of the availability of outside warm air **(Florides et al., 2002)**. However, the indoor air temperature during summer is greatly influenced by introducing cool outside air. The indoor air temperature is dropped by 2°C with 1 ACH, 3°C with 2 ACH, and 7°C with 11 ACH. A maximum reduction of 7.7% in annual cooling load was achieved when outside cool summer air is introduced. The indoor air temperature was 46°C without ventilation.

Using a validated computer program “QUICK”, different air change rates were investigated in low mass and heavy mass buildings in a hot climate region **(Mathews et al., 1992)**. It was found that the indoor air temperature in low mass building is less sensitive to the increases in air change rates but rather follow the outdoor temperature regardless of increased ACH. However, a reduction of 1.5°C in indoor air temperature was achieved in the heavy mass building when the air change rates increased during night time. An increase of 2°C in indoor air temperature was observed when the air change rates increased both during day and night. An experimental study in hot climate has indicated that using a high air change rates in heavy mass buildings during night would keep the indoor air temperature 7.5 -10.5 K below the outdoor maximum temperature **(Givoni, 1991)**. Givoni has further stated that “as a rule of thumb it can be estimated that in arid and desert regions, with a diurnal temperature range of 15-20 K, the expected reduction of the average daytime indoor temperature is 2-3 K below the level of similar buildings without night ventilation”. A field study in hot arid climate of Riyadh has concluded that a continuous day and night ventilation through outside windows is worse thermally than keeping the building closed without ventilation **(Al-Hemiddi and Al-Saud, 2001)**.

Givoni (1998) has studied the effect of air change rates on indoor air temperature of a low-mass room (conventional stud-wall construction) and a high-mass room (insulated concrete walls) with a similar thermal resistance in Pala, South California. In summer (average outdoor temperature was 25°C: max didn't exceed 37.5°C and min was 16°C), the night ventilation was introduced into the rooms from 7 p.m. to 7 a.m. by using fans with three speeds (30, 37 and 45 calculated ACH for low , medium and high fan speed respectively). The max indoor air temperature in the low mass room was following the max outdoor air temperature while the max indoor air temperature for the high mass room was below that of the outdoor max temperature.

While most of the studies on utilizing the outside cool air assumes that the occupants will open the windows or doors to achieve thermal comfort, an experimental study using two test rooms (control and experimental room) have been conducted to evaluate the performance of an intelligent ventilation system (air change rate is allowed to float from 0.7-3.9 ACH) to control the indoor air temperature within thermal comfort limits compared to a fixed infiltration rate system (0.7 ACH is kept constant) **(La Roche and Milne, 2003)**. The smart ventilation controller operates under specific control limits (i.e. coupling the outside air conditions with the indoor thermal environment). The increase in air change rates by the smart controller (varies according to the setting control limits) reduce the indoor air temperature by 3.1°C when additional mass is used, compared to the control room. The outside average maximum temperature was 26.5°C.

The impact of increasing air change rates have also been investigated in hot humid climates. In a ventilated courtyard house in the tropic climate of Japan, the indoor air temperature was dropped by 1.3°C with an air change rate range of 1.5 to 2.0 ACH **(Rajapaksha et al., 2002)**. In a warm humid day of Sri Lanka, a simulation study utilizing TRANSYS was utilized to investigate the impact of natural air change rates to reduce the indoor air temperature in residential buildings **(Ratnaweera and Hestnes, 1996)**. It was found that if windows are opened from 17:00 hrs to the next morning 8:00 hrs, the indoor air temperature is reduced from 30.2°C to 29.1°C.

A simulation study using ENERGY was performed to investigate four level of night ventilation in different level of massive construction for a typical apartment building in hot-humid climate regions **(Shaviv et al., 2001)**. The night ventilation levels assumed in this study were: natural infiltration rate of 2 ACH (base case), natural night ventilation rate of 5 ACH, forced night ventilation of 20 and 30 ACH. The study concluded that it is possible to achieve a reduction of 3-6°C in a heavy constructed building without air conditioner. The reduction of indoor air temperature depends on the amount of thermal mass, the rate of nigh ventilation and the temperature swings between the day and night.

Another simulation study for free-floating building (Thai Buddhist Temple) in hot-humid regions indicated that the nighttime-only natural ventilation reduces both the peak indoor air temperatures and daily indoor temperature fluctuation during summer and hence improves the overall building performance **(Sreshthaputra et al., 2004)**.

General conclusions could be drawn from these studies on the impact of high infiltration rates on the indoor thermal environment. In hot climates, the indoor air temperature follows the outdoor air temperature in light mass buildings regardless of high infiltration rates. On contrary, the indoor air temperature is more sensitive to air infiltration in high mass buildings. For thermal comfort, it is therefore important to keep the air infiltration at minimum rates when the outside air temperature is always above the indoor air temperature but rather beneficial at times when the outdoor air temperature is below that of the indoor and within the comfortable limits. Givoni has given a temperature limit of using the outside air for thermal comfort **(Givoni, 1991)**. He suggested that the comfort is not influenced by the outside air if its maximum temperature doesn't exceed 28-32 °C, assuming an indoor air speed of 1.5-2.0 m/s. From energy consumption point of view, infiltration rates are more sensitive in heating seasons compared to cooling seasons.

2.5 Thermal Comfort Requirements and Studies in Hot Climates

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment" **(ASHRAE 1992, ISO 1984)**. Thermal comfort is a basic requirement for occupants to perform their day to day activities. Thermal comfort is influenced by many variables that can be divided into environmental parameters: air temperature, mean radiant temperature, humidity, relative air velocity and personal parameters: clothing and activity **(Fanger, 1972)**. In order to provide a thermally comfortable environment, proper combinations of the above variables have to be sought.

Many laboratory and field studies have been conducted to define the thermal conditions that satisfy a wide range of occupants. Two widely used models developed in laboratories are the Fanger model and the Gagge two-node model **(Jones, 2002)**. The models are based on heat balance equations of human body with the surrounding environment. Among the two, Fanger model "Comfort Equation" is the widely accepted model that combines the six thermal comfort variables. For any type of clothing and activity, the comfort equation can calculate the combinations of air temperature, humidity, mean radiant temperature and relative velocity that creates the optimal thermal comfort condition **(Fanger, 1970)**. Solving this equation by a computer program, Fanger has developed many thermal comfort charts that can be easily used by engineers.

In order to evaluate the indoor thermal environment at a wider scale beyond that of the optimal, Fanger has introduced the concept of Predicted Mean Vote "PMV" and Predicted Percentage of Dissatisfied "PPD" to predict the actual thermal sensation **(Fanger, 1970)**. PMV (Predicted Mean Vote) is an index that gives, on the ASHRAE seven-point thermal sensation scale (+3 hot, +2 warm, +1 slightly warm, 0 neutral,–1 slightly cool, –2 cool, –3 cold), a mean value of the votes of a large group of persons exposed to a given combination of variables. PPD (Predicted Percentage Dissatisfied) expresses the percentage of thermally dissatisfied people. PPD is determined from PMV and is graphically presented as shown in **Figure 2.13**. PPD index is based on the assumption that people voting ±2 or ±3 on the thermal sensation scale are dissatisfied, and it is symmetric around a neutral PMV **(ASHRAE-55, 2004)**.

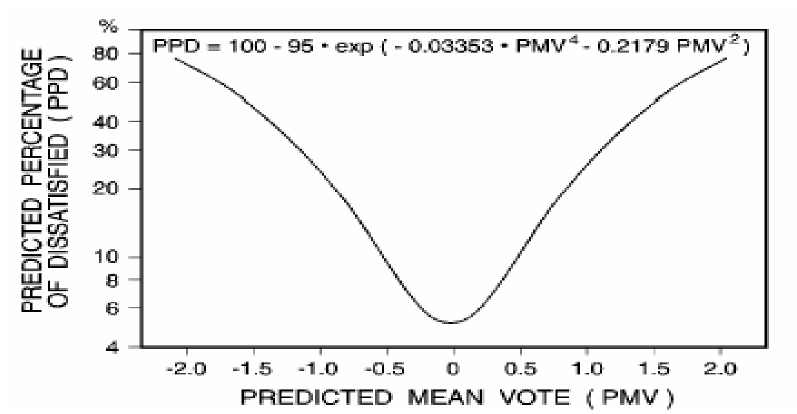


Figure 2.13 Predicted Percentage Dissatisfied (PPD) as a function of predicted mean vote (PMV) **(ASHRAE-55, 2004)**

2.5.1 International Standards for Indoor Thermal Comfort

Fanger model (PMV-PPD) is adopted in international thermal comfort standards: ISO-7730 **(ISO, 1994)**, ASHRAE-55 **(ASHRAE 55, 1992)**, and CR 1752 **(CR 1752, 1998)** to predict thermal comfort under steady state conditions. ISO-7730-94 and ASHRAE-55 -92 specify the acceptable thermal comfort conditions based on a 10% PPD dissatisfaction criteria for general thermal comfort (Class B) and 10 % dissatisfaction due to local discomfort which makes the level of thermal acceptability at 80%. On the other hand, CR 1752 is more flexible and recommends levels of acceptance for three classes of environment: Class A (–0.2 < PMV < +0.2, PPD<6%), Class B (–0.5 < PMV < +0.5, PPD<10%) and Class C (–0.7 < PMV < +0.7, PPD<15%) **(CR 1752, 1998)**. However, the new ASHRAE standard **(ASHRAE-55, 2004)** includes all three classes as inclusion while it is expected that wider PMV range (Class C) will be included in ISO-7730 revision **(Olesen and Parsons, 2002)**.

The old ASHRAE thermal comfort standard **(ASHRAE-55, 1992)** gives an ideal indoor thermal environment for two seasons: winter and summer at a specific combination of thermal comfort variables at 50% relative humidity: light activity level, typical summer and winter clothing habits, equal air and mean radiant temperature, and low relative air velocity. The shortcomings of the provided ideal thermal environment and new research findings in the field of thermal comfort under different climates have necessitated ASHRAE to update their old thermal comfort standards such as ASHRAE-55-92 and its amendment 55-95a.

ASHRAE has recently released the new thermal comfort standard ASHRAE-55 2004 **(Olesen and Brager, 2004)**. Since both ISO-7730 standard and ASHRAE-55 2004 uses the same approach for thermal comfort zone determination, ASHRAE-55 2004 is chosen to represent the international thermal comfort standard in this research. The major departure from the old standards is the addition of the PMV-PPD method of determining the comfort zone without specifying the minimum level for humidity. It also introduces a new optional method for determining acceptable thermal conditions in naturally ventilated buildings.

A range of operative temperatures or a simple average of the air temperature and mean radiant temperature defines the comfort zone that provides acceptable comfort thermal environmental conditions. It is determined by specifying the values of humidity, air speed, metabolic rate and clothing insulation. The temperature limits might be either determined graphically for many typical applications or by using a computer program based on a heat balance model (PMV-PPD model) to determine the comfort zone for a wider range of applications. The graphical method is also based on PMV-PPD model but assuming two different levels of clothing: 0.5 clo (typical for summer) and 1.0 clo (typical for winter), 10% PPD dissatisfaction criteria for general thermal comfort, metabolic rates between 1.0 to 1.3 met, and air speed less than 0.20 m/s. for these conditions, thermal comfort zones ca n be graphically presented as shown in **Figure 2.14**.

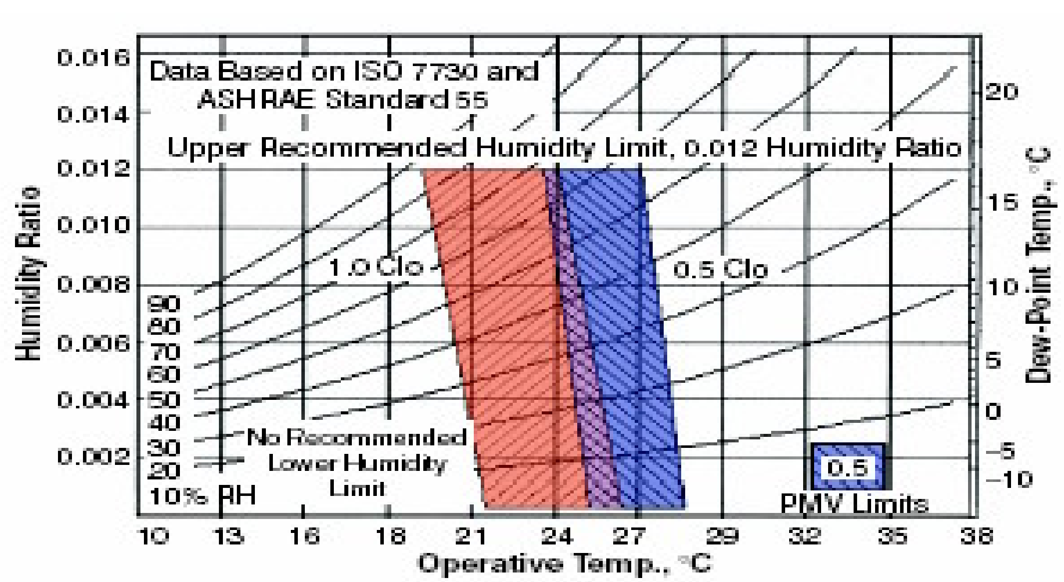


Figure 2.14 Graphical Method for Determination of Thermal Comfort Zone **(Olesen and Brager, 2004)**

Computer program can also be used when the space conditions are different from those described in the graphical method. The specific values of humidity, air speed, clothing, and metabolic rate are the main input data to the program. Consequently, the operative temperature range can be determined based on a PMV range of $-0.5 < PMV < +0.5$, which corresponds to a PPD of 10%.

2.5.2 Thermal Comfort Adaptive Concept

Many recent field studies have questioned the validity of PMV-PPD in predicting the thermal comfort conditions in naturally ventilated buildings **(Olesen and Parsons, 2002)**. Field studies have found that thermal comfort can still be met at higher temperature ranges than those predicted by PMV-PPD model. This discrepancy has led to a new concept of Adaptive Model **(Humphreys and Nicol, 1998)**. Humphreys has further defined this concept, which doesn't depend on the existence of acclimatization, as follows: **"If a change occurs such as to produce discomfort, people react to restore their comfort"**. However, other studies have also shown that the adaptation could be achieved by many ways: (1) behavioral adjustments (personnel, environmental, technological or cultural), (2) physiological (genetic adaptation or acclimatization) and (3) psychological (habituations or expectation) **(Brager and deDear, 1998)**. Based on these variables, "the term "adaptation" is broadly interpreted as the gradual diminution of the organism's response to repeat environmental stimulation" **(deDear et al., 1997)**.

According to many field studies, people can be comfortable at wider temperature range. ASHRAE has recognized the importance of updating its thermal comfort standard and as a result, a research project was initiated to review the up-to-date thermal comfort studies and incorporate them in a new recommended variable temperature standard **(deDear and Brager, 2002)**. The project has collected a high number and quality data from field studies in 160 different office buildings located on four continents and covering a broad spectrum of climate zones. The database contains field studies from Bangkok, Indonesia, Singapore, Athens, Michigan, several locations in California, England and Wales, six cities in Australia and five cities in Pakistan. The database was statically analyzed for buildings with centralized HVAC and naturally ventilated buildings where occupants had access to operable windows. From the analysis, the observed data from field studies and predicted data from PMV were found well correlated in HVAC buildings. This shows that the PMV model can be confidently used to predict the thermal comfort in controlled HVAC buildings. However, no agreement was found in naturally ventilated buildings. This has indicated that the behavioral adaptations, physical (acclimatization) and physical components are the main reasons behind this difference which demonstrated the adaptive concept **(Brager and deDear, 2000)**. Therefore, the adaptive Comfort Standard has been derived from the statistical analyses and has been included in the new ASHRAE-55 2004 as depicted in **Figure 2.15**.

The range of acceptable operative temperatures is a function of mean monthly outdoor temperature and has been derived from the adaptive model of thermal comfort. This range is applicable only for spaces where the thermal conditions are regulated by the occupants through opening and closing of windows, there is no mechanical cooling in operation (mechanical ventilation is allowed), and metabolic rates range from 1.0 to 1.3 met **(Olesen and Brager, 2004)**.

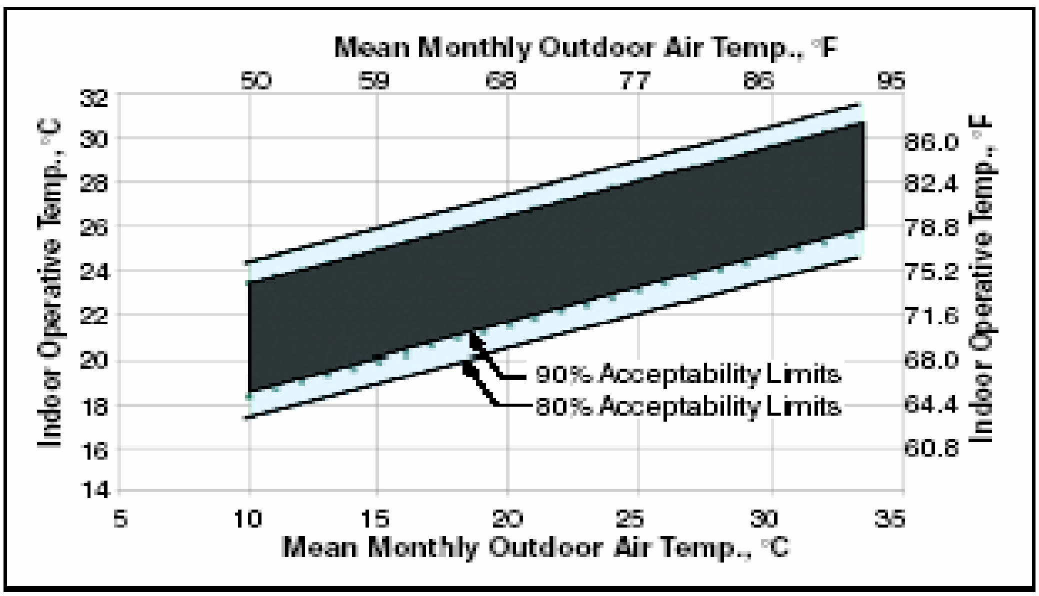


Figure 2.15 Acceptable Operative Temperature Ranges for Naturally Conditioned Spaces **(ASHRAE-55, 2004)**

Field experiments of controlled HVAC buildings have shown that Fanger PMV-PPD model is accurate enough to predict thermal comfort conditions in hot climate of Saudi Arabia. In a limited number of university classrooms in a hot humid climate of Saudi Arabia, a comparative study between field measurements, using B&K 1212 Comfort Meter instrument based on Fanger’s method, and subjective assessment based on mean responses of 15 subjects in 6 different rooms has concluded that both are in good agreement **(Abdelrahman, 1991)**. Field experiments in the climate of Riyadh, Saudi Arabia consist of sixteen sets of measurements conducted in fully air-conditioned lecture theatres and design studios yielded 290 responses in the cool season, 515 responses in the hot season were carried out **(Saeed, 1993)**. The data was statistically analyzed and found that the Fanger's equation correlated well at predicting subjective responses. A follow up study on 525 subjects exposed to hot environment in a mosque also confirmed the earlier findings **(Saeed, 1996)**.

2.6 Simulation of Thermal Performance of Building

The thermal performance of a building should better be evaluated at the early design stage when many vital decisions related to building physics are taken. In many countries where designs are to comply with prescriptive standards, simplified methods are utilized for quick compliance purposes. Detailed energy simulation programs are however sought to accurately simulate the thermal performance with additional flexibility to identify design trade-offs for cost effectiveness, yet complying with performance based standards.

2.6.1 Energy Simulation Programs for Building Evaluation

Many detailed simulation tools are nowadays available to aid designers to implement new technologies and evaluate innovative ideas that increase the energy savings in their proposed designs. Detailed energy simulation tools use mathematical models to calculate the envelope heat gains or loss, (annual and peak) space heat and cooling load, evaluate indoor thermal conditions, predict energy performance of buildings and analyze the life cycle costing. Detailed simulation tools perform their computation on hourly or sub-hourly bases for better consideration of the dynamic interactions between all thermal-based elements associated with comfort and energy consumption, including the building envelope, HVAC systems, lighting and control devices **(Hong et al., 2000)**. It is difficult to categorize simulation programs because of their continuous development and improvement. Many building simulation tools are listed at the U.S. Department of Energy (DOE) web directory (http://www.eren.doe.gov/buildings/tools_directory). The most common detailed energy simulation programs that are considered accurate and capable of handling the dynamic behavior of building and its systems are DOE-2, BLAST, EnergyPlus, and ESP-r. However, a lot of data input is usually required for accurate results.

DOE-2 is a public domain program that was developed by the Simulation Research Group at Lawrence Berkeley Laboratory (LBL). It performs an hourly simulation of the building thermal performance and is widely used to design energy-efficient buildings, to analyze the impact of new technologies and to develop energy conservation standards. The program needs a detailed input of weather data, building materials, operating schedules, and description of HVAC equipment. Many commercial user friendly programs using DOE-2 main code such as VisualDOE (Eley Associates) and EZDOE (Elite Software) have been developed to provide a graphical user interface. While these programs were intended to offer a graphical user interface of the DOE-2, they don't provide the full capabilities of DOE-2.

BLAST (**B**uilding **L**oad **A**nalysis and **S**ystem **T**hermodynamics) is a set of computer programs for predicting heating and cooling energy consumption in buildings, and analyzing energy costs. BLAST was developed by Department of Mechanical and Industrial Engineering, University of Illinois at Urbana Champaign and sponsored by the U.S. Department of Defense (DOD). BLAST can be used to investigate the energy performance of new or retrofit building design options.

The main difference between DOE-2 and BLAST is their load calculation method; DOE–2 uses a room weighting factor approach while BLAST uses a heat balance approach. With many capabilities of the two and new added capabilities, a new building performance simulation program "EnergyPlus" was developed to combine the best capabilities and features of the two programs **(Crawley, 1999)**. The major improvement in the EnergyPlus is the integrated solution of loads, system and plant.

ESP-r (Environmental System Performance, European version) is a public domain transient energy simulation system capable of assessing problems related to several domains: air and moisture transport within physical spaces (typically buildings), fluid flow within HVAC systems, and electrical power flow within heterogeneous networks **(Hand, 1998)**. ESP-r is based on a finite volume approach in which a building model and its description are transformed into a set of conservation equations which are then integrated at successive time-steps in response to climate, occupant and control system influences.

2.6.2 Program Selection for Energy Performance Evaluation

Despite the availability of many energy simulation programs nowadays; many challenges are encountered when detailed simulation methods are sought. Designers are not able to select suitable program to carry out their analysis. It is perhaps difficult to set an explicit procedure for selecting a simulation program that suits every one. Many factors such as accuracy, sensitivity, speed and cost, reproducibility, usability, input complexity, output quality, weather data availability are generally considered during the selection process **(ASHRAE, 1997)**. While these factors are related to the energy simulation programs, other factors related to the users should also be considered. There are three factors that the users need to consider: matching the need or the purpose to the program capability, the budget (to purchase, training, use, and maintain the software), and the availability of existing computer facilities **(Hong et al., 2000)**.

A high effort has been done in Canada to defining the methodology for the Next-Generation HOT2000 Simulator **(NRCan, 1998)**. The project work started by listing all potential software tools (about 31 simulation programs) that can be used for the HOTCAN-3000. A number of levels were developed to screen out the programs according to specific conditions where only those programs passing a given screening level were considered at the next level. The levels considered for this task are listed as follows:

Level 1: Preliminary review of modeling methods for 31 simulation tools

Level 2: Availability, rights to use, technical collaboration and support (8 programs at this level were identified).

Level 3: Technical documentation and source-code structure (6 programs were identified at this level)

Level 4: Detailed review of modeling methods (3 programs were finally identified: Energyplus, ESP-r and TRNSYS)

ESP-r was finally selected to be the base for developing the HOTCAN-3000. While this approach is applicable for a similar project task, the selection procedure can also be adopted with a shallower scope.

2.6.3 Energy Simulation Program: VisualDOE

VisualDOE is a Windows interface to the DOE-2.1E energy simulation program. VisualDOE provides a graphical user interface where users can construct their building model using the standard block shapes, using a built-in drawing tool, or importing DXF files. VisualDOE is useful for studies of building envelope and HVAC design alternatives. Many generations have been developed by Eley Associates such as version

VisualDOE2.6, 3.0, 3.1 and finally VisualDOE4.0 and its update 4.1 . VisualDOE uses the DOE2.1E calculation engine which uses the transfer function method to calculate the building heat and cooling loads assuming a constant indoor air temperature. The DOE-2.1E energy simulation program has undergone extensive validation exercises and shown to be accurate with measurements **(Sullivan, 1998)**. The old DOE2 code (DOE-2.1A) has also been validated for accuracy in Dhahran, Saudi Arabia **(Bahel et al., 1989).**

VisualDOE requires many data inputs including floor plan, occupancy type, location, walls, roof and floor constructions; window area and type; HVAC system type and parameters; and lighting and equipment power density. Some databases are also available for easier input through the library and templates. Most data needed for creating the building model in the program can be easily retrieved from the building drawings or library databases. However, weather data is the most difficult to obtain in a format suitable to the simulation programs. Through the building energy simulation, a user can obtain an accurate estimate of the building's energy consumption, interior environmental conditions and energy operation cost. The program can model conditioned and unconditioned spaces where indoor air temperature is freely floating. The program has been widely used in the world for building design and energy conservation studies **(Hui and Allison, 2002)**. The objective of developing the VisualDOE was to provide a user interface. Hence, VisualDOE implements about 95% of DOE-2.1E functionalities which is adequate for many common applications, yet the flexibility is available for advance applications by modifying the DOE-2 input files.

2.6.4 Sources of Weather Data for Saudi Arabia

Weather data is an important input data element in the detailed simulation programs. The design of active system such as Heating Ventilation and Air Conditioning (HVAC) is only achieved after careful considerations of outdoor climatic conditions. The dynamic behavior of building and its system is influenced by the weather. The weather data is a prerequisite in the detailed simulation programs to analyze different energy conservation measures. It is also important in evaluation studies of indoor environmental indices and structural design strategies. Therefore, it is important for engineers and researches to obtain this piece of information for their professional studies.

In Saudi Arabia, many organizations keep the records of weather data. The data are normally recorded at stations in airports. The raw weather data includes the hourly values of dry-bulb temperature, wet-bulb temperature, relative humidity, cloud cover and wind speed. Some data are available for a period of 20 years like the one that are recorded in 20 stations of **M**eteorology and **E**nvironmental **P**rotection **A**dministrations (**MEPA**) and Department of Water Resources under the Ministry of Agriculture **(Said et al., 1996)**. Other organizations such as ARAMCO and Energy Research Institutes and centers at Universities are also recording the weather data but rarely available for long period of time **(Said, 1992)**.

Hourly solar radiation is perhaps the most important parameter in the analysis of building thermal design but has received little attention by many worldwide metrological organizations. In Saudi Arabia, **M**eteorology and **E**nvironmental **P**rotection **A**dministrations (**MEPA**) and Department of Water Resources keep the records of hard formats of scattered daily average solar radiation data for limited cities in Saudi Arabia. Unfortunately this information is not measured for many cities in Saudi Arabia **(Said et al., 2003)**. For the purpose of updating the Saudi Solar Radiation Atlas by **K**ing **A**bdelaziz **C**ity for **S**cience and **T**echnology (**KACST**), twelve locations in the following cities were selected to measure the global solar radiation: Riyadh, Gassim, Al-Ahsa, Al-Jouf, Tabuk, Madinah, Jeddah, Qaisumah, Wadi Al-Dawasir, Sharurah, Abha, and Gizan. However, diffusive solar radiation is only recorded at four stations in the following cities: Gassim, Al-Ahsa, Wadi Al-Dawasir and the Solar Village which is 50 Km north-west of Riyadh **(Alnaser et al., 2004)**.

In the USA, **I**nternational **S**urface **W**eather **O**bservations (**ISWO**) keeps the records of weather data for many stations around the world including the Saudi's local stations. The ISWO database contains many important weather variables such as dry-bulb and dew-point temperatures, atmospheric pressure, wind speed and direction, and the amounts of cloud cover at various heights. However, solar radiation readings are not available in this database. The weather variables from local stations in the world are transmitted via **G**lobal **T**elecommunications **S**ystem (**GTS**) and archived by **A**ir **F**orce **C**ombat **C**limatology **C**enter (**AFCCC**), **N**ational **C**limate **D**ata **C**enter (**NCDC**) in Ashevill, N.C.

(Zhang et al., 2002). For many local stations in the world, the ISWO database contains readings at three hour interval.

Researches normally use the cloud cover information in the weather data and utilize special algorithms to estimate solar radiation and its components **(Thevenard and Brunger, 2002)**. At stations where these variables are not available at hourly bases, researches develop algorithms from the available limited measured data to create hourly weather data by filling the missing data.

2.6.5 Weather Data for Energy Simulation Programs

The weather data is available in raw data formats for many years, typically 20-30 years in developing countries. This raw data is not suitable for the detailed energy simulation programs. A typical weather year, representing many years of weather data, has to be selected for the energy analysis. In developing countries, this obstacle has hindered the use of energy simulation programs in the analysis of building thermal design.

Many typical weather data sets are internationally recognized for use in detailed energy simulation programs. In North America, well known weather data sets available for energy simulation are: **T**ypical **R**eference **Y**ear (**TRY**) **(NCDC, 1976)**, **T**ypical **M**etrological **Y**ear (**TMY**), **W**eather **Y**ear for **E**nergy **C**alculation (**WYEC**), **C**anadian **W**eather for **E**nergy **C**alculations (**CWEC**) **(WATSUN, 1992)**, Typical Metrological

Year: Version 2 (TMY2) **(Marion and Urban, 1995)**, and **W**eather **Y**ear for **E**nergy **C**alculation Version: 2 (**WYEC**2) **(Stoffel and Rymes 1998, Huang 1998)**. TMY2 are developed for 239 USA locations but California has its own weather data set (**C**alifornia **T**hermal **Z**one Version2: CTZ2) which is used for the state code compliance. For Canadian locations, CWEC weather data set is mainly used and 5 locations are developed with WYEC2 format.

In Europe, the standard method of generating **T**est **R**eference **Y**ear (TRY) is proposed under ISO Standard prEN ISO 15927-4 (Thermal Performance of Buildings-Climate Data-Part 4: Data for Assessing the Annual Energy Demand for Cooling and Heating System) **(Levermore and Doylend, 2002)**. Another form of TRY is proposed by **C**hartered **I**nstitution of **B**uilding **S**ervices **E**ngineers (**CIBSE**) in UK **(Holmes and Hitchen, 1978)**. The ISO TRY is proposed for near-extreme plant design or near-extreme performance assessment whereas the CIBSE-TRY format is for average energy estimation and analysis. Therefore, ISO TRY is more appropriate for HVAC Design and short term performance analysis.

Except for the American version of TRY, all weather data sets TMY2, WYEC2, CWEC and CIBSE-TRY are a synthetic year that has an hourly weather data which represents the long term trend of weather variables. The methodology to select the representative monthly weather data is similar but different weights are applied to weather variables in the selection process. The American version of TRY represents an actual historic year weather data that is selected from a list of many years. The year weather data is rejected from the candidate years based on their extreme high or low temperature until only one actual mild year is selected **(Crawely, 1998)**.

Many efforts have been done to create suitable weather data files for energy simulation programs **(Clarke, 2001)**. In 1997, ASHRAE technical committee 4.2 (Weather Information) decided to look for possibility to develop typical weather years called International Weather for Energy Calculation (IWEC) for international locations outside USA by using the database at **N**ational **C**limate **D**ata **C**enter (NCDC) in Ashevill, N. Carolina **(Thevenard and Brunger, 2002)**. Due to the lack of solar radiation data, solar radiation algorithms were used to generate the IWEC. The weather data years are selected based on the standard methodology of TMY2 **(Marion and Urban, 1995)**. IWEC files were developed for 227 selected sites outside US and Canada.

In the kingdom of Saudi Arabia, the suitable weather data format for detailed energy programs is not available to conduct energy design analysis. The need for suitable weather data format in disseminating energy efficient designs in Saudi Arabia has been recognized by **(Said et al., 2003)**. The breadth and depth of weather data are the main challenges. The breadth determines the number of years recording the weather data while the depth determines the detailed hourly coverage of the main weather variables. The main hourly weather variables required for detailed energy simulations includes: dry-bulb temperature, wet-bulb temperature and dew-point temperature or relative humidity, wind speed, wind direction, global horizontal solar radiation or cloud cover information and atmospheric pressure. Nevertheless, individual efforts continue to develop weather data sets. For example, **Said and Kadry (1994)** has processed the 22 years (1970-1991 inclusive) weather data for 5 main cities (Dhahran, Riyadh, Jeddah, Khamis-Mushyt and Hail) to develop **T**ypical **W**eather **Y**ears (TWY). These cities represent the climate conditions of Saudi Arabia. In the developed TWYs, solar data was not included due to the lack of solar radiation data. Although the development of TWY is not suitable for energy simulation programs but it is perhaps an important effort that helps to establish the methodology of developing typical weather years in Saudi Arabia. Under the project sponsored by ASHRAE to develop IWEC files for international locations, IWEC file was developed for Riyadh city. Although the solar data disagree with the 1983 Saudi Solar Radiation Atlas but it does agree well with the recent measurements data that was taken by KACST **(KACST and NREL, 2001)**. For other cities of Saudi Arabia, researches normally utilize the available hourly weather data of any actual year.

The types of different weather data sets and the selection methodologies of a typical weather year have brought up many issues related to the reliability of estimating energy. This problem has been recently addressed **(Crawley, 1998)**. In this study, simulation runs using different reference years (TRY, TMY, TMY2, WYEC, WYEC2) were compared with another simulation runs using the 30 years period of actual hourly weather data. A typical office building was simulated with DOE-2.1E program for eight U.S. locations. Crawley studied the impact of using various weather data sets on the annual energy use and costs and annual peak electrical demand, heating load, and cooling load. He concluded that the American version of TRY-type weather data should be avoided since no single year can represent the typical long-term weather patterns. TMY2 and WYEC2 were found more rigorous in predicting the energy consumption since improved solar models are used to estimate the solar data. Therefore, they are more closely matching the long-term average climatic conditions.

Another study was conducted to study the influence of different sets of weather data on residential buildings and to compare them with 30 years of actual historical records by utilizing DOE-2.1E **(Huang, 1998)**. The study concluded that TMY2 and WYEC2 weather data gives results within 5% of that for 30 years records. He justified the use of the typical weather year to simulate the peak building loads because the selection process doesn't eliminate the peak design conditions. He found that the American version of TRY is less reliable in replicating the average historical conditions.

CHAPTER THREE

THERMAL AND PHYSICAL CHARACTERSTICS OF RESIDENTIAL BUILDINGS IN SAUDI ARABIA

3.1 Introduction

In Saudi Arabia, residential buildings have undergone a dramatic change in their design, construction materials used and electrical appliances utilized. Every region in Saudi Arabia has its own social, cultural, economical and climatic parameters that dominate its design characteristics. Studies have been conducted to evaluate design parameters adopted in different climates of Saudi Arabia **(Talib 1984, Al-Haddad 1986 and Al-Haddad 1988)**. **Talib (1984)** has reviewed the design parameters of traditional housings for different climatic regions of Saudi Arabia. A questionnaire survey was distributed to 16 Architectural Engineering offices to determine the use, location, types and typical thickness of thermal insulation in opaque envelope of residential buildings **(Al-Haddad, 1986)**. The study has concluded that many ways are available to place the insulation in the walling system such as placing 50 mm insulation in cavity walls, or placed at interior side and covered with gypsum boards, or filling the hollow masonry blocks with insulation material inserts. However, the roof insulation is followed a standard construction method where it is always placed on top of the roof slab. Another study has conducted a field survey on more than 300 houses in major cities in Saudi Arabia including Al-Khobar and Riyadh to develop a typical villa for energy simulation studies **(Al-Haddad, 1988)**. The summary outcome of this study is shown in **Table 3.1.**

Table 3.1 Thermal and Physical Characteristics of Residential Buildings (Villa) in Saudi Arabia **(Al-Haddad, 1988)**

Design Parameter	**Riyadh**	**Al-Khobar**
1. Floor Area (m^2)	244	252
Windows Area (m^2) >97% single glazing+ no exterior shading	33.5	42.5
2. Roof Construction Method		
a. Un-insulated Hourdi Slab	20.0%	84.5%
b. Insulated Hourdi Slab	37.5%	5.7%
c. Un-insulated Con. Slab	32.0%	4.9%
d. Insulated Con. Slab	10.0%	4.9%
3. Wall Construction Method		
a. Single Block Walls	79.0% (CMU: 51%, Clay: 28%)	98.4%, (CMU: 79.4%, Clay: 19%)
b. Double Block Walls	9.4% (CMU: 4.7%, Clay: 4.7%)	0.0%
c. Cavity Walls	11.6% (CMU: 9.3%, Clay: 2.3%)	1.6%, (CMU: 1.6%)
4. Finishing Materials		
a. Paint	40.0%	20%
b. Marble	3.7%	2%
c. Combination of above or others (i.e. Natural Stone + Granolith)	56.3%	78%
5. Number of Floors	2	2
6. Height (m) 3.5 m /Floor	7.0	7.0
7. Shape of the Plan		
a. Rectangular	55.0%	56.0%
b. L-Shape	10.0%	12.0%
c. U-Shape	6.0%	4.0%
d. Others	29.0%	28.0%

During the last 15 years, the construction practices in Saudi Arabia have undergone major changes, therefore, it was found important to survey the current design practices of single family houses in representative cities in eastern province (i.e. Khobar, Dammam and Dhahran) and Riyadh.

3.2 Questionnaire Design

The questionnaire design was developed to cover the main important design parameters that are required for the energy simulation program.

3.2.1 Contents of Questionnaire

The questionnaire as shown in APPENDIX-A is divided into four sections. The first section covers the general information about the respondent such as name, company, address, years of experience and the yearly average number of the designed houses. The second section contains the general characteristics of single-family house such as the average floor area, common geometrical shape and number of floors.

The third major section is divided into four sub-sections covering the main building exterior envelope: wall, roof, type of insulation used, and windows. The first sub-section contains the generic wall designs and location of thermal insulation relative to the main building material, main building materials normally used in wall designs, exterior finishing and the surface colors. The second sub-section details the generic roof designs and location of insulation materials, main building material, flooring or exposed layer of the roof construction, special features of roof systems, and roof's surface colors. The third sub-section includes different types of insulation materials that are normally used for both walls and roofs and the required minimum level of thermal resistance. The fourth sub-section consists of window designs and its assembly including glazing types, exterior shadings, windows ratio and window types.

The last part of the questionnaire covers the level of air leakage and measures that are taken to control the leakage rate, lighting requirements and open ended space for the respondents to add more design parameters that were not mentioned in the questionnaire.

3.2.2 Data Collection

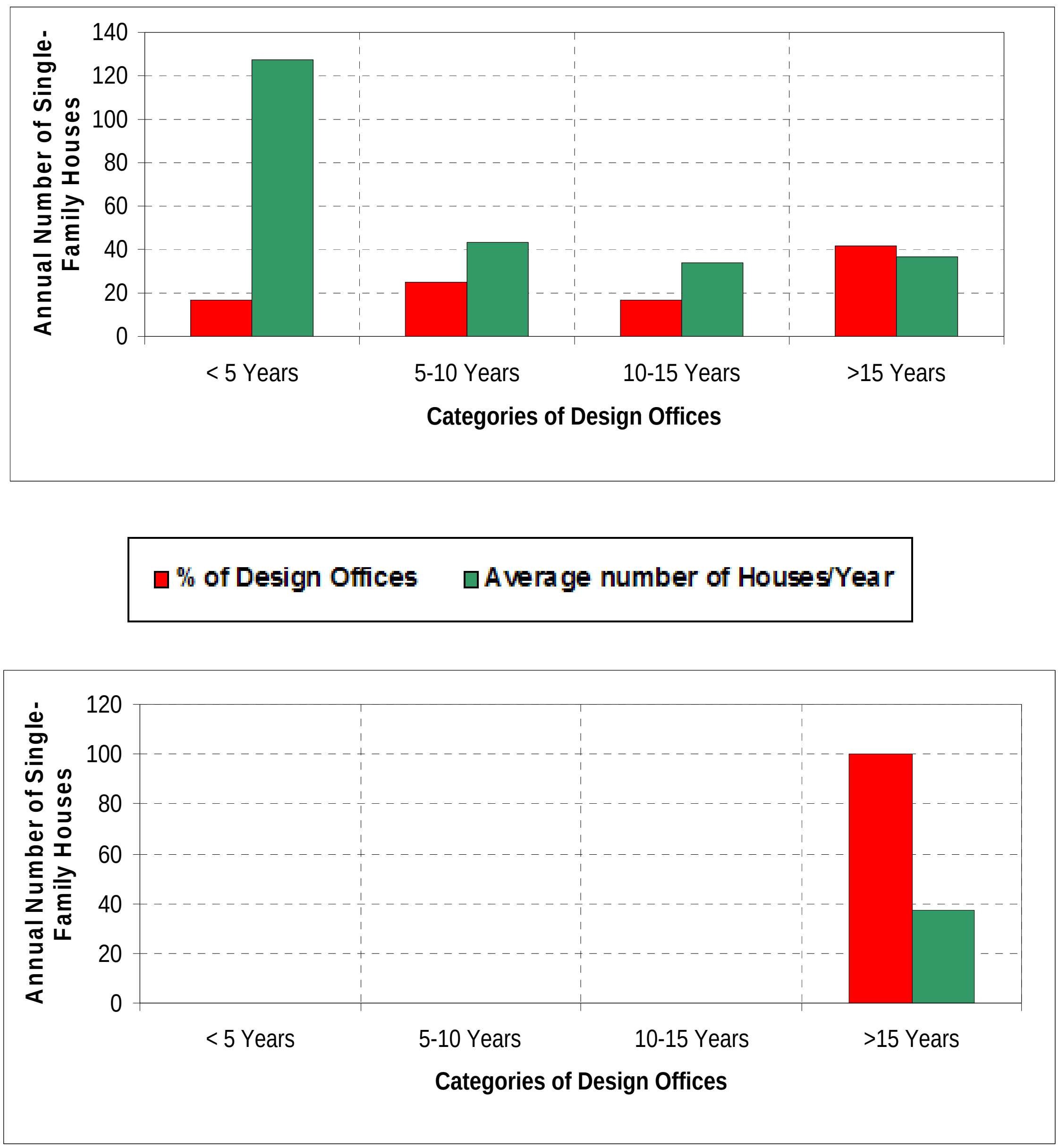
The research survey questionnaires were initially faxed to design offices in eastern province (i.e. Dammam and Khobar) and Riyadh with follow-up telephone calls. The responses were quite below expectation. Therefore, the questionnaires were mailed to design offices. The completed questionnaires were requested to be dispatch or faxed to the researcher. In many instances, questionnaires were answered by the general managers or senior architects in the design offices. Over a period of six months after dispatching the questionnaires and contacting the consultants, the researcher collected 12 responses from Dammam and Khobar and 7 were responded by the designers in Riyadh. There was one questionnaire responded by a general contractor which was rejected. The questionnaires were then analyzed using an easy and simple frequency approach. The results are presented in the following sections.

3.3 Analysis and Discussion of Results

3.3.1 General Information

The first section of the questionnaire includes general information about the design consultants. The design consultants are classified in terms of their years of experience in design of residential buildings. From the results of the questionnaires, the design offices can be classified in to four categories according to their number of years of experience in the design of single-family houses: with less than 5 years of experience, with 5 to 10 years of experience, with 10 to 15 years of experience and with more than 15 years of experience. From **Figure 3.1 (a)**, it is clear that the less experienced design offices design more houses than those with more experience in Dhahran. The average number of houses that are annually designed by the less experienced design offices is more than 120 houses. **Figure 3.1 (b)** shows that all surveyed design offices in Riyadh are with more than 15 years of experience and they design an average number of 37 houses per year.

The second section covers general information about the building including: average floor area, common geometrical shape and number of floors. The building area has been categorized into four groups: <250, 250-350, 350-450 and >400 m^2. Many designers use a space area in the range of 250-350 m^2. It was found that the average floor area of houses in Dhahran and Riyadh are 301 m^2 and 300 respectively as shown in **Figure 3.2 (a)** and **(b)**.



(a)

(b)

Figure 3.1 Annual Designed Houses by Different Design Office Categories in **(a)** Dhahran and **(b)** Riyadh

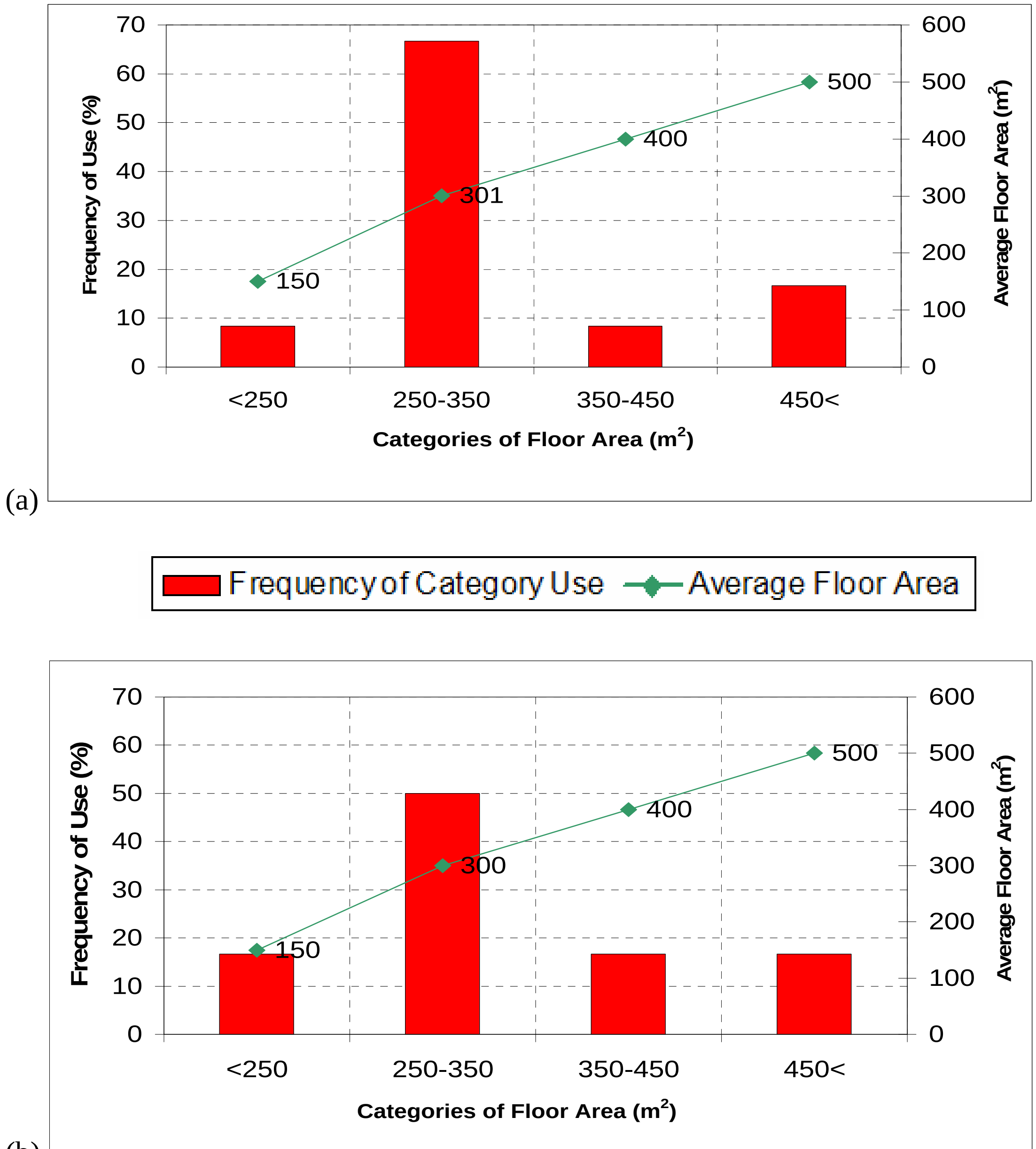
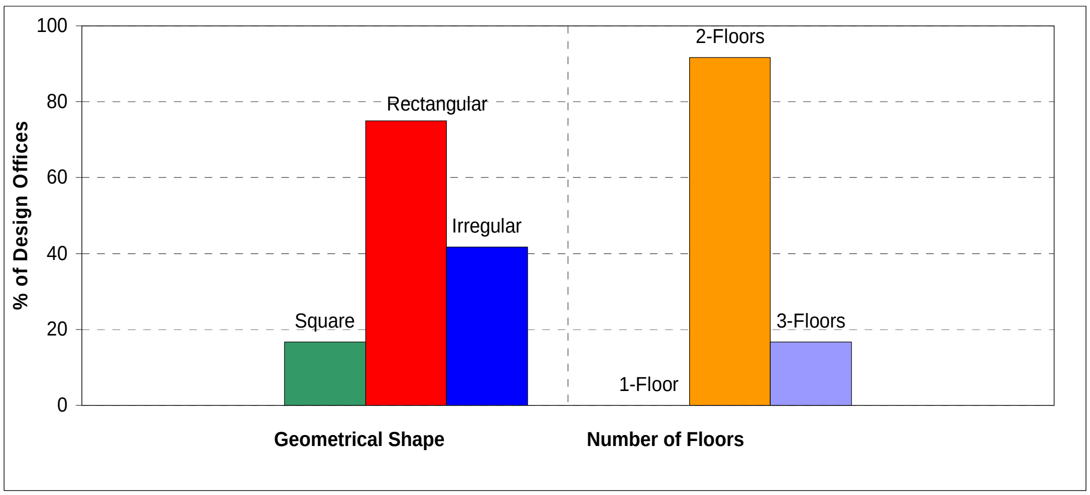
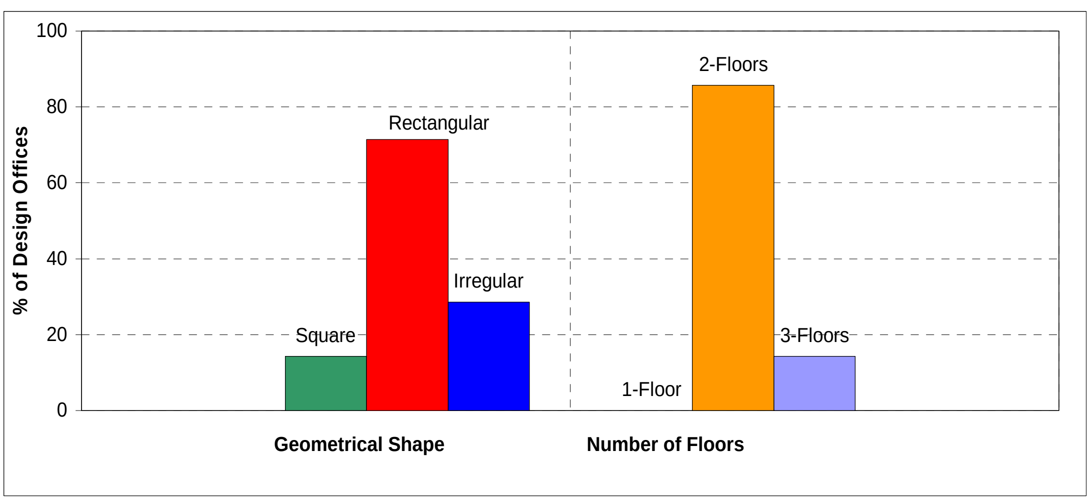


Figure 3.2 Frequency of Category Use and Average Floor Area in **(a)** Dhahran and **(b)** Riyadh

The common geometrical shape and number of floors are presented in **Figure 3.3 (a)** and **(b)**. From these figures, the common geometrical shape in Dhahran and Riyadh is rectangular with a majority of houses are with two floors.



(a)



(b)

Figure 3.3 Geometrical Shape and Number of Floors in Residential Buildings in **(a)** Dhahran and **(b)** Riyadh

3.3.2 Building Envelope Design Parameters

The third major section is divided into four sub-sections covering the main building exterior envelope: wall, roof, type of insulation used, and windows.

3.3.2.1 Wall System Designs

The first sub-section contains the common wall designs and location of thermal insulation relative to the main building material, main building materials normally used in wall designs, exterior finishing and the surface colors. This information is presented in **Figure 3.4** and **Table 3.2**.

From **Figure 3.4 (a)**, the most common wall types that are normally used in the design of single family house in descending order in Dhahran is the single leaf wall (83%), sandwich panel wall (58%), cavity wall (33%), and double walls (17%).The majority of single leaf walls are designed with no insulation and the rest with insulation material located to the exterior or to the interior of the main wall. Cavity walls are also designed with insulation materials that are located to the exterior side of the cavity. Similarly, double leaf walls are design with insulation on the exterior side of the wall.

Similarly in Riyadh as shown in **Figure 3.4 (b)**, the most common wall types that are normally used in the design of single family houses in descending order is the single leaf wall (71%), cavity wall (57%), sandwich panel wall (43%), and double walls (43%). The majority of single leaf and double leaf walls are designed with no insulation. If insulation is used for single leaf walls, then majority will have insulation to the interior and the remaining to the exterior. Double leaf walls are design with insulation on the exterior side of the wall. Cavity walls are also designed with insulation materials that are located to the exterior side of the cavity.

Table 3.2 shows the main building materials, exterior finishing and surface colors that are normally used for wall designs in single family houses in Dhahran and Riyadh respectively. In Dhahran, the main materials used in walls are the concrete masonry units (CMU), clay bricks, cast-in-place and pre-cast concrete and siporex blocks. Hollow CMU are the most widely used material. Design offices also use the hollow CMU with insert-insulation material. Precast and cast-in-place concrete walls are becoming more popular in the design of single family houses. Clay bricks, siporex blocks and stones are the least used building material in wall designs.

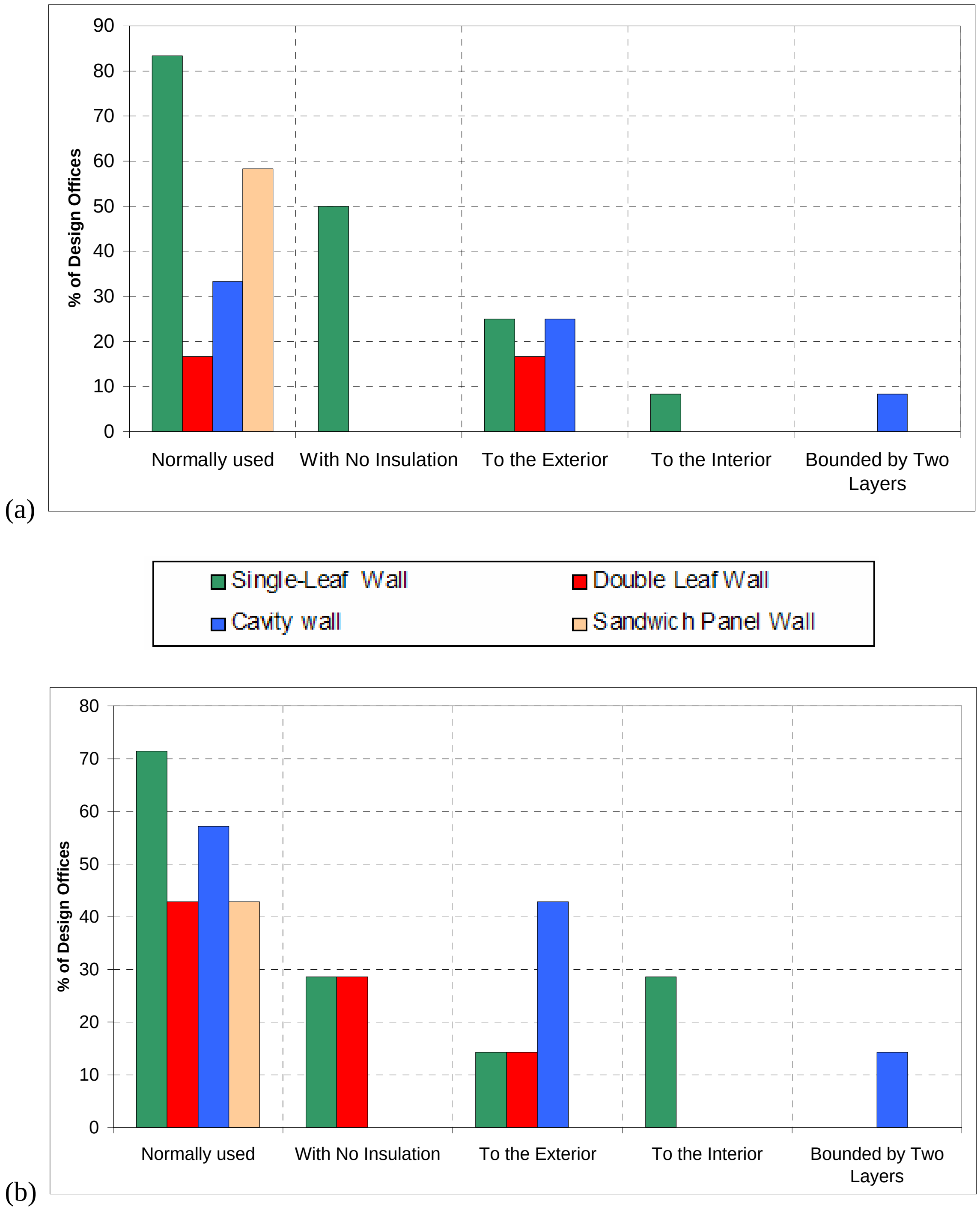


Figure 3.4 Wall Designs and Location of Insulation used by **(a)** Dhahran and **(b)** Riyadh Design Offices

Table 3.2 Main Building Materials, Exterior Finishing and Surface Colors Normally used for Wall Designs in Dhahran and Riyadh

Main Building Material	Dhahran (%)	Riyadh (%)
1. Concrete Masonry Blocks (CMU):		
a. Solid	0	14
b. Hollow	83	14
c. Hollow with insulation material inserts	75	71
2. Aerated Concrete Blocks (e.g. Autoclaved, Siporex)	25	29
3. Clay Bricks		
a. Solid	17	14
b. Hollow	25	14
c. Hollow with insulation material inserts	8	21
4. Reinforced Concrete:		
a. Cast-in-Place	33	100
b. Pre-Cast	58	14
5. Stone	8	29
6. Adobe	0	0
Exterior Finishing for Walls		
1. Cement Plaster (e.g. Stucco)	83	86
2. Stone Veneer	42	71
3. Marble Cladding	17	43
Surface Colors used for Walls		
1. Light Color (white paint)	42	14
2. Medium Color (off-white, cream)	67	100
3. Dark Color (Brown, red or other dark colored paints)	17	0

Similarly in Riyadh**,** the main materials used in walls are the concrete masonry units (solid and hollow), clay bricks (solid and hollow), cast-in place and pre-cast concrete, siporex blocks and stone veneer. Hollow CMU and clay bricks with insert-insulation material are widely used by design offices in Riyadh. In Riyadh, solid CMU and clay bricks, siporex blocks and stones are the least used building material in wall design. For both Dhahran and Riyadh, it is clear from the table that the cement plaster is the most common exterior finishing followed by stone veneer and marble cladding. The walls are normally painted with medium colors.

3.3.2.2 Roof System Designs

The second sub-section details the generic roof designs and location of insulation materials, main building material, flooring or exposed layer of the roof construction, special features of roof systems, and roof's surface colors as shown in **Figure 3.5 and Table 3.3**.

Hourdi slabs are found to be the most widely used roof design in a single family housing in Dhahran (75%) and Riyadh (100%) as shown in **Figure 3.5 (a)** and **(b)**. Pre-cast Hollow core slabs and reinforced concrete slabs are also used in single family houses in Saudi Arabia. In Riyadh, it is noticed that reinforced concrete slabs are more widely used than pre-cast concrete slabs when compared to Dhahran. Hourdi slabs and reinforced concrete slabs are either used with or without insulation. Based on the customer requirement, many design offices offers both hourdi designs: with or without insulation.

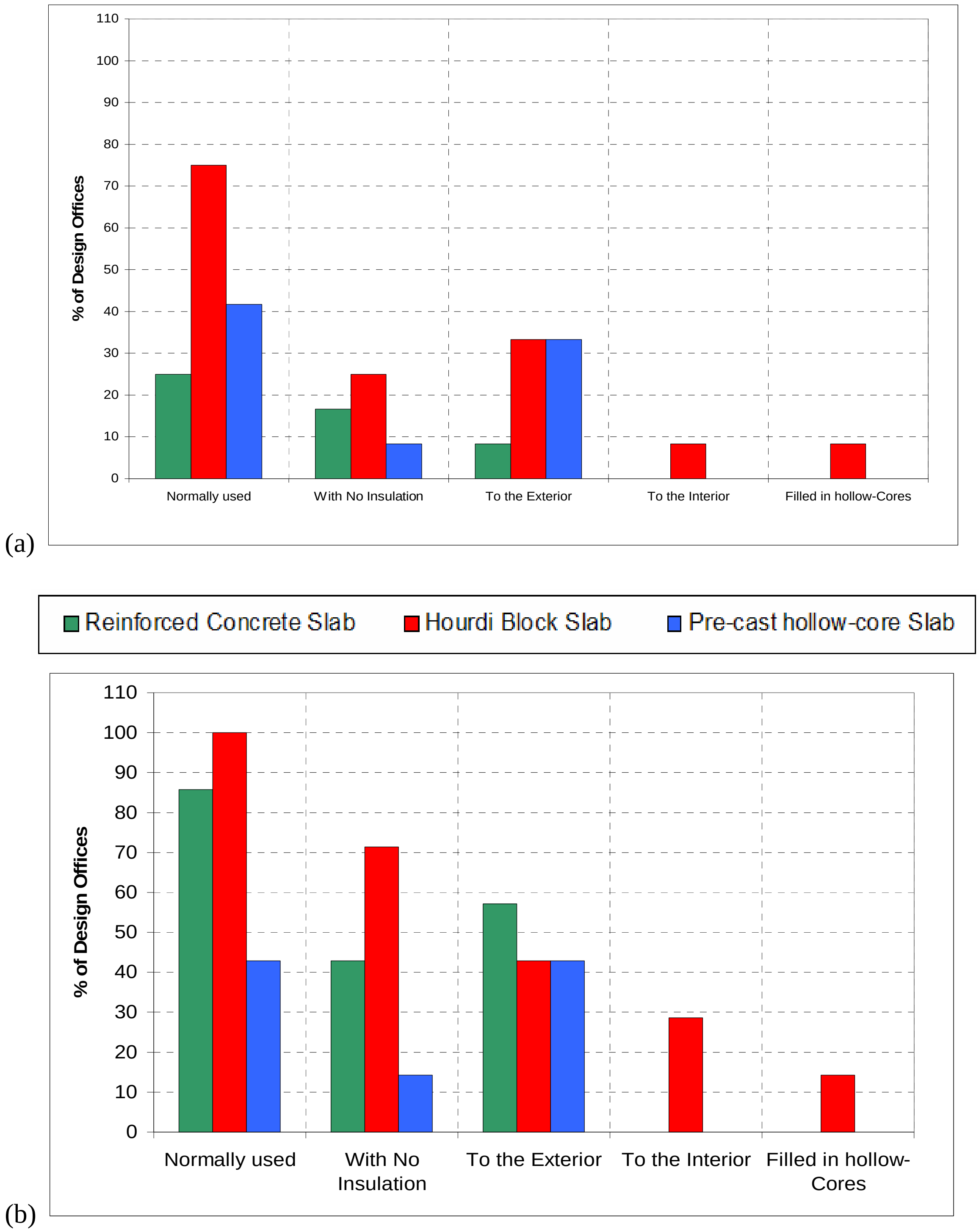


Figure 3.5 Roof Designs and Location of Insulation used by **(a)** Dhahran and **(b)** Riyadh Design Offices

In Riyadh, more than 70% of the designers use hourdi slabs without insulation compared 25% in Dhahran. For hourdi slab in Riyadh, more than 25% of the designers use the insulation materials to the interior of the slab and more than 40% of them to the exterior insulation compared to less than 10% for interior insulation and 30% for exterior insulation in Dhahran. Additionally, insulation materials are filled into the hollow cores of the hourdi blocks. More than 40% of the designers in Riyadh use reinforced concrete slabs without insulation compared to 16% in Dhahran. If insulation material is used for reinforced concrete slab, it is normally placed to exterior of the slab. Pre-cast hollow core slabs are becoming more popular in single family houses as approximately 42% of the designers use them both in Dhahran and Riyadh.

Many building materials can be used in the design of roof systems. **Table 3.3** shows the most common materials, flooring exposed layers, features of roof system and surface colors that are commonly used with the main deck slab in Dhahran and Riyadh. Concrete screeds are used by majority of the designers for roof slope and drainage purposes. Foam concrete and plain concrete (sand/cement) are two types of concrete screeds that are normally used in roof designs. The average layer thickness of foam concrete is 131 mm and 85 mm for plain concrete in Dhahran compared to 73 mm for foam and 85 mm for plain concrete in Riyadh. Hollow CMU and clay bricks are widely used in hourdi slabs. In Dhahran, more than 67% of designers use hollow CMU hourdi blocks for Hourdi slabs compared to 43% of the designers in Riyadh. Hollow clay bricks are used by 29% of designers in Riyadh compared to 17% in Dhahran. More than 8% of designers use siporex panels in the design of roof systems in Dhahran and no designers in Riyadh indicated the use of siporex in their roof system design.

Table 3.3 Main Building Materials, Flooring Layer, Special Features of Roof Design and Surface Colors Normally used for Roof Designs in Dhahran and Riyadh

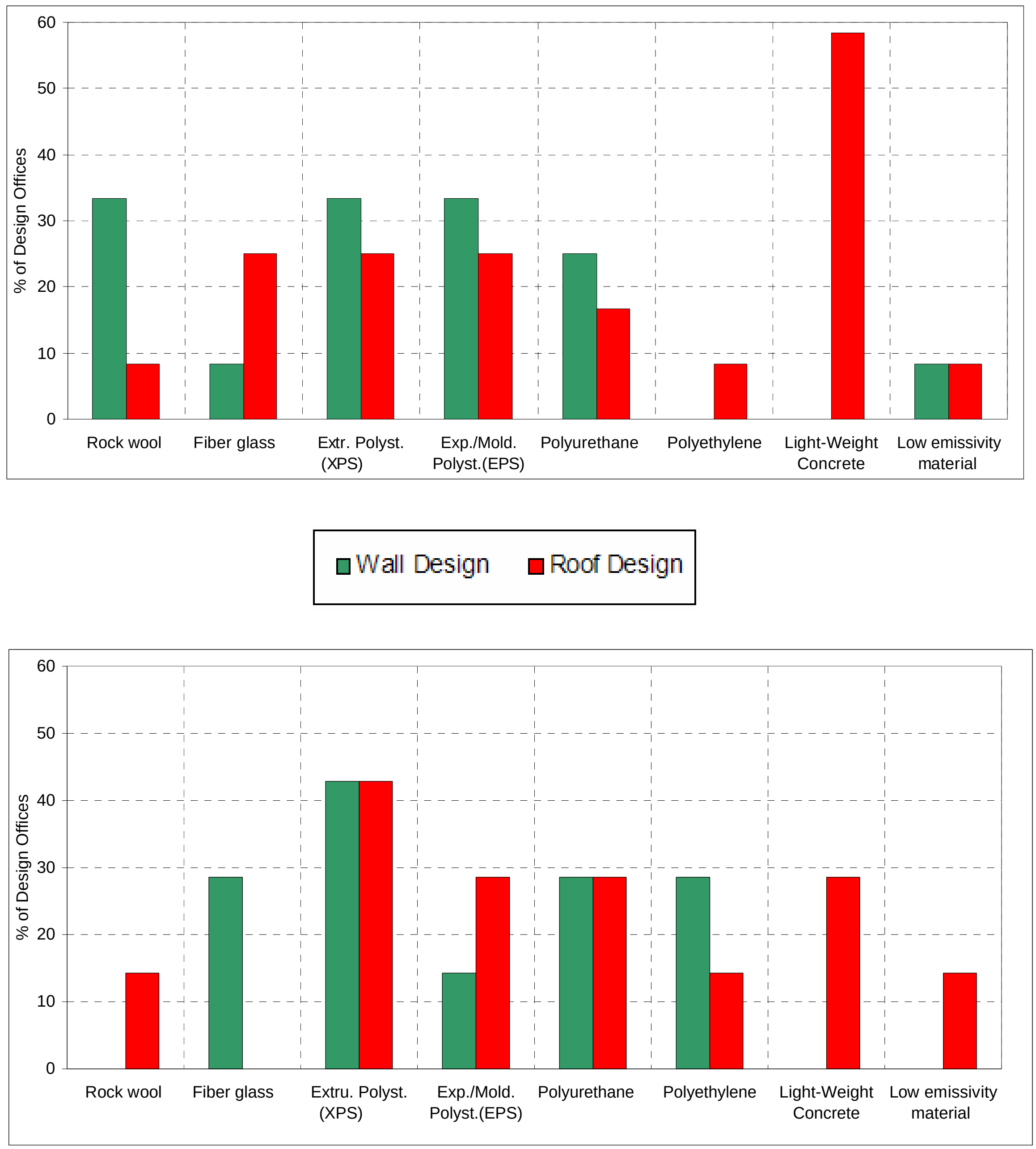
Main Building Material	**Dhahran (%)**	**Riyadh (%)**
1. Sloping Foam Concrete Screed	67	43
2. Sloping Plain (sand/cement) Concrete Screed	50	29
3. Sand Fill	0	14
4. Hollow Clay bricks for hourdi Slab	17	29
5. Hollow CMU blocks for hourdi Slab	67	43
6. Others (Siporex)	8	0
Flooring (Exposed) Layer of the Roof Construction:		
1. Tiles (i.e. Terrazzo, Cement)	83	86
2. Gravel Layer	50	43
3. Soil Layer	0	0
Special Features of Roof System		
1. Shading (e.g. metal corrug. sheets, pergolas)	8	57
2. False Ceiling	67	43
Surface Colors used for Roofs		
1. Light Color (white paint)	42	43
2. Medium Color (off-white, cream)	33	29
3. Dark Color (Roofs with gravel, red tile)	17	29

Cement and terrazzo tiles are widely used as flooring or exposed layer in roof system design as depicted from **Table 3.3** for Dhahran and Riyadh. It is found that a gravel layer with an average thickness of 90 mm is used in Dhahran and 40 mm in Riyadh. In Dhahran, the false ceiling is used by more than 67% of the designers while shading is rarely specified at the design stage. In Riyadh, false ceiling is used by 43% of the designers and shading is common in the design of roof systems in Riyadh where it is used by 57% of the designers. While dark and medium colors are used by less than 33% of the designers for roof system, light colors is used by more than 40% of the designers in Dhahran as well as in Riyadh.

3.3.2.3 Insulation Materials for Walls and Roofs Design

It is found that many types of insulation materials are used in roof and walling system as shown in **Figure 3.6 (a)** and **(b)**. In Dhahran, the most common insulation materials used in walls are ranked in descending order according to its use: Rockwood, Expanded or molded polystyrene, Extruded polystyrene, and Polyurethane. Other insulation materials such as fiberglass, cellulose and low emissivity materials are used by less than 10% of the designers. Wide range of insulation materials are used for roofs. The most usable insulation materials ranked in descending order are lightweight concrete, fiberglass, expanded or molded polystyrene, extruded polystyrene and polyurethane. Other insulation materials are used by less than 10% of the designers in Dhahran. It is found that the allowable air gap that is normally used in cavity walls is 53 mm. Only two design offices in Dhahran mentioned the required minimum thermal resistance (R-Value) value for both walls and roof which are 1.35 m^2. °C/W and 1.75 m^2. °C/W for wall and roof design respectively.

(a)



(b)

Figure 3.6 Insulation Materials used for Wall and Roof System Design in **(a)** Dhahran and **(b)** Riyadh

In Riyadh, the most common insulation materials used in walls are ranked in descending order according to its use: extruded polystyrene, fiberglass, polyurethane, polyethylene and expanded or molded polystyrene. Other insulation materials are not used by the designers in Riyadh. The most usable insulation materials in Roofs are ranked in descending order: extruded polystyrene expanded or molded polystyrene, polyurethane and lightweight concrete. Other insulation materials are used by less than 15% of the designers. In Riyadh, it is found that the allowable air gap that is normally used in cavity walls is 40 mm. None of the design offices in Riyadh indicated any requirement of wall or roof resistance value.

3.3.2.4 Fenestration System Designs

The physical characteristics of windows including the windows and glazing types are listed in **Table 3.4**. In Dhahran, single and double clear glazing are the most widely used by the designers while single and double tinted, and double low-e glazing are the second widely used. Exterior shadings are rarely used by the designers. Only two designers have specified the exterior shadings where side fin and overhang projections are 200 mm and 400 mm respectively. The average window to wall ratio (WWR) is found to be 21%.

In Riyadh, single clear and tinted, double clear and tinted glazing are the most widely used by the designers while double low-e glazing and triple clear glazing are the secondly used glazing. It is observed that the designers in Riyadh also use triple glazing and high performance glazing. None of the designers in Riyadh use the exterior shadings for windows. The average window to wall ratio (WWR) is found to be 20%. Majority of designers in Riyadh (85%) and Dhahran (100%) use operable windows in residential buildings compared to only 17% of designers use fixed windows in Dhahran.

Table 3.4 Physical Characteristics of Windows normally used in Residential Buildings in Dhahran and Riyadh

Glazing Types	**Dhahran (%)**	**Riyadh (%)**
1. Single-glazed layer:		
a. Clear	42	43
b. Bronze/Gray/Green Tint	33	43
2. Double-glazed layers:		
a. Clear	67	43
b. Bronze/Gray/Green Tint	50	43
c. Low-e with High-Solar-Gain (Pyrolitic or hard coat Low-E glass)	17	29
d. Low-e with Moderate-Solar-Gain, (Sputtered or soft-coat products)	0	0
e. Low-e with Low-Solar-Gain, (Spectrally Selective)	0	14
3. Triple-glazed layers:		
a. Clear	0	29
b. Low-e	0	14
4. Average Window-to-Wall Ratio (WWR)	21	20
5. Types Of Windows:		
a. Operable Windows	100	86
b. Fixed Windows	17	0

3.3.2.5 Air Leakage and Lighting Requirements

Section four of the questionnaire has examined the level of air leakage and measures that are taken to control the leakage rate and lighting requirements as shown in **Table 3.5**. Majority of the designers in Dhahran (67%) as well as Riyadh (71%) feel that their buildings are air-tight as many control measures are applied. Air barrier are not used in walls or roof in Dhahran compared to 28% of the designers in Riyadh who indicated that they are using air barrier in wall design. It is found that designers in Dhahran and Riyadh use air infiltration reduction measures such as weather stripping, caulking and gaskets for windows and doors. However, designers in Dhahran feel that no systematic measures are currently followed to control air infiltration. Designers use three main sources of lighting in residential buildings: fluorescent, incandescent and energy efficient lamps. In Dhahran, more than 92% of the designers use fluorescent lamps, 42% use incandescent and 8% use energy efficient lamps. In Dhahran, the average lighting power density (LPD) in a single family house is 18 W/m^2. In Riyadh, more than 86% of designers use fluorescent lamps, 43% use incandescent and 29% use energy efficient lamps with an average lighting power density (LPD) of 13 W/m^2.

Table 3.5 Air Leakage and Lighting Requirements in Residential Buildings in Dhahran and Riyadh

	Dhahran (%)	**Riyadh (%)**
Level Of Air Tightness		
a. Air Tight	67	71
b. Average Tight	33	43
c. Air Loose	0	0
Measures to Reduce Air Leakage		
a. Air barrier are installed in walls and roofs	0	29
b. Weather-stripping is used in windows and doors	67	43
c. Caulking and gaskets are used in windows and doors	67	43
d. None is used	8	0
Lighting Requirements		
a. Fluorescent lamps	92	86
b. Incandescent lamps	42	43
c. Energy efficient lamps	8	29
Lighting Power Density (LPD) W/m^2	18	13

3.4 Internal Loads and their Profile in Residential Buildings

Internal heat gain emitted by people, lighting and appliances has a significant impact on total heat load and consequently energy consumption. Additionally, the occupant's activities and their schedule, lighting and equipment operation profiles have all to be determined for the whole building simulation. For the purpose of this study, the number of people, their schedules and activity, lighting and appliances and their operation schedules will be based on previous energy studies of residential buildings in Saudi Arabia **(Aftab and Elhadidy 2002, Said and Abdelrahman 1989, Al-Maziad 1999 and Ahmed 1991)**. **Table 3.6** summarizes the internal loads that have been used in previous energy simulation studies.

All previous simulation studies have agreed on the average number of individuals of a Saudi's family which is in the range of 6 members. These studies have also assumed the lighting and equipment power density in the range of 10-22 W/m^2 and 1.6-32 W/m^2 respectively. Although no survey studies have been conducted to confirm the above figures, a recent case study on a one floor single family house in Dhahran has indicated that the lighting load is in the range of 11 W/m^2 and equipment load varies from 26 to 46 W/m^2 **(Al-Mofeez, 2002)**. Although the survey results in this study has shown that on average the lighting power density (LPD) is 18 W/m^2 in Dhahran and 12 W/m^2 in Riyadh, it is indicated by many architectural firms that they use 4 fluorescent Lamps (4 x 40 Watts) in a room of 4m x 4m (16 m^2). This is equivalent to a lighting power density

(LPD) of 10 W/m^2 for living zone. Considering 80% of this level in the sleeping zone will give a LPD of 8 W/m^2. This level is found appropriate for the simulation of the typical residential buildings.

The schedules of occupancy, lighting and equipment are difficult to determine in residential buildings. The previous studies have assumed a representative schedules based on their personal experience or a logic judgment with the exception of **Al-Maziad (1999)** who did a field questionnaire. Many of these assumptions have agreed well for the nighttime schedule. However, the main difference appears in the morning, afternoon and evening times where different activities are performed.

3.5 Development of the Base Case Residential Building

Based on the survey results, it is found that the architectural design of residential buildings in Dhahran and Riyadh is similar. However, the only difference found is the type of walling system that is commonly used in these two cities. In Dhahran, the most widely used wall design in Residential buildings is the single CMU hollow block compared to CMU hollow block with insert insulation material in Riyadh. **Table 3.7** shows the architectural system characteristics of residential building in Dhahran and Riyadh based on the survey results as well as literature review for the lighting and mechanical systems. Based on the literature, representative schedules for occupancy, lighting, equipment profile are shown in **Table 3.8** for both living and sleeping zones.

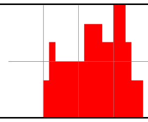
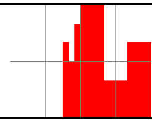
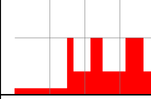
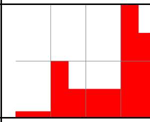
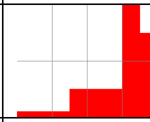
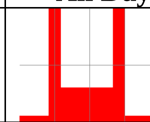
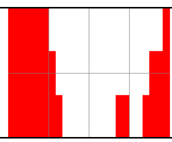
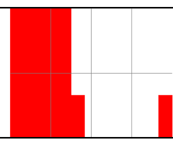
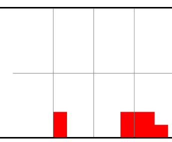
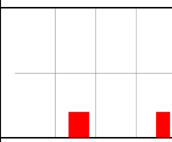
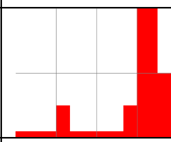
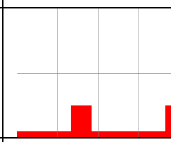
Table 3.6 People, Lighting and Equipment Profile used in Energy Simulation for Residential Buildings in Saudi Arabia

		Type of Internal Load		
Reference	Schedule	People	Lighting (W/m^2)	Equipment(W/m^2)
(Aftab and Elhadidy, 2002)		6 people	19	11.4
	Week-Days	100%(1h-7h), 50% (8h-12h), 100% (13h) , 50% (14h-16h), 100%(17h-19h), 80% (20h-22h), 100%(23h-24h)	5%(1h-6h), 30% (7h), 10% (8h-17h), 90% (18h-19h), 70% (20h-22h), 5% (23h-24h)	5%(1h-6h), 50% (7h), 30% (8h-17h), 60% (18h-20h), 15% (21h-24h)
	Week-Ends	100%(1h-7h), 50% (8h-12h), 100%(13h), 90% (14h-16h), 10% (17h-20h) , 100% (21h-24h)		
(Said and Abdelrahman, 1989)	Schedule	6 people	19	1.6
	Week-Days	100%(1h-7h), 50% (8h-12h), 100%(13h), 50% (14h-16h), 100%(17h-19h), 80% (20h-22h), 100%(23h-24h)	10%(1h-6h), 40% (7h), 10% (8h-17h), 90% (18h-19h), 70% (20h-22h), 10%(23h-24h)	5% (1h-6h), 50% (7h), 30% (8h-17h), 60% (18h-20h), 20% (21h-24h)
	Week-Ends	100%(1h-7h), 50% (8h-12h), 100%(13h), 90% (14h-16h), 10% (17h-20h) 100% (21h-24h)		
(Al-Maziad, 1999)	Schedule	6 people	10	32
	Week-Days	100%(1h-6h), 50% (7h-12h), 80%(13h-14h), 100%(15h-16h), 80%(17h-21h), 100% (22h-24h)	10% (1h-6h), 30% (7h), 20% (8h-17h), 60% (18h-19h), 50% (20h-22h), 40% (23h-24h)	15% (1h-6h), 50% (7h), 15% (8h-10h), 60% (11h-12h), 15% (13h-20h), 50% (21h), 15% (22-24)
	Week-Ends	100%(1h-9h), 75% (10h-11h), 100% (12h-15h), 10% (16h-19h), 80% (20h-23h), 100% (24h)		
(Ahmed, 1991)	Schedule	7 people	22	15
	Week-Days	90% (1h-7h), 50%(8h-12h), 75%(13h-17h), 100% (18h-24h)	5% (1h-5h), 50% (6h-9h), 25% (10h-17h), 100%(18h-20h), 75%(21h-23h),50%(24h)	0% (1h-5h), 50% (6h-17h), 100%(18h-22h), 30%(23h-24h)
	Week-Ends	90% (1h-8h), 50%(9h-21h), 100% (22h-24h)	5% (1h-6h), 40% (7h-17h), 100%(18h-24h)	0% (1h-6h), 70% (7h-17h), 100%(18h-24h)

Table 3.7 Characteristics of Architectural System for the Typical Single-Family Residential Building in Dhahran and Riyadh

Characteristics	**Description of the Base Case**
Location	Dhahran (26.27 N latitude, 50.15 E longitude, and 17m above sea level), Riyadh (24.72 N latitude, 46.72 E longitude, and 612 m. above sea level),
Orientation	Front Elevation facing East
Plan Shape	Rectangular
Number of floor	Two
Floor to Floor Height	3.5 m (7.0 m for the two floors)
Floor Area	300 m^2
Floor Dimension	15 x 20 m
Gross Wall Area	490 m^2
Window Area	20% of the gross wall area (98 m^2), Uniformly Distributed
Type of Glass	6 mm Single glazing
Solar Absorbance (for Exterior Surfaces)	0.55 for external walls (medium color) 0.35 for the roof (light color)
Exterior Walls	**Dhahran:** 15mm Stucco + 200 mm CMU Hollow Block + 15mm Stucco (with no Insulation) **Riyadh:** 15mm Stucco + 200 mm CMU Hollow Block (with insulation insert material) + 15mm Stucco
Roof	Tiles + 10 mm Mortar + 4 mm Membrane + 100mm LWC + 200 mm Hourdi Slab + 15 mm Cement Plaster
Floor	100 mm slab on grade
Occupancy Density	6 People
Lighting Power Density	10 W/m^2 (lower level), 8 W/m^2 (higher level)
Equipment Power Density	12 W/m^2 (lower level), 5 W/m^2 (higher level)
Infiltration	0.5 ACH (Airtight)
System Type	Residential System (Constant-Volume DX AC) with Electric Heating
Thermostat	Two-Position with Cooling & Heating
Thermostat Setting	25ºC for Cooling, 21ºC for Heating
COP	2.87
Weather File	Dhahran:2002, Riyadh: TMY (1983-1999)

Table 3.8 Occupancy, Lighting, Equipment and Domestic Hot Water Profiles for Living and Sleeping Zones in Residential Buildings

	Occupancy		**Home Appliances**		**Lighting**		**Hot Water**
	Weekdays	**Weekends**	**Weekdays**	**Weekends**	**Weekdays**	**Weekends**	**All Days**
Living Area							
	0% (23h-5h), 33% (6), 67% (7h), 50% (8h-12h) , 83% (13h-15h), 67% (16h-17h), 100% (18h-19h), 67% (20h), 33% (21-22h)	0% (24h-8h), 67% (9h), 50% (10h), 83% (11h), 100% (12h-15h) , 33% (16h-19h), 67% (20h-23h)	5% (23h-5h), 50% (6h-7h), 20% (8h-10h) , 50% (11h-12h), 20% (13h-18h) , 50% (19h-20h), 10% (21h-22h)	5% (24h-8h), 50% (9h), 20% (10h-12h) , 50% (13h-14h), 20% (15h-18h) , 50% (19h-21h), 20% (22h-23h)	5% (23h-5h), 50% (6h-8h), 25% (9h-17h) , 100% (18h-20h), 75% (21h-22h)	5%(1h-8h), 25% (9h-17h), 100% (18h-20h), 75% (21h-23h)	5%(18h-4h), 100% (5h-6h), 30% (7h-15h) , 100% (16h-17h)
Sleeping Area							
	100% (23h-5h), 67% (6), 33% (7h), 0% (8h-15h) , 33% (16h-17h), 0% (18h-19h), 33% (20h), 67% (21-22h)	100% (24h-8h), 33% (9h-10h), 0% (11h-21h), 33% (22h-23h)	0% (23h-5h), 20% (6h-7h), 0% (8h-15h) , 20% (16h-20h), 10% (21h-22h)	0% (23h-7h), 20% (8h-10h), 0% (11h-20h) , 20% (21h-22h),	5% (23h-5h), 25% (6h-7h), 5% (8h-15h) , 25% (16h-17h), 100% (18h-20h), 50% (21h-22h)	5% (24h-7h), 25% (8h-10h), 5% (11h-21h) , 25% (22h-23h),	

3.6 Selection of Building Envelope for Energy Simulation in Residential Buildings

From the questionnaire survey, a series of possible wall types that are normally used in the design practice of residential buildings in Saudi Arabia has been generated. This list consists of more than 202 possible wall designs with a variety of building materials and using many thermal insulation types and thicknesses. The thermal resistance and the thermal mass (heat capacity) of these walls and roofs designs are determined using the VisualDOE and listed in APPENDIX-B. The thermal characteristics of possible wall designs are shown in **Figure 3.7**.

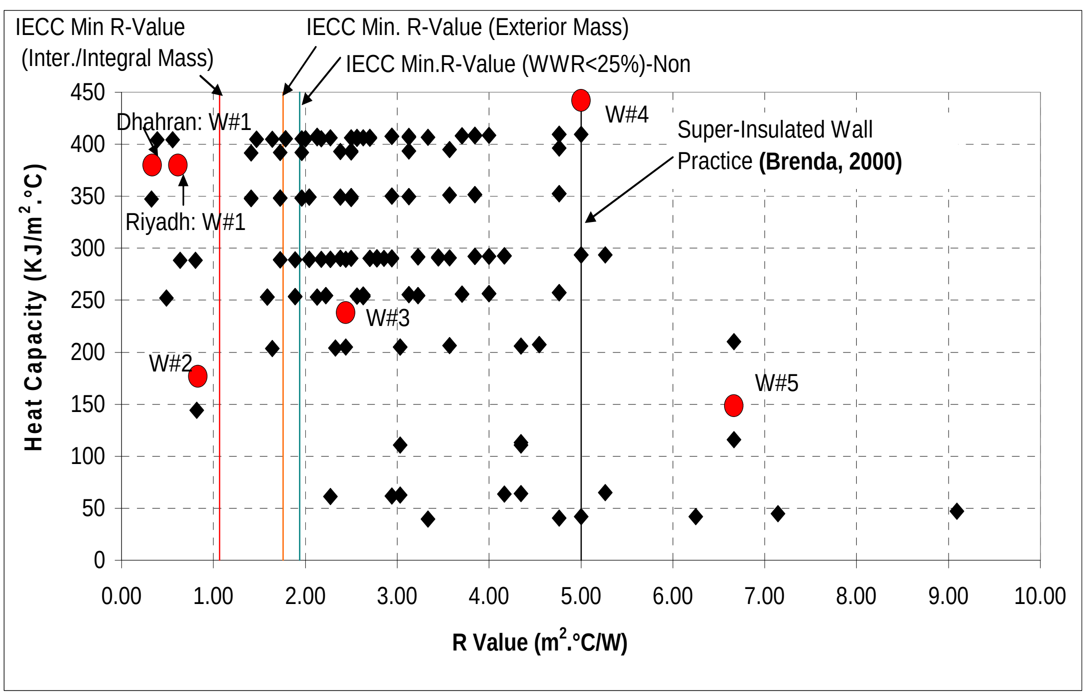


Figure 3.7 Thermal Resistance & Heat Capacity for Possible Wall Assemblies

The figure also shows the minimum requirement for thermal resistance for walls assembly with various window-to-wall ratio based on International Energy Conservation Code and the super-insulated wall design based on literature **(IECC, 2000 & Brenda, 2000)**. These figures are taken as a reference benchmark to the survey results.

In order to simulate walls that have different thermal characteristics, the generated wall designs have been categorized based on their thermal mass and thermal resistance. According to their thermal mass, walls are categorized into three levels: light thermal mass which have heating capacity from 0 to150 kJ/m^2.ºC, medium thermal mass which have a heating capacity from 150 to 300 kJ/m^2.ºC, and heavy thermal mass which have a heating capacity from 300 to 450 kJ/m^2.ºC. Furthermore, the categorized walls are classified according to their thermal resistance based on the IEEC minimum R-value into: low thermal resistance walls that have R-value from 0 to 1.066 m^2.ºC/W, standard thermal resistance walls that have R-value from 1.066 to 5 m^2.ºC/W and super insulated walls that have R-value of more than 5 m^2.ºC/W. **Table 3.9** shows the categories of the generated wall designs according to their thermal characteristics.

Table 3.9 Categorization of Generated Wall Designs in Saudi Arabia

Thermal Mass (kJ/m^2.ºC) / Thermal Resistance (m^2.ºC/W)	0-150 (M1)**	150-300 (M2)	300-450 (M3)
0-1.066 (R1) *	1	3	3
1.066-5 (R2)	10	85	88
Above 5 (R3)	6	5	1

Notes:
* R1, R2 and R3 represent the level of thermal resistance
** M1, M2 and M3 represent the level of thermal mass

For the purpose of this study, five walls are selected to represent the wide range of the thermal characteristics of wall systems. The selected walls are shown in **Figure 3.17** and their thermal characteristics are listed in **Table 3.10**.

Table 3.10 Representative Wall Designs for Energy Simulation in Residential Buildings

Wall No.	Wall Description	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	Heat Capacity ($KJ/m^2.°C$)	RSI
W#1	**Dhahran:** Single 200 mm Hollow CMU Wall+ No insulation+ 15 mm Stucco finishes on both sides	2.98	0.34	379.97	2
	Riyadh: CMU with insulation material insert	1.63	0.61	379.97	3.59
W#2	Single 245 mm Siporex Wall+ No insulation+ 15 mm Stucco finishes on both sides	1.2	0.83	176.93	5
W#3	50 mm Precast Concrete Panel on both sides+ 50 mm Polyurethane + + 15 mm Stucco on both sides	0.41	2.44	237.78	14
W#4	Cavity Hollow CMU Block Wall+50 mm Air Space+ 100 mm Polyurethane (ext)+15 mm Stucco finishes on both sides	0.2	5.00	442.18	28
W#5	75 mm Polyurethane on both sides+ 50 mm Precast Concrete + 15 mm Stucco finishes on both sides	0.15	6.67	148.58	38

Similarly, many roof assemblies have been generated using the basic main building materials that are normally used in the design practice of residential buildings in Saudi Arabia. The list consists of more than 62 roof assemblies. The thermal resistance and heat capacity of generated roof designs are calculated using the VisualDOE and presented in **Figure 3.8**.

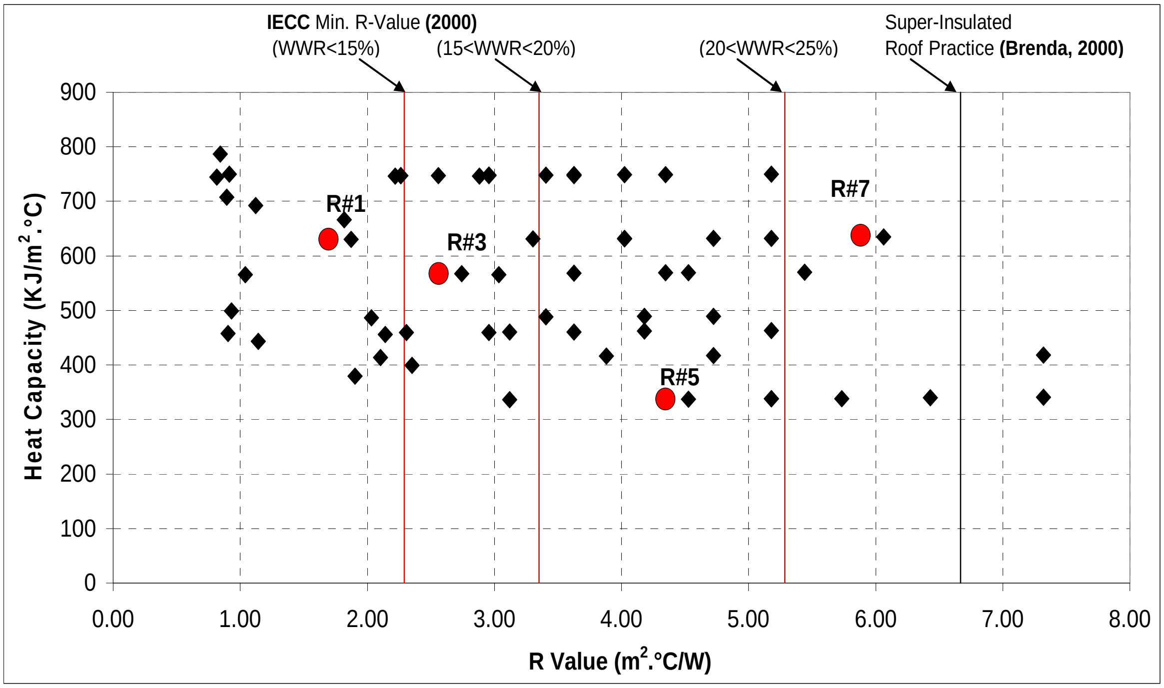


Figure 3.8 Thermal Resistance & Heat Capacity for Possible Roof Assemblies

A similar procedure is also applied to roofs for the purpose of simulating a representative sample of roof assemblies. The roof assemblies have been categorized based on their thermal mass and thermal resistance as listed in **Table 3.11**. According to their thermal mass, roofs are categorized into three levels: light thermal mass which have heating capacity from 0 to 300 kJ/m^2.C, medium thermal mass which have a heating capacity from 300 to 600 kJ/m^2.C and heavy thermal mass which have a heating capacity from 600 to 900 kJ/m^2.C. Furthermore, the categorized walls are classified according to their thermal resistance in to: low thermal resistance walls that have R-value from 0 to 2.3 m^2.ºC/W, standard thermal resistance walls that have R-value from 2.3 to 6.67 m^2.ºC/W and super insulated walls that have R-value of more than 6.67 m^2.ºC/W.

Table 3.11 Categorization of Generated Roof Designs in Saudi Arabia

Thermal Mass (kJ/m².ºC) / Thermal Resistance (m².ºC/W)	0-300 (M1)**	300-600 (M2)	600-900 (M3)
0-2.3 (R1)*	0	8	10
2.3-6.67(R2)	0	24	18
Above 6.67(R3)	0	2	0

Notes:
* R1, R2 and R3 represent the level of thermal resistance
** M1, M2 and M3 represent the level of thermal mass

For the purpose of this study, four roofs are selected to represent the wide range of the thermal characteristics of roof systems. The selected roofs are shown in **Figure 3.25** and their thermal characteristics are listed in **Table 3.12**.

A combination of 4 roof designs and 5 wall designs make 20 possible designs. Some of this combination is not practical or the variation in the thermal characteristics is not wide. Therefore, only 8 envelope designs are considered for further study. **Table 3.13** shows the 8 represented envelope designs that are used for further analysis study and analysis. Some of the selected wall designs **(Table 3.10)** and roof designs **(Table 3.12)** for energy simulation in Dhahran and Riyadh meet the minimum requirements for thermal insulation. According to International Energy Conservation Code **(IECC, 2000)** and Gulf Council Countries thermal insulation regulation **(GCC, 1984)**, the thermal insulation requirements for building envelope in hot climates with Heating Degree Day 0-499 (Riyadh: 263, Dhahran: 178) are listed in **Table 3.14**.

Table 3.12 Representative Roof Designs for Energy Simulation in Residential Buildings

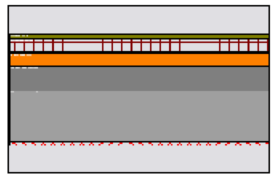
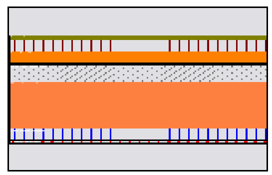
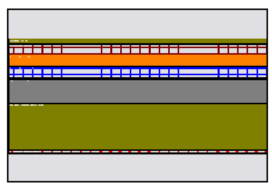
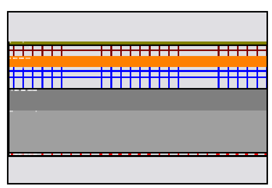
Roof No.	Roof Description	Roof Design	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	Heat Capacity ($KJ/m^2.°C$)	RSI
R#1	15 mm Cement plaster +200 mm CMU Hourdi Slab+ 100mm Foam Conc.+4 mm water proof membrane+ 25 mm Sand Fill+ 50mm Mortar +Terrazzo		0.59	1.69	629.83	10
R#3	15 mm Cement plaster+ 50 mm Ext Polystyrene+ 200 mm Clay Brick Hourdi + 100 mm Plain Concrete+4 mm water proof membrane+ 25mm Sand+ 50 mm Mortar+ Tiles		0.39	2.56	567.13	15
R#5	15 mm Cement plaster+200 mm Siporex Hourdi + 100 mm Foam Concrete+ 50 mm Exp Polystyrene +4 mm water proof membrane+ 25mm Sand+ 50 mm Mortar+ Tiles		0.23	4.35	337.03	25
R#7	15 mm Cement plaster+200 mm CMU Hourdi Slab + 100 mm Foam Concrete+ 100 mm Polyurethane +4 mm water proof membrane+ 25mm Sand+ 50 mm Mortar+ Tiles		0.17	5.88	637.91	35

Table 3.13 Representative Envelope Designs for Energy Simulation in Residential Buildings in Saudi Arabia

Design #	Design Description	Qualitative Thermal Resistance	Qualitative Thermal Mass	Remark
Design #1	Wall #1	Poorly Insulated	High Mass	Base Case Scenario (Dhahran)*
	Roof#1	Poorly Insulated	High Mass	
Design #4	Wall#1	Poorly Insulated	High Mass	
	Roof#7	Highly Insulated	High Mass	
Design #6	Wall#2	Poorly Insulated	Low Mass	
	Roof#5	Medium Insulated	Medium Mass	
Design #7	Wall#3	Standard Insulated	Medium Mass	
	Roof#1	Poorly Insulated	High Mass	
Design #9	Wall#3	Standard Insulated	Medium Mass	
	Roof#7	Highly Insulated	High Mass	
Design #10	Wall#4	Highly Insulated	High Mass	
	Roof#1	Poorly Insulated	High Mass	
Design #13	Wall #5	Super-Insulated	Low Mass	
	Roof#3	Standard Insulated	High Mass	
Design #15	Wall#5	Super-Insulated	Low Mass	
	Roof#7	Highly Insulated	High Mass	

* For Riyadh: Wall#1 is CMU Hollow Block with insulation insert Material.

Table 3.14 Thermal Insulation Requirements for Building Envelope in Hot Climates (HDD: 0-499) **(IECC 2000 & GCC 1984)**

Heating Degree Days @ 18°C	**I**nternational **E**nergy **C**onservation **C**ode **(IECC, 2000)**				**GCC Thermal Insulation Regulation (1984)**
	WWR ≤15%	15<WWR ≤18%	18<WWR ≤20%	20<WWR ≤25%	NA
Maximum Glazing U-Value	Any	0.8	0.8	0.7	NA
Minimum Ceiling R-Value	R-13* (2.29 m^2.ºC/W)	R-19 (3.35 m^2.ºC/W)	R-19	R-30 (5.283 m^2.ºC/W)	1.75 m^2.ºC/W
Minimum Wall R-Value	R-11 (1.94 m^2.ºC/W)	R-11	R-11	R-11	1..35 m^2.ºC/W
Minimum Floor R-Value	R-11 (1.94 m^2.ºC/W)	R-11	R-11	R-11	NA
Massive Wall Assembly R-Value					
Interior or Integral Mass	R-3.8 (0.67 m^2.ºC/W)	R-6 (1.066 m^2.ºC/W)	R-6	R-6	NA
Exterior Mass	R-9.7 (1.71 m^2.ºC/W)	R-10	R-10	R-10	NA

* R-value *0.1761=R (SI); U-value*5.687=U (SI)

CHAPTER FOUR

INDOOR TEMPERATURE BEHAVIOR AND COMFORT CONDITIONS FOR NON-CONDITIONED RESIDENTIAL BUILDINGS

4.1 Introduction

Indoor thermal environment is one of the main important characteristics of buildings. A comfortable thermal environment is a prerequisite for a human to perform his day to day activities. In traditional buildings, a comfortable environment was solely achieved by utilizing a proper combination of building materials and natural resources. The availability of cheap energy resources and the lack of energy codes have promoted building houses with ineffective envelope designs and without considering the utilization of natural resources. This has resulted in a complete reliance on the mechanical means to manipulate the indoor temperature and finally achieve the thermal comfort at high energy consumption. Thus, it is important to evaluate the dynamic behavior of different envelope designs under different ventilation strategies to properly select the combination that minimize the dependence on mechanical means and reducing the energy consumption.

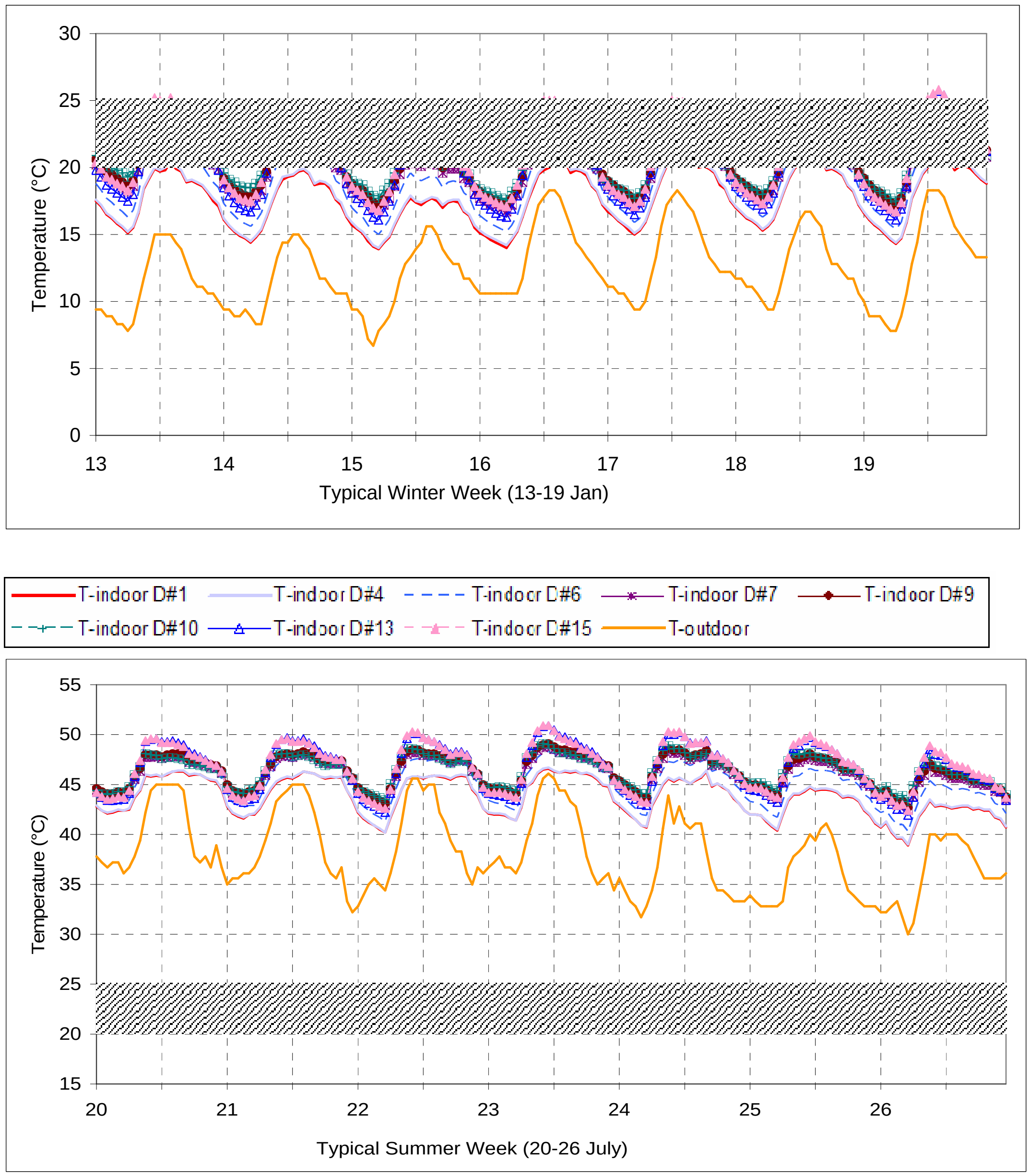
4.2 Performance Indicators for Building Thermal Evaluation

Selecting a proper performance indicator to evaluate the effectiveness of a specific design strategy is an important activity. While the objective of using different performance indicators is the same, many performance indicators were quoted in literature. In the following sections, potential performance indicators are discussed.

4.2.1 Representative Summer and Winter Week

In many studies, a representative winter/summer week or day is used to evaluate the condition of indoor air temperature and compared to international standards on the thermal comfort zones (i.e. over-heated or under-cooled). This method is a good indicative tool to assess the thermal performance of buildings in a well characterized and stable climate. In this study, the winter and summer weeks were initially used to evaluate the performance of building envelopes. Utilizing the Dhahran weather data of year 2002 and using VisualDOE weather summary data, a summer week was identified from 20-26 July and a winter week from 13-19 January. A base case unconditioned residential building design in Dhahran is used to illustrate the use of this method. **Figure 4.1 (a)** and **(b)** show a typical week of summer/winter. From this figure, it is noticed that the performance of building envelopes depends on outdoor temperature as well as the internal generated heat within the space. In winter, the indoor air temperature for the poorly insulated designs: D#1 and D#4 is below the minimum thermal comfort zone.

(a)



(b)

Figure 4.1 Indoor Air Temperatures for **(a)** Typical Extreme Winter Week (13-19 Jan) and **(b)** Typical Extreme Summer Week (20-26 July) in a Non-Conditioned Residential Building in Dhahran

On contrary, the super insulated designs: D# 13 and D#15 are overheated during the noon time. Other building designs (the standard designs: D#6, #7, #9 and #10) are within the thermal comfort zones during the day. All designs are below the thermal comfort zones during the night time. In summer, the poorly insulated designs: D#1 and D#4 perform better in terms of their indoor air temperature when compared to super-insulated and standard insulated designs. The super-insulated designs (D#13 & D#15) have achieved the highest indoor air temperature. However, it is known that the super-insulated designs perform better in summer compared to the other designs when mechanical systems are used. According to this method, the mechanical means is needed in both summer and winter weeks to achieve the thermal comfort. This method can be better utilized when the indoor temperature swings below and above the thermal comfort zone under natural condition when the climate is stable throughout the year.

4.2.2 Mean Hourly Indoor Air Temperature

This method has been mostly used in literature to evaluate the thermal comfort under different conditions. It helps to make a quick and simple performance evaluation of buildings. However, much information is not clear especially when peak indoor air temperature occurs. For example, if the indoor air temperature of a space in two weeks of a month is within the thermal comfort zones and above or below the limit in the other two weeks of the month, then the average value will either be below or above the desired range of thermal comfort. **Figure 4.2** shows the average hourly of the indoor air temperature of the typical residential building under Dhahran climate for sample months.

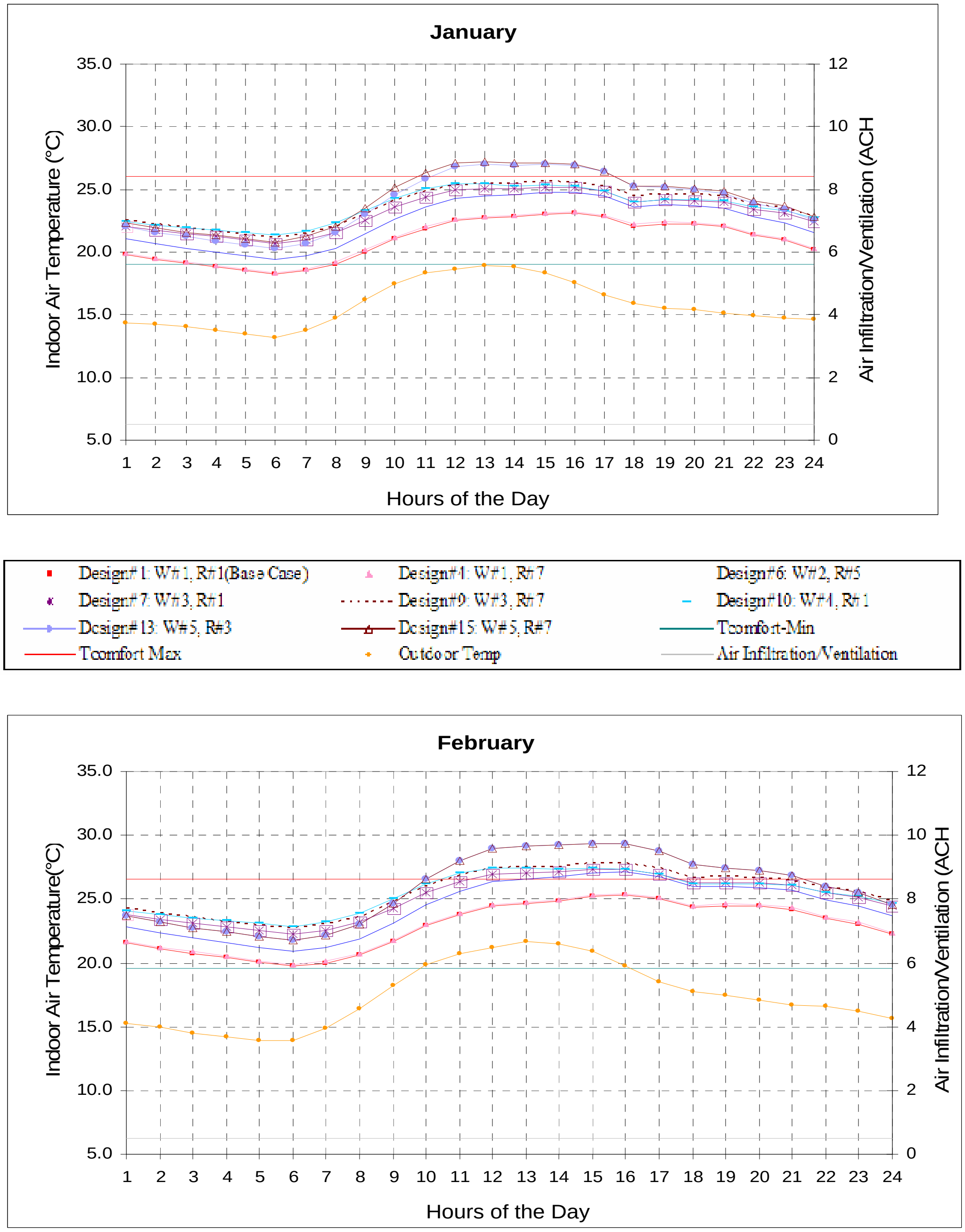


Figure 4.2 Average Hourly Indoor Air Temperatures in a Non-Conditioned Residential Building in Dhahran

This figure gives the flexibility to treat every month separately and therefore propose dynamic strategies throughout the year for the evaluated envelope design. This method is primarily used in this study to evaluate and identify different ventilation strategies and therefore the schedules of introducing the outside air for cooling. In this case, the hourly indoor air temperature of the first hour is averaged for the whole month.

4.2.3 Cumulative Temperature Difference and the Comparison to Energy Performance

The cumulative temperature difference between the indoor air temperature in a naturally operated building and the thermal comfort temperature should be directly related to the amount of cooling and heating energy required to achieve thermal comfort when mechanical system is used. The area under the curve represents the cooling and heating temperature difference as shown in **Figure 4.3**. This area should be compared to the amount of the energy required to bring the indoor air temperature to the level of cooling or heating setting point.

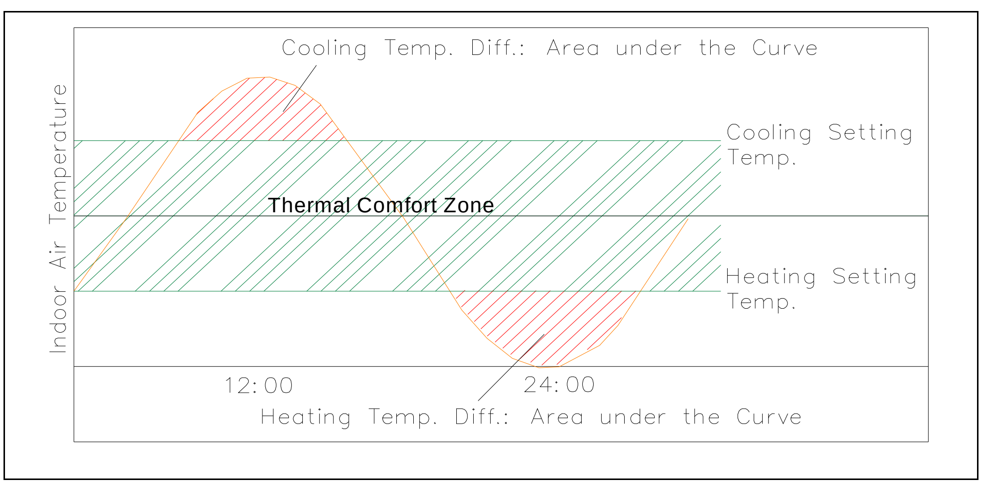


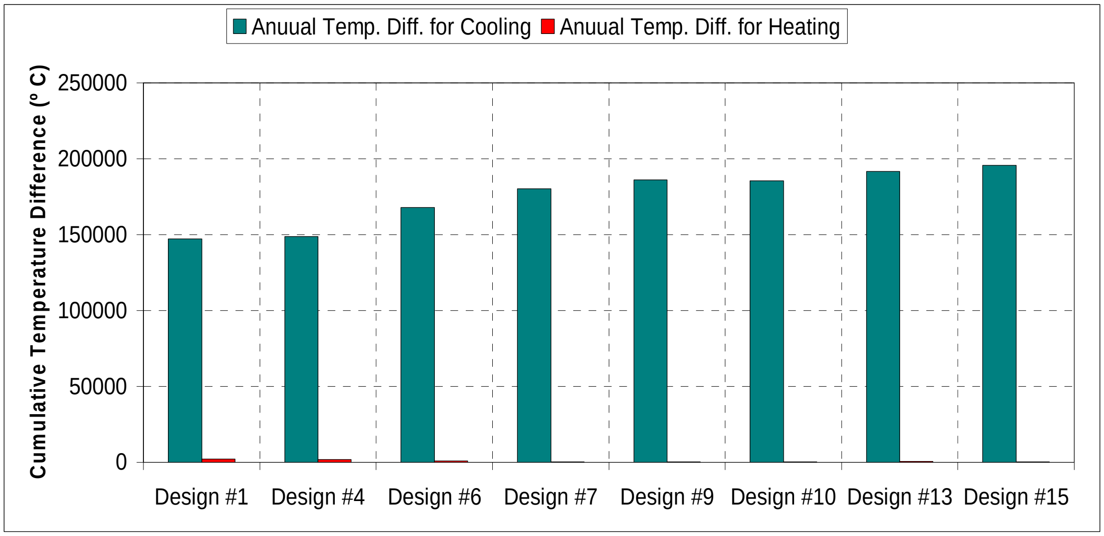
Figure 4.3 Cumulative Temperature Difference Compared to Setting Temperature Points

In this study, this method was tried to assess its appropriateness to evaluate the building envelope design. **Figure 4.4 (a)** and **(b)** show the annual cumulative temperature difference of the base case non-conditioned house under Dhahran climate. **Figure 4.4 (a)** shows that the super-insulated designs (D#13 & D#15) have more temperature difference than the poorly insulated designs (D#1 & D#4). Therefore and according to this concept, the super-insulated designs needs more energy to keep the indoor air temperature within the thermal comfort than the poorly insulated designs.

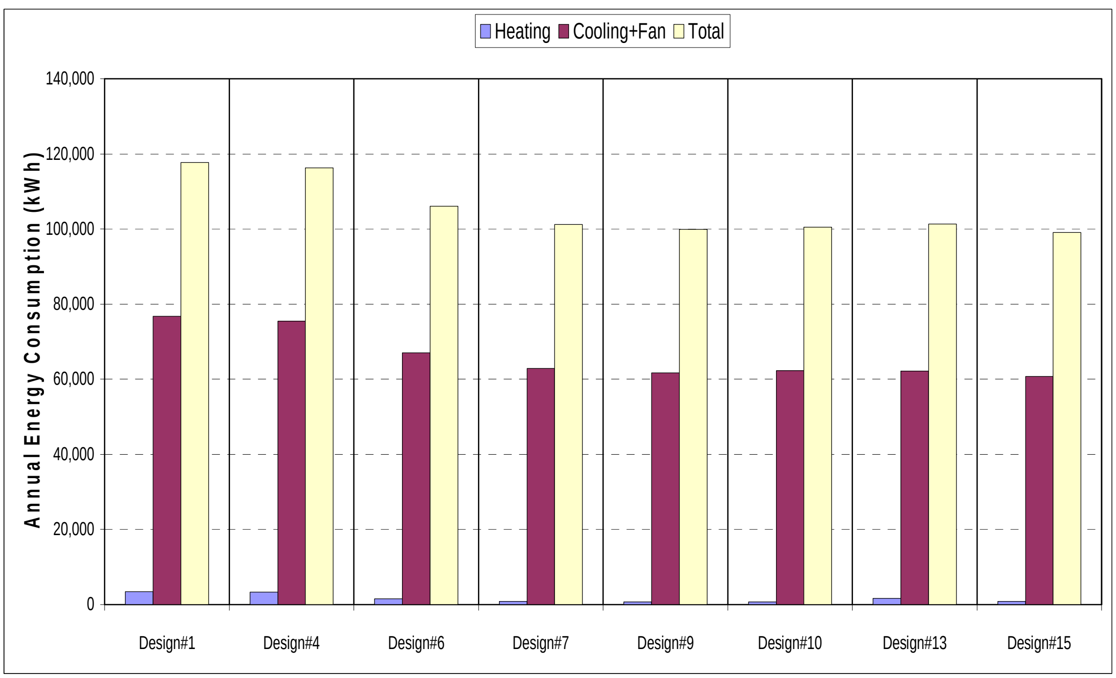
However, **Figure 4.4 (b**) shows that the super-insulated designs have lower energy consumption compared to the poorly insulated designs. Comparing the two figures, it is clear that there is no correlation between annual temperature difference and the annual cooling energy. The heating energy correlates well with the temperature difference. Therefore, this performance indicator is discarded from this study as an indicator for the evaluation of thermal performance of buildings.

4.2.4 Annual Percentage of Thermal Comfort

This concept is widely used in this study to evaluate the performance of different building envelopes at different ventilation strategies. The percentage of thermal comfort is the ratio of number of hours at which the indoor air temperature lies within the comfort zones to total hours in the year. The use of this method is illustrated in the following sections.



(a) Annual Cumulative Temperature for a Non-Conditioned Residential Building in Dhahran



(b) Annual Energy consumption for a Conditioned Residential Building in Dhahran

Figure 4.4 Comparisons of the Cumulative Temperature Difference and the Total Energy Consumption for a Typical Residential Building in Dhahran

4.3 Effective Ventilation Strategies for Residential Building in Dhahran

For this part of the study, the Hourly Average (Mean) Indoor Air Temperature is extensively used to evaluate the effectiveness of ventilation strategies on various envelope designs. Utilizing this method, it was possible to assess different ventilation strategies at different timings. Additionally, the resulted data is also manipulated to determine the percentage of thermal comfort achieved for different envelope designs at specific ventilation strategies. In order to develop preliminary ventilation strategy, two conditions should be met to utilize the outside air for cooling:

1. When the outdoor air temperature is within the thermal comfort zones and the indoor air temperature is outside the thermal comfort zones, then outside cool air is introduced to improve the indoor thermal conditions.
2. When the indoor air temperature is above the outdoor air temperature, then outside air is considered cool enough to reduce the indoor air temperature and consequently improve the indoor thermal conditions.

Two thermal comfort zone criteria are used in this study; the natural ventilation thermal comfort criterion, and the thermal comfort criteria for mechanically operated buildings. Both of these methods are approved in the recent version of ASHRAE standards 55 **(ASHRAE 55, 2004)**. The first method is applicable to the naturally ventilated buildings and is much dependent on the monthly average outdoor air temperature which is entered in the following equation: $T_{comfort}=0.31T_{outdoor}+17.8$. The thermal comfort zone is dynamic and different form month to month as shown in **Table 4.1** for Dhahran.

Although in the recent ASHRAE thermal comfort standard, the relative humidity is not considered as a major factor in thermal comfort in naturally operated buildings, it is listed in **Table 4.1** for comparison purposes. The relative humidity ranges from 42% in transition months to 85% during winter months. Since the outside cool air is mostly utilized in transition months, the relative humidity is not considered as a major factor for thermal comfort.

Table 4.1 Thermal Comfort Criteria as per ASHRAE Naturally Ventilated Buildings and Average Relative Humidity in Year 2002 for Dhahran

Month	Average Outdoor Temperature(ºC)	Naturally Indoor Thermal Comfort Temperature (ºC) at 80% Accept.	Average Relative Humidity (%)
Jan	15.8	19.1-26.1	85
Feb	17.4	19.7-26.7	78
March	22.5	21.3-28.3	60
April	25.9	22.3-29.3	60
May	32.6	23.4-31.41	42
Summer	34.8	Not Applicable	Not Applicable
September	33.2	24.6-31.6	55
October	30.4	23.7-30.7	70
November	22.7	21.3-28.3	69
December	18.6	20.1-27.1	84

The use of outside cool air is an effective way of reducing indoor air temperature. This can either be achieved through the natural force of wind and stack effect or by mechanical systems. The effectiveness of introducing a specific amount of outdoor air to produce an acceptable indoor environment will mainly depend on the behavior of envelope designs under the admitted solar radiation and the generated heat within the building. Therefore, the impact of ventilation strategies is studied for the base case 0.2 Window-Wall- Ratio (WWR), 0.1 WWR and windowless (0 WWR) building. Window-less building represents a building that has a high performance (its thermal insulation level is equivalent to or better than that of the wall) and a fully shaded glazing (no solar radiation is introduced to the indoor environment). Under this condition, the thermal performance of envelope designs is expected to behave differently when no solar radiation is present and therefore is found important to evaluate this building.

4.3.1 Effective Ventilation Strategy for Window-Less Residential Building

The window-less building was modeled to evaluate the impact of ventilation strategies on the indoor air temperature. The hourly indoor air temperature from Visual DOE is averaged for every month and the specific ventilation strategy is analyzed for a specific envelope design. **Figure 4.5** shows the thermal performance of envelope designs when no ventilation is applied. In January, the winter month, the indoor air temperature of the poorly insulated designs D#1 and D#4 is outside the thermal comfort zone from 1:00 am to 12:00 noon. These two designs are also on the lower edge limit of thermal comfort zones in February and start to pick up when the outdoor temperature lies within the thermal comfort zones in afternoon. However, during December, the poorly insulated designs D#1 & D#4 are within the thermal comfort zones. On the other hand, other designs are within the thermal comfort zones in all three winter months; December, January and February. Due to the high thermal characteristics of insulated designs, the heat generated within the building is stored and utilized for heating purposes. It is concluded that in winter months the insulated designs for a window-less building can passively provide thermal comfort.

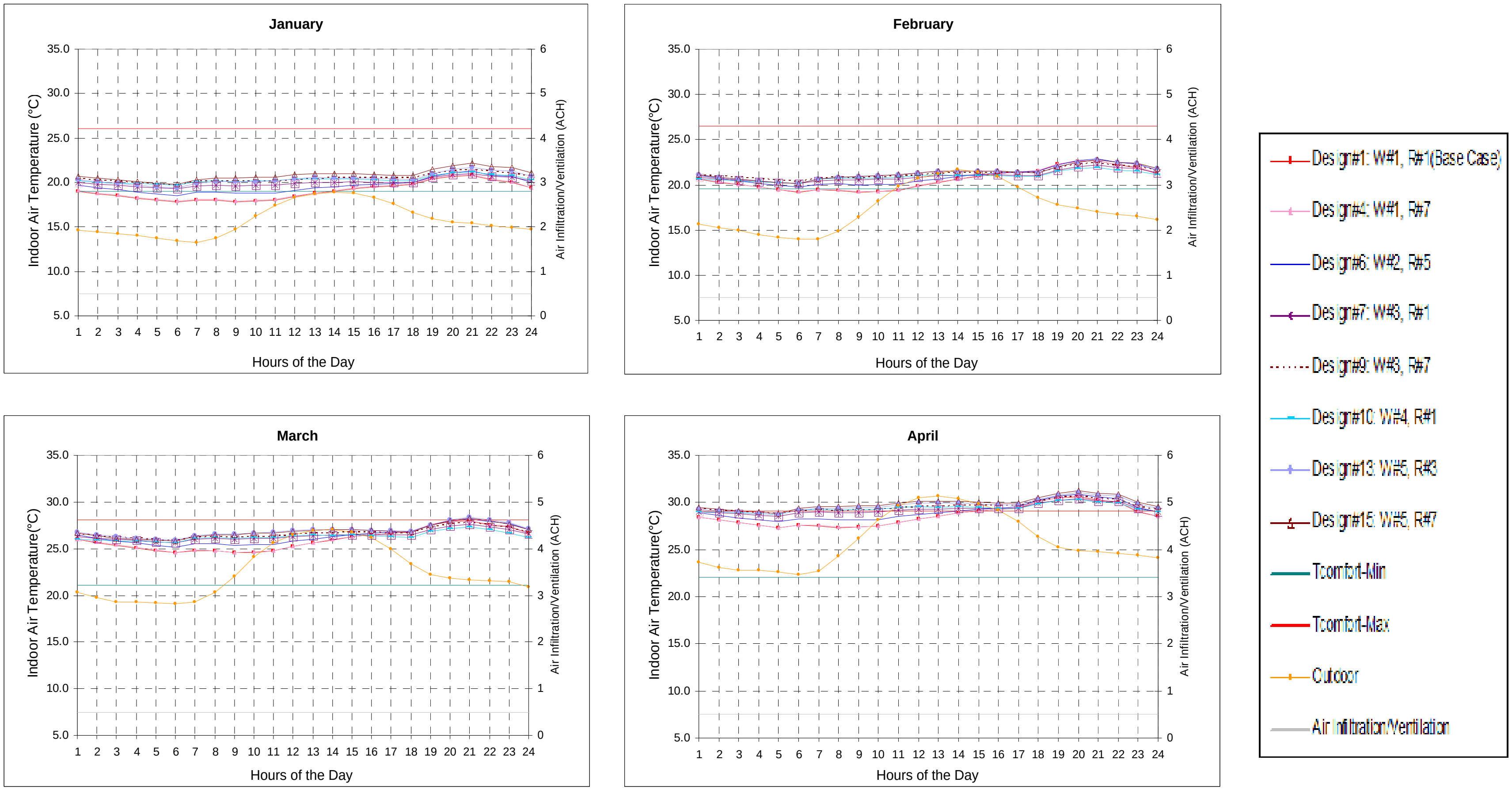


Figure 4.5 Average Hourly Indoor Air Temperatures in a Non-Conditioned Window-Less Residential Building in Dhahran

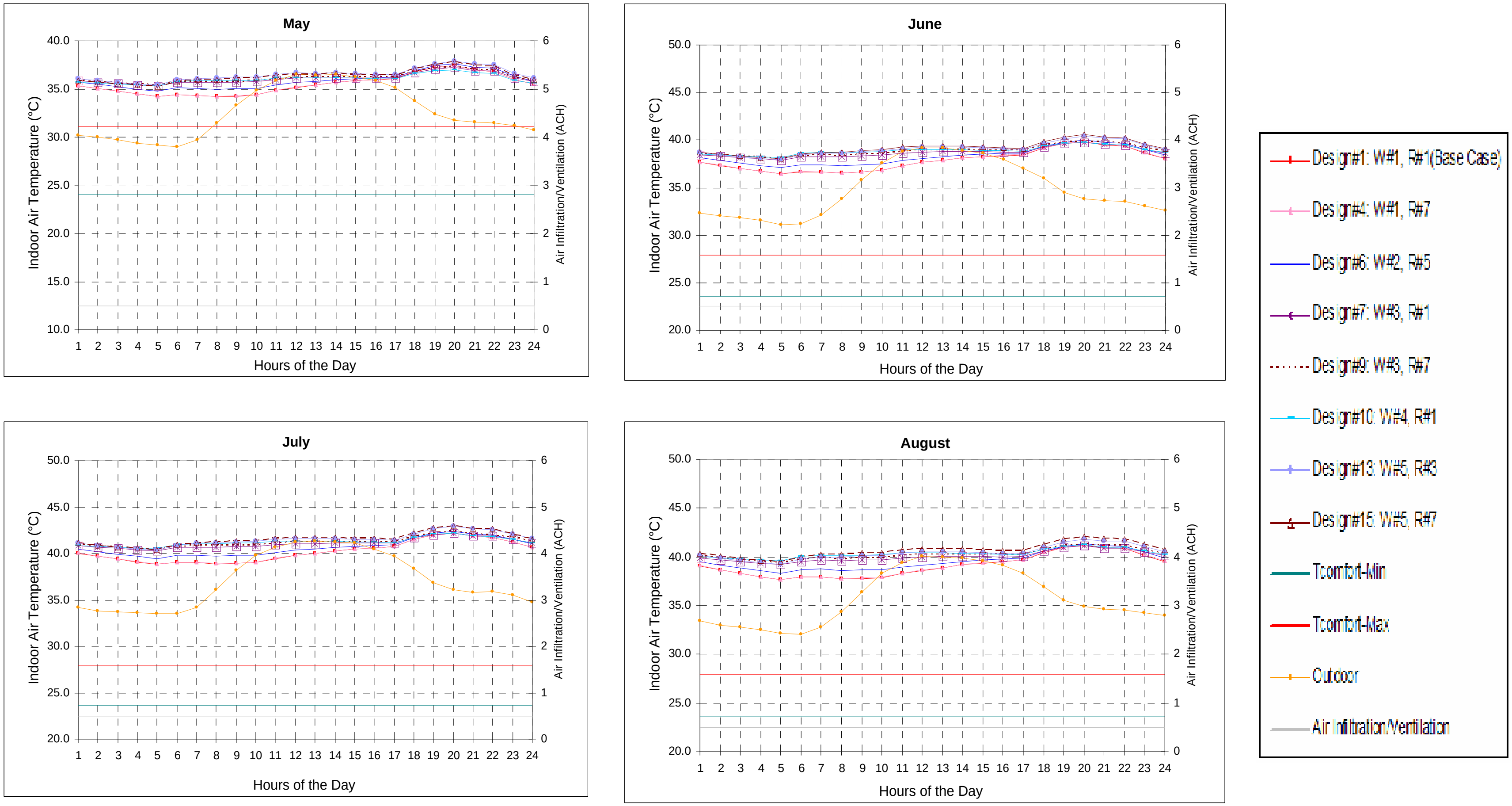


Figure 4.5 Average Hourly Indoor Air Temperatures in a Non-Conditioned Window-Less Residential Building in Dhahran (cont.)

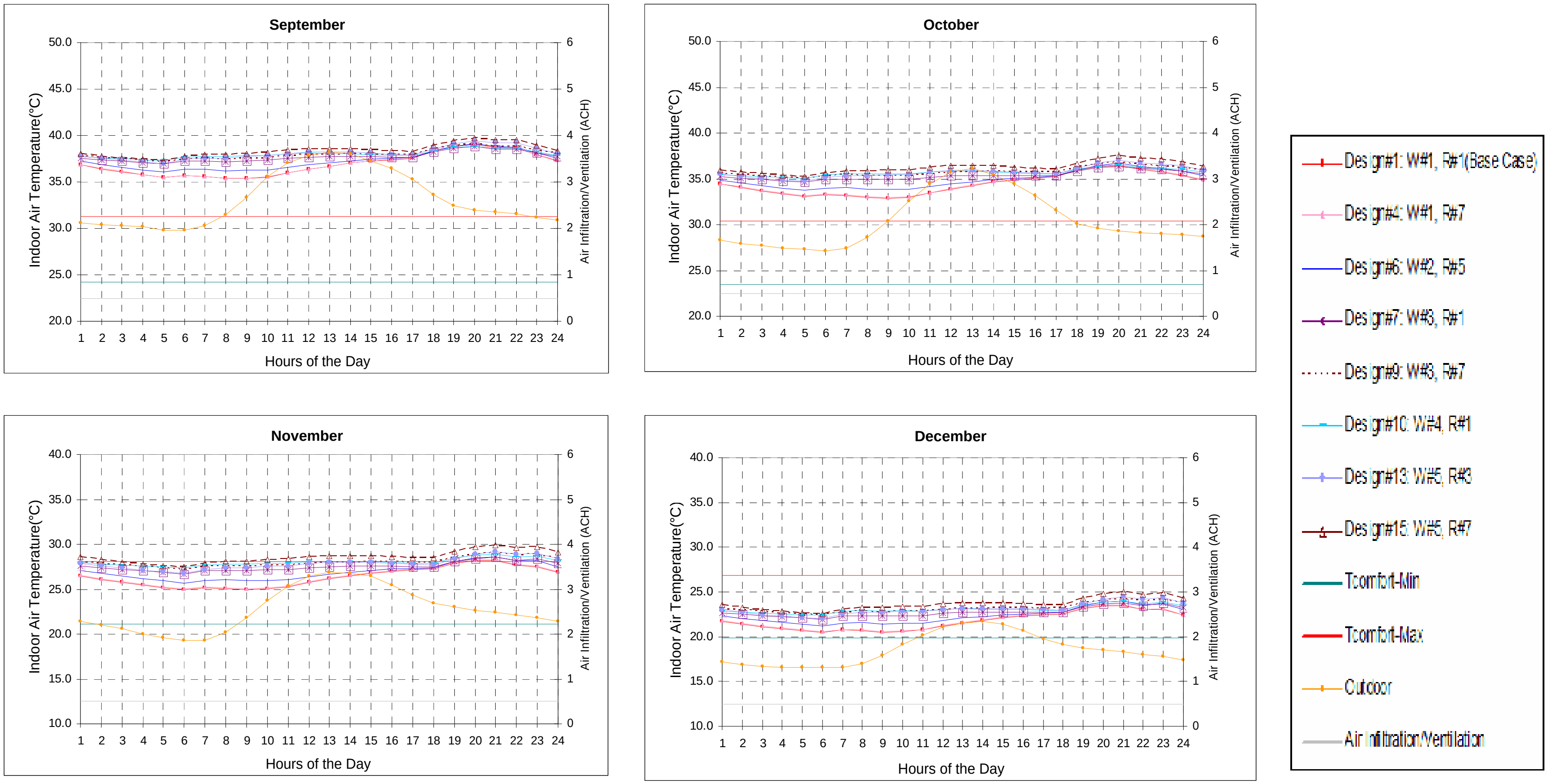


Figure 4.5 Average Hourly Indoor Air Temperatures in a Non-Conditioned Window-Less Residential Building in Dhahran (cont.)

Outside air can be utilized during transition months (transition from winter to summer or vice versa); March, April, May, September, October and November. The utilization of outside air to reduce the indoor air temperature varies from one month to another. Because outdoor air temperature is almost within the thermal comfort zones during the cool transition months November & March, it can be introduced to the indoor environment at any time during the day. A careful consideration should be given when the outside air is introduced during the warm transition months; April, May, September and October. The outside air temperature of Dhahran is examined and **Table 4.2** shows Preliminary timings for ventilation strategies in Dhahran for Window-Less residential building.

Table 4.2 Preliminary Ventilation Strategies and Timings for Passive Cooling in Window-Less Residential Buildings in Dhahran

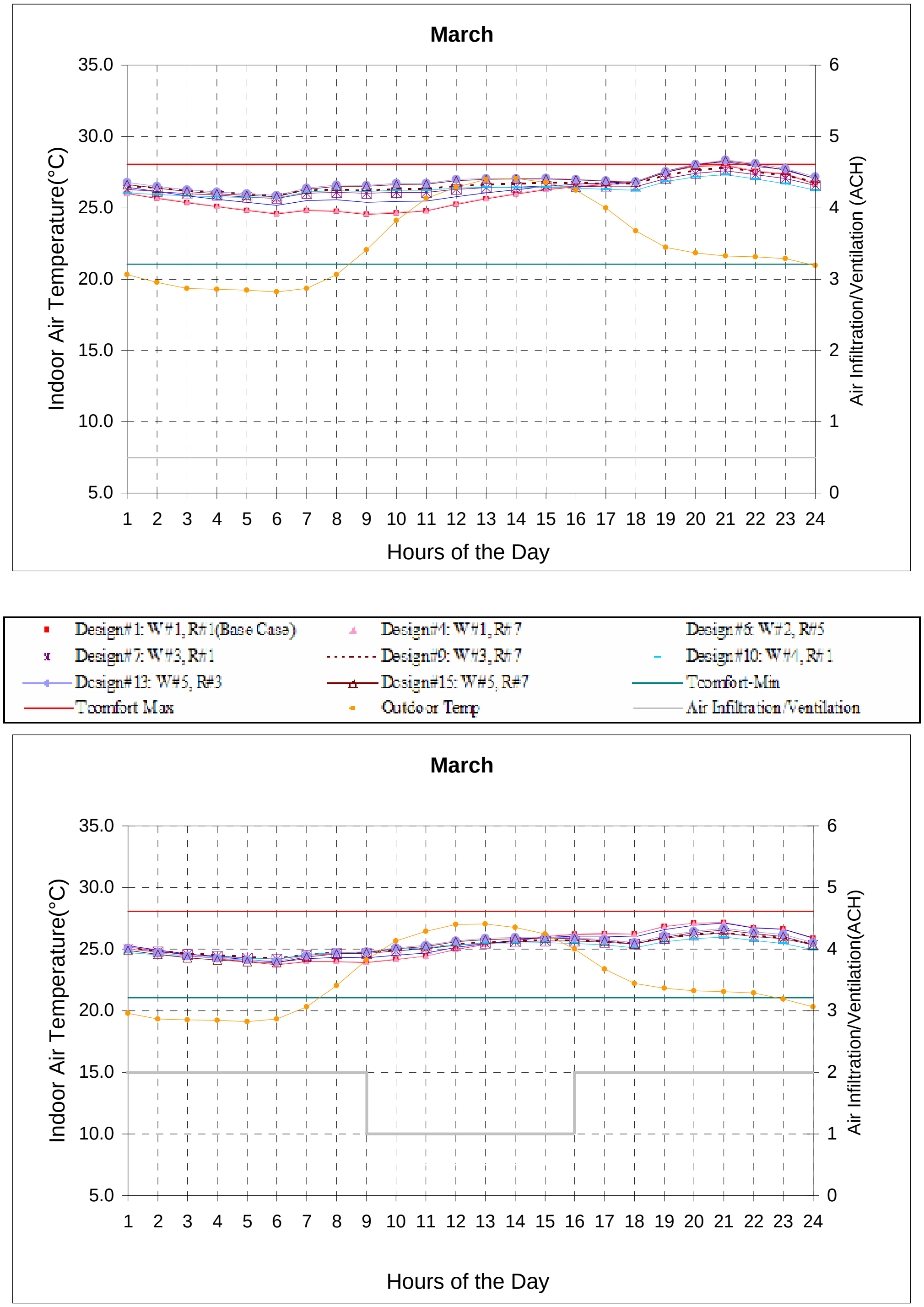
Month	No-Ventilation (Airtight)	Ventilation Strategy#1	Ventilation Strategy#2
January, February	0.5 ACH (24h)	0.5 ACH (24h)	0.5 ACH (24 h)
March	0.5 ACH (24h)	2 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	Similar to S#1
April	0.5 ACH (24h)	2 ACH (24 h)	3 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00
May	0.5 ACH (24h)	5 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	Similar to S#1
June, July, August	0.5 ACH (24h)	0.5 ACH (24 h)	0.5 ACH (24 h)
September	0.5 ACH (24h)	5 ACH: 22:00-07:00 0.5 ACH: 08:00-21:00	5 ACH: 14:00-05:00 0.5 ACH: 06:00-1300
October	0.5 ACH (24h)	5 ACH: 18:00-08:00 0.5 ACH: 09:00-17:00	5 ACH: 14:00-05:00 0.5 ACH: 06:00-13:00
November	0.5 ACH (24h)	2 ACH (24 h)	3 ACH (24 h)
December	0.5 ACH (24h)	0.5 ACH (24 h)	0.5 ACH (24 h)

Table 4.2 Preliminary Ventilation Strategies and Timings for Passive Cooling in Window-Less Residential Buildings in Dhahran (cont.)

Month	**Ventilation Strategy#3**	**Ventilation Strategy#4**	**Ventilation Strategy#5**	**Ventilation Strategy#6**	**Ventilation Strategy#7**
January, February	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)
March	Similar to S#1	Similar to S#1	Similar to S#1	Similar to S#1	Similar to S#1
April	5 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	Similar to S#3	Similar to S#3	Similar to S#3	Similar to S#3
May	10 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	15 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	20 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	30 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	40 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00
June, July, August	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)
September	10 ACH: 16:00-07:00 0.5 ACH: 08:00-1500	15 ACH: 16:00-07:00 0.5 ACH: 08:00-1500	20 ACH: 16:00-07:00 0.5 ACH: 08:00-1500	30 ACH: 16:00-07:00 0.5 ACH: 08:00-1500	Similar to S#6
October	10 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	15 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	20 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	30 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	Similar to S#6
November	Similar to S#2	Similar to S#2	Similar to S#2	Similar to S#2	Similar to S#2
December	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)

The proposed ventilation strategies are applied to the window-less building in Dhahran. **Figure 4.6 (b)** show the effect of Ventilation Strategy #1 on indoor air temperature of the residential building in Dhahran during March. It is clear that the indoor air temperature has been enhanced for all envelope designs. When no ventilation is applied as shown in **Figure 4.6 (a)**, there is a risk of overheating for standard and super-insulated designs in evening time after 20:00. In order to avoid the overheating effect, the outside cool air is utilized. It is noticed that introducing 2 ACH keeps the indoor air temperature within the comfort zones. It is also found that introducing the outside air during the day time enhances the indoor air temperature and reduces the risk of overcooling during the night. Therefore, a better strategy is to introduce the outside cool air during the day to avoid the over cooling in the evening.

Figure 4.7 depict the effect of Ventilation Strategy #1, #2 and #3 on indoor air temperature of the residential building in Dhahran during April. When no ventilation is applied, the indoor air temperature for the poorly insulated designs D#1 and D#4 is within the thermal comfort zones during the early morning time as shown in **Figure 4.7 (a)**. During the daytime, the indoor air temperature of the poorly insulated designs (D#1 & D#4) dynamically responds to the increases in outdoor air temperature and the internal generated heat.



(a)

(b)

Figure 4.6 Average Hourly Indoor Air Temperatures in March for a Window-Less Residential Building (R.B.) in Dhahran under **(a)** No Ventilation and **(b)** Ventilation Strategy #1

The indoor air temperature of the insulated designs (D#6 to D#15) has improved during the early morning time when outdoor air is introduced at 2 ACH as shown in **Figure 4.7 (b)**. A little improvement in indoor air temperature of the poorly insulated designs (D#1 and D#4) is also observed. During the evening time (after 17:00) when the outdoor air temperature is within the thermal comfort zones, the insulated designs (D#6 to D#15) tends to respond more significantly than the poorly insulated designs (D#1 & D#4). A sharp increase in the indoor air temperature is observed during the evening after 20:00. In order to reduce this effect, selective ventilation is applied to introduce the outside cool air when the temperature is within thermal comfort zones.

The indoor air temperature for envelope designs has improved when selective ventilation (Strategy#2: 3 ACH 16:00-09:00) is applied as shown in **Figure 4.7 (c)**. Further improvement is noticed as depicted from **Figure 4.7 (d)** when more ACH is introduced (Ventilation Strategy#3: 5 ACH). It is clear that the indoor air temperature of different envelope designs can be further enhanced when the selective ventilation is applied. Since, the objective is to achieve thermal comfort; Ventilation Strategy #3 in April is found adequate to keep the indoor air temperature within the thermal comfort zones for all envelope designs.

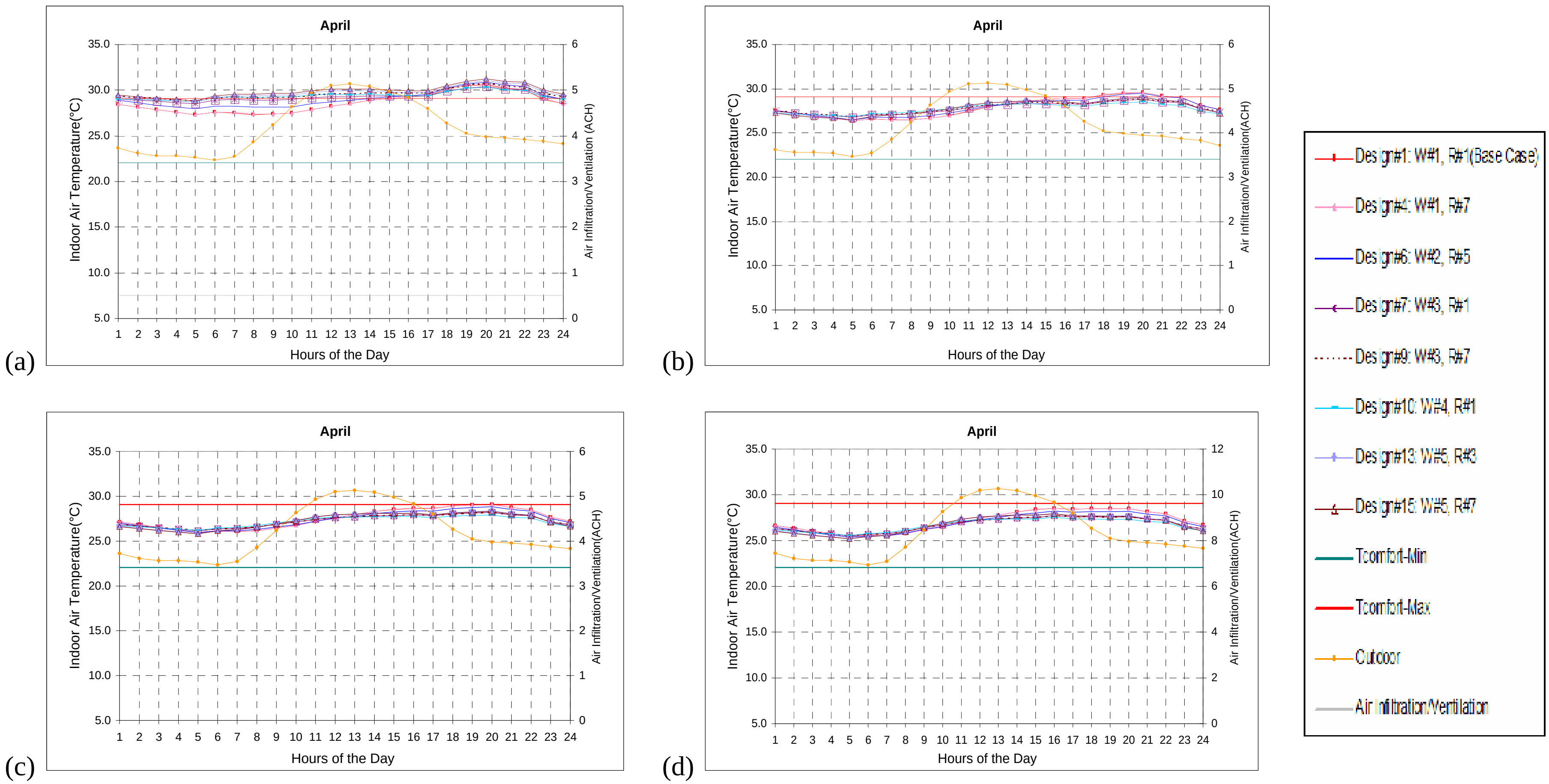


Figure 4.7 Average Hourly Indoor Air Temperatures in April for a Window-Less R. B. in Dhahran under **(a)** No Ventilation, **(b)** Ventilation Strategy #1, **(c)** Ventilation Strategy #2 and **(d)** Ventilation Strategy #3

The indoor air temperature of the residential building in Dhahran during November under No Ventilation, Ventilation Strategy #1 and Ventilation Strategy (VS) #2 is shown in **Figure 4.8 (a)**, **(b)** and **(c)** respectively. The response of envelope designs in November is similar to that of other transition months, March and April. When no ventilation is permitted, the indoor air temperature of insulated designs (D#6 to 15) is outside the thermal comfort zones whereas the poorly insulated designs (D#1 & D#4) are within the thermal comfort during the early morning. As the outdoor air is introduced at a rate of 2 ACH (Ventilation Strategy #1) for 24 hours continuously, the indoor air temperature decreases and is kept within the comfort zones. More ACH enhances the indoor air temperature. This shows that during the cooled transition months, the natural cooling energy associated with the outside air can be effectively utilized to achieve the thermal comfort and reduce the dependence on mechanical systems.

Although, the outside air temperature is within the thermal comfort zones in early mornings and late evenings, **Figure 4.9 (a)** shows that the indoor air temperature is always outside the thermal comfort zones when no ventilation is used during May. The figure shows that there is a potential to use the outside air at specific timings. Selective ventilation strategies can be identified based on some criteria. The criteria in utilizing the outside air are either when the temperature is within thermal comfort zones (24:00-07:00) or when the outside air temperature is below the indoor air temperature (17:00-23:00). **Figure 4.9 (b)** to **(g)** shows the effect of different ventilation strategies (ACH) on the indoor air temperature.

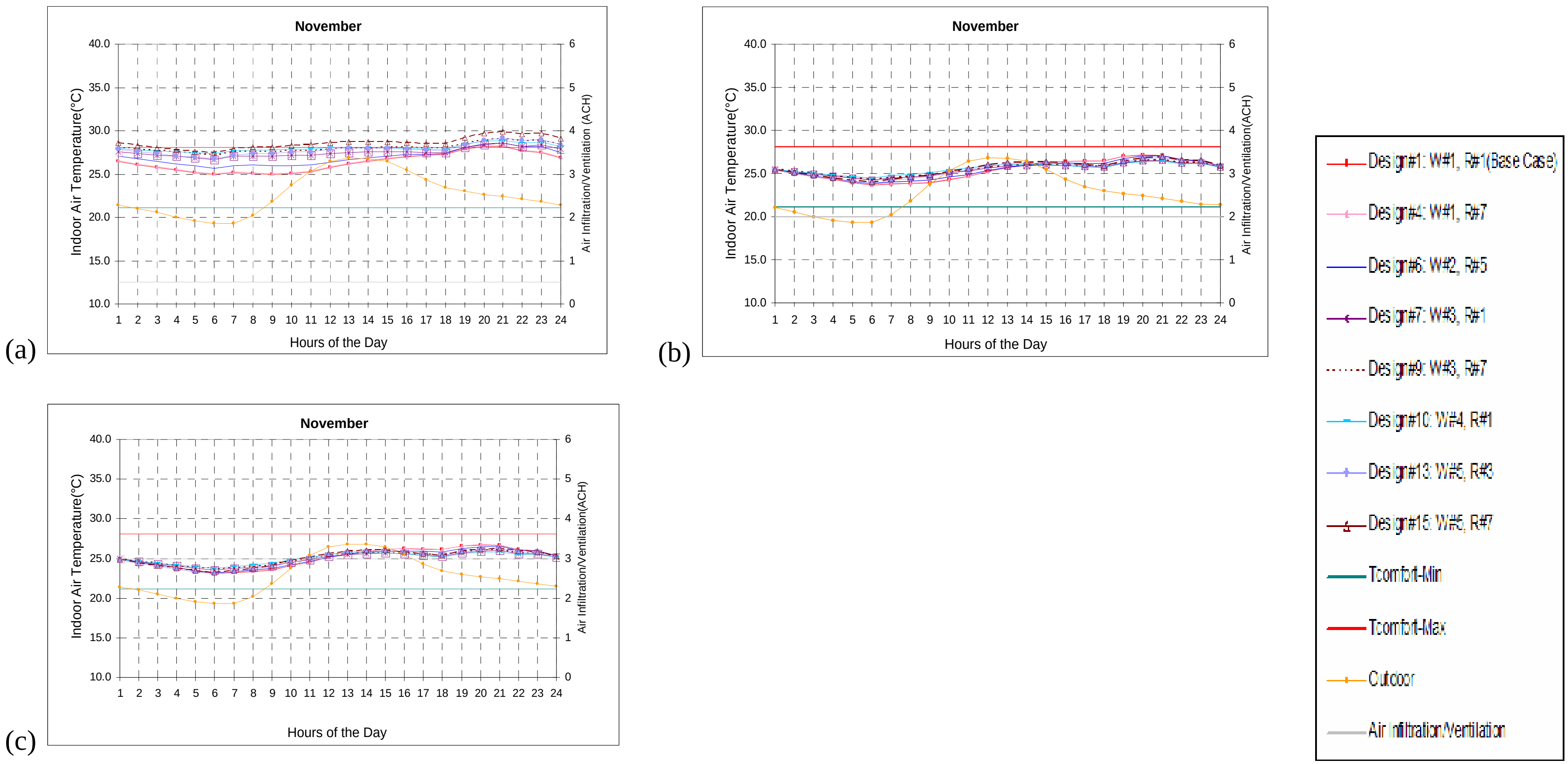


Figure 4.8 Average Hourly Indoor Air Temperatures in November for a Window-Less R. B. in Dhahran under **(a)** No Ventilation, **(b)** Ventilation Strategy #1 and **(c)** Ventilation Strategy #2

The indoor air temperature for all envelope designs is reduced by 2.5 ºC when Ventilation Strategy#1 (5 ACH) is applied. Further increases of ACH to Ventilation Strategy # 7 (40 ACH) decreases the indoor air temperature in the range of 1.4 ºC compared to Ventilation Strategy#1. Although the reduction in indoor air temperature is small when more ACH is introduced, the indoor air temperature tends to be within thermal comfort zones during the early morning time (24:00 to 07:00) when VS#5 (20 ACH) is applied. At evening (17:00-23:00), the indoor air temperature is reduced and almost following the trend of outside air temperature. It is concluded that increasing the outside air beyond 20 ACH is not attractive in May. However, it is helpful during the startup period of the HVAC system when the space in not occupied. The HVAC systems can startup at a temperature of 30 ºC rather than 34-36 ºC when no ventilation is applied.

During September, the effect of ventilation strategies on indoor air temperature of envelope designs is similar to that in May as shown in **Figure 4.10 (a)** to **(g)**. The figures show that introducing the outside air at different volumes (5 ACH to 30 ACH) reduces the indoor air temperature. Nevertheless, the indoor air temperature will not be effectively reduced to the level of comfort. Therefore, introducing the outside air during the month of September doesn’t help to achieve thermal comfort but can be used to reduce the indoor air temperature when the space is not occupied to reduce the energy consumption for the machine startup.

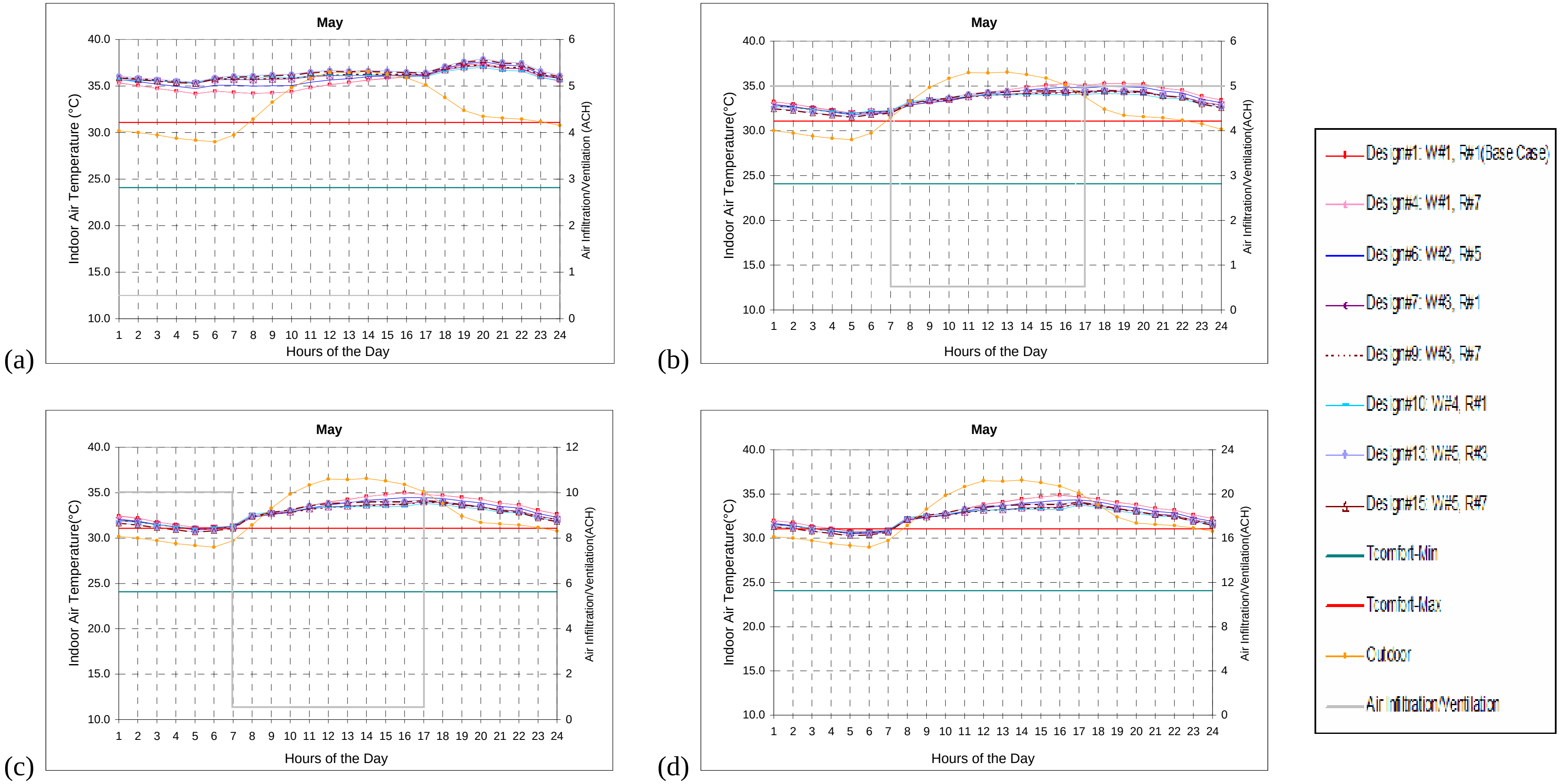
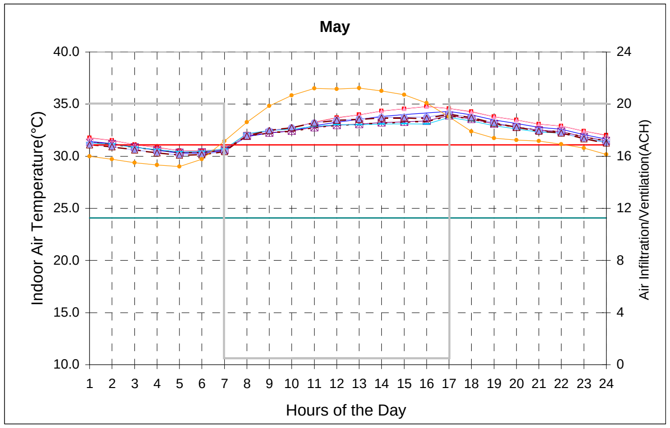
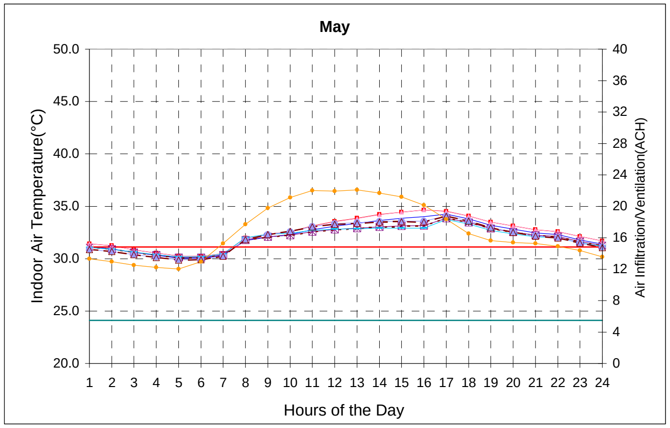


Figure 4.9 Average Hourly Indoor Air Temperatures in May for a Window-Less R. B. in Dhahran under **(a)** No Ventilation, **(b)** Ventilation Strategy #1, **(c)** Ventilation Strategy #3 and **(d)** Ventilation Strategy #4

(e)



(f)



(g)

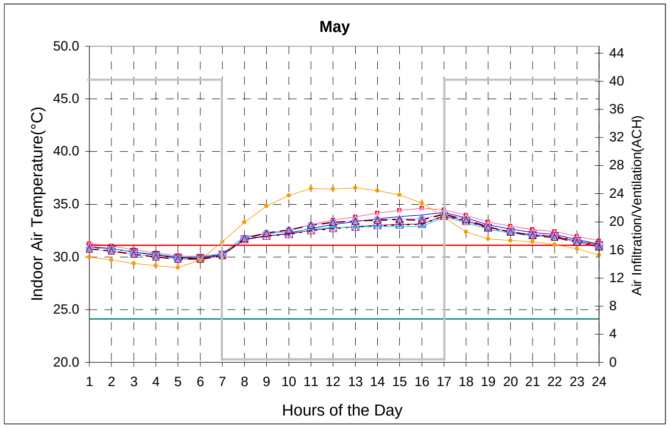


Figure 4.9 Average Hourly Indoor Air Temperatures in May for a Window-Less R. B. in Dhahran under **(e)** Ventilation Strategy #5, **(f)** Ventilation Strategy #6 and **(g)** Ventilation Strategy #7 (cont.)

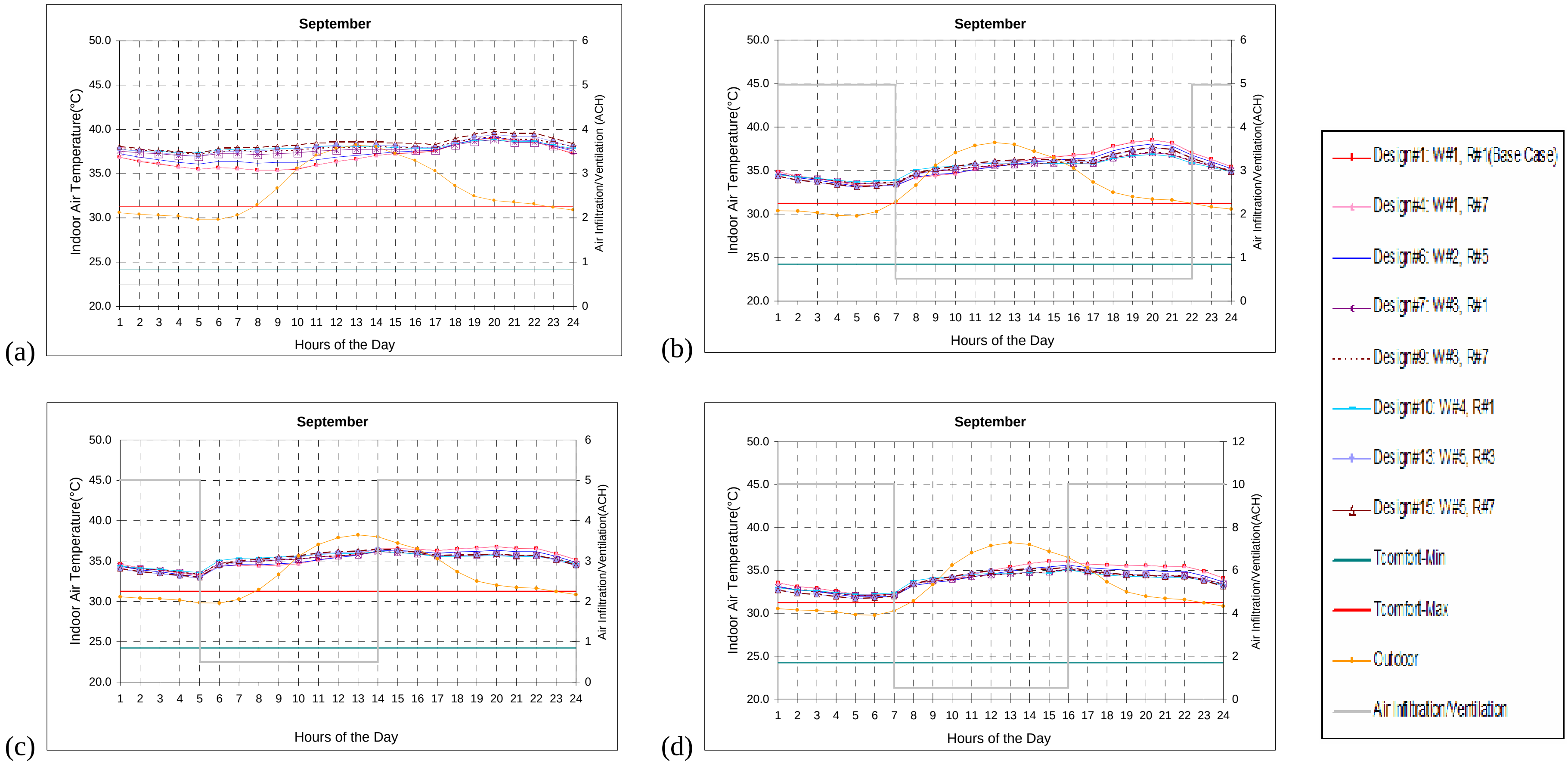


Figure 4.10 Average Hourly Indoor Air Temperatures in September for a Window-Less R. B. in Dhahran under **(a)** No Ventilation, **(b)** Ventilation Strategy #1, **(c)** Ventilation Strategy #2 and **(d)** Ventilation Strategy #3

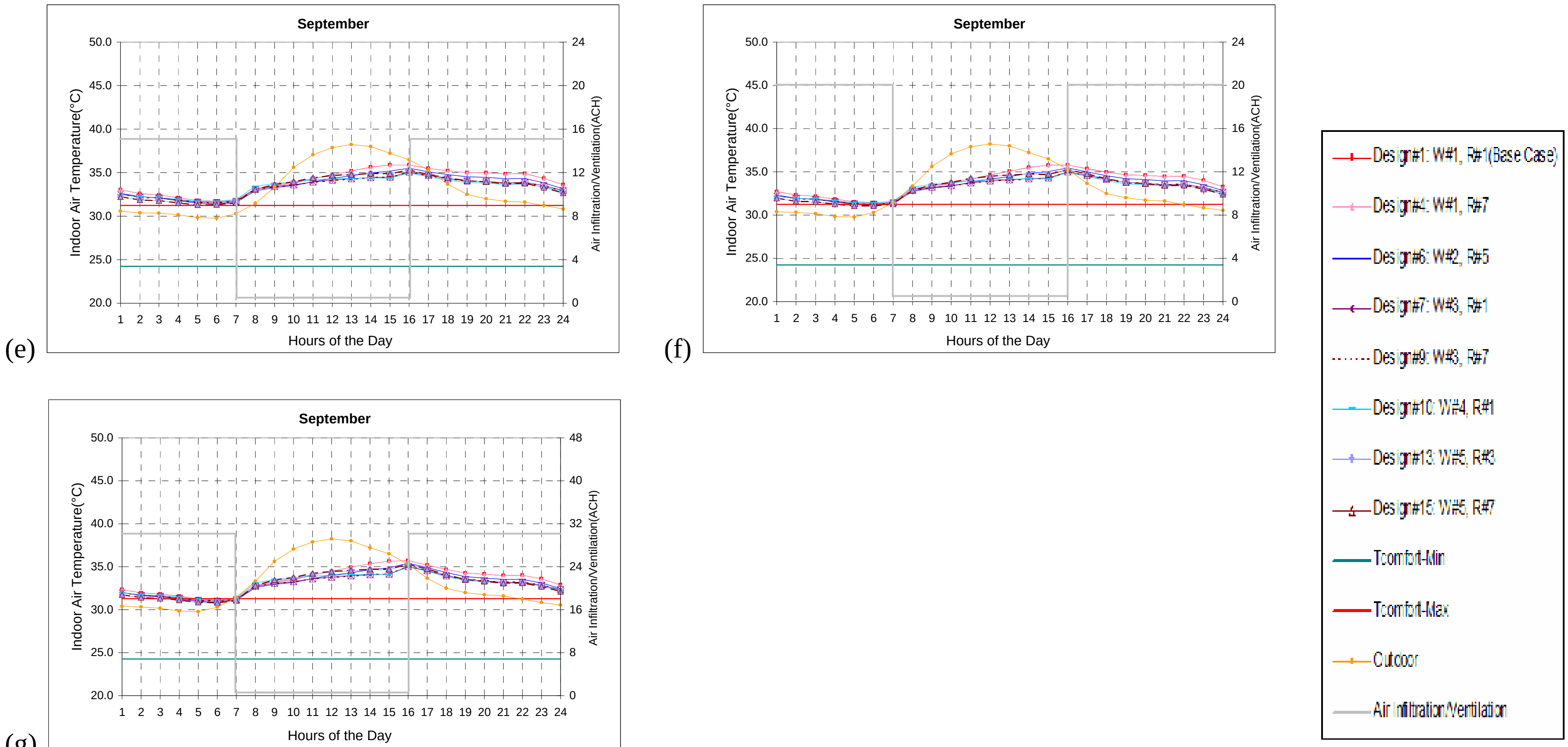


Figure 4.10 Average Hourly Indoor Air Temperatures in September for a Window-Less R. B. in Dhahran under **(e)** Ventilation Strategy #4, **(f)** Ventilation Strategy #5 and **(g)** Ventilation Strategy #6 (cont.)

Figure 4.11 (a) to **(g)** show the impact of ventilation strategies on indoor air temperature of residential building in Dhahran during October. During this month, the indoor air temperature responds to the introduced cool air compared to the other transition months; May and September. At Ventilation Strategy#1 (5 ACH: 18:00-08:00), the indoor air temperature touches the upper limit of thermal comfort zone (30º C) at early morning (03:00 a.m. to 07:00 a.m.). During the evening (after 18:00), the indoor air temperature of insulated envelope designs decreases from 37.5º C (peak temperature at no ventilation) to 33º C at 5 ACH. When the air is introduced 4 hours early in evening (at 14:00) and 3 hours early in the morning (at 05:00) as is in Ventilation Strategy #2, the indoor air temperature doesn’t change during the evening but a slight change is observed in the morning as shown in **Figure 4.11 (c)**. Increasing the outside air to 10 ACH (Ventilation Strategy #3) brings the indoor air temperature to the thermal comfort zone during the early morning. However, the improvement in the indoor air temperature during the early morning is insignificant after 15 ACH (Ventilation Strategy #3) but is enhanced with more ACH (as in Ventilation Strategy #6: 30 ACH) in the evening (after 20:00) as shown in **Figure 4.11 (g)**.

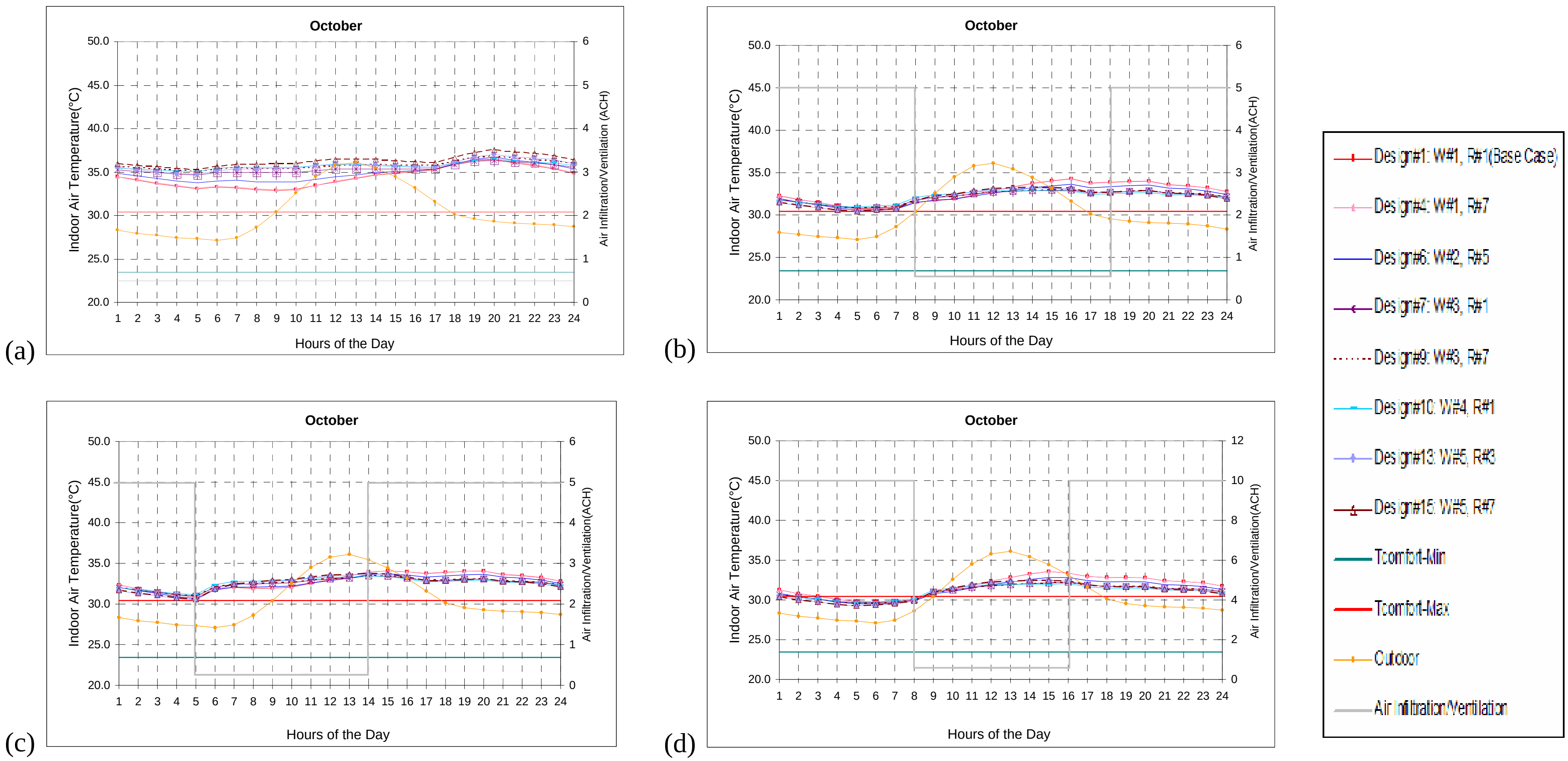
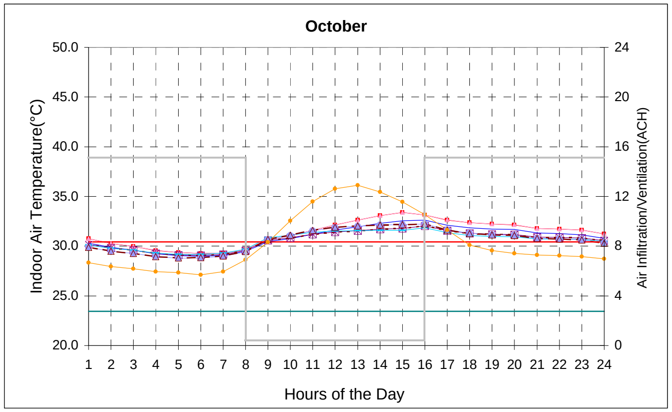
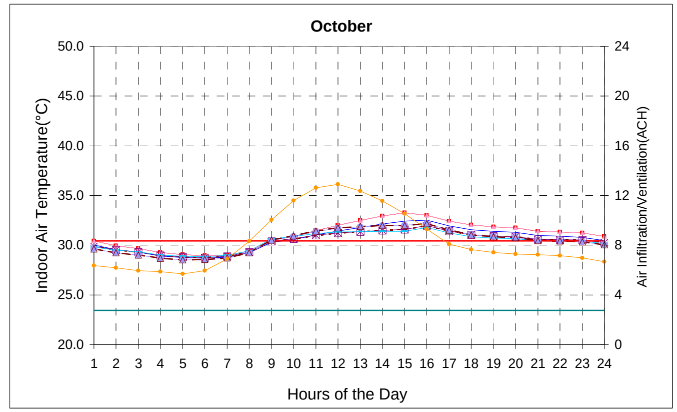


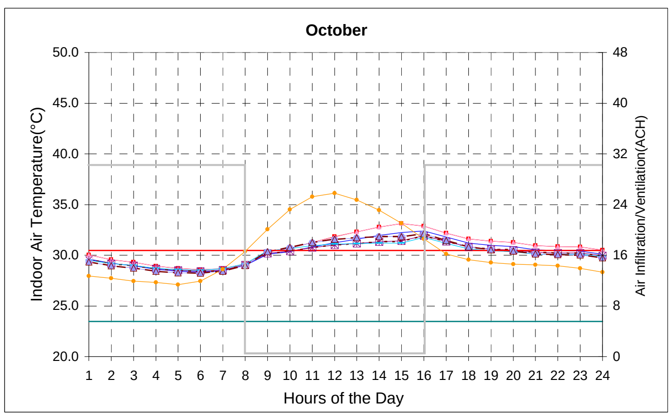
Figure 4.11 Average Hourly Indoor Air Temperatures in October for a Window-Less R. B. in Dhahran under **(a)** No Ventilation, **(b)** Ventilation Strategy #1, **(c)** Ventilation Strategy #2 and **(d)** Ventilation Strategy #3



(e)



(f)



(g)

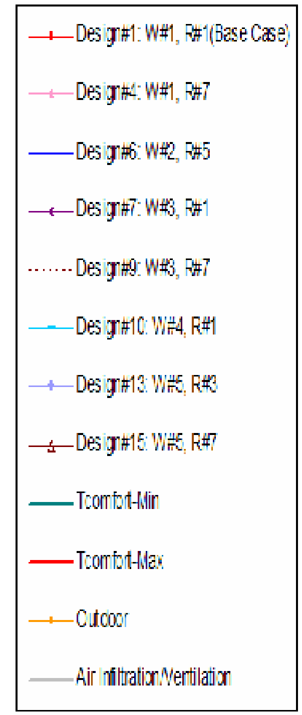


Figure 4.11 Average Hourly Indoor Air Temperatures in October for a Window-Less R. B. in Dhahran under **(e)** Ventilation Strategy #4, **(f)** Ventilation Strategy #5 and **(g)** Ventilation Strategy #6 (cont.)

The thermal performance of different envelope designs under various ventilation strategies has been analyzed in a qualitative way in the earlier discussion. **Figure 4.12** show the percentage of thermal comfort of different envelope designs under different ventilation strategies. ASHRAE thermal comfort for naturally ventilated buildings is used to calculate the percentage of thermal comfort.

It is clear from the figure that as the ACH increases the percentage of thermal comfort increases for both the living and sleeping zones. This is obvious when Ventilation Strategy #1 (5 ACH) and Ventilation Strategy #3 (10 ACH) is applied. However, the increases in thermal comfort are significant for the super-insulated designs (D#9 and D#15) as shown in **Figure 4.12 (b)**. Although the sleeping area is exposed to solar radiation through the roof in the transition months, it is noticed that Ventilation Strategy#7 deteriorate the thermal comfort (over-cooling) in this zone but a little enhancement is observed for the living area. This is due to the fact that the living area is mostly occupied during the daytime. Additionally, it is characterized by the high internal generated heat which needs more air to remove the generated heat.

The degree of response of the envelope designs varies under various ventilation strategies. Therefore, a further analysis is performed to identify the proper ventilation strategy for every envelope design. The analysis involves a comparison between how much every ventilation strategy improves the thermal comfort and selects the one that achieves more thermal comfort.

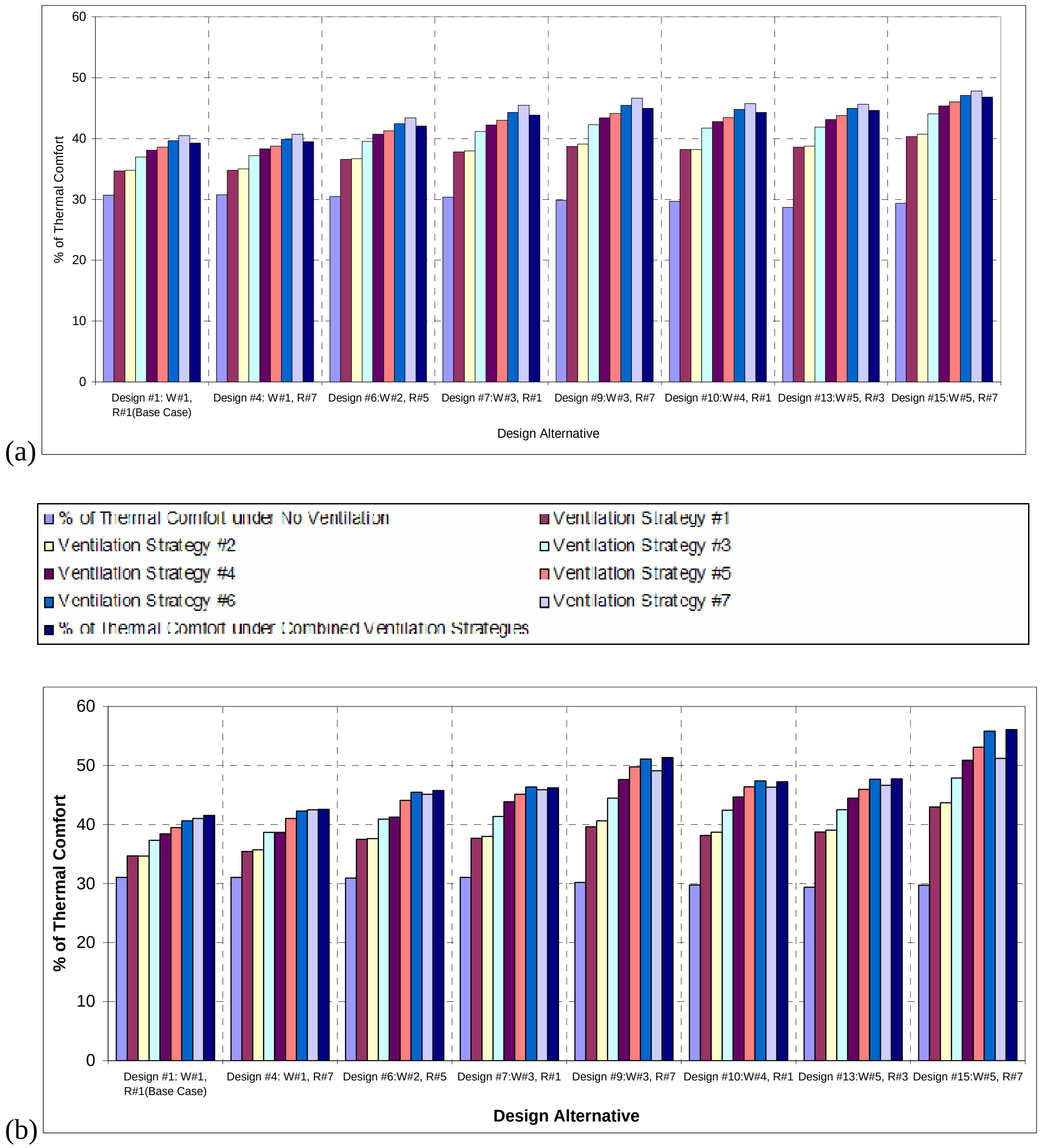


Figure 4.12 Percentage of Thermal Comfort in **(a)** Living Area and **(b)** Sleeping Area of a Window Less R. B. in Dhahran under Various Ventilation Strategies

The thermal comfort under specific ventilation strategy for envelope designs is compared to the thermal comfort under the next ventilation strategy for the same envelope design. For example, the percentage of thermal comfort of Desgin#1 in April under Ventilation Strategy #1 is compared to the percentage of thermal comfort of Desgin#1 in April under Ventilation Strategy #2. This procedure is done month by month for every envelope design under various ventilation strategies. The result of this process helps to identify the combined ventilation strategy for every envelope design. Some of ventilation strategies are discarded due to their insignificance to enhance the thermal comfort. The impact of combined ventilation strategy on thermal comfort for different envelope designs in living and sleeping areas is shown in **Figure 4.13 (a)** and **(b)**.

The thermal comfort of envelope designs when no ventilation is applied varies from 31% for poorly insulated design (D#1) to 29-30% for super-insulated design (D#15) in both living and sleeping area. In living area, the thermal comfort increases with proper ventilation strategies to 39% for the poorly insulated design to 47% for the super-insulated design as shown in **Figure 4.13 (a)**.

The improvement in thermal comfort is significant with the insulated designs (59%) compared to the poorly insulated design (28%) when the combined ventilation strategy is applied. **Figure 4.13 (b)** shows the impact of the envelope designs and the combined ventilation strategies on the thermal comfort in the sleeping area. It is clear that the thermal comfort in the sleeping area is higher than that in the living area. The thermal comfort under the super-insulated designs (D#9 and D#15) is high compared to other envelope designs. The thermal comfort improvement in the sleeping area ranges from 34% for the poorly insulated designs to 89% for the super-insulated designs.

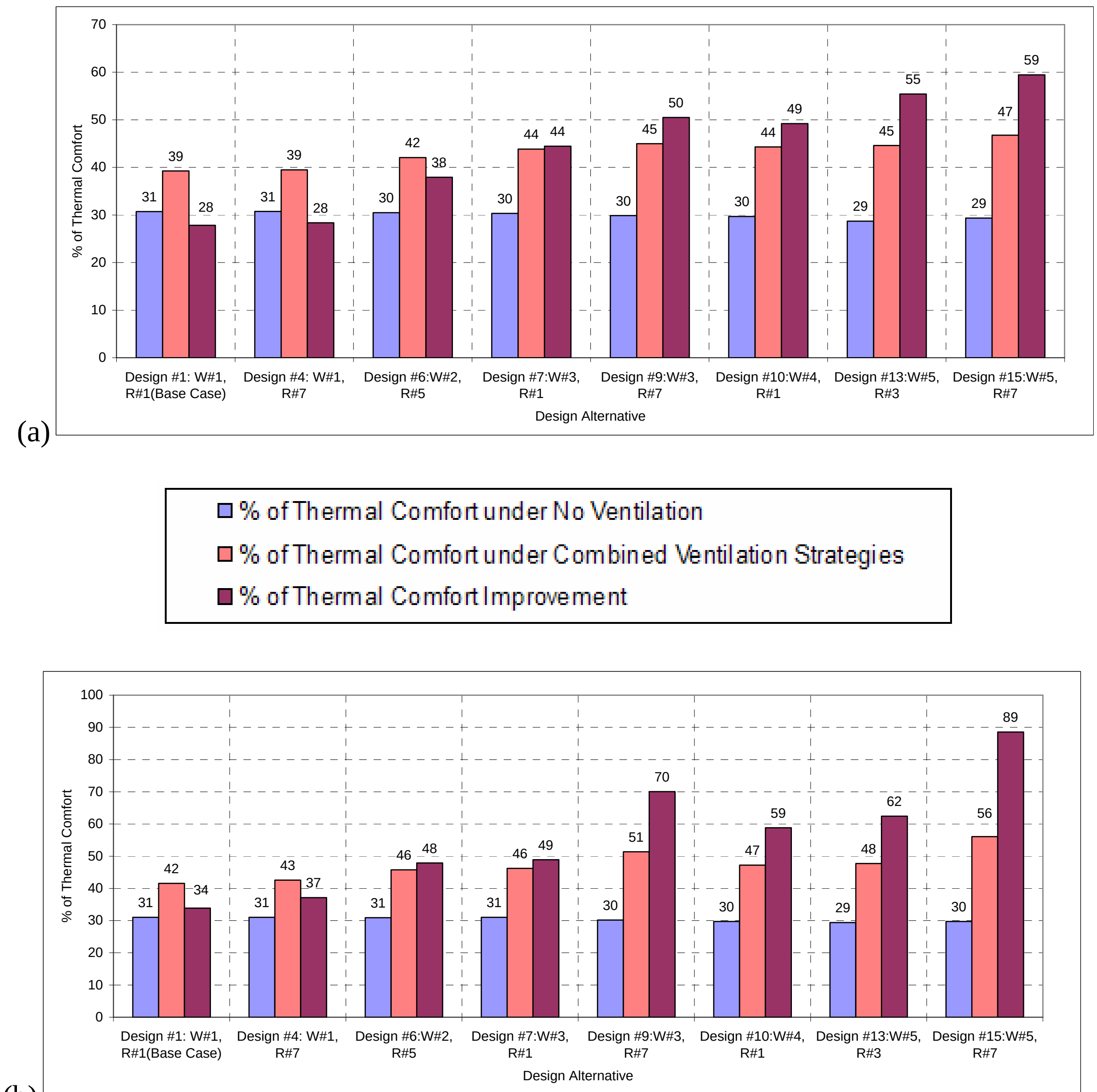


Figure 4.13 Impacts of Combined Ventilation Strategies on Thermal Comfort for Envelope Designs in the **(a)** Living Area and **(b)** Sleeping Area in a Window-Less R. B. in Dhahran

In VisualDOE, the values for the air change per hour are entered and then corrected for the effect of wind and stack. The entered values for the combined ventilation strategy for various envelope designs in transition months are included in APPENDIX-C. **Table 4.3 (a)** lists the corrected combined ventilation strategies during transition months for the studied envelope designs when ASHRAE thermal comfort for naturally ventilated buildings is used. **Table 4.3 (b)** is developed based on the ASHRAE thermal comfort for mechanically operated buildings. It is clear that when using the ASHRAE thermal comfort for naturally ventilated buildings, the thermal comfort can be achieved during the nights of May and October. It is also obvious that when the ASHRAE thermal comfort for mechanically operated buildings is used, more air volume is required in April to achieve thermal comfort. In addition, it is not possible to achieve thermal comfort in warm transition months; May and October without using the mechanical systems. In winter (December, January and February), introducing the outside cool air for window-less building deteriorates the thermal comfort. In summer (July, June and August, September), the outside air is always above the thermal comfort zone and therefore insignificant in achieving thermal comfort. However, it can be used to reduce the machine startup in summer since the indoor air temperature is always above the outside air temperature when the mechanical system is off.

Table 4.3 Actual Ventilation Strategies in Transition Months for a Window-Less R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for **(a)** Naturally Ventilated Buildings and **(b)** Mechanically Operated Buildings

(a)

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*1 ACH 08:00-18:00, 0.28 ACH 19:00-07:00*	*1.64 ACH 16:00-9:00, 0.34 ACH 10:00-15:00*	*8.72 ACH 20:00-6:00, 0.45 ACH 7:00-19:00*	*12.32 ACH 20:00-6:00, 0.4 ACH 7:00-19:00*	*1.78 ACH 07:00-18:00, 0.36 ACH 19:00-06:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

(b)

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*1 ACH 08:00-18:00, 0.28 ACH 19:00-07:00*	*3.26 ACH 16:00-9:00, 0.34 ACH 10:00-15:00*	*0.32 ACH (24 h)*	*0.21 ACH (24 h)*	*1.78 ACH 07:00-18:00, 0.36 ACH 19:00-06:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

4.3.2 Effective Ventilation Strategy For 10% Windows Residential Building

The residential building (R.B.) with 10 % of windows area is modeled to evaluate the effectiveness of ventilation strategies on the indoor air temperature. **Table 4.4** shows the initial ventilation strategies that are used with different envelope designs to identify the suitable ventilation strategies for a residential building with 10 % single glazing window. A similar procedure is applied to identify the proper ventilation strategy as mentioned in the previous section.

Table 4.4 Preliminary Ventilation Strategies and Timings for Passive Cooling in a 10 % Single Glazing Window Residential Building in Dhahran

Month	**Ventilation Strategy#1**	**Ventilation Strategy#2**	**Ventilation Strategy# 3**
January, February	0.5 ACH (24 h)	1 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	Similar to VS#2
March	5 ACH (24)	10 ACH (24 h)	30 ACH (24 h)
April	10 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	20 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	30 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00
May	10 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	20 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	30 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00
June, July, August	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)
September	10 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	20 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	30 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00
October	10 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	20 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	30 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00
November	3 ACH (24 h)	6 ACH (24 h)	Similar to VS#2
December	0.5 ACH (24h)	1 ACH (24 h)	1.5 ACH (24 h)

The thermal comfort in living area is enhanced by proper ventilation strategies as shown in **Figure 4.14 (a)**. As the volume of cool air is increased, the thermal comfort increases. However, minor improvement is observed when high air change per hour is introduced throughout the day (Ventilation Strategy#3: 30 ACH for 24h). This implies that introducing high volume of outside cool air to living area is not significant.

A similar behavior is observed in the sleeping zone as shown in **Figure 4.14 (b)**. However, when high volume of outside cool air(Ventilation Strategy#3: 30 ACH) during the cooled transition months (March and November), the thermal comfort of poorly insulated designs (D#1 and D#4) and standard insulated designs (D#6 to D#10) deteriorates.

Applying selective ventilation strategies such as daytime ventilation only during these two months can significantly enhance the indoor thermal environment without deteriorating the thermal comfort. These strategies take into account two basic concerns: overcooling due to the effect of cooled outside air during nights of cooled transition months (March and November) and overheating due to the effect of hot outside air during daytime of warm transition months (May and October).

Taking in to account this observation, proper ventilation strategies are selected for 10% window single glazing building as listed in **Table 4.5 (a)** and **(b)** and **Table 4.6 (a)** and **(b)** for transition and winter months respectively. These ventilation strategies are developed based on both thermal comfort criteria; naturally ventilated buildings and mechanically operated buildings. The entered values for ventilation strategies in VisualDOE are included in APPENDIX-C.

During the warm transition months; May and October, air-conditioning systems are required to achieve thermal comfort when the criteria for mechanically operated buildings is considered. Using this criterion, more outside cool air is required to achieve thermal comfort in March. It is observed that night ventilation is more effective in achieving thermal comfort in May and October when the criterion of naturally ventilated buildings is considered. Utilizing the natural ventilation criterion in winter months, super-insulated designs require outside cool air during February. However, other envelope designs require outside cool air when the mechanically operated buildings criterion is used. The developed strategies are also appropriate for double glazing.

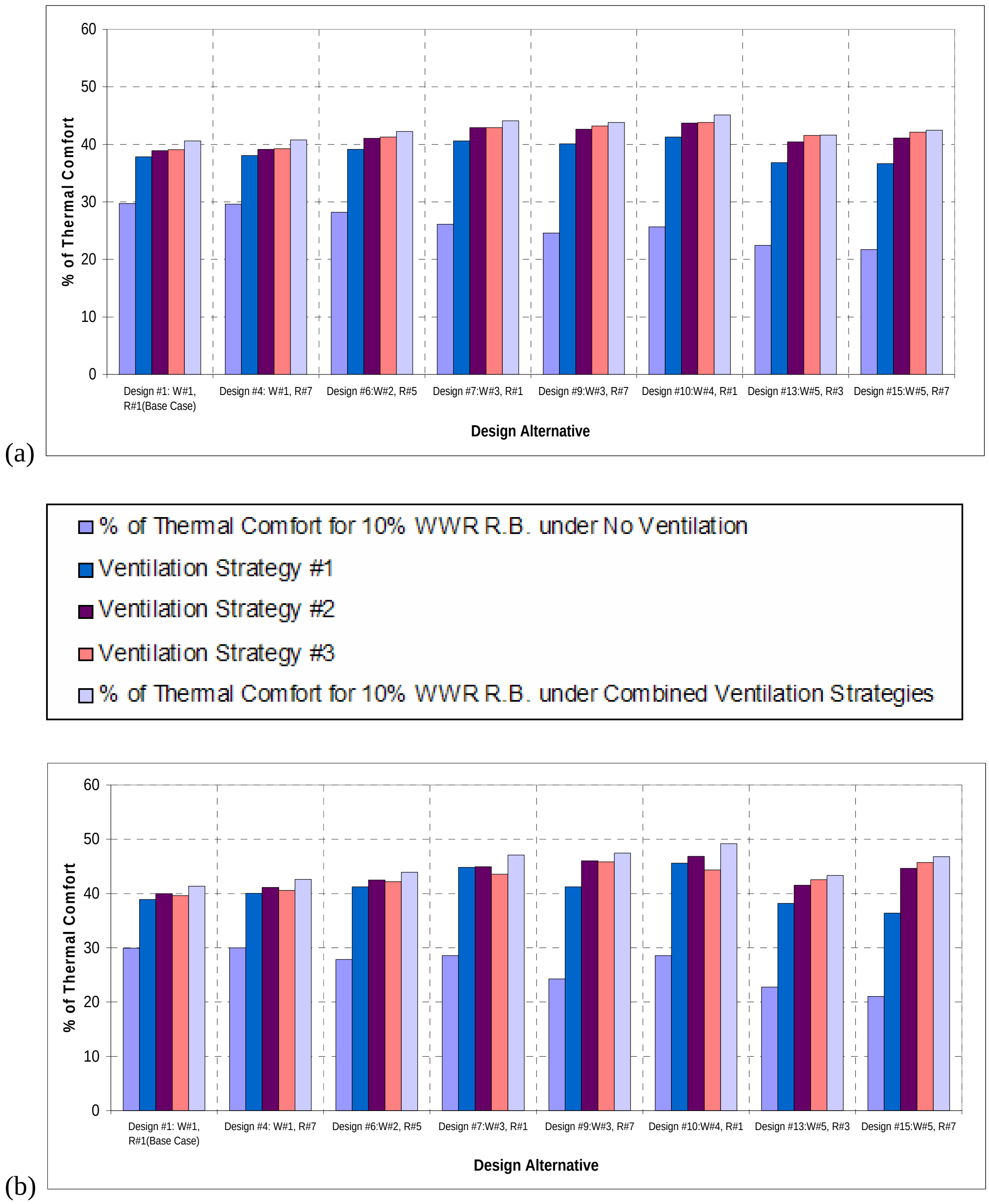


Figure 4.14 Percentage of Thermal Comfort in **(a)** Living Area and **(b)** Sleeping Area of a 10% Window R. B. in Dhahran under Various Ventilation Strategies

Table 4.5 Actual Ventilation Strategies in Transition Months for a 10% Windows R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for **(a)** Naturally Ventilated Buildings and **(b)** Mechanically Operated Buildings

(a)

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*2.56 ACH 08:00-18:00, 0.38 ACH 19:00-07:00*	*10.73 ACH 16:00-9:00, 0.23 ACH 10:00-15:00*	*11.86 ACH 20:00-6:00, 0.3 ACH 7:00-19:00*	*8.48 ACH 20:00-6:00, 0.18 ACH 7:00-19:00*	*3.56 ACH 07:00-18:00, 0.24 ACH 19:00-06:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

(b)

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*5 ACH 08:00-18:00, 0.38 ACH 19:00-07:00*	*10.73 ACH 16:00-9:00, 0.23 ACH 10:00-15:00*	*0.3 ACH (24 h)*	*0.18 ACH (24 h)*	*3.56 ACH C, 0.24 ACH 19:00-06:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

Table 4.6 Actual Ventilation Strategies in Winter Months for a 10% Windows R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for **(a)** Naturally Ventilated Buildings and **(b)** Mechanically Operated Buildings

(a)

<table>
<tr><th>Month / Design Alternative</th><th>December</th><th>February</th></tr>
<tr><td>Design #1: W#1, R#1 (Base Case)</td><td rowspan="4">0.25 ACH (24 h)</td><td rowspan="4">0.26 ACH (24 h)</td></tr>
<tr><td>Design #4: W#1, R#7</td></tr>
<tr><td>Design #6:W#2, R#5</td></tr>
<tr><td>Design #7:W#3, R#1</td></tr>
<tr><td>Design #9:W#3, R#7</td><td rowspan="2">0.61 ACH 07:00-18:00, 0.25 ACH 19:00-06:00</td><td rowspan="2">0.26 ACH (24 h)</td></tr>
<tr><td>Design #10:W#4, R#1</td></tr>
<tr><td>Design #13:W#5, R#3</td><td rowspan="2">0.61 ACH 07:00-18:00, 0.25 ACH 19:00-06:00</td><td rowspan="2">0.67 ACH 08:00-18:00, 0.26 ACH 19:00-07:00</td></tr>
<tr><td>Design #15:W#5, R#7</td></tr>
</table>

(b)

<table>
<tr><th>Month / Design Alternative</th><th>December</th><th>February</th></tr>
<tr><td>Design #1: W#1, R#1 (Base Case)</td><td rowspan="4">0.25 ACH (24 h)</td><td rowspan="4">0.26 ACH (24 h)</td></tr>
<tr><td>Design #4: W#1, R#7</td></tr>
<tr><td>Design #6:W#2, R#5</td></tr>
<tr><td>Design #7:W#3, R#1</td></tr>
<tr><td>Design #9:W#3, R#7</td><td rowspan="4">0.61 ACH 07:00-18:00, 0.25 ACH 19:00-06:00</td><td rowspan="4">0.67 ACH 08:00-18:00, 0.26 ACH 19:00-07:00</td></tr>
<tr><td>Design #10:W#4, R#1</td></tr>
<tr><td>Design #13:W#5, R#3</td></tr>
<tr><td>Design #15:W#5, R#7</td></tr>
</table>

Applying the combined ventilation strategy, the thermal comfort of envelope designs when no ventilation is applied varies from 30% for poorly insulated design (D#1) to 21% for super-insulated design (D#15) in both living and sleeping area. In living area, the thermal comfort increases when using proper ventilation strategies to 41% for the poorly insulated design and to 43-45% for the insulated designs as shown in **Figure 4.15 (a)**. The improvement in thermal comfort is significant with the insulated designs (95%)

compared to the poorly insulated design (37%) when the combined ventilation strategy is applied.

Figure 4.15 (b) shows the impacts of the combined ventilation strategy on building envelope designs in the sleeping area. In the sleeping area, it is clear that the thermal comfort is higher than that of the living area. The thermal comfort under the super-insulated designs (D#9, D#13 and D#15) is high compared to other envelope designs. The thermal comfort improvement in the sleeping area ranges from 38% for the poorly insulated designs to 122% for the super-insulated designs.

It can be noticed that although the buildings with 10% windows have a lower thermal comfort compared to Window-Less buildings when no ventilation is applied, its final thermal comfort improvement is higher than that for Window-Less buildings. This due to the fact that the high generated heat in 10% windows buildings can be significantly removed when ventilation strategies are properly applied.

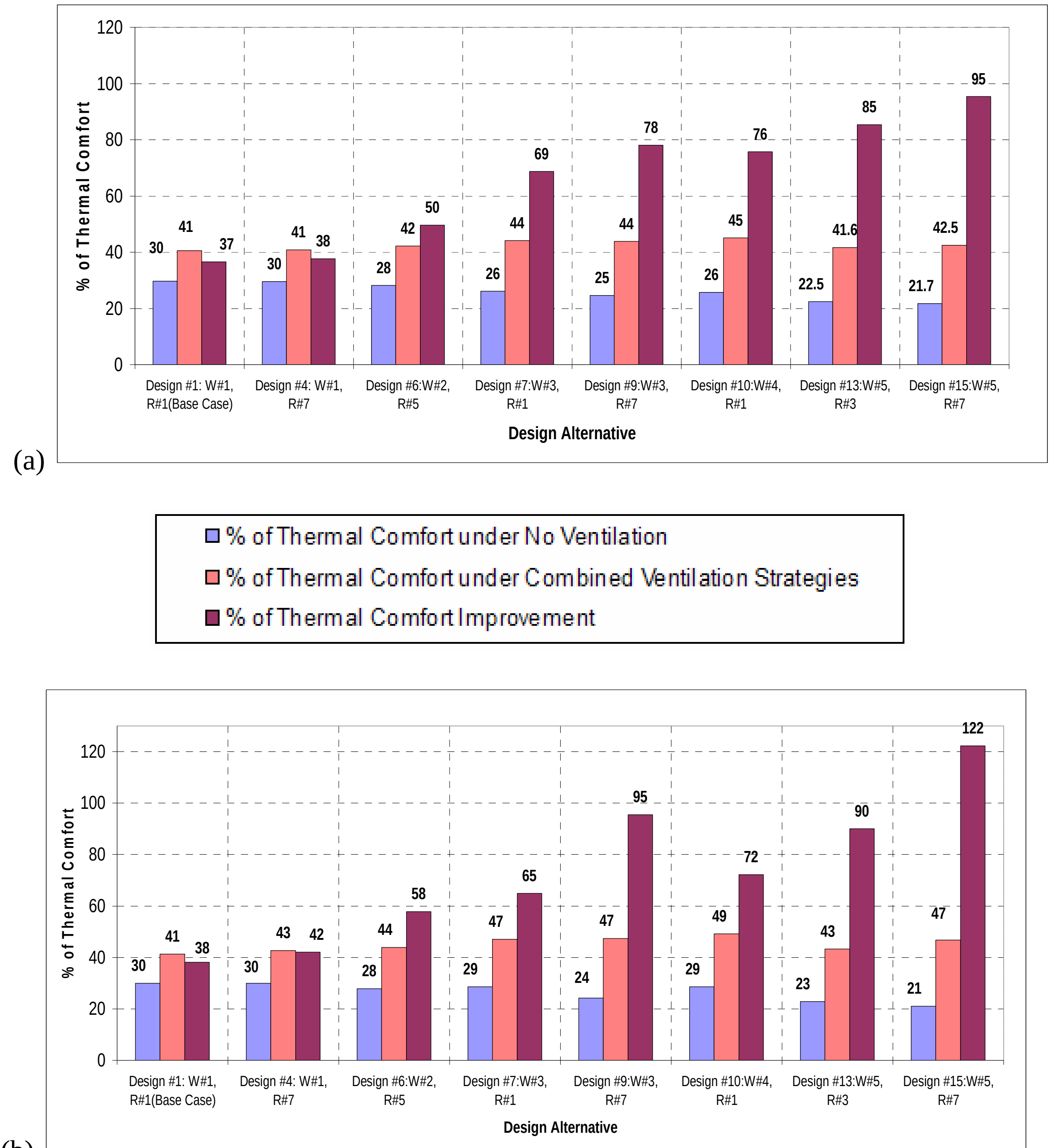


Figure 4.15 Impacts of Combined Ventilation Strategies on Thermal Comfort for Envelope Designs in the **(a)** Living Area and **(b)** Sleeping Area in a 10 % Windows R. B in Dhahran

4.3.3 Effective Ventilation Strategy for 20% Windows Residential Building

The residential building (R.B) with 20 % of windows (Base-Case) is modeled to evaluate the effectiveness of ventilation strategies on the indoor air temperature. **Table 4.7** shows the initial ventilation strategies that are used with different envelope designs to identify the suitable ventilation strategies for a residential building with 20 % single glazing glass window.

Figure 4.16 (a) shows that the thermal comfort in living area is enhanced by introducing proper ventilation strategies. As the volume of cool air is increased, the thermal comfort increases. However, the thermal comfort deteriorates with the high air change per hour (Ventilation Strategy#3: 30 ACH). This implies that introducing high volume of outside air randomly to living area in winter months (December, January and February) and cool transition months (March and November) results in thermal discomfort and therefore more energy consumption. A similar behavior is observed in the sleeping zone as shown in **Figure 4.16 (b)**.

Applying selective ventilation strategies such as daytime ventilation only during winter months (December, January and February) and cool transition months (March and November) and night ventilation only during warm transition months (April, May, and October) help to avoid the overcooling and overheating during cool and hot seasons respectively.

Table 4.7 Preliminary Ventilation Strategies and Timings for Passive Cooling in a 20 % Single Glazing Window Residential Building in Dhahran

Month	**Ventilation Strategy# 1**	**Ventilation Strategy# 2**	**Ventilation Strategy# 3**	**Ventilation Strategy# 4**
January	2 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	4 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	6 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	12 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00
February	4 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	8 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	12 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00	24 ACH: 08:00-18:00 0.5 ACH: 19:00-07:00
March	10 ACH (24 h)	20 ACH (24 h)	30 ACH (24 h)	60 ACH (24 h)
April	10 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	20 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	30 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00	60 ACH: 16:00-09:00 0.5 ACH: 10:00-15:00
May	10 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	20 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	30 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	60 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00
June, July, August	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)	0.5 ACH (24 h)
September	10 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	20 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	30 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00	60 ACH: 17:00-07:00 0.5 ACH: 08:00-16:00
October	10 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	20 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	30 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00	60 ACH: 16:00-08:00 0.5 ACH: 09:00-15:00
November	10 ACH (24 h)	20 ACH (24 h)	30 ACH (24 h)	60 ACH (24 h)
December	4 ACH: 08:00-17:00 0.5 ACH: 18:00-07:00	8 ACH: 08:00-17:00 0.5 ACH: 18:00-07:00	12 ACH: 08:00-17:00 0.5 ACH: 18:00-07:00	24 ACH: 08:00-17:00 0.5 ACH: 18:00-07:00

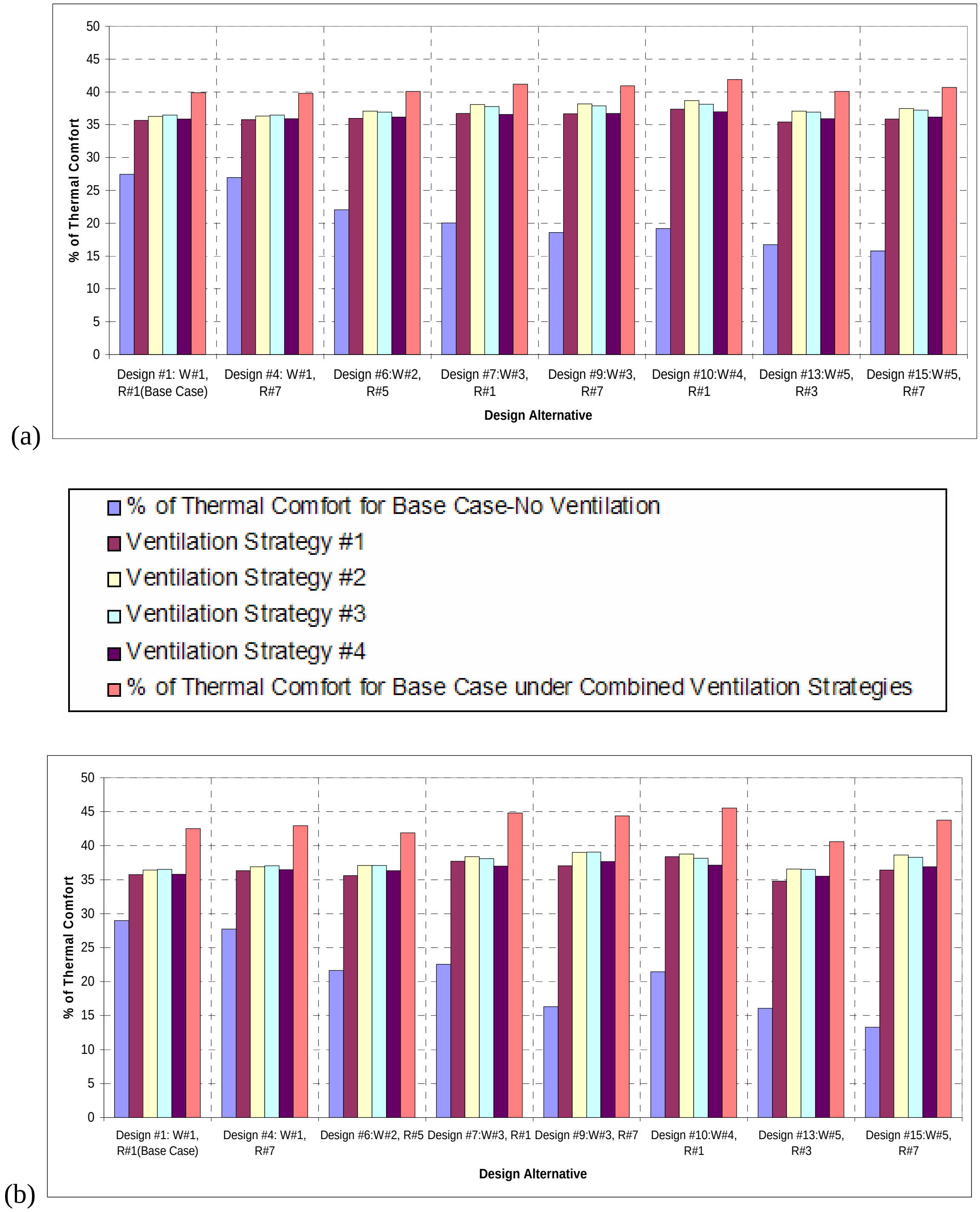


Figure 4.16 Percentage of Thermal Comfort in **(a)** Living Area and **(b)** Sleeping Area of a 20% Window R. B. in Dhahran under Various Ventilation Strategies

Proper ventilation strategies are selected for 20% window single glazing building as listed in **Table 4.8 (a)** and **(b)** and **Table 4.9 (a)** and **(b)** for transition and winter months respectively. When double glazing is used, similar strategies can be used with little modifications as highlighted in the tables.

The thermal comfort of envelope designs when no ventilation is applied varies from 27% for poorly insulated design (D#1) to 16% for super-insulated design (D#15) in both living and sleeping area. Applying proper ventilation strategies in living area, the thermal comfort increases to 40% for the poorly insulated design and to 41% for the super-insulated design as shown in **Figure 4.17 (a)**. It is noticed that all envelope design achieves similar thermal comfort level. However, the improvement in thermal comfort is significant with the insulated designs (above 100%) compared to the poorly insulated design (45%) when the combined ventilation strategy is applied.

Figure 4.17 (b) shows the impacts of the combined ventilation strategy on the thermal comfort in sleeping area. It is clear that the thermal comfort in the sleeping area for super-insulated designs (D#9, D#13 and D#15) is higher than that in the living area. The thermal comfort improvement in the sleeping area ranges from 47% for the poorly insulated designs to 229% for the super-insulated designs.

Table 4.8 Actual Ventilation Strategies in Transition Months for a 20 % Window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for **(a)** Naturally Ventilated Buildings and **(b)** Mechanically Operated Buildings

(a)

<table>
<tr><th>Month / Design Alternative</th><th>March</th><th>April</th><th>May</th><th>October</th><th>November</th></tr>
<tr><td>Design #1: W#1, R#1 (Base Case)</td><td rowspan="6">4.93 ACH 08:00-18:00, 0.27 ACH 19:00-07:00</td><td rowspan="6">Single Glazing: 5.36 ACH 16:00-9:00 Double Glazing: 10.73 ACH 16:00-9:00, 0.23 ACH 10:00-15:00</td><td rowspan="6">11.86 ACH 20:00-6:00, 0.3 ACH 7:00-19:00</td><td rowspan="6">8.48 ACH 20:00-6:00, 0.18 ACH 7:00-19:00</td><td rowspan="6">5.94 ACH 07:00-18:00, 0.24 ACH 19:00-06:00</td></tr>
<tr><td>Design #4: W#1, R#7</td></tr>
<tr><td>Design #6:W#2, R#5</td></tr>
<tr><td>Design #7:W#3, R#1</td></tr>
<tr><td>Design #9:W#3, R#7</td></tr>
<tr><td>Design #10:W#4, R#1</td></tr>
<tr><td>Design #13:W#5, R#3</td><td rowspan="2">4.93 ACH 08:00-18:00, 0.27 ACH 19:00-07:00</td><td rowspan="2">10.73 ACH 16:00-9:00, 0.23 ACH 10:00-15:00</td><td rowspan="2">11.86 ACH 20:00-6:00, 0.3 ACH 7:00-19:00</td><td rowspan="2">8.48 ACH 20:00-6:00, 0.18 ACH 7:00-19:00</td><td rowspan="2">5.94 ACH 07:00-18:00, 0.24 ACH 19:00-06:00</td></tr>
<tr><td>Design #15:W#5, R#7</td></tr>
</table>

(b)

<table>
<tr><th>Month / Design Alternative</th><th>March</th><th>April</th><th>May</th><th>October</th><th>November</th></tr>
<tr><td>Design #1: W#1, R#1 (Base Case)</td><td rowspan="8">5 ACH 08:00-18:00, 0.38 ACH 19:00-07:00</td><td rowspan="8">10.73 ACH 16:00-9:00, 0.23 ACH 10:00-15:00</td><td rowspan="8">0.27 ACH (24 h)</td><td rowspan="8">0.18 ACH (24 h)</td><td rowspan="8">11.87 ACH 07:00-18:00, 0.24 ACH 19:00-06:00</td></tr>
<tr><td>Design #4: W#1, R#7</td></tr>
<tr><td>Design #6:W#2, R#5</td></tr>
<tr><td>Design #7:W#3, R#1</td></tr>
<tr><td>Design #9:W#3, R#7</td></tr>
<tr><td>Design #10:W#4, R#1</td></tr>
<tr><td>Design #13:W#5, R#3</td></tr>
<tr><td>Design #15:W#5, R#7</td></tr>
</table>

Table 4.9 Actual Ventilation Strategies in Winter Months for a 20 % Window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for **(a)** Naturally Ventilated Buildings and **(b)** Mechanically Operated Buildings

(a)

Month / Design Alternative	December	January	February
Design #1: W#1, R#1 (Base Case)	**Single Glazing:** *2.46 ACH 08:00-17:00, 0.25 ACH 18:00-07:00* **Double Glazing:** *0.25 ACH(24 h)*	*0.27 ACH (24 h)*	*0.26 ACH (24 h)*
Design #4: W#1, R#7			
Design #6:W#2, R#5	*2.46 ACH 07:00-18:00, 0.25 ACH 19:00-06:00*	*0.27 ACH (24 h)*	*2.66 ACH 08:00-18:00, 0.26 ACH 19:00-07:00*
Design #7:W#3, R#1			
Design #9:W#3, R#7			
Design #10:W#4, R#1	*2.46 ACH 07:00-18:00, 0.25 ACH 19:00-06:00*	**Single Glazing:** *1.32 ACH 08:00-18:00, 0.25 ACH 19:00-07:00* **Double Glazing:** *0.25 ACH(24 h)*	*2.66 ACH 08:00-18:00, 0.26 ACH 19:00-07:00*
Design #13:W#5, R#3	*2.46 ACH 07:00-18:00, 0.25 ACH 19:00-06:00*	*1.32 ACH 08:00-18:00, 0.25 ACH 19:00-07:00*	*2.66 ACH 08:00-18:00, 0.26 ACH 19:00-07:00*
Design #15:W#5, R#7			

(b)

Month / Design Alternative	December	January	February
Design #1: W#1, R#1 (Base Case)	***Single Glazing:*** *2.46 ACH 07:00-18:00, 0.25 ACH 19:00-06:00* ***Double Glazing:*** *0.25 ACH (24h)*	*0.27 ACH (24 h)*	***Single Glazing:*** *2.66 ACH 08:00-18:00, 0.26 ACH 19:00-07:00* ***Double Glazing:*** *0.25 ACH (24h)*
Design #4: W#1, R#7			
Design #6:W#2, R#5	*2.46 ACH 07:00-18:00, 0.25 ACH 19:00-06:00*	*0.27 ACH (24 h)*	*2.66 ACH 08:00-18:00, 0.26 ACH 19:00-07:00*
Design #7:W#3, R#1			
Design #9:W#3, R#7			
Design #10:W#4, R#1			
Design #13:W#5, R#3	*2.46 ACH 07:00-18:00, 0.25 ACH 19:00-06:00*	*1.32 ACH 08:00-18:00, 0.25 ACH 19:00-07:00*	*2.66 ACH 08:00-18:00, 0.26 ACH 19:00-07:00*
Design #15:W#5, R#7			

(a)

(b)

Figure 4.17 Impacts of Combined Ventilation Strategies on Thermal Comfort for Envelope Designs in the **(a)** Living Area and **(b)** Sleeping Area in a 20 % Windows R. B in Dhahran

4.4 Impact of Passive Envelope Designs on Thermal Performance of the Base-Case Residential Building

VisualDOE is used to simulate the base case scenario (20% of windows) of a typical residential building in Dhahran without utilizing the mechanical air conditioning systems. The thermal performance of the typical residential building is shown in **Figure 4.18**. It is interesting to note that the poorly insulated designs D#1, D#4 are performing better in terms of thermal comfort than the super-insulated designs D#13 and D#15 when no ventilation is applied. The big difference in temperature between the indoor and outdoor temperature promotes the reverse heat exchange; from indoor to outdoor which subsequently makes the poorly insulated designs perform better in transition and winter months when no ventilation is applied. On contrary, the thermal characteristics of insulated designs don’t allow the heat losses to the outside cooled environment. As a result, the indoor air temperature in the insulated buildings tends to be above the thermal comfort zones and consequently creates the thermal discomfort.

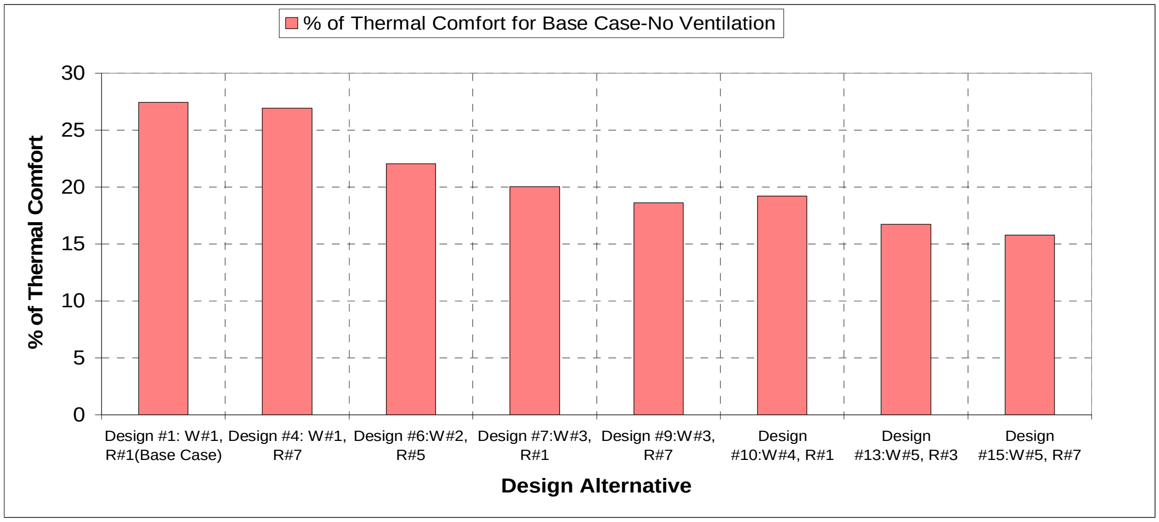
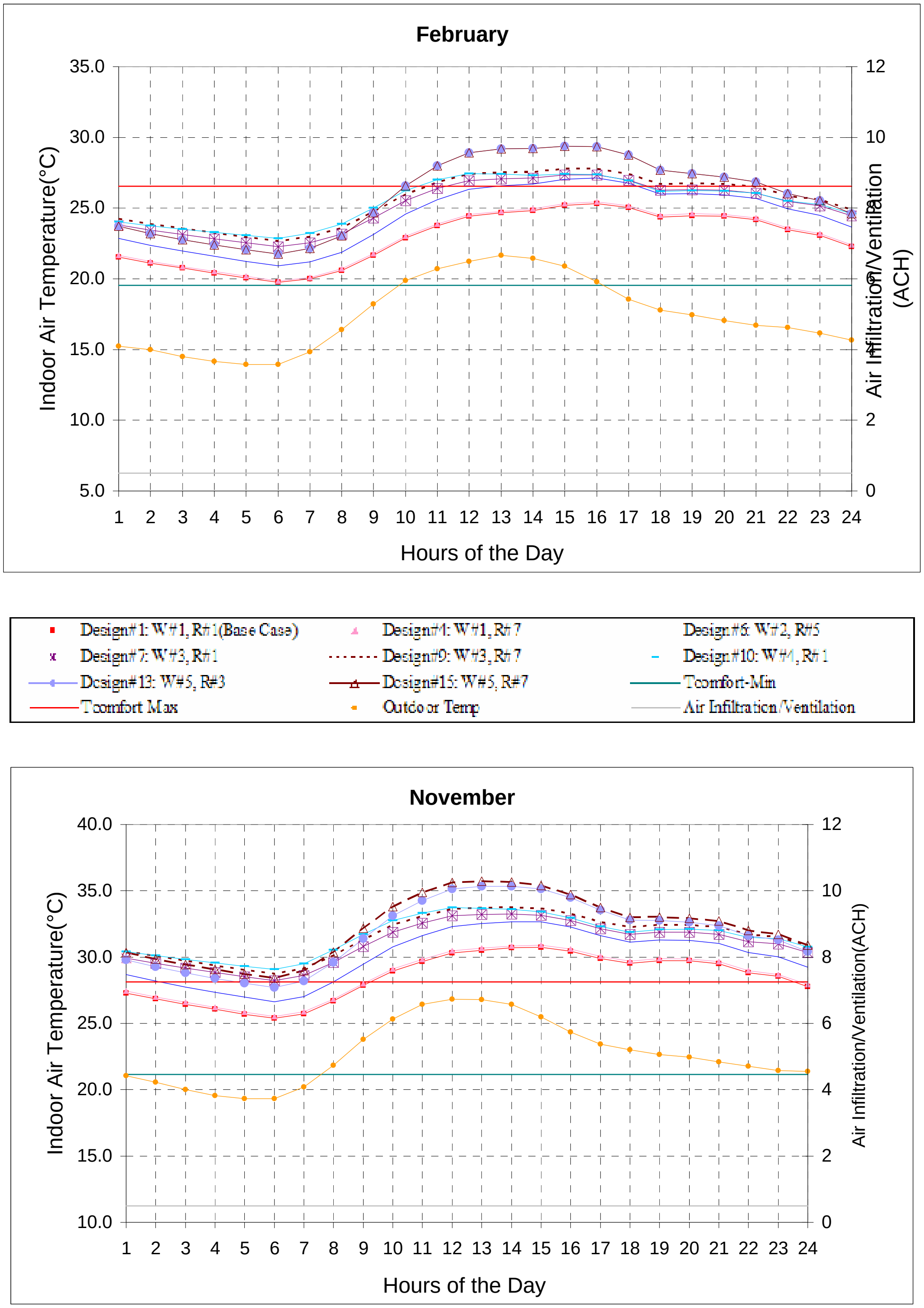


Figure 4.18 Thermal Performance of a Typical Unconditioned Residential Building in Dhahran without Ventilation

This phenomenon occurs in winter and transition months; January, February, March, April, October, November and December as shown in **Figure 4.19 (a)** and **(b)** for February and November. In winter, the non-insulated designs performed better than the insulated designs. The figures show that there is a risk of overheating at 12:00 for the insulated designs while the non-insulated designs achieve thermal comfort throughout the day. This is true for other winter months: December and January. In transition months, there is a risk of overheating for all designs but it happens early in the case of insulated designs. This explains the reason behind the better performance of poorly insulated designs compared to insulated designs when no ventilation is applied.

(a)



(b)

Figure 4.19 Monthly Average Hourly Indoor Air Temperatures for the base case Residential Building in Dhahran in **(a)** February and **(b)** November

4.5 Impact of Window to Wall Ratio (WWR) On Thermal Performance of Envelope Designs

The thermal performance of building envelopes can be greatly affected by the amount of solar radiation that is introduced through the fenestration system. The generated heat within the indoor environment increases with the admitted solar radiation which is greatly dependent on the percentage of glazing area in the exterior building envelope. Different window to wall ratio (WWR) are evaluated; 0.20 (base case), 0.10 and window-less (0.0). **Figure 4.20** shows the effect of reducing the WWR on the improvement of the thermal comfort of the occupants.

Generally, the reduction of window to wall ratio has a positive impact on the thermal performance of the building. The thermal environment of the super-insulated and standard insulated designs has improved more than the non-insulated designs. **Figure 4.21** shows the improvement of thermal comfort due to the variation of WWR for every design alternative compared to the base case (0.2 WWR). At a ratio of 0.1 WWR, the thermal comfort improvements for the standard and super-insulted designs are from 28% to 38% compared to the base case scenario (0.2 WWR). On the other hand, the improvement for the windowless (0 WWR) building varies greatly from 38% for D#6 to 86% for D#15. The non-insulated designs don’t have more than 15% improvement and no major improvement is observed when compared to the insulated designs.

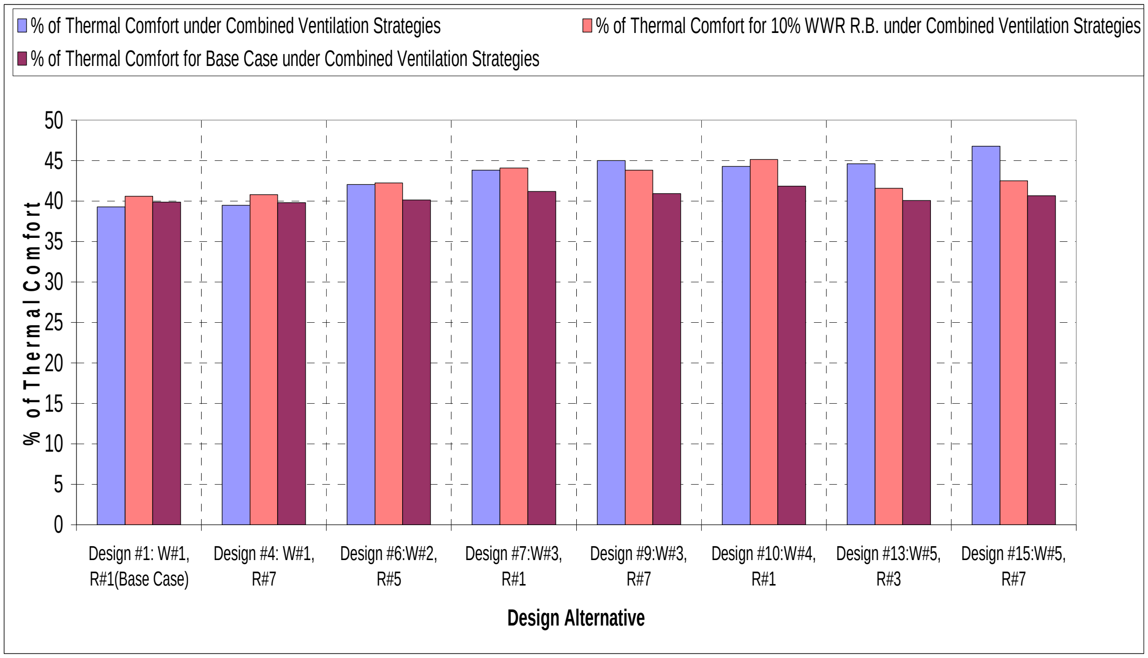


Figure 4.20 Thermal Performance of Non Ventilated R.B. in Dhahran under Different WWR

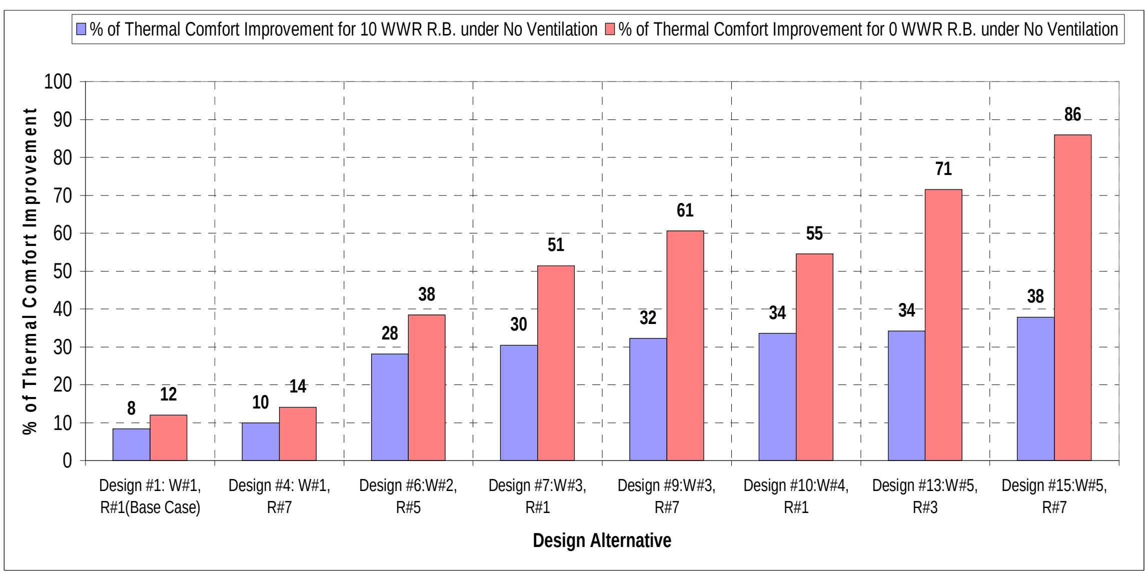


Figure 4.21 Improvement of the Thermal Performance of Non-Ventilated R.B. in Dhahran under Different WWR

4.6 Impact of Glazing Types on Thermal Performance of Envelope Designs

Glazing type plays an important role in the dynamic behavior of indoor thermal environment and subsequently, the thermal comfort. The recent development in fenestration system and windows technology has helped to improve the thermal performance of buildings. The thermal performance of windows depends largely on its U-value which represents the heat loss coefficient. The lower the U-value of a window, the better is its thermal performance. This coefficient can be improved by many methods including increasing the number of glazing layers, using specific coatings to control solar radiation and filling the spaces between the two layers with low thermal conductive gases such as argon or krypton. If all these measures are combined, the U-value can be reduced from 5.9 $W/m^2.K$ for a single glazing to 1 $W/m^2.K$ for a coated Double glazing with a gas fill. For a comparison purpose, the U-value of a concrete masonry unit (CMU) wall system is 2.98 $W/m^2.K$.

The objective of this part is to assess the effects of two common glazing types: single and double glazing on the thermal performance of residential building with different WWR (0.2, 0.1 and window-less) in Dhahran under unconditioned mode. The glazing types were concluded from the conducted survey and their thermal and physical characteristics are listed in **Table 4.10**.

Table 4.10 Thermal and Physical Characteristics of Typical Glazing Types used in Saudi Arabia

Description	Code	# of glazing	**Frame Type**	**U-Factor ($W/m^2.K$)**	**SC**	**SHGC**	**Visible Transmittance (VT)**
Single Clear 6 mm	SG	1	Al.	6.172	0.95	0.82	0.88
Double Green Glazing 3/12/3 mm	DG	2	Al.	2.788	0.71	0.613	0.743

Figure 4.22 and **Figure 4.23** show the thermal performance of the residential building at 0.2 WWR (base case) and at 0.1 WWR in Dhahran with the two glazing types: single and double, compared with non-glazed building. The thermal comfort for all building envelope designs has improved when double glazing is used at 0.2 WWR and 0.1 WWR as shown in **Figure 4.24**. The improvement in thermal comfort for all envelope designs for 0.2 WWR follows a similar trend but with more improvement in poorly insulated designs (D#1 & D#4) and standard envelope designs (D#6, D#7, D#9 and D#10). On contrary, the thermal comfort of super-insulated designs (D#13 and D#15) at 0.1 WWR has increased by more than 7-8% compared to only 4-6% at 0.2 WWR. Therefore, the double glazing was found more effective in improving the thermal comfort for super insulated design with low window wall ratio and more effective for poorly insulated deigns with high window wall ratio.

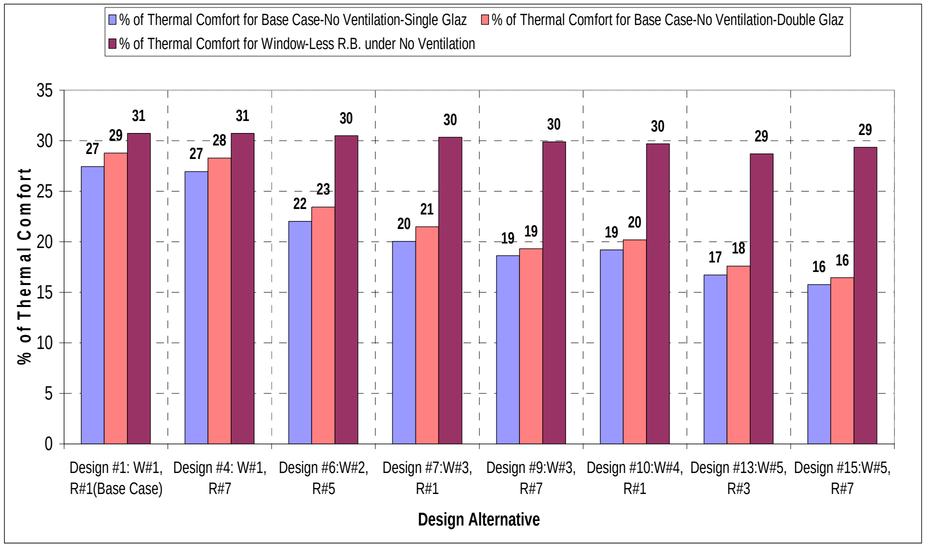


Figure 4.22 Thermal Performance of the Base Case R.B. in Dhahran for Two Glazing Types and Window-less

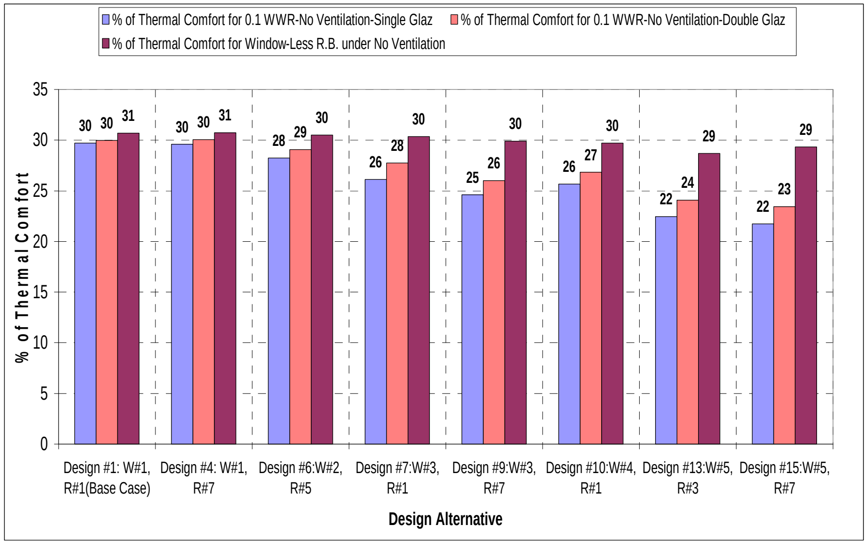


Figure 4.23 Thermal Performance of 0.1 WWR Residential Building in Dhahran for Two Glazing Types and Window-less

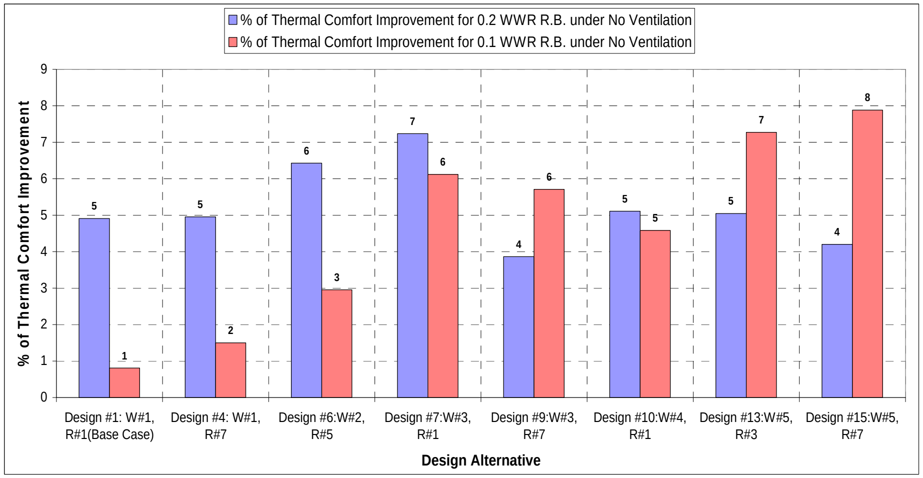


Figure 4.24 Thermal Comfort Improvements of Residential Building in Dhahran at 0.2 WWR (Base Case) and 0.1 WWR due to Double Glazing

CHAPTER FIVE

IMPACT OF ENVELOPE THERMAL DESIGN ON ENERGY PERFORMANCE OF RESIDENTIAL BUILDINGS

5.1 Introduction

Energy simulation programs have been successfully utilized to develop energy codes in many countries such as USA, Canada, UK and Australia. These programs have been used to evaluate the energy and thermal performance of different design alternatives. Subsequently, design guidelines have been incorporated in to energy standards and codes. The guidelines for energy simulation have also been developed to help engineers and architects to properly understand the energy and thermal performance of buildings for code compliance as well as for new technology implementation. In Saudi Arabia and particularly in Dhahran, energy simulation programs have been used to simulate energy and economic performance of building envelopes in single family houses. Many of these studies were done few years back. Since then, many practices are introduced into the design of residential buildings. In Riyadh, some approved mathematical models have been used to evaluate the thermal performance of individual components of building systems such as roof or walls. In Riyadh, no study was found to simulate the energy performance of residential building in an integral format with all building systems. In the following sections, energy performance of different envelope designs and the impact of their thermal characteristics are evaluated.

5.2 Energy Simulation of the Base Case Residential Building

The characteristics of the typical residential building in Dhahran and Riyadh have been identified in Chapter three of this research. In order to investigate the impact of envelope designs on energy consumption, the developed residential building was modeled and simulated using VisualDOE 4.1 energy simulation program. The simulation was performed using weather data file for the year 2002 for Dhahran and typical metrological year (TMY) from 1983 to 1999 for Riyadh which was developed for this study. The initial base case model was developed based on the conducted survey for the two cities and considering the following assumptions:

1. The living area and sleeping area were assumed to be two separate zones and served by two different air conditioning systems.
2. The air-conditioning system is continuously operating for 24 hrs a day for a constant thermal comfort.
3. The building was assumed to be an air tight with a constant infiltration rate of 0.5 ACH as interpreted from the survey.
4. The thermostat setting was assumed to be fixed at 25 ºC for cooling and 21 ºC for heating throughout the year.

5.2.1 Simulation Results of Base Case Residential Building Model

The annual energy consumption of the base case residential building model for Dhahran and Riyadh is presented in **Table 5.1**. The table shows that the residential buildings in Dhahran consume 16% more energy than those in Riyadh. In terms of energy intensity, the energy index for residential building in Dhahran and Riyadh is 196 and 169 kWh/m^2/year respectively. For comparison purposes, studies in Dhahran show that the average energy intensity for poorly insulated residential buildings is 263 kWh/m^2/year and for properly insulated buildings is 153 kWh/m^2/year **(Ahmed, 2004)**. The values obtained for the base case lies between these two figures. However, many different assumptions were found between this research and the literature. The thermostatic settings for the literature studies are 22 ºC for heating and 24 ºC for cooling compared to 21 ºC and 25 ºC for heating and cooling respectively for this study. The window to wall ratio used in literature is 13% compared to 20% used as a base case in this study. The weather data used for the literature studies is for year 93 and the roof system selected is 150 mm Normal Concrete Slab compared to weather data of 2002 and 200 mm Hourdi Slab with 100 mm lightweight concrete for this research study. Therefore, it is concluded that the no further calibration is needed since wide variations in building and weather characteristics are found.

Table 5.1 Annual Energy Consumption of the Base Case Residential Building in Dhahran and Riyadh

Energy Use (kWh)	Dhahran-Base Case D#1	Riyadh-Base Case D#1
Lights	13,365	13,365
Equip.	6,609	6,609
Heating	3,459	1,123
Cooling	58,062	49,018
Fans	18,724	13,449
Hot Water	17,531	17,886
Total	**117,750**	**101,450**

The monthly energy consumption for the typical residential building is shown in **Figure 5.1**. The figure shows the diversity of the energy consumption in different months. It is clear that for the many months in the year the energy consumption for the residential buildings in Dhahran is more than those in Riyadh.

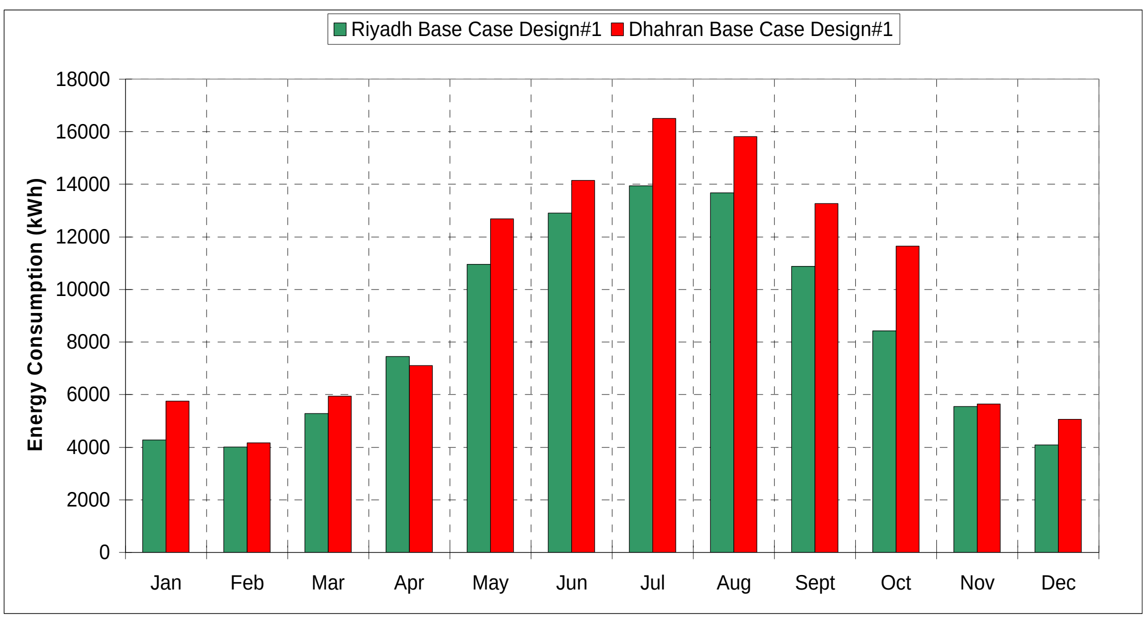


Figure 5.1 Monthly Energy Consumption of Base Case Residential Building in Dhahran and Riyadh

5.3 Impact of Envelope Designs on Energy Performance of Residential Building

The energy consumption of residential buildings can be reduced with proper selection of envelope designs. Since the residential buildings are envelope-load dominated buildings, they are significantly influenced by the climate characteristics. In this section, the energy performance of the typical residential building in Dhahran and Riyadh is evaluated under various envelope designs. **Table 5.2** and **Table 5.3** list the wall and roof designs that cover a wide range of thermal characteristics. The base case residential building (Design#1) in Dhahran and Riyadh is a combination of W#1 and R#1.

Table 5.2 Wall Designs for Energy Simulation in Residential Buildings

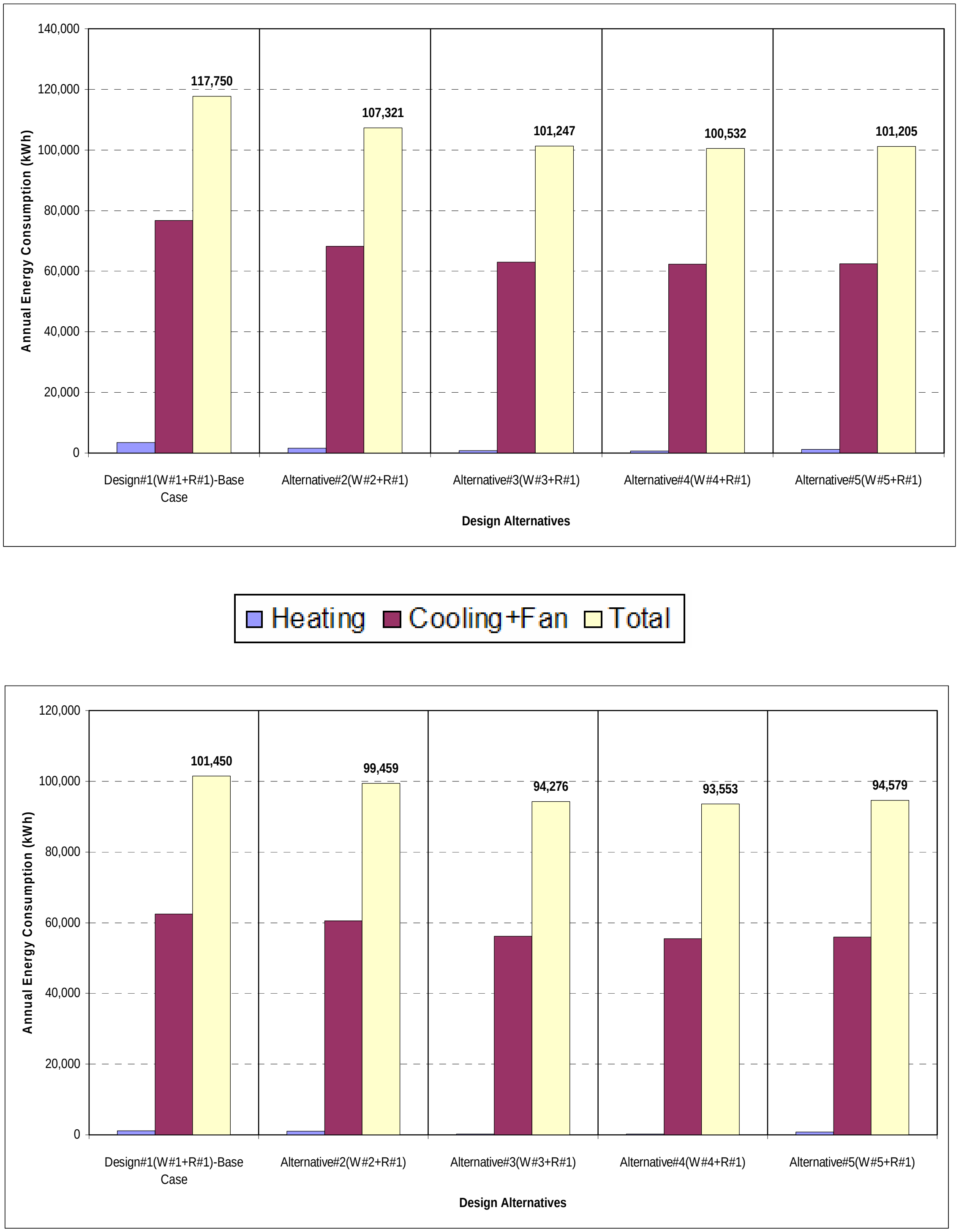
Wall No.	Wall Description	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	Heat Capacity ($KJ/m^2.°C$)	RSI
W#1	**Dhahran:** Single 200 mm Hollow CMU Wall+ No insulation+ 15 mm Stucco finishes on both sides	2.98	0.34	379.97	2
	Riyadh: CMU with insulation material insert	1.63	0.61	379.97	3.59
W#2	Single 245 mm Siporex Wall+ No insulation+ 15 mm Stucco finishes on both sides	1.2	0.83	176.93	5
W#3	50 mm Precast Concrete Panel on both sides+ 50 mm Polyurethane + + 15 mm Stucco on both sides	0.41	2.44	237.78	14
W#4	Cavity Hollow CMU Block Wall+50 mm Air Space+ 100 mm Polyurethane (ext)+15 mm Stucco finishes on both sides	0.2	5.00	442.18	28
W#5	75 mm Polyurethane on both sides+ 50 mm Precast Concrete + 15 mm Stucco finishes on both sides	0.15	6.67	148.58	38

Table 5.3 Roof Designs for Energy Simulation in Residential Buildings

Roof No.	Roof Description	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	Heat Capacity ($KJ/m^2.°C$)	RSI
R#1	15 mm Cement plaster+200mm CMU Hourdi Slab+100mm Foam Conc.+4mm water proof membrane+25 mm Sand Fill+ 50mm Mortar +Terrazzo	0.59	1.69	629.83	10
R#3	15 mm Cement plaster+50mm Ext Polystyrene+200mm Clay Brick Hourdi+100mm Plain Concrete+ 4mm water proof membrane+ 25mm Sand+ 50mm Mortar+ Tiles	0.39	2.56	567.13	15
R#5	15 mm Cement plaster+200 mm Siporex Hourdi + 100 mm Foam Concrete+50mm Exp Polystyrene + 4mm water proof membrane +25mm Sand+ 50 mm Mortar+ Tiles	0.23	4.35	337.03	25
R#7	15 mm Cement plaster+200mm CMU Hourdi Slab+100 mm Foam Concrete+ 100 mm Polyurethane +4mm water proof membrane+ 25mm Sand+ 50mm Mortar+ Tiles	0.17	5.88	637.91	35

5.3.1 Impact of Wall Designs on Energy Performance of Residential Building

The base case scenario of the residential building has been modeled using VisualDOE 4.1 to evaluate the energy consumption. **Table 5.1** lists the energy consumption of the base case for both Dhahran and Riyadh. The energy consumption for the base case is evaluated under various wall designs. **Figure 5.2 (a)** and **(b)** show the impact of wall designs on energy consumption of Residential Building in Dhahran and Riyadh respectively.



(a)

(b)

Figure 5.2 Energy Consumption of Base Case Residential Building in **(a)** Dhahran, **(b)** Riyadh under Various Wall Designs

Figure 5.2 (a) and **(b)** show that when the thermal resistance of the walls increases the energy consumption decreases. In Dhahran, increasing the thermal resistance of the base case wall (W#1) by 2.4 (W#2), 7.2 (W#3), 14.7 (W#4) and 19.6 times (W#5) decreases the energy consumption by 9%, 14%, 16% and 14% respectively as shown in **Figure 5.3 (a)**. Similarly in Riyadh, increasing the thermal resistance of the base wall by 1.4 (W#2), 4 (W#3), 8 (W#4) and 11 times (W#5) decreases the energy consumption by 2%, 7%, 8% and 7%. The fact that the base wall design in Riyadh has a higher thermal resistance than that for Dhahran makes the reduction in energy consumption more in Dhahran. Although the thermal resistance of W#5 (6.67 m^2.°C/W) is higher than W#4 (5 m^2.°C/W) by more than 25%, it is interesting to note that the energy consumption increases by 0.7% in Dhahran and 1.1% in Riyadh. The impact of W#5 on energy consumption can be related to the effect of heat capacity. The heat capacity (thermal mass) of W#5 is 3 times less than the W#4. Therefore, the light thermal mass in the wall design has a slight negative impact on the heat energy consumption when compared to a similar resistance wall.

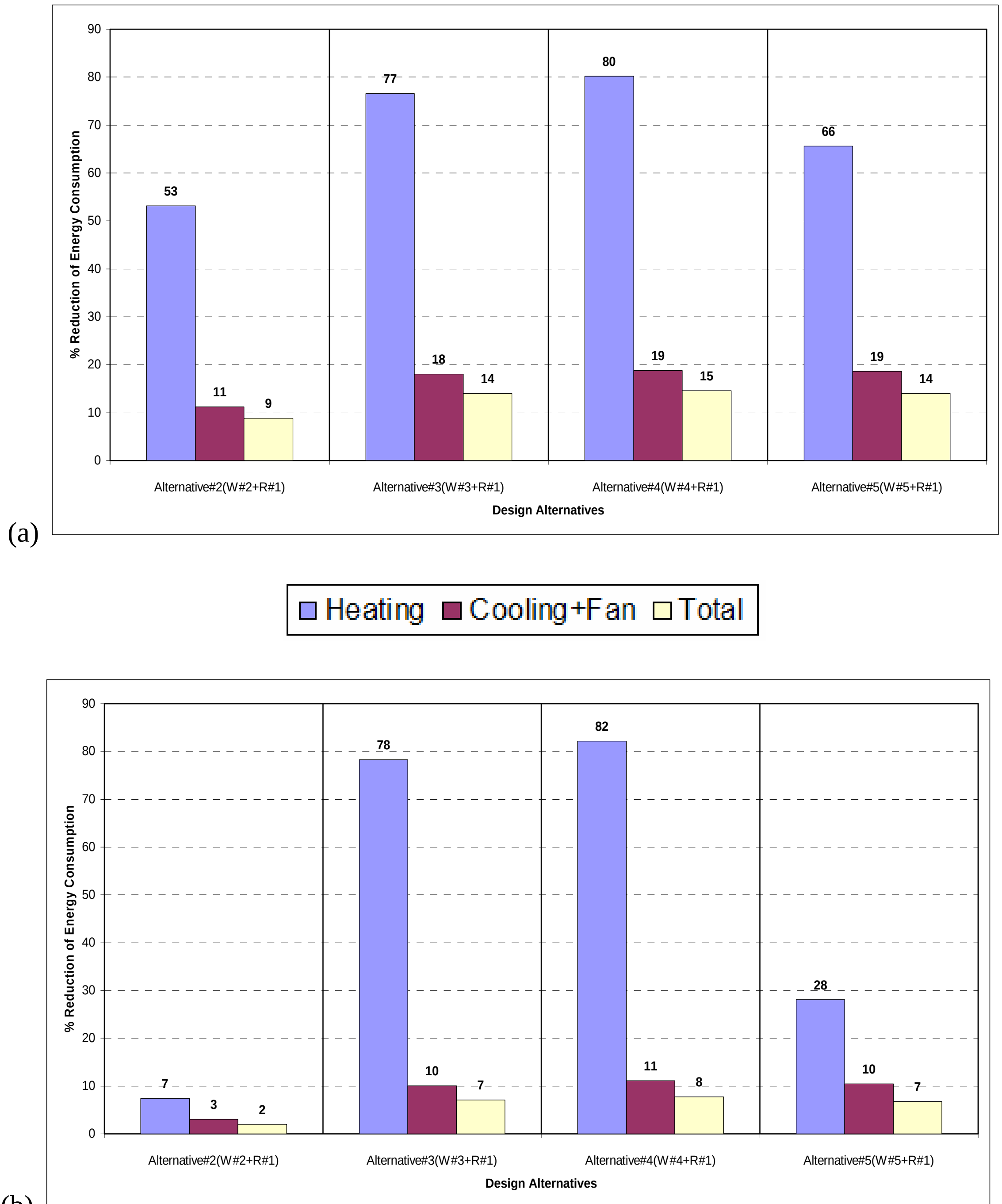


Figure 5.3 Impact of Wall Designs on Energy Consumption of Base Case Residential Building in **(a)** Dhahran and **(b)** Riyadh

5.3.2 Impact of Roof Designs on Energy Performance of Residential Building

The energy consumption for the base case is evaluated under various roof designs at fixed wall design. For this building, the sleeping zone is influenced by the roof deigns. Hence, the impact of the different roof designs is not significant when taking into account the thermal characteristics of the base case roof design (R#1). **Figure 5.4 (a)** and **(b)** show the impact of roof designs on energy consumption of Residential Building in Dhahran and Riyadh respectively. In Dhahran, **Figure 5.4 (a)** shows that when the thermal resistance of the roofs increases, the energy consumption decreases.

Increasing the thermal resistance of the roof by 1.5 times as in (R#3), 2.6 times as in (R#5) and 3.5 times (R#7) decreases the energy consumption by 0.1%, 0.9% and 1.2% respectively in Dhahran as shown in **Figure 5.5 (a)**. It is also clear that when R#3 and R#5 are used, the heating energy has increased by 8% and 1% respectively. For R#3, the interior side of the slab is covered with insulation material which doesn’t store the indoor generated heat for the heating purposes. Similarly for R#5, the thermal mass has decreased by more than 50% and therefore the potential to store some generated heat is reduced. For heating purposes in continuous operating buildings, low thermal mass material should be avoided. Additionally, the thermal insulation should be placed to the exterior of the heavy thermal mass material.

(a)

(b)

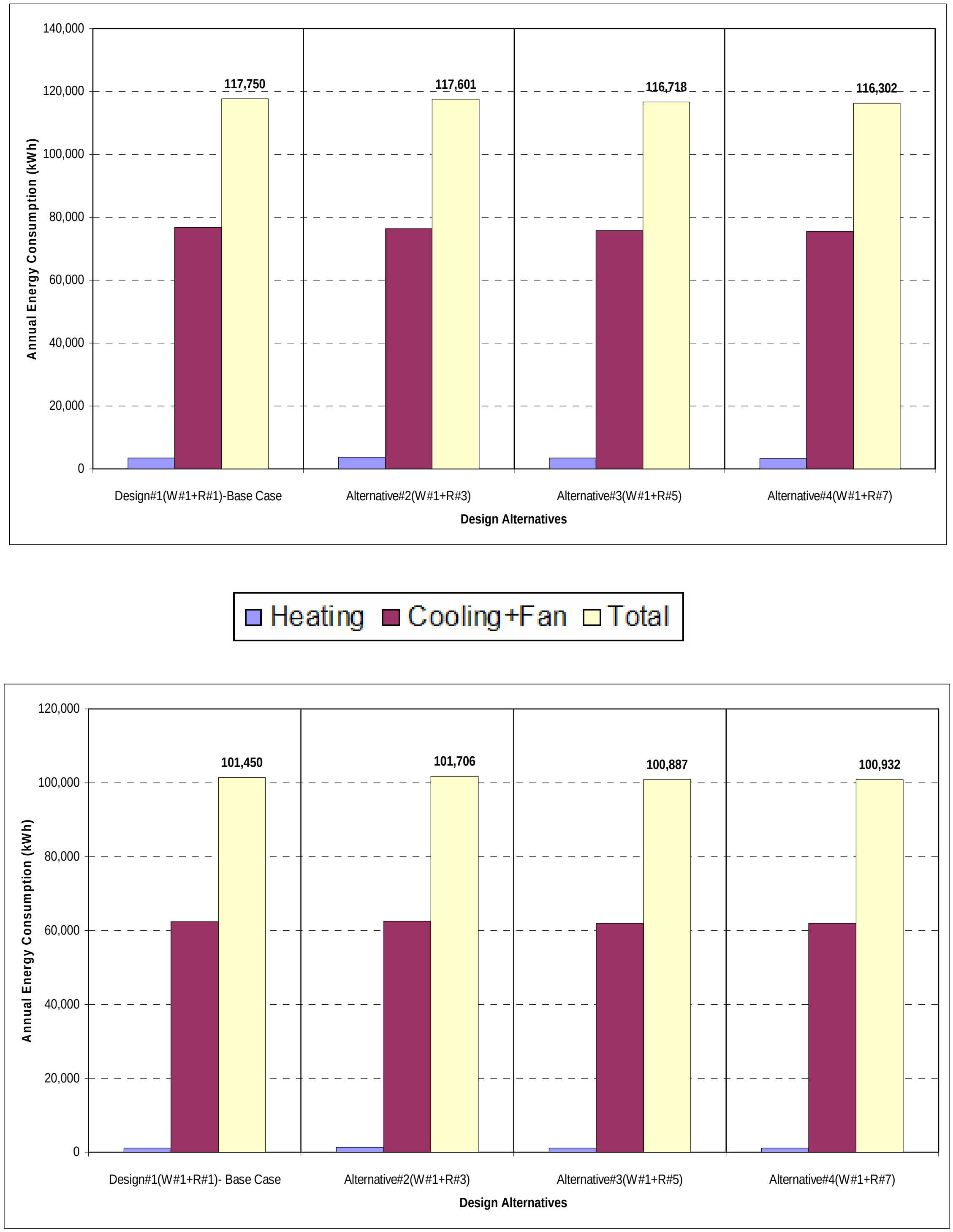


Figure 5.4 Energy Consumption of Base Case Residential Building in **(a)** Dhahran and **(b)** Riyadh under Various Roof Designs

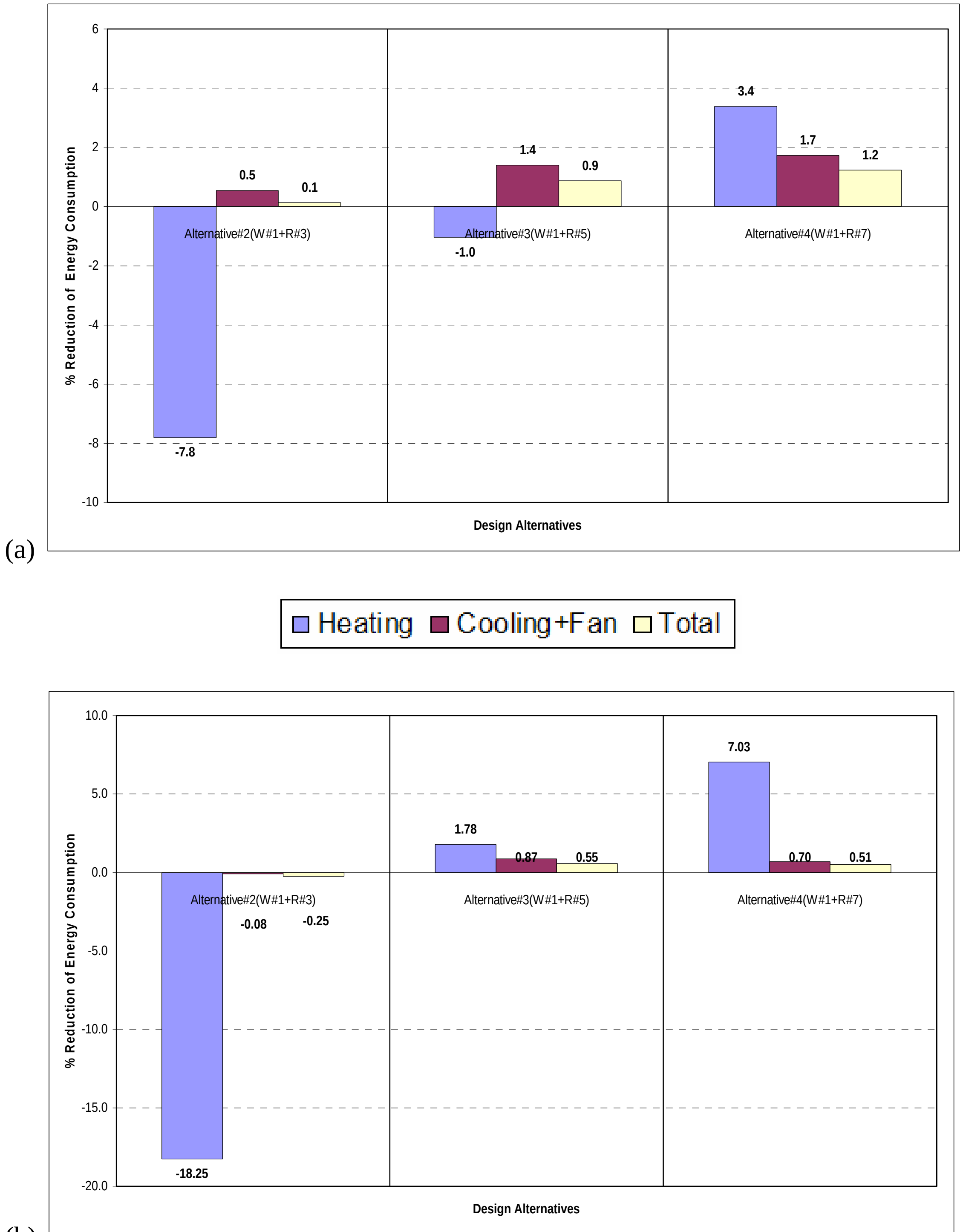


Figure 5.5 Impact of Roof Designs on Energy Consumption of Base Case Residential Building in **(a)** Dhahran and **(b)** Riyadh

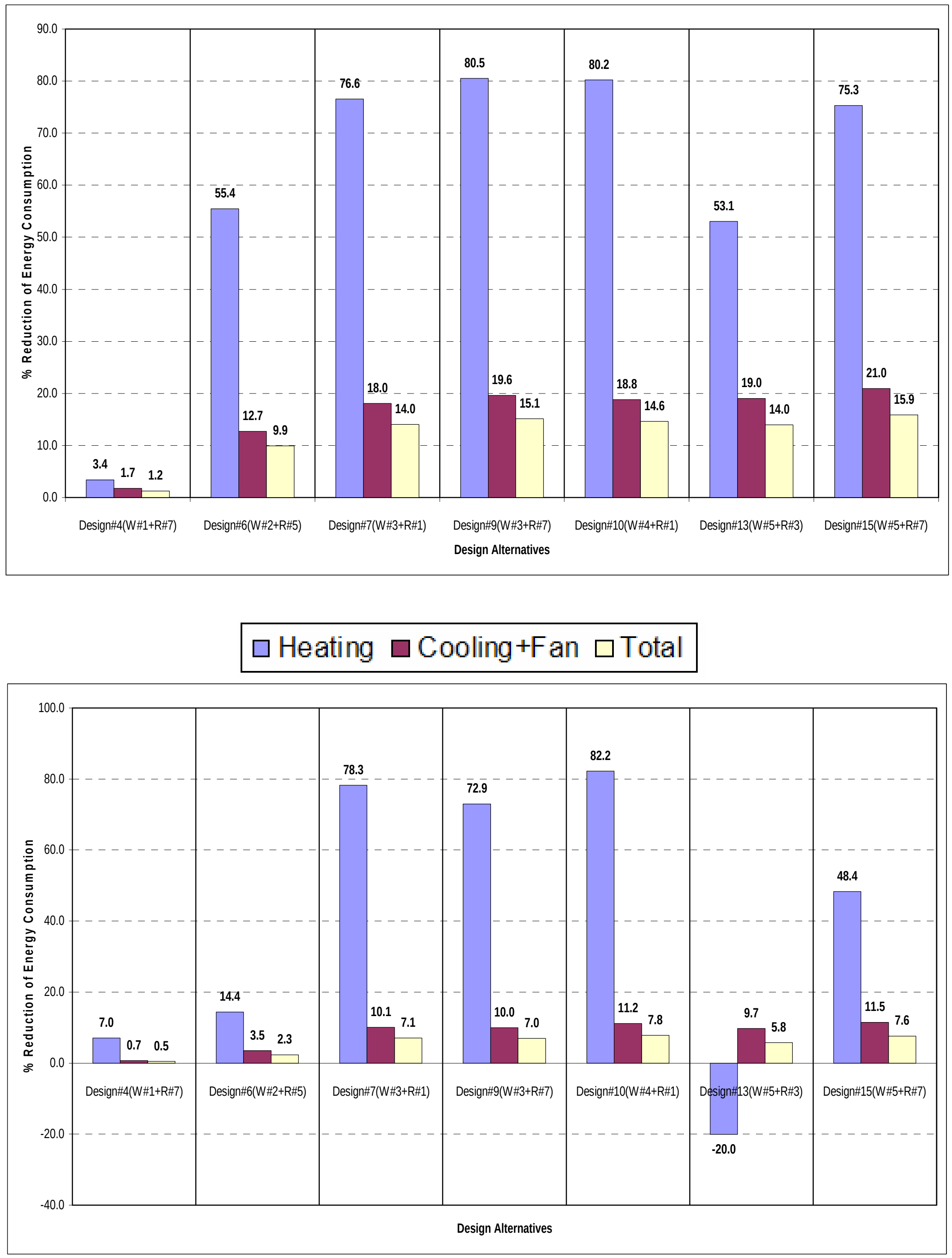
In Riyadh, **Figure 5.4 (b)** shows that when the thermal resistance of the roofs increases, the energy consumption decreases. However, the energy consumption increases when R#3 is used. For this particular roof design, the thermal insulation is on interior side of the thermal mass. Hence and similar to Dhahran, an increase of 18% in heating energy consumption is observed when the insulation is placed on interior side of the main roof material as shown in **Figure 5.5 (b)**. The low roof thermal mass is not a concern when the thermal resistance and thermal mass for the wall is equate which consequently reduces the heat loss to outdoor as can be seen when R#5 is used with W#1. Since the thermal resistance of the base case wall in Riyadh is higher than that of Dhahran, this observation is supported.

5.3.3 Impact of Combination of Wall and Roof Designs on Energy Performance of Residential Building

In chapter three, eight envelope designs were proposed for further analysis as presented in **Table 3.13**. These designs are selected to represent a wide range of thermal characteristics of common wall and roof designs used in Saudi Arabia. In this section, the envelope designs are evaluated to analyze the combined effect of wall and roof designs on energy consumption. **Figure 5.6 (a)** and **(b)** show the impact of the wall and roof designs on the annual heating, cooling and total energy.

In Dhahran, the reduction in energy consumption ranges from 1.2% for D#4 to 15.9% for D#15 as shown in **Figure 5.6 (a)** whereas in Riyadh the reduction in energy consumption ranges from 0.5% for D#4 to 7.8% for D#10 as shown in **Figure 5.6 (b**). While all envelope designs reduces both the heating and cooling energy in Dhahran, some designs perform better in reducing the heating energy and others are better in reducing the cooling energy. The best designs in Dhahran are those that effectively reduce the heating and cooling energy and subsequently the total heat energy are Design#9 (Wall#3, Roof#7), Design#10 (Wall#4, Roof#1), and Design#15 (Wall#5, Roof#7). In Riyadh, the best envelope designs are Design#10 (Wall#4, Roof#1), Design#15 (Wall#5, Roof#7), Design#7 (Wall#3, Roof#1) and Design#9 (Wall#3, Roof#7). In Riyadh, the effect of both the low thermal mass in W#5 and interior thermal insulation in R#3 on increasing the heating energy (20%) is clear as shown in **Figure 5.6 (b)**.

It is interesting to note that although roof#1 is poorly insulated but performed very well when combined with insulated designs. It is worth considering that all roofs are considered with light color. This good performance can be related to the high thermal mass which helps in reducing heating energy in winter and its light color which helps in reducing the cooling energy in summer and transition months.



(a)

(b)

Figure 5.6 Impact of Envelope Designs on Energy Consumption of Base Case Residential Building in **(a)** Dhahran and **(b)** Riyadh

5.4 Impact of Fenestration System on Energy Performance of Residential Building

Glazed windows are becoming an important component of contemporary architecture. They allow natural light, offer a visual communication with outdoors, reduce a structural load and enhance aesthetic appearance of buildings. With many benefits that the glazed windows do offer to the occupants and the designers, they are not free of introducing problems if they are not properly selected. Poor thermal performance that leads to high energy cost and specific optical properties that deteriorate the color rendering are two issues that have to be considered during the design and selection process of window's system.

In harsh climates, window is the weakest component of the building envelope if no special treatment is done. A thermally insulated opaque building envelope might be under performed if the window's system has poor thermal characteristics. Traditionally, the thermal performance of the window's system is improved by either using exterior or interior shadings or both. However, this solution might not be acceptable to some architects and occupants. Recent development in window's technology has offered many choices that are appropriate to specific application and various climates. Many driving factors have influenced the substantial improvements in the thermal performance of building fenestration system including the energy efficiency, decreased heating and cooling power demand and improving the occupant comfort. Many parameters in fenestration system are important when energy performance is evaluated. However, two parameters; window to wall ratio and types of glazing are evaluated for energy performance for this study.

5.4.1 Impact of WWR on Energy Consumption

Based on the survey conducted in this research, window to wall ratio (WWR) ranges from 0.1-0.3 and the average is 0.2 in residential buildings in Saudi Arabia. The trend in using high windows area in the design practices of residential buildings in Saudi Arabia makes it important to evaluate the impact on the energy consumption. **Figure 5.7 (a)** shows the effect of window-wall ratio on energy consumption of the base case residential building in Dhahran. It is clear that the energy consumption increases with the increases in WWR. For insulated designs, energy consumption rises steadily with WWR (15% increase in energy consumption with every 0.1 WWR) while it rises smoothly with poorly insulated designs (10% increase in energy consumption with every 0.1 WWR). At higher WWR (>0.30), all envelope designs converge to a similar value regardless of the thermal characteristics of envelope designs. **Figure 5.7 (b)** shows the impact of WWR when high performance windows are used. For this case, a Double Tint Low-e4 Argon 6/12/6 mm (e2=0.04) **(Table 5.4)** is used with different envelope designs and at various WWR. The figure shows that for poorly insulated designs, the effect of WWR on energy consumption is minimal (on average 2% increase in energy consumption with every 0.1 WWR). When WWR increases for poorly insulated designs, the increase in energy cons-

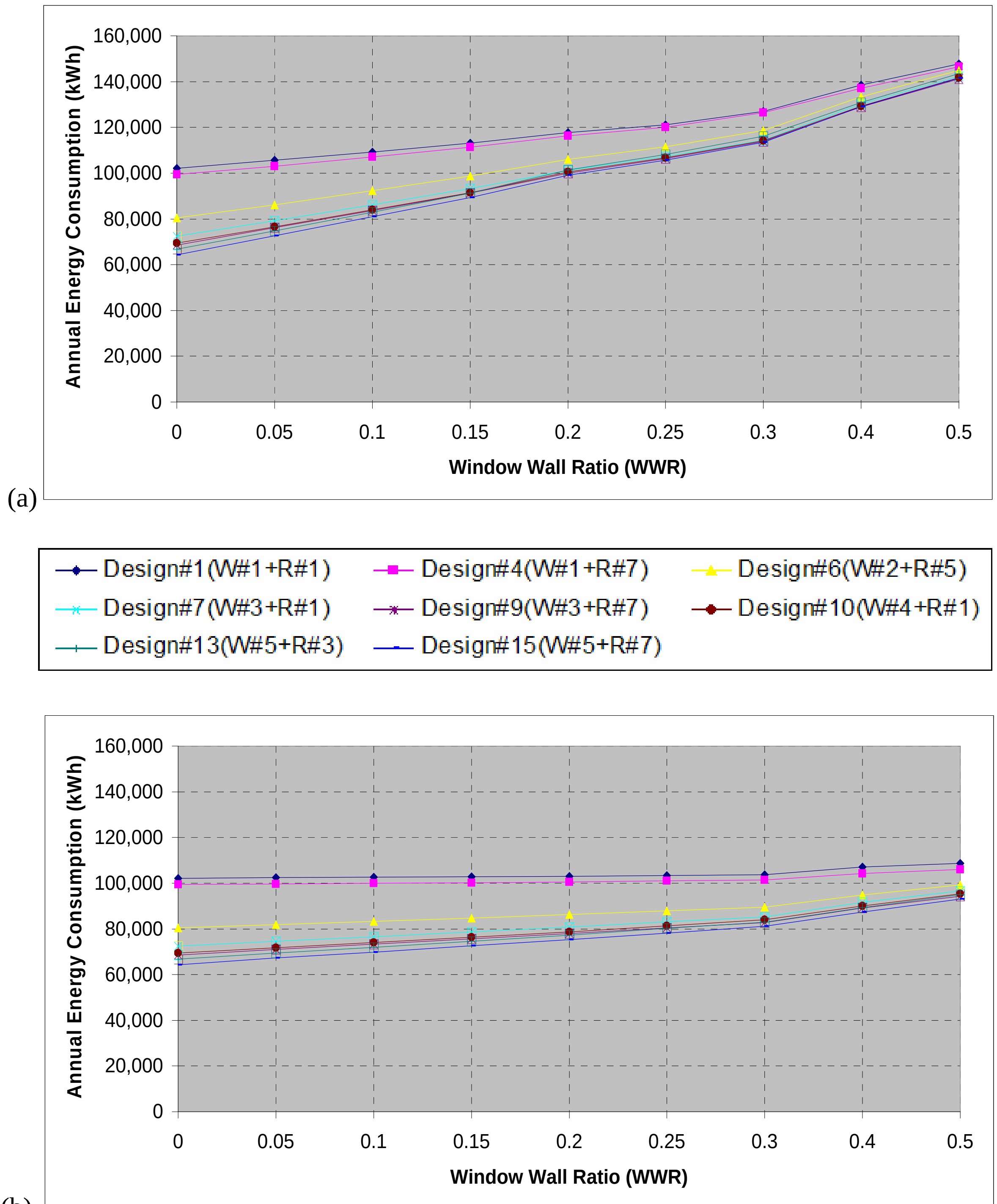
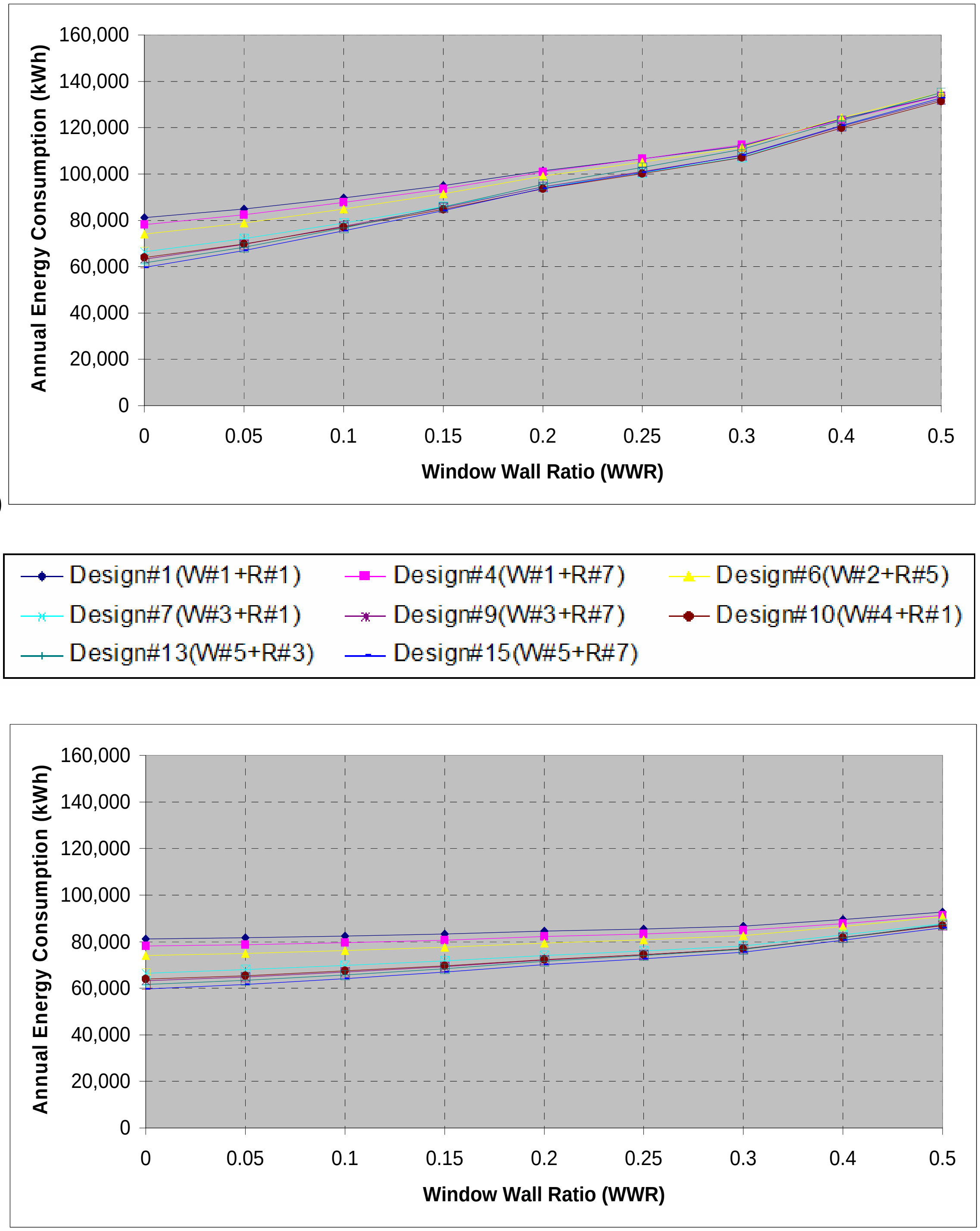


Figure 5.7 Impact of WWR on Energy Consumption of **(a)** Single Glazed and **(b)** High Performance Glazed Base Case Residential Building in Dhahran

umption is not significant. Similarly for insulated designs, it is observed that the energy consumption smoothly increases with the increases in WWR (on average 7% increase in energy consumption with every 0.1 WWR).

Figure 5.8 (a) shows the effect of window-wall ratio on energy consumption of the base case residential building in Riyadh. It is clear that the energy consumption increases with the increases in WWR. The base case of envelope design in Riyadh has high thermal characteristics when compared to the base case of Dhahran. Therefore, the base case of Riyadh is likely to behave similar to the insulated designs. This is clear form **Figure 5.8 (a)** where the energy consumption for all envelope designs rises steadily with WWR (12-15% increase in energy consumption with every 0.1 WWR). At higher WWR (>0.30), all envelope designs converge to a similar value regardless of the thermal characteristics of envelope designs. **Figure 5.8 (b)** shows the impact of WWR when high performance windows are used. For this case, a Double Tint Low-e4 Argon 6/12/6 mm (e2=0.04) **(Table 5.4)** is also used with different envelope designs and at various WWR. For Riyadh, the figure shows that for poorly insulated designs, the effect of WWR on energy consumption is minimal (on average 3-4% increase in energy consumption with every 0.1 WWR). Similarly for insulated designs, it is observed that the energy consumption smoothly increases with the increases in WWR (on average 7% increase in energy consumption with every 0.1 WWR).

(a)



(b)

Figure 5.8 Impact of WWR on Energy Consumption of **(a)** Single Glazed and **(b)** High Performance Glazed Base Case Residential Building in Riyadh

5.4.2 Impact of Glazing Types on Energy Consumption

The energy consumption can be greatly reduced with well designed and energy efficient windows. While many glazing types are available in market today, four glazing types are evaluated to assess the impact of their thermal characteristics on energy consumption. The thermal and physical properties are presented in **Table 5.4**.

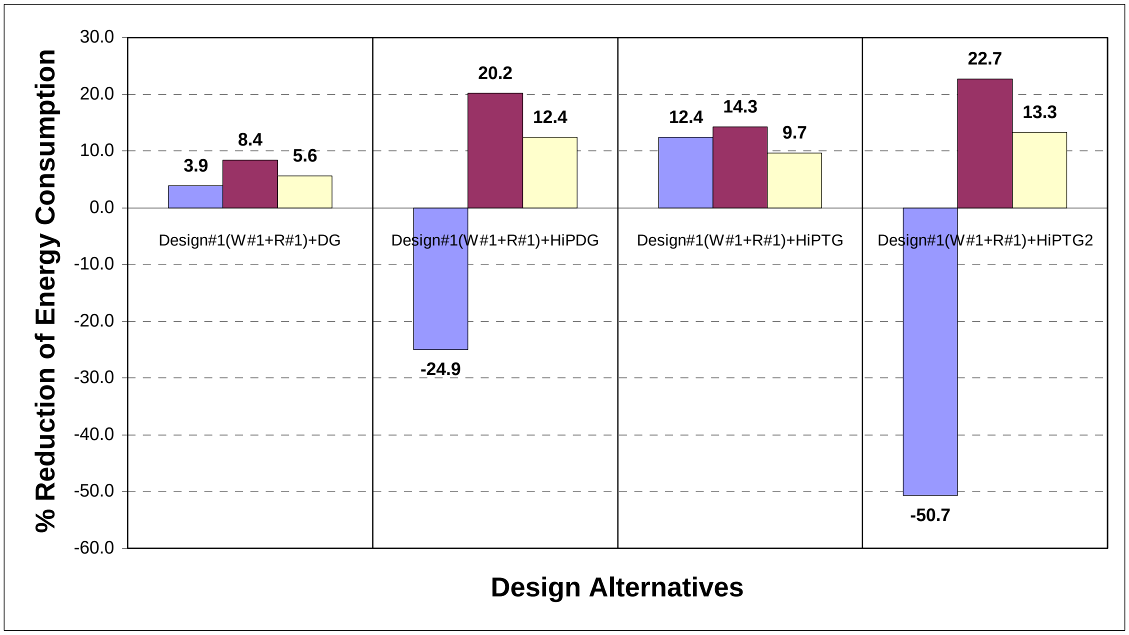
Table 5.4 Thermal and Physical Characteristics of Evaluated Glazing Types

Description	Code	# of glazing	Frame Type	U-Factor ($W/m^2.K$)	SC	SHGC	VT
Single Clear 6 mm		1	Al.	6.172	0.95	0.82	0.88
DG 3/12/3 mm	DG	2	Al.	2.788	0.71	0.613	0.743
HiPDG Tint Low-e4 Argon 6/12/6 mm (e2=0.04)	HiPDG	2	Al.	1.317	0.32	0.278	0.407
HiPTG-1 Clear 2Low-e1 Argon 3/12/3/12/3 mm (e2=e5=0.1)	HiPTG	3	Al.	0.772	0.55	0.471	0.656
HiPTG-2 Tint HM33 6/12/0/12/6 mm	HiPTG2	3	Al.	1.198	0.17	0.149	0.168

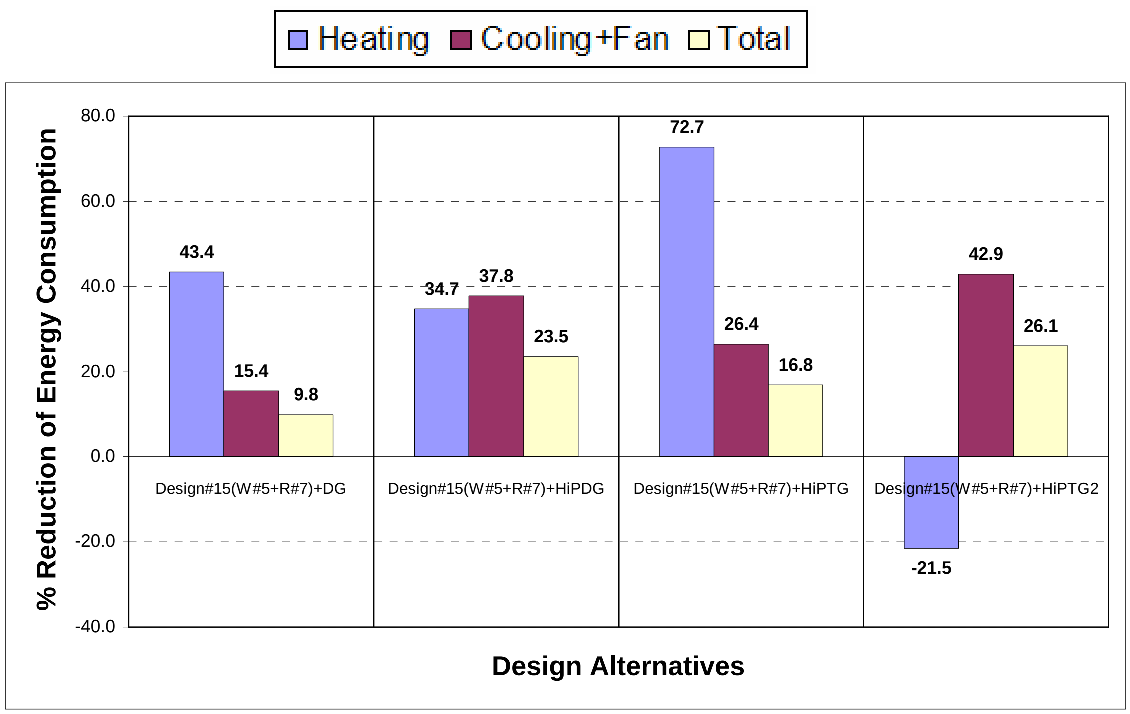
Notes:
DG: Double Green Glazing
HiPDG : High Performance Double Glazing
SC: Shading Coefficient
VT: Visible Transmittance
HiPTG : High Performance Triple Glazing
SHGC: Solar Heat Gain Coefficient

Figure 5.9 (a) shows the percentage reduction of heating, cooling and total energy consumption when various glazing types are applied to the base case in Dhahran. As the thermal resistance of the glazing increases, the total energy consumption decreases. However, the cooling and heating energy has to be balanced by the proper selection of thermal resistance and solar heat gain coefficient. The triple glazing-1 has a thermal resistance more than that of the double glazing but it admits more solar radiation to the space (high SHGC). As a result, triple glazing-1 performs better in terms of its heating energy with poorly insulated design (Base Case) in winter due to the utilization of solar radiation for heating purposes. Although the thermal characteristics (R value) of triple glazing-1 is 50% more than that of double glazing, the improvement in cooling energy is less than that of double glazing. When the thermal resistance of triple glazing is reduced (case: HiPTG-2) to the level of Double glazing and solar heat gain coefficient (low SHGC) of the triple glazing is also reduced, the heating energy increases with a significant reduction in cooling energy. While the previous discussion considers the poorly insulated designs (Base case:D#1), **Figure 5.9 (b)** shows the impact of the glazing types on the energy consumption of the high insulated design (D#15). It is clear that the reduction in energy consumption of insulated design is more than that of the poorly insulated designs. Therefore, the high performance glazing is more efficient with insulated designs than the poorly insulated design. Similar to the base case, the domination of solar characteristics of glazing on the energy consumption is observed with the insulated designs.

Figure 5.10 shows the percentage reduction of heating, cooling and total energy consumption when various glazing types are applied to the base case in Riyadh. As the thermal resistance of the glazing increases, the total energy consumption decreases. Similar to Dhahran, with proper selection of thermal (R-Value) and solar characteristics (SHGC), the cooling and heating energy are balanced for maximum reduction in total energy consumption.



(a)



(b)

Figure 5.9 Impact of Glazing Types on Energy Consumption of **(a)** Base Case (D#1) and **(b)** Insulated Design (D#15) Residential Building in Dhahran

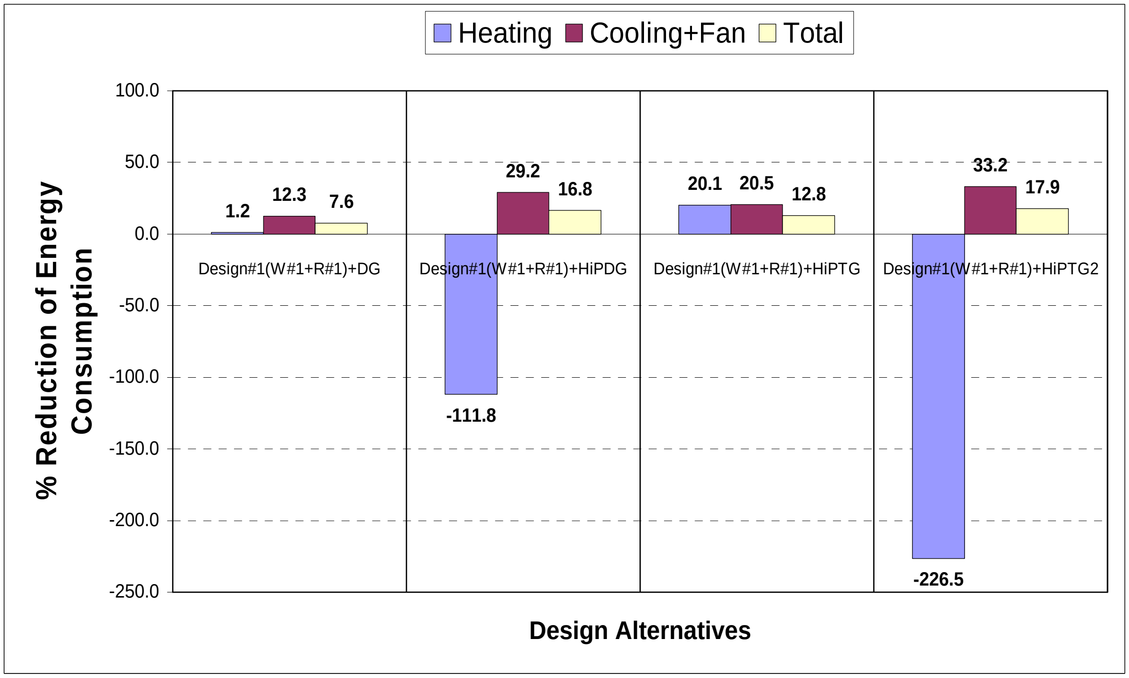


Figure 5.10 Impact of Glazing Types on Energy Consumption of Base Case Residential Building in Riyadh

Form the previous discussion, it is concluded that the solar characteristics (SHGC) are more dominant than the thermal characteristics (R-value) of glazing for both poorly and high insulated designs. To achieve maximum reduction in total energy consumption, it is imperative to use high performance glazing that has low solar heat gain coefficient (low SHGC) and high thermal resistance (high R-value) even if it increases the heating energy. Since the winter season in Saudi Arabia is normally short and mild and the transition and summer season is long and harsh with high solar radiation, the heating energy is not a major component of total energy consumption. It is important therefore to control the solar radiation during the transition and summer months. Dynamic solar control is an optimum strategy in Saudi Arabia climate where the solar radiation is admitted in winter but rejected in summer and transition months.

5.5 Impact of Building Orientation on Energy Performance of Residential Building

Many town planners ignore the effect of orientation on the energy consumption of buildings. The effect of building layout on energy consumption can be easily identified during the town planning activity. However, building plots are normally planned based on the streets layout. Energy studies have investigated the impact of orientation on the energy consumption of buildings. The severity of building orientation mainly depend on the windows area, type of glazing, solar shading in specific orientation and the wall design and its exposed area. In this study, the base case scenario is based on the assumption that the building entrance is to the north. In this section, the east-west orientation is addressed.

Figure 5.11 (a) shows the percentage increases of heating, cooling and total energy consumption when east-west orientation is considered in Dhahran. It is clear from the figure that the heating, cooling and therefore the total energy consumption increases by 1.8%. Similarly for Riyadh as shown in **Figure 5.11 (b)**, the heating, cooling and therefore the total energy consumption increases by 2.2%. It is concluded that for Saudi Arabia, the best orientation is the north-south.

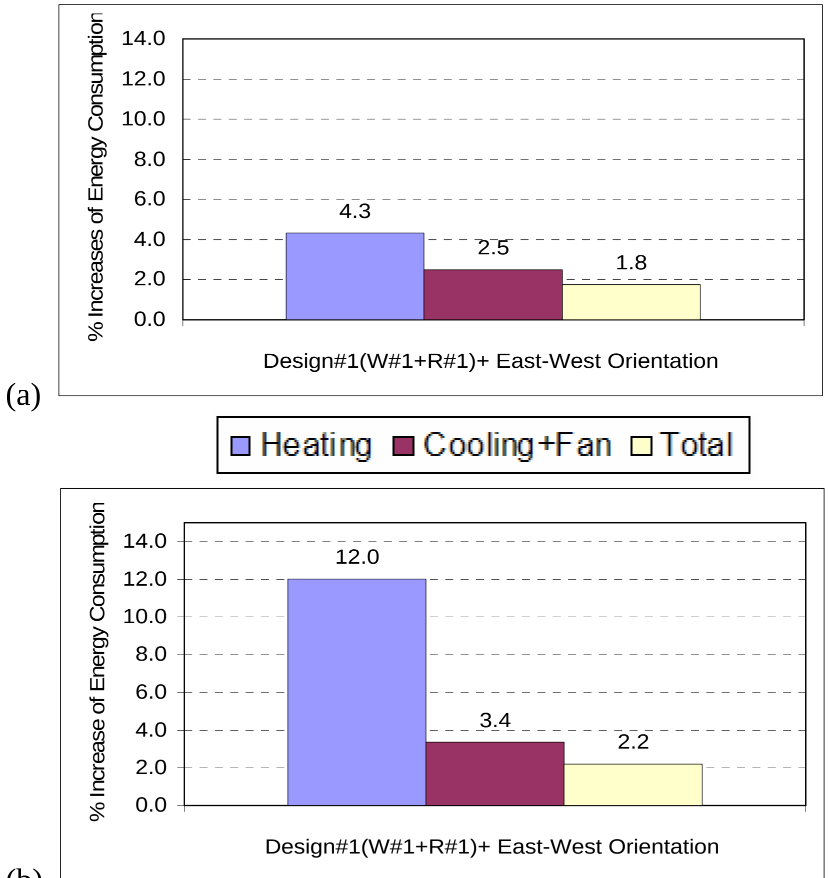


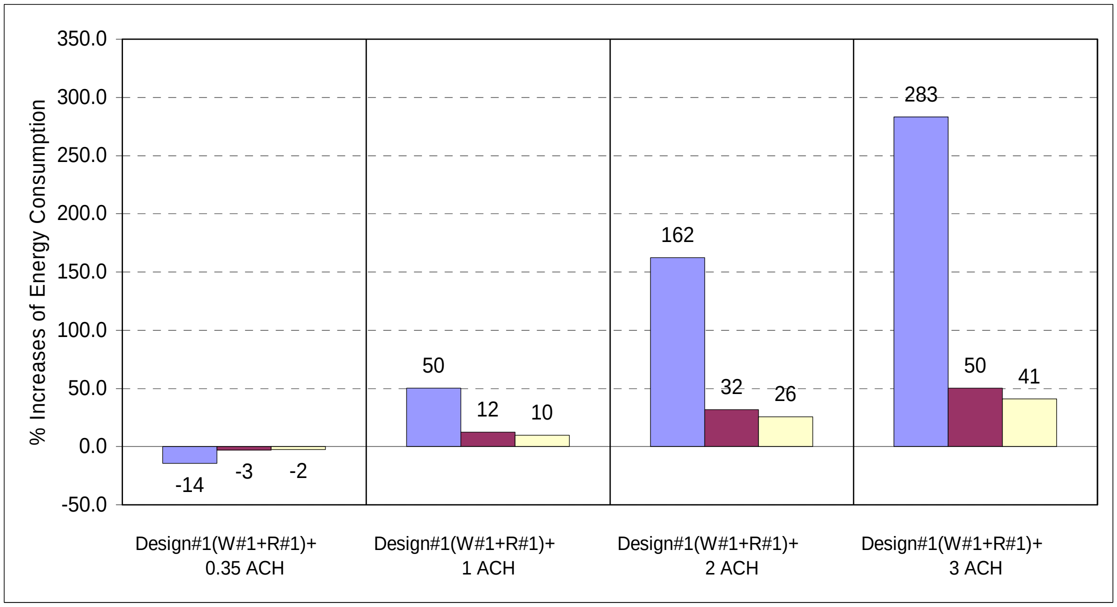
Figure 5.11 Impact of Orientation on Energy Consumption of Base Case Residential Building in **(a)** Dhahran and **(b)** Riyadh

5.6 Impact of Air Infiltration on Energy Performance of Residential Building

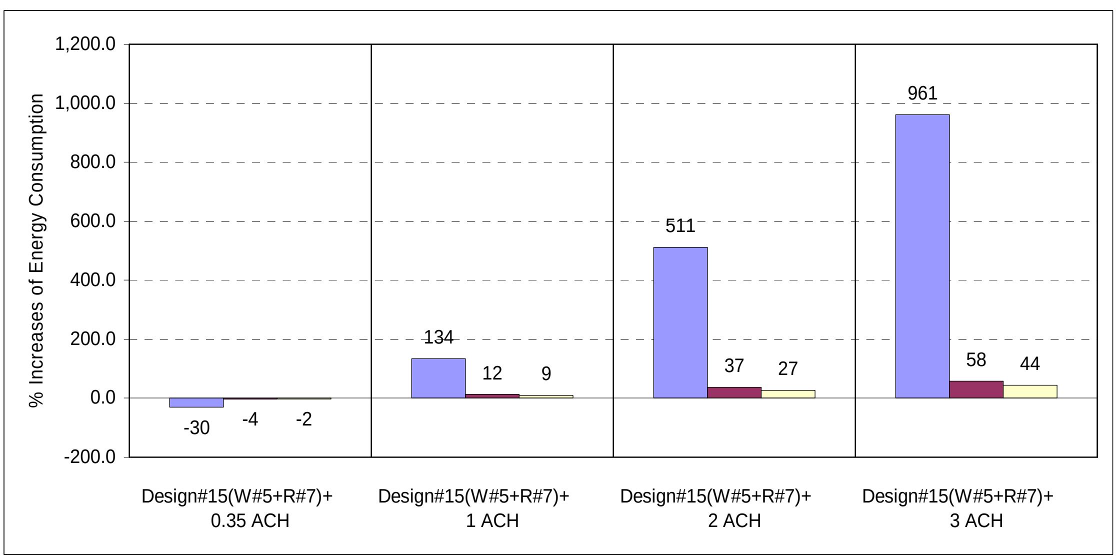
Infiltration can be defined as an uncontrolled flow of outdoor air into a building through weak points in buildings such as cracks in walls, floors, and ceilings, and around windows and doors and other unintentional openings and through the normal use of exterior doors for entrance and egress. While the infiltration is an important parameter that directly influences the thermal comfort and energy use, it has received little attention in hot climates. The level of building airtightness depend on many parameters such as extreme weather conditions, poor workmanship, and building age, its operation strategies, and occupants activity patterns. All these parameters influence the magnitude of air leakage. It has been identified in this research's literature that the buildings can be categorized as low leaky buildings, normal leaky, high leaky and extremely leakage buildings when their ACH is 0.5, 1, 2, and 3 ACH respectively. This section evaluates the impact of air infiltration (0.35, 1, 2, 3 ACH) of poorly insulated design (the base case) and the insulated design (D#15) residential building in Dhahran and Riyadh.

Figure 5.12 (a) and **(b)** show the increases of heating, cooling and total energy consumption in poorly insulated (base case) and insulated design (D#15) residential building under different air infiltration. As the air infiltration increases the energy consumption increases. It is clear also that there are steadily increases in heating energy, cooling and total energy consumption. For every increases of 1 ACH there is an increase of more than 100%, 20% and 15% of heating, cooling and total energy consumption for the poorly insulated designs in Dhahran. For well insulated design (D#15), for every 1 ACH increases in air infiltration there is an increase of more than 300%, 20% and 19% of heating, cooling and total energy consumption for the well insulated designs in Dhahran. It is clear that all envelope designs either poorly or well insulated designs) are very sensitive to air infiltration. For leaky buildings (3ACH) in Dhahran, the total energy consumption increases by 41% for poorly insulated designs whereas increases by 44% for the well insulated designs. The heating energy is more sensitive to air infiltration especially for the well insulated designs. When the air infiltration is reduced in poorly insulated design (base case) to 0.35 ACH the heating, cooling and total energy consumption is reduced by 14%, 3% and 2% respectively. Similarly for insulated designs, when air infiltration is reduced the heating, cooling and total energy consumption reduced by 30%, 4% and 2% respectively. Therefore, reducing the air infiltration below the 0.5 ACH will significantly reduce the heating energy.

Figure 5.13 (a) and **(b)** show the increases of heating, cooling and total energy consumption in poorly insulated (base case) and insulated design (D#15) residential building under different air infiltration in Riyadh. As the air infiltration increases the energy consumption increases. It is clear also that there are steadily increases in heating energy, cooling and total energy consumption. In Riyadh, for every increases of 1 ACH there is an increase of more than 200%, 10% and 10% of heating, cooling and total energy consumption for the poorly insulated designs. Similarly for well insulated design (D#15) in Riyadh, for every 1 ACH increases in air infiltration there is an increase of more than 300%, 10% and 10% of heating, cooling and total energy consumption for the well insulated designs. It is clear that all envelope designs either poorly or well insulated designs are very sensitive to air infiltration. For leaky buildings (3ACH) in Riyadh, the total energy consumption increases by 21% for both poorly insulated designs and well insulated designs (D#15). The heating energy is more sensitive to air infiltration especially for the well insulated designs.



(a)



(b)

Figure 5.12 Impact of Air Infiltration on Energy Consumption of **(a)** Base Case (D#1) and **(b)** Insulated Design (D#15) Residential Building in Dhahran

When the air infiltration is reduced in poorly insulated design (base case) to 0.35 ACH the heating, cooling and total energy consumption is reduced by 18%, 2% and 1% respectively. Similarly for insulated designs, when air infiltration is reduced the heating, cooling and total energy consumption is reduced by 17%, 2% and 1% respectively. Therefore, reducing the air infiltration below the 0.5 ACH will significantly reduce the heating energy.

5.7 Combined Effect of Envelope Design Parameters on Energy Consumption of Residential Building

The impact of individual design alternatives on heating, cooling and total energy consumption has been investigated. This section evaluates the combined effect of the envelope designs and passive strategies on the energy consumption and is compared to the recommended envelope design requirements from the international energy conservation code and the Gulf Countries Cooperative Council (GCCC) thermal insulation requirement. The requirements from standards are listed in **Table 3.14**.

Sensitivity analysis has indicated that the WWR has a minor impact on energy consumption when high performance glazing is used. Therefore, WWR of 0.2 is unchanged as in the base case. Air infiltration is reduced to 0.35 ACH for residential buildings. A high performance glazing with low solar gain coefficient and the eight envelope designs are used for comparison purposes as shown in **Table 5.5**.

(a)

(b)

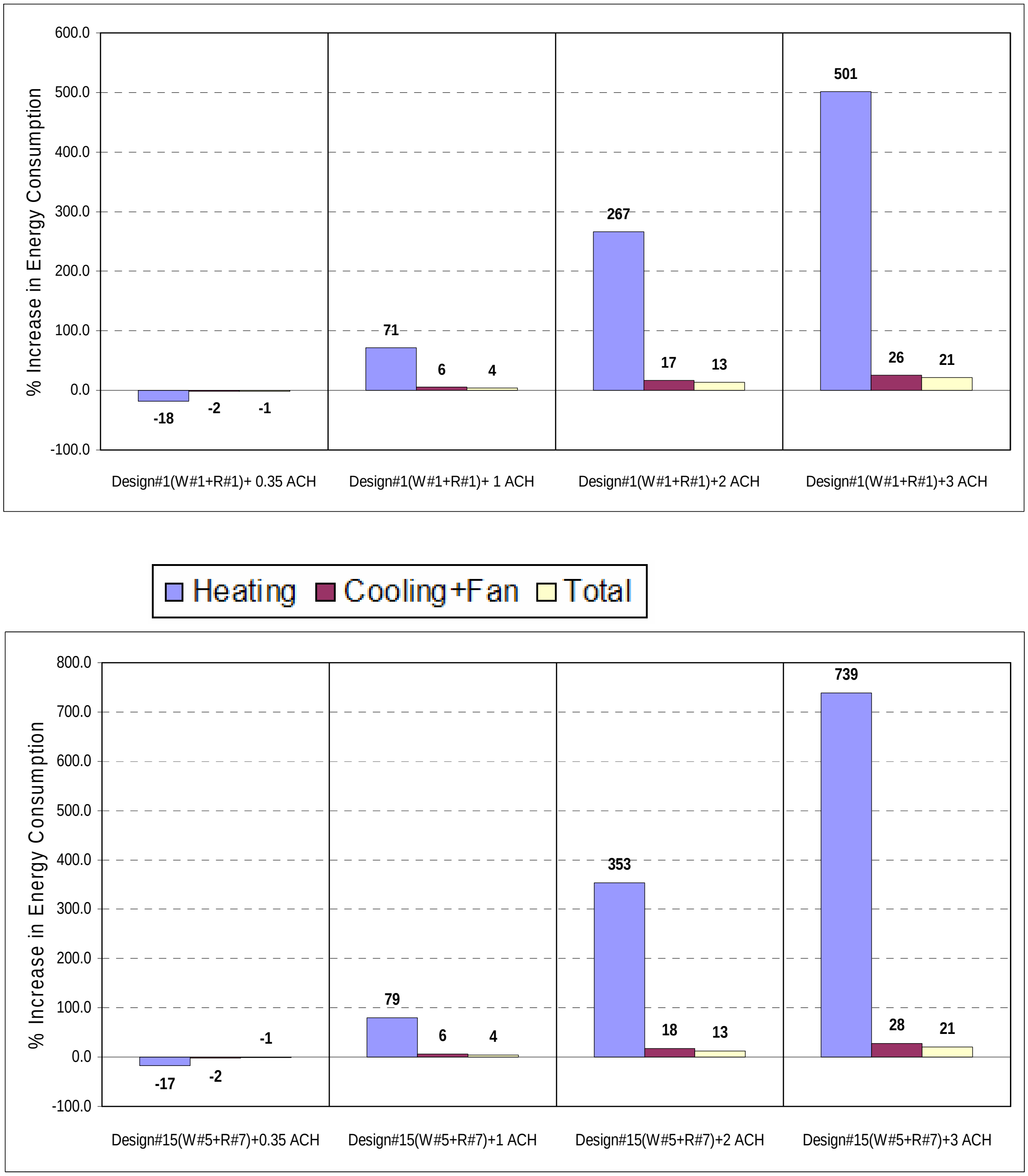


Figure 5.13 Impact of Air Infiltration on Energy Consumption of **(a)** Base Case (D#1) and **(b)** Insulated Design (D#15) Residential Building in Riyadh

Table 5.5 Proposed and Benchmark Envelope Design Alternatives for Residential Buildings in Saudi Arabia

Combined Design Alternative	Dhahran & Riyadh	Envelope Design (GCC Standard, 1984)	Envelope Design (IECC, 2000)
Wall Design	8 Envelope Designs (Combined Wall and Roof Designs)	Single 200 mm Hollow CMU Wall+ 50 mm Rock Wall+ 15 mm Stucco finishes on both sides (R Value= 1.43 m^2.K/W)	Single 200 mm Hollow CMU Wall+ 50 mm Rock Wall+ 15 mm Stucco finishes on both sides (R Value= 1.96 m^2.K/W)
Roof Design		200 Reinforced Concrete-50 mm Concrete screeding +50 mm Fiber Glass insulation (R Value=2.041 m^2.K/W)	15 mm Cement plaster+200 mm CMU Hourdi Slab + 100 mm Foam Concrete+ 100 mm Polyurethane +4 mm water membrane+ 25mm Sand+ 50 mm Mortar+ Tiles (R Value= 5.88 m^2.K/W)
Glazing	HiPDG Tint Low-e4 Argon 6/12/6 mm (e2=0.04), (low SHGC)	Single Clear 6 mm Glazing (Base Case)*	Double Bronze IG 3/6/3 mm (U-Value= 3.321 W/ m^2.C) **Note:** Max. U-Value is 4.55 W/ m^2.C as per IECC
WWR	0.2	0.2*	0.2*
Air Infiltration	0.35 ACH	Base Case (0.5 ACH)*	Base Case (0.5 ACH)*

Notes: * No requirement as per standard

Table 5.6 shows the impact of envelope designs, high performance glazing, and reduced air infiltration on the reduction of heating, cooling and total energy consumption in Dhahran. The table shows that reducing the air infiltration to 0.35 ACH and using a high performance glazing can reduce the total energy consumption by 15% for poorly insulated design. For well insulated envelope design such as Design#15, the heating, cooling and total energy consumption is reduced by 91%, 53% and 38% respectively. The table also shows the energy intensity of the base case residential building and the evaluated 8 envelope designs. The energy intensity of the base case residential building is 196 kWh/m^2/year and for well insulated designs is 123 kWh/m^2/year compared to 263 kWh/m^2/year for a typical non-insulated and well insulated residential housing in Dhahran **(Ahmed, 2004)**. Additionally, the energy intensity of the residential building with envelope design recommended by GCC regulation and IECC is 172 and 153 kWh/m^2/year respectively. It is observed that when the GCC regulation is used as a benchmark for envelope design, the poorly insulated design Design#1 can meet the requirement with the use of high performance glazing and reduced air infiltration. The GCC regulation ignores the thermal characteristic of glazing and the air infiltration and therefore a major review is sought. When IECC envelope design is selected as a benchmark, the energy intensity is met with Design#6 onwards. For Dhahran, it is clear from the table that the envelope design can meet the IECC requirement (IECC requires that the roof R-value is 5.88 m^2.K/W, wall R-value is 1.96 m^2.K/W and a glazing U-value of 4.55 W/ m^2.K) even when the roof is poorly insulated (R value=1.60 m^2.K/W) as is the case for Design#7 and Design#10. However, the wall thermal resistance (R-value) has to be at least equal or more than 2.44 m^2.K/W with high performance glazing (U-value 1.317 W/ m^2.K) and reduced air infiltration (0.35 ACH).

Table 5.7 shows the impact of envelope designs, high performance glazing, and reduced air infiltration on the heating, cooling and total energy consumption in Riyadh. The table shows that reducing the air infiltration to 0.35 ACH and using a high performance glazing increases the heating energy consumption by 82% for poorly insulated design. However, the cooling and total energy consumption reduces by 31% and 18% respectively. For well insulated envelope design such as Design#15, the heating, cooling and total energy consumption is reduced by 85%, 50% and 32% respectively. The energy intensity of the base case residential building is 169 kWh/m^2/year and for well insulated designs is 115 kWh/m^2/year. Additionally, the energy intensity of the residential building with envelope design recommended by GCC regulation and IECC is 161 and 145 kWh/m^2/year respectively. It is observed that when the GCC regulation and IECC are used as a benchmark for envelope design, the poorly insulated design Design#1 can easily meet the requirement of both requirements with the use of high performance glazing and reduced air infiltration. The GCC regulation and the IECC are prescriptive standards and ignore the credit of reducing the air infiltration. Similar to Dhahran, the envelope design in Riyadh can meet the IECC requirements even when the roof and wall are poorly insulated (Wall R value=0.61 m^2.K/W & Roof R-value=1.69 m^2.K/W) as is the case for Design#1. However, the poorly insulated design has to be with high performance glazing (U-value 1.317 W/ m^2.K) and reduced air infiltration (0.35 ACH).

Table 5.6 Combined Effects of Thermal Envelope Design Parameters on Energy Consumption of Residential Building in Dhahran

Alternative	Heating Energy (kWh)	% Reduction in Heating	Cooling + Fan Energy (kWh)	% Reduction in Cooling	Total Energy Consumption (kWh)	% Reduction in Total Energy	Domestic Energy Intensity (kWh/m^2/year)
Design#1(W#1+R#1)- Base Case (S. Glazing)	**3459**		**76786**		**117750**		**196***
Design (GCC Standard)	**1003**	**71**	**64689**	**16**	**103197**	**12**	**172**
Design(IECC)	**443**	**87**	**54040**	**30**	**91988**	**22**	**153**
Design#1(W#1+R#1)+ Final Case	4004	-16	58999	23	100508	15	168
Design#4(W#1+R#7)+ Final Case	3283	5	56788	26	97576	17	163
Design#6(W#2+R#5)+ Final Case	1523	56	45119	41	84147	29	140
Design#7(W#3+R#1)+ Final Case	881	75	40408	47	78794	33	131
Design#9(W#3+R#7)+ Final Case	404	88	37864	51	75773	36	126
Design#10(W#4+R#1)+ Final Case	590	83	38677	50	76772	35	128
Design#13(W#5+R#3)+ Final Case	632	82	37205	52	75342	36	126
Design#15(W#5+R#7)+ Final Case	307	91	35759	53	73571	38	123**

* Energy Intensity of Typical non-Insulated Residential Building in Dhahran= 263 (kWh/m^2/year) **(Ahmed, 2004)**

** Energy Intensity of Typical insulated Residential Building in Dhahran= 153 (kWh/m^2/year) **(Ahmed, 2004)**

Table 5.7 Combined Effects of Thermal Envelope Design Parameters on Energy Consumption of Residential Building in Riyadh

Alternative	Heating Energy (kWh)	% Reduction in Heating	Cooling + Fan Energy (kWh)	% Reduction in Cooling	Total Energy Consumption (kWh)	% Reduction in Total Energy	Domestic Energy Intensity (kWh/m^2/year)
Design#1(W#1+R#1)-Base Case (S-Glazing)	**1123**		**62467**		**101450**		**169**
Design (GCC Standard)	**567**	**50**	**58378**	**7**	**96805**	**5**	**161**
Design(IECC)	**341**	**70**	**49048**	**21**	**87249**	**14**	**145**
Design#1(W#1+R#1)+ Final Case	2045	-82	43014	31	82919	18	138
Design#4(W#1+R#7)+ Final Case	1291	-15	41517	34	80668	20	134
Design#6(W#2+R#5)+ Final Case	1156	-3	38881	38	77897	23	130
Design#7(W#3+R#1)+ Final Case	619	45	34142	45	72621	28	121
Design#9(W#3+R#7)+ Final Case	215	81	32877	47	70952	30	118
Design#10(W#4+R#1)+ Final Case	389	65	32708	48	70957	30	118
Design#13(W#5+R#3)+ Final Case	448	60	31826	49	70134	31	117
Design#15(W#5+R#7)+ Final Case	173	85	30936	50	68969	32	115

5.8 Energy and Thermal Performance of Residential Buildings under Combined Conditioned and Un-Conditioned Strategies

In traditional buildings, outside cool air has been utilized to reduce the indoor air temperature and improves the thermal comfort conditions. The impact of introducing outside cool air for different envelope designs under unconditioned space has been investigated in Chapter Four of this study research. Ventilation strategies for every envelope designs were developed for maximum thermal comfort with the two accepted ASHRAE thermal comfort criteria; for naturally operated and mechanically operated buildings. The results presented in Chapter Five demonstrate that the energy performance of various envelope designs could be significantly enhanced with the application of high performance glazing and reduced air infiltration. The ventilation strategies developed in Chapter Four and the enhancement strategies for envelope designs in Chapter Five are combined to form a hybrid strategy that improve the thermal comfort and reduces the energy consumption in residential buildings. **Table 5.8** show the developed combined ventilation strategy for the base case residential building in Dhahran with reduced air infiltration and high performance double glazing. It is clear from the table that there are three ventilation strategies proposed for various envelope designs.

Table 5.8 Developed Combined Ventilation Strategy for the Base Case Residential Building in Dhahran Based on ASHRAE Thermal Comfort Criteria for Mechanically Operated Buildings

Month / Design Alternative	January	February	March	April	November	December
Design #1: W#1, R#1 (Base Case)	0.35 ACH (24 h)	0.35 ACH (24h)	**10 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**20 ACH 16:00-9:00, 0.35 ACH 10:00-15:00**	**20 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**	0.35 ACH (24h)
Design #4: W#1, R#7	Similar to D#1	Similar to D#1	**10 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**20 ACH 16:00-9:00, 0.35 ACH 10:00-15:00**	**20 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**	Similar to D#1
Design #6:W#2, R#5	Similar to D#1	**4 ACH 08:00-18:00, 0.350 ACH 19:00-07:00**	**10 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**20 ACH 16:00-9:00, 0.35 ACH 10:00-15:00**	**20 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**	**4 ACH 07:00-18:00, 0.350 ACH 19:00-06:00**
Design #7:W#3, R#1	Similar to D#1	**4 ACH 08:00-18:00, 0.350 ACH 19:00-07:00**	**10 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**20 ACH 16:00-9:00, 0.35 ACH 10:00-15:00**	**20 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**	**4 ACH 07:00-18:00, 0.350 ACH 19:00-06:00**
Design #9:W#3, R#7	Similar to D#1	**4 ACH 08:00-18:00, 0.350 ACH 19:00-07:00**	**10 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**20 ACH 16:00-9:00, 0.35 ACH 10:00-15:00**	**20 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**	**4 ACH 07:00-18:00, 0.350 ACH 19:00-06:00**
Design #10:W#4, R#1	Similar to D#1	**4 ACH 08:00-18:00, 0.350 ACH 19:00-07:00**	**10 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**20 ACH 16:00-9:00, 0.35 ACH 10:00-15:00**	**20 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**	**4 ACH 07:00-18:00, 0.350 ACH 19:00-06:00**
Design #13:W#5, R#3	**2 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**4 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**10 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**20 ACH 16:00-9:00, 0.35 ACH 10:00-15:00**	**20 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**	**4 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**
Design #15:W#5, R#7	**2 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**4 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**10 ACH 08:00-18:00, 0.35 ACH 19:00-07:00**	**20 ACH 16:00-9:00, 0.35 ACH 10:00-15:00**	**20 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**	**4 ACH 07:00-18:00, 0.35 ACH 19:00-06:00**

5.8.1 Energy Simulation of the Envelope Designs under Developed Ventilation and Air-Conditioning Strategy

The energy and thermal performance of the base case residential building with high performance glazing and reduced air infiltration is investigated when ventilation strategy is combined with mechanical systems to achieve thermal comfort and reduce energy consumption. The percentage of thermal comfort for every envelop design in Dhahran is listed in **Table 5.9**. From the results, it is clear that introducing the outside air may deteriorate the thermal comfort if careful consideration is not taken. Generally, the thermal comfort is achieved in more than 90% of the time annually. The results show that the in March and April the thermal comfort is achieved in less than 80% of the month time. Therefore, the ventilation strategy should be revised to achieve maximum thermal comfort in all months and at low energy consumption.

Table 5.9 Percentage of Thermal Comfort of Envelope Designs in Living Zone under Combined Ventilation and Air-Conditioning Strategy in Dhahran

Design Alternative	Jan	Feb	Mar	Apr	May, Jun, Jul, Aug, Sep, Oct	Nov	Dec	Yearly % of Thermal Comfort
Design #1: W#1, R#1(Final Case)	100	100	76	73	100	82	100	**94.29**
Design #4: W#1, R#7	100	100	76	73	100	82	100	**94.32**
Design #6:W#2, R#5	100	92	76	75	100	83	86	**92.73**
Design #7:W#3, R#1	100	95	78	80	100	84	89	**93.78**
Design #9:W#3, R#7	100	95	77	80	100	84	89	**93.78**
Design #10:W#4, R#1	100	96	78	79	100	84	90	**93.95**
Design #13:W#5, R#3	91	95	76	78	100	84	87	**92.48**
Design #15:W#5, R#7	91	95	76	78	100	84	88	**92.66**

The ventilation strategy in March and April is revised to achieve more thermal comfort. In March several attempts were done to achieve high percentage of thermal comfort by changing the timings and volume of outside cooled air. It was found difficult to improve the thermal comfort with outside cooled air. The weather characteristic in March is not stable in the whole month. In early march, the outside air temperature is far below the thermal comfort zone and it quickly rises in the middle of the month. Additionally, in the middle of the month, the outside temperature is above thermal comfort during the day and below the thermal comfort during the night. Therefore, it was difficult to reach a suitable ventilation strategy as very complex analysis is required. In April, it was easier to improve the thermal comfort when the outside air is scheduled from 19:00 to 07:00 instead of the proposed one from 16:00-9:00. The thermal comfort in April has improved from less than 80% to more than 85% for many design alternatives as depicted in **Table 5.10 (a)** and **(b)** for living and sleeping zone respectively. The yearly percentage of thermal comfort for all envelope designs has increased by 3%. It is clear that the thermal comfort in sleeping zone is more than that of the living area due the impact of low internal heat load.

Table 5.11 shows the impact of the modified developed ventilation and air-conditioning strategies on heating, cooling and total energy consumption of the final design residential building in Dhahran. Based on the strategy proposed in this study, the introduced outside cool air increases the heating energy but the cooling energy has decreased. Subsequently, the total energy consumption is reduced. The total energy consumption is reduced by

19% for the poorly insulated design and by 41% for the well insulated design compared to 15% and 38% for poorly and well insulated design respectively when no ventilation strategy is applied. When ventilation and air-conditioning strategy is applied, the energy intensity of the poorly residential building is 161 kWh/m^2/year and for well insulated designs is 117 kWh/m^2/year compared to 168 kWh/m^2/year for poorly insulated design and 123 kWh/m^2/year well insulated design when no ventilation is applied.

Table 5.10 Percentage of Thermal Comfort of Envelope Designs in **(a)** Living Zone and **(b)** Sleeping Zone under Modified Ventilation and Air-Conditioning Strategy in Dhahran

(a)

Design Alternative	Jan	Feb	Mar	Apr	May, Jun, Jul, Aug, Sep, Oct	Nov	Dec	Yearly % of Thermal Comfort
Design #1: W#1, R#1(Final Case)	100	100	100	84	100	82	100	**97.18**
Design #4: W#1, R#7	100	100	100	84	100	82	100	**97.18**
Design #6:W#2, R#5	100	92	100	85	100	83	86	**95.62**
Design #7:W#3, R#1	100	95	100	88	100	84	89	**96.36**
Design #9:W#3, R#7	100	95	100	88	100	84	89	**96.37**
Design #10:W#4, R#1	100	96	100	89	100	84	90	**96.62**
Design #13:W#5, R#3	91	95	100	88	100	84	87	**95.37**
Design #15:W#5, R#7	91	95	100	88	100	84	88	**95.51**

(b)

Design Alternative	Jan	Feb	Mar	Apr	May, Jun, Jul, Aug, Sep, Oct	Nov	Dec	Yearly % of Thermal Comfort
Design #1: W#1, R#1(Final Case)	100	100	100	86	100	85	100	**97.63**
Design #4: W#1, R#7	100	100	100	86	100	85	100	**97.63**
Design #6:W#2, R#5	100	92	100	87	100	85	87	**95.95**
Design #7:W#3, R#1	100	93	100	89	100	87	89	**96.58**
Design #9:W#3, R#7	100	97	100	90	100	87	90	**97.00**
Design #10:W#4, R#1	100	94	100	90	100	88	89	**96.80**
Design #13:W#5, R#3	90	94	100	89	100	85	87	**95.34**
Design #15:W#5, R#7	94	97	100	90	100	86	90	**96.48**

Table 5.11 Impact of Ventilation and Air-Conditioning Strategy on Energy Performance of Envelope Designs in Residential Building in Dhahran

Alternative	Heating Energy (kWh)	% Reduction in Heating	Cooling + Fan Energy (kWh)	% Reduction in Cooling	Total Energy Consumption (kWh)	% Reduction in Total Energy	Domestic Energy Intensity ($kWh/m^2/year$)
Design#1(W#1+R#1)-Base Case (S-Glazing)	3,459		76,786		117,750		196
Design (GCC Standard)	1003	71	64689	16	103197	12	172
Design(IECC)	443	87	54040	30	91988	22	153
Design#1(W#1+R#1)+ Final Case	4209	-22	55020	28	96734	18	161
Design#4(W#1+R#7)+ Final Case	4490	-30	52965	31	94960	19	158
Design#6(W#2+R#5)+ Final Case	2178	37	41747	46	81430	31	136
Design#7(W#3+R#1)+ Final Case	1657	52	37297	51	76459	35	127
Design#9(W#3+R#7)+ Final Case	1053	70	34622	55	73180	38	122
Design#10(W#4+R#1)+ Final Case	1294	63	35550	54	74349	37	124
Design#13(W#5+R#3)+ Final Case	1644	52	33220	57	72369	39	121
Design#15(W#5+R#7)+ Final Case	1253	64	31660	59	70418	40	117

5.8.2 Ventilation and Air-Conditioning Strategies for Thermal Comfort and Reduced Energy Consumption in Residential Buildings

The preceding sections have demonstrated the effectiveness of ventilation and Air-Conditioning Strategy on heating, cooling and total energy consumption and the achieved thermal comfort for various envelope designs. The ventilation strategy in **Table 5.8** is the entered values in Visual DOE and needs to be corrected for wind and stack effects. **Table 5.12** shows the corrected air change per hour which has the actual effect that was described in previous sections. The actual values were found dynamically fluctuating due to the effect of wind speed and therefore were averaged for proper application. **Table 5.13** shows the air-conditioning strategy at which the fan is on and off based on the introduced outside air. It is assumed that when the outside cool air is introduced the fan is off and on when the ventilation is not applied.

Table 5.12 Actual Ventilation Strategy for the Base Case Residential Building in Dhahran Based on ASHRAE Thermal Comfort Criteria for Mechanically Operated Buildings

<table>
<tr><th>Month / Design Alternative</th><th>January</th><th>February</th><th>March</th><th>April</th><th>November</th><th>December</th></tr>
<tr><td>Design #1: W#1, R#1 (Base Case)</td><td colspan="2" rowspan="2">0.25 ACH (24 h)</td><td rowspan="2">0.35 ACH (24h)</td><td rowspan="8">11 ACH: 19:00-7:00, 0.23 ACH: 08:00-18:00</td><td rowspan="8">12 ACH: 7:00-18:00, 0.24 ACH: 19:00-06:00</td><td rowspan="2">0.35 ACH (24h)</td></tr>
<tr><td>Design #4: W#1, R#7</td></tr>
<tr><td>Design #6:W#2, R#5</td><td rowspan="4">0.25 ACH (24 h)</td><td rowspan="6">3 ACH: 08:00-18:00, 0.26 ACH: 19:00-07:00</td><td rowspan="6">0.35 ACH (24h)</td><td rowspan="6">2.5 ACH: 7:00-18:00, 0.25 ACH: 19:00-06:00</td></tr>
<tr><td>Design #7:W#3, R#1</td></tr>
<tr><td>Design #9:W#3, R#7</td></tr>
<tr><td>Design #10:W#4, R#1</td></tr>
<tr><td>Design #13:W#5, R#3</td><td rowspan="2">1 ACH: 08:00-18:00, 0.25 ACH: 19:00-07:00</td></tr>
<tr><td>Design #15:W#5, R#7</td></tr>
</table>

Table 5.13 Air-Conditioning Strategy for the Base Case Residential Building in Dhahran

<table>
<tr><th>Month / Design Alternative</th><th>January</th><th>February</th><th>March</th><th>April</th><th>November</th><th>December</th></tr>
<tr><td>Design #1: W#1, R#1 (Base Case)</td><td colspan="2" rowspan="2">Fan On (24h)</td><td rowspan="2">Fan On (24h)</td><td rowspan="8">Fan Off: 19:00-7:00, Fan On: 08:00-18:00</td><td rowspan="8">Fan Off: 7:00-18:00, Fan On: 19:00-06:00</td><td rowspan="2">Fan On (24h)</td></tr>
<tr><td>Design #4: W#1, R#7</td></tr>
<tr><td>Design #6:W#2, R#5</td><td rowspan="4">Fan On (24h)</td><td rowspan="6">Fan Off: 08:00-18:00, Fan On: 19:00-07:00</td><td rowspan="6">Fan On (24h)</td><td rowspan="6">Fan Off: 07:00-18:00, Fan On: 19:00-06:00</td></tr>
<tr><td>Design #7:W#3, R#1</td></tr>
<tr><td>Design #9:W#3, R#7</td></tr>
<tr><td>Design #10:W#4, R#1</td></tr>
<tr><td>Design #13:W#5, R#3</td><td rowspan="2">Fan Off: 08:00-18:00, Fan On: 19:00-07:00</td></tr>
<tr><td>Design #15:W#5, R#7</td></tr>
</table>

CHAPTER SIX

SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Summary and Conclusion

This research study has been carried out to evaluate the thermal and energy performance of residential buildings in hot-humid and hot-dry climate of Saudi Arabia utilizing energy simulation program VisualDOE 4.1. The objectives of the study were to investigate the impact of thermal performance of exterior envelope and air leakage characteristics on indoor air temperature in a typical residential building, subsequently to define those that enhance the indoor air temperature and improve the energy consumption, and finally to develop design guidelines for envelope thermal design and air leakage characteristics to achieve thermal comfort at reduced energy consumption. In order to achieve these objectives, the study went through many phases including a literature review, conducting a survey questionnaire to identify the design practices of envelope designs in residential buildings, simulating the developed base case with and without the mechanical systems, and analyzing the simulation results.

From the review of literature in many energy simulation studies in Saudi Arabia, it was found that the annual energy consumption is considered as a thermal performance indicator but no study has considered the indoor air temperature as a performance indicator for building envelope evaluation. The mechanical systems are used to control the indoor air temperature and energy conservation technologies and measures (ECMs) are then investigated in order to reach an energy conservative design. Additionally, studies have been carried out to evaluate individual building envelope system without considering the building as an integral system. The air leakage characteristics were not thoroughly investigated to be utilized for thermal comfort and reduce the energy consumption.

For energy simulation program VisualDOE 4.1, many data input were required to simulate the base case residential building. A survey questionnaire was conducted to identify the base case residential building in hot-humid climate represented by Dhahran and hot-dry climate represented by Riyadh. From the results of the questionnaire, it was found that the characteristics of residential buildings in Dhahran don’t vary much from those used in Riyadh. However, it was found that the wall design in Riyadh has more thermal resistance than those used in Dhahran but both were below the international energy conservation code (IECC) for the same climatic conditions. It was also found that many architectural design offices select the envelope design based on the client requirement and in many cases poorly insulated envelope designs are always used. One design office in Dhahran and another in Riyadh has identified the required thermal resistance of the wall and roof designs. This illustrated that the architectural firms are still unaware of the local or international requirements of thermal resistance in the design of residential building. Therefore, the practice of envelope designs in residential building doesn’t vary much from whatever found in literature.

Based on the survey results, more than 202 wall possible assemblies and 62 roof assemblies were generated with a variety of building materials and using many thermal insulation types and thicknesses. The thermal resistance and heat capacity of these assemblies were calculated using the VisualDOE 4.1. Five wall designs and four roof designs were selected to represent the wide variation of thermal characteristics of the generated wall and roof designs. These assemblies were combined to form eight envelope designs that were evaluated throughout this study. The lighting level, equipment and occupancy profiles were defined based on the literature review. Accordingly, a base case residential building (Design#1) was defined for Dhahran and Riyadh.

6.1.1 Indoor Temperature Behavior and Comfort Conditions for Non-Conditioned Residential Buildings

Many thermal performance indicators were tested to evaluate the performance of building envelope including the indoor air temperature profile in a representative summer and winter week or day, monthly mean hourly indoor air temperature, cumulative temperature difference and the percentage of thermal comfort. Among these performance indicators, the monthly mean hourly indoor air temperature and percentage of thermal commfort were found suitable to idenitfy the impact of envelope designs and ventilation strategies on thermal comfort when no air conditioning system is used. Two thermal comfort zone criteria were used in this study; the thermal comfort criteria for naturally operated buildings, and the thermal comfort criteria for mechanically operated buildings.

The developed base case (0.2 window wall ratio), 0.1 WWR and window-less residential building with various envelope designs were simulated in VisualDOE 4.1 when no ventilation and no air conditioning strategy is used. The thermal comfort for naturally operated building was used to evaluate the effectiveness of ventilation strategies. For a window-less residential building, the mean hourly indoor air temperature in December, January, and February were outside the thermal comfort zones for poorly insulated designs (Design#1 and Design#4) and within the thermal comfort zones for the insulated envelope designs. For all envelope designs, the hourly mean air temperature in other months was outside the thermal comfort zones. The annual percentage of thermal comfort of envelope designs when no ventilation was applied varied from 31% for poorly insulated design (Base Case: Design#1) to 29-30% for well insulated design (Design#15) in both living and sleeping area.

Based on the profile of outdoor and indoor air temperature, Preliminary ventilation strategies were developed to identify the best schedule and volume of outside cool air that improves the thermal comfort. Many ventilation strategies were evaluated and consequently two effective ventilation strategies were developed for all envelope designs considering both the thermal comfort criteria for naturally operated building and mechanically operated building.

When ASHRAE thermal comfort criteria for the naturally ventilated building is considered, the thermal comfort has significantly improved in the living zone by 59% for the super-insulated design (Design #15) compared to 28% for the poorly insulated design (Design#1). In sleeping zone, the thermal comfort has improved by 34% for the poorly insulated design (Design#1) and by 89% for the super-insulated designs (Design#15). Due to low internal heat load in sleeping zone, the thermal comfort was found better compared to living zone. The effective ventilation strategy was based on the entered values in ViusalDOE 4.1 and a proper correction for wind and stack effects was applied. The corrected values were the hourly output data from VisualDOE and were averaged due to the fluctuation of wind speed. It was found that the thermal comfort can be achieved in the night of warm transition months; May and October.

A similar procedure was applied to develop ventilation strategies for envelope designs when the ASHRAE thermal comfort for mechanically operated buildings is considered. Utilizing this criterion, more air volume was required in April to achieve thermal comfort and it was not possible passively to achieve thermal comfort in warm transition months; May and October. In winter (December, January and February), introducing the outside cool air for window-less building deteriorates the thermal comfort.

Preliminary ventilation strategies were developed for the residential building with 0.10 window wall ratio. Similar to window-less building, many ventilation strategies were evaluated. When the ASHRAE comfort criteria for naturally operated building is considered, it was observed that introducing high volume of outside air continuously during warm transition months (May and October) beyond 30 ACH is not significant in improving the thermal comfort. The night ventilation in May and October was found more appropriate in improving the thermal comfort. On the other hand, introducing outside cool air continuously during cooled transition months; March and November deteriorated the thermal comfort. Therefore, day time selective ventilation was used to avoid the overcooling problem in these two months. It was also found necessary to utilize the outside cool air during the winter months of December and February to achieve thermal comfort for well insulated designs Design#9, Dsign#10, Design#13 and Design#15. When the ASHRAE comfort criterion for mechanically operated buildings is considered, the thermal comfort was not attained by passive means in May and October. Using this criterion, more outside cool air was required to achieve thermal comfort in March. Accordingly, two effective ventilation strategies were developed for all envelope designs considering both the thermal comfort criteria for naturally ventilated building and mechanically operated building.

Utilizing the developed ventilation strategy and based on the ASHRAE thermal comfort criteria for the naturally ventilated building, the thermal comfort increased in living area when proper ventilation strategy is applied to 41% for the poorly insulated design

(Design#1) and to 43-45% for the insulated designs (43% for super-insulated Desgin#15). The improvement in thermal comfort was significant with the super-insulated design Design#15 (95%) compared to the poorly insulated design Design#1 (37%) when the combined ventilation strategy is applied. The thermal comfort improvement in the sleeping area ranged from 38% for the poorly insulated design (Design#1) to 122% for the super-insulated design (Design#15).

The base case residential building (0.2 WWR) was evaluated under different ventilation strategies when single and double glazing are used. When the ASHRAE comfort criteria for naturally operated building is considered, it was observed that introducing high volume of outside air beyond 30 ACH continuously during winter months (December, January and February), transition months (March , April, May, October and November) deteriorate the thermal comfort for single glazed building. It was found that the application of selective ventilation strategies such as daytime ventilation only during winter months (December, January and February) and cool transition months (March and November) and night ventilation only during warm transition months (April, May, and October) improved the thermal comfort. For the double glazed building, it was found that more air volume is required in April to improve thermal comfort while no air is required in winter months. When the ASHRAE comfort criterion for mechanically operated buildings was considered, the thermal comfort in May and October was not attained by passive means. Using this criterion, more outside cool air is required to achieve thermal comfort in November. All designs require outside cool air to improve the thermal comfort in winter months; December, January and February when single glazed is used while no requirement for outside air when double glazed is used. Accordingly, two effective ventilation strategies were developed for all envelope designs considering both the thermal comfort criteria for naturally ventilated building and mechanically operated building.

Based on the ASHRAE thermal comfort criteria for the naturally operated building, the thermal comfort increased in living area when proper ventilation strategy is applied to 40% for the poorly insulated design (Design#1) and to 41% for the insulated designs (Desgin#15). It was noticed that all envelope design achieves similar thermal comfort level. The thermal comfort improvement in the living area is significant with the insulated design Design#15 (above 100%) compared to the poorly insulated design Design#1(45%). In sleeping area, the thermal comfort improvement ranges from 47% for the poorly insulated design to 229% for the super-insulated designs.

The thermal performance of envelope designs for the base case residential building in Dhahran was also evaluated when no ventilation is applied. It was interesting to find that the poorly insulated designs Design#1, Design#4 performed better in terms of thermal comfort than the super-insulated designs Design#13 and Design#15 when no ventilation is applied. It was found that the indoor air temperature for the insulated designs in winter and transition months is above the thermal comfort zones in winter due to their high thermal characteristics. It was also found that there is a risk of overheating in transition months but happened early for the insulated designs.

The base case residential building under different window to wall ratio (0.1 WWR and window-less) was investigated. It was found that reducing the WWR improves the thermal comfort of the building. This improvement was found more with well insulated designs. At a ratio of 0.1 WWR, the thermal comfort improvements for the standard (Design#6 to Design#10) and super-insulted designs (Design#13 and Design#15) were from 28% to 38% compared to the base case scenario (0.2 WWR). On the other hand, the improvement for the windowless (0 WWR) building varied greatly from 38% for Design#6 to 86% for Design#15. The improvement in thermal comfort for the non-insulated designs (Design#1 and Design#4) was found below 15%.

The base case (0.2 WWR) and 0.1 WWR residential building was evaluated under two glazing types; single glazing panel and double green glazing panels. It was found that the thermal comfort has improved in all envelope designs but 5% improvement was noticed with the poorly insulated designs (Design#1 & Design#4) and the 6-7% improvement with standard insulated designs (Design#6, Design#7) when double glazing is used. The super-insulated design (Design#15) has improved the thermal comfort by 4%. When the WWR is reduced to 0.1, the super-insulated designs (Design#13 and Design#15) improved the thermal comfort by 7-8%. The double glazing was found more effective in improving the thermal comfort for super-insulated design with low window wall ratio and more effective for poorly insulated deigns with high window wall ratio when no air conditioning is used.

6.1.2 Impact Of Envelope Thermal Design On Energy Performance Of Residential Buildings

The base case residential building was simulated under the climatic conditions of Riyadh and Dhahran when air conditioning (cooling and heating) is available throughout the year. It was found that the residential buildings in Dhahran consume 16% more energy than those in Riyadh. In terms of energy intensity, the energy index for residential building in Dhahran and Riyadh was found to be 196 and 169 kWh/m^2/year respectively. For comparison purposes, studies in Dhahran showed that the average energy intensity for poorly insulated residential buildings is 263 kWh/m^2/year and for well insulated buildings is 153 kWh/m^2/year. A sensitivity analysis was conducted for wall designs, roof designs, combination of wall and roof designs, glazing types, window wall ratio, orientation and various air infiltrations. Finally, the combined effect of all design parameters was simulated.

It was found that when the thermal resistance of wall assembly increases, the energy consumption is reduced. However, it was interesting to find that the light thermal mass in wall design with poorly insulated glazing has a negative impact on energy consumption. Although, the thermal resistance of wall#5 (R-value= 6.67 m^2.°C/W) was higher than

W#4 (R-value= 5 m^2.°C/W), the energy consumption when wall#5 is used has increased by 0.7% in Dhahran and 1.1% in Riyadh. This observation was related to the effect of low heat capacity (low thermal mass) of wall#5 which was 3 times less than the wall#4. Similarly for roof designs, the energy consumption was reduced with the increases of thermal resistance. Although their thermal resistance has increased, it was interesting to find that when the thermal insulation is placed to the interior side of the roof slab such as the case in Roof#3, the heating energy consumption increases by 8% in Dhahran and 18% in Riyadh. It was also found that when the thermal mass is reduced by 50% (case: Roof#5), the heating energy increased by 1% in Dhahran. This observation was not found in Riyadh due to the high thermal characteristics of their base case wall design which diminished the effect of roof thermal mass when compared to Dhahran case.

The impact of eight possible combinations of wall and roof designs on energy performance of base case residential building in Dhahran and Riyadh was investigated. It was found that all envelope designs reduced both the heating and cooling energy but some designs performed better in reducing the heating energy and others are better in reducing the cooling energy. The best envelope designs in Dhahran are those that effectively reduce the heating and cooling energy and subsequently the total heat energy are Design#9 (Wall#3, Roof#7), Design#10 (Wall#4, Roof#1), and Design#15 (Wall#5, Roof#7). In Riyadh, the best envelope designs are Design#10 (Wall#4, Roof#1), Design#15 (Wall#5, Roof#7), Design#7 (Wall#3, Roof#1) and Design#9 (Wall#3, Roof#7). In Riyadh, the effect of both the low thermal mass in Wall#5 and interior thermal insulation in Roof#3 was clear in increasing the heating energy by 20%. It was interesting to note that although Roof#1 is poorly insulated, it performed very well when combined with insulated wall designs. This good performance was related to the high thermal mass which helps in reducing the heating energy in winter and its light color which helps in reducing the cooling energy in summer.

The energy performance of the residential building with single clear 6 mm glazing and high performance double glazing Tint Low-e4 Argon 6/12/6 was evaluated under various windows to wall ratios (WWR). In Dhahran, with every 0.1 increase in window to wall ratio (WWR) there was an increase of 15% and 10% in energy consumption for well insulated and poorly insulated designs respectively. In Riyadh, with every 0.1 increase in window to wall ratio (WWR) there was an increase of 12-15% in energy consumption for all envelope designs. It was observed in both Dhahran and Riyadh that at higher WWR (>0.30), all envelope designs converged to a similar value regardless of the thermal characteristics of envelope designs. When the high performance double glazing was used, the effect of WWR on energy consumption for the poorly insulated designs (Design#1 and Design#4) in both Dhahran and Riyadh was minimal. For these designs, with every 0.1 increase in WWR there was a 2% increase in energy consumption for Dhahran and 3-4% increase in energy consumption in Riyadh. Similarly for insulated designs, with every 0.1 increase in WWR there was a 7% increase in energy in both Dhahran and Riyadh.

The poorly insulated (base case: Dsign#1) and well insulated (Design#15) residential building were evaluated under four glazing types; double green 6mm, high performance double tinted low-e glazing, high performance triple clear low-e glazing and high performance triple tinted reflected glazing were evaluated in Dhahran and Riyadh. It was noticed that as the thermal resistance of the glazing increases, the total energy consumption decreases. However, the cooling and heating energy should be balanced by the proper selection of thermal resistance and solar heat gain coefficient. It was found that the clear triple glazing performed better during the winter where more solar radiation is admitted and used for heating purposes. However, it was less effective than double tinted and triple glazing in the reduction of cooling energy. Therefore, proper balance between the thermal and solar characteristics is important in reducing the energy consumption. It was found that high performance glazing is more efficient with insulated designs than the poorly insulated design. It was concluded that to achieve maximum reduction in total energy consumption, it is imperative to use high performance glazing that has low solar heat gain coefficient (low SHGC) and high thermal resistance (high R-value) even if it increases the heating energy. Since the winter season in Saudi Arabia is normally short and mild and the transition and summer season is long and harsh with high solar radiation, the heating energy is not a major component of total energy consumption. It is important therefore to control the solar radiation during the transition and summer months. Dynamic solar control is an optimum strategy in Saudi Arabia climate where the solar radiation is admitted in winter but rejected in summer and transition months.

The base case residential building was assumed to be on south-north orientation where the building faces north. The east-west orientation was investigated in Dhahran and Riyadh. The energy consumption increased by 1.8% and 2.2% in Dhahran and Riyadh respectively. It is concluded that south north orientation is best for residential building in hot climates.

The leakage characteristics of the base case residential building was investigated in Dhahran and Riyadh climate. The building was assumed to be very air tight (0.35 ACH), normal leaky (1 ACH), high leaky (2 ACH) and extremely leaky (3 ACH). The energy performance was evaluated with poorly insulated design (Design#1) and well insulated design (Design#15). In Dhahran, for poorly insulated design (Design#1) in normal leaky building, it was found that for every increase of 1 ACH there was an increase of more than 100%, 20% and 15% of heating, cooling and total energy consumption for the poorly insulated designs. For well insulated design (Design#15) in normal leaky building, for every 1 ACH increases in air infiltration there is an increase of more than 300%, 20% and 19% of heating, cooling and total energy consumption for the well insulated designs in Dhahran. When the air infiltration was assumed to be very air tight (0.35 ACH), the energy consumption was reduced. The reduction in heating energy was significant in well insulated design (30%) compared to poorly insulated design (14%). It is concluded that the energy consumption is sensitive to air infiltration. However, the heating energy is more sensitive to air infiltration especially for the well insulated designs. The cooling energy in hot humid climate of Dhahran has increased due to infiltration.

In Riyadh, for every increases of 1 ACH there was an increase of more than 200%, 10% and 10% of heating, cooling and total energy consumption for the poorly insulated design (Design#1) and an increase of more than 300%, 10% and 10% of heating, cooling and total energy consumption for the well insulated designs in normally leaky buildings. When the air infiltration was reduced to 0.35 ACH (very air tight) the heating, cooling and total energy consumption was reduced by 18%, 2% and 1% in poorly insulated design (Design#1: base case) and is reduced by 17%, 2% and 1% in well insulated design (Design#15).

The most effective strategies were selected and simulated as the final case for the eight envelope designs in Dhahran and Riyadh. The energy performance of the residential building was compared to the energy performance of the envelope design when the GCC thermal resistance regulations and the international energy conservation code (IECC) are considered. In Dhahran, the energy intensity of the base case residential building was 196 kWh/m^2/year and for well insulated design (Design#15) is 123 kWh/m^2/year compared to 263 kWh/m^2/year for a typical non-insulated and 153 kWh/m^2/year for well insulated residential housing in Dhahran. The energy intensity of the residential building with envelope design recommended by GCC regulation and IECC is 172 and 153 kWh/m^2/year respectively. Based on GCC requirement, the poorly insulated design Design#1 can meet the requirement with the use of high performance glazing and reduced air infiltration. However and according to IECC requirement, Design#6 and above meet this requirement. The comparisons showed that even poorly insulated roof could meet the IECC if R-value of the wall is more than 2.44 m^2.K/W (R-14) with high performance glazing in an airtight building. In Riyadh, the energy intensity of the base case residential building was 169 kWh/m^2/year and for well insulated design (Design#15) is 115 kWh/m^2/year compared to 161 and 145 kWh/m^2/year for the GCC and IECC requirements respectively. The poorly insulated design (Design#1) could easily meet the requirement of GCC and IEC with use of high performance glazing and reduced air infiltration.

The energy and thermal performance of the base case residential building with high performance glazing and reduced air infiltration was investigated when ventilation strategy is combined with mechanical systems to achieve thermal comfort and reduce energy consumption. The ventilation strategy was developed in Chapter four for the residential building with double glazed window. The ASHRAE thermal comfort criterion for the mechanically operated building was used in this investigation. Although, the thermal comfort was achieved in more than 90% of the time annually, it was found that introducing the outside cool air may deteriorate the thermal comfort if careful consideration is not taken. This was clear when the thermal comfort in March and April was achieved in less than 80% of the time. Therefore, the ventilation strategy was revised to avoid the overheating in these months. Several strategies were tested in March and there was no improvement in thermal comfort. The thermal comfort was improved to more than 85% for many design alternatives in April when the outside air is scheduled to

16:00-9:00. It was observed that the thermal comfort in sleeping zone is more than that of the living area due the impact of low internal heat load.

The impact of the modified ventilation and air-conditioning strategy on heating, cooling and total energy consumption was investigated. The introduced outside cool air increased the heating energy but the cooling energy was reduced. The results showed that the total energy consumption is reduced by 18% for the poorly insulated design and by 40% for the well insulated design compared to 15% and 38% for poorly and well insulated design respectively when no ventilation strategy is applied to the final case. When ventilation and air-conditioning strategy was applied in Dhahran, the energy intensity of the poorly residential building is 161 kWh/m^2/year and for well insulated design is 117 kWh/m^2/year compared to 168 kWh/m^2/year for poorly insulated design and 123 kWh/m^2/year well insulated design when no ventilation is applied. Based on the results, ventilation and air-conditioning strategy was developed to achieve thermal comfort and reduced energy consumption.

6.2 Recommendations

Based on the conclusions of this study, the following recommendations are made to achieve thermal comfort at reduced energy consumption in residential buildings in hot humid and hot dry climates:

1. Outside cool air should be utilized to achieve thermal comfort and reduce the energy consumption. Since the indoor air temperature is above the outside temperature in many months in the year, the outside air should be introduced during unoccupied period to reduce the mechanical system start-up energy consumption.
2. The well insulated designs should always be used as it was found that they performed well when the passive, active or hybrid strategies are applied.
3. In hot humid climate, when the building is under unconditioned mode, **Table 6.1** gives the general recommendations for outside cool air requirements considering the ASHRAE thermal comfort criteria for naturally operated and mechanically operated buildings (for detail schedules refer to **Table 4.3**, **Table 4.5** and **Table 4.8**).

Table 6.1 Recommendations for the Utilization of Outside Cool Air under Unconditioned Residential Building in Dhahran

Residential Building Characteristics	**ASHRAE Thermal Comfort for Naturally Operated Building**	**ASHRAE Thermal Comfort for Mechanically Operated Building**
Window-Less Building	• The night ventilation (20:00-6:00) should be utilized to improve the thermal comfort in May (9 ACH) and October (12 ACH). • Avoid introducing outside cool air in winter months (December, January and February) to avoid thermal discomfort.	• Mechanical system is needed for thermal comfort in warm transition months: May and October • More outside cool air is required in April to achieve thermal comfort.
0.1 WWR Building	• The night ventilation (20:00-6:00) should be utilized to improve the thermal comfort in May (12 ACH) and October (9 ACH). • The day time selective ventilation should be used and the night ventilation should be avoided to achieve thermal comfort in March (3 ACH: 08:00-18:00) and November (4 ACH: 07:00-18:00). • The day time selective ventilation should be utilized for well insulated designs Design#9,	• Mechanical system is needed for thermal comfort in warm transition months: May and October • The day time selective ventilation should be used to achieve thermal comfort in March (08:00-18:00) and November (07:00-18:00). More outside cool air (5 ACH more) is required in March to achieve thermal comfort. • The day time selective ventilation should be utilized for well insulated designs Design#9, Dsign#10, Design#13 and Design#15 in winter

	Dsign#10, Design#13 and Design#15 in winter months of December (1 ACH: 07:00-18:00) and February (1 ACH:08:00-18:00).	months of December and February.
0.2 WWR Building	• **Single Glazed:** Avoid high volume of outside cool air (>30ACH) continuously in winter and cooled transition months (March and November). Outside cool air should be utilized for all envelope designs (except for poorly insulated design in February) in December & February, well insulated designs in January to improve the thermal comfort. • The day time selective ventilation should be used in winter and cooled transition months and the night ventilation in warm transition months (April, May, and October) • **Double Glazed:** More cool air should be used in April and no requirement for outside air for poorly insulated designs. Outside air should be used for insulated designs in December and February.	• More outside cool air is required in November to achieve thermal comfort. • **Single Glazed:** outside cool air should be utilized for all envelope designs in December & February, well insulated designs in January to improve the thermal comfort. • **Double Glazed:** no requirement for outside air for poorly insulated designs. Outside air should be used for insulated designs in December and February.

4. To exceed the requirement of the International Energy Conservation Code (IECC), the building envelope of the residential buildings should be designed with high performance glazing (U-value<1.317 W/m^2.K) and be airtight (0.35 ACH). Additionally, it should meet the following thermal envelope design requirements:
   4.1. If the wall R-value is 0.83 m^2.°C/W (RSI-5), the roof R-value should be 4.35 m^2.°C/W (RSI-25).
   4.2. If the wall R-value is 2.44 m^2.°C/W (RSI-14), the roof R-value can be 1.69 m^2.°C/W (RSI-10).
5. To reduce the heating energy in mild winter of Saudi Arabia, a medium thermal mass or heat capacity of > 200 kJ/m^2.C should be at least provided in the design of walls in the single glazed poorly insulated buildings. Many building materials can provide this level of thermal mass.
6. Similarly for roof, to reduce heating energy in mild winter of Saudi Arabia, the thermal mass or heat capacity of > 500 kJ/m^2.C should be at least provided in the design of roofs in the single glazed poorly insulated buildings.
7. The window-wall ratio should be less than 0.3 as more than this limit increase the energy consumption regardless of the thermal characteristics of building envelope.
8. A balance between the thermal and solar characteristics of glazing should be considered seriously in hot climates of Saudi Arabia. A high performance glazing that has low solar heat gain coefficient (<0.4) and high thermal characteristics should be

considered to reduce the cooling energy in hot season and allow some solar in the mild winter.

9. An external dynamic solar radiation protection should be used where it allows solar radiation in winter and protects the space in high solar season.
10. A south-north orientation should be considered in the design practice of residential buildings in Saudi Arabia.
11. The residential buildings should be air tight especially when the well insulated envelope designs are used as they are more sensitive to air infiltration in winter. Air infiltration should be limited in hot humid climates as it increases the cooling energy in addition to its increases effect on heating energy in winter.
12. In order to reduce the air infiltration, improve the workmanship during the construction of new residential buildings, keep the indoor environment in positive pressure during the operation of the building especially in windy and hot climate to reduce the effect of wind and stack on infiltration.
13. The envelope design should be designed with vapor retarders to reduce the air infiltration through the wall and roof structures. The windows, wall openings and cracks should be sealed with Weather-stripping and chalking material. The doors undercut should be minimized especially the external doors.
14. Maximize the window size (but WWR should be <0.3) in the direction of dominant wind direction to utilize the natural ventilation and utilize the high performance glazing.

15. For GCC thermal regulation should be seriously revised to include the fenestration system and air leakage requirements in the hot climates.
16. To reduce the total energy consumption by 24% from the IECC (envelope design requirement) energy intensity level and to achieve a reduction of 40% of total energy consumption compared to the base case, a combined well insulated envelope design (Design#15), air infiltration (0.35 ACH), solar (SHGC<0.4) and thermal characteristics (high thermal insulation) of fenestration system should be incorporated with the developed ventilation and air-conditioning strategy as in **Table 5.12 and Table 5.13** respectively.

6.3 Envelope Design Guidelines for Residential Buildings in Hot Climates of Saudi Arabia

Based on the analysis, conclusions and recommendations in this research work and with the consultation of International Energy Conservation Code **(IECC 2000)** and with the series of design guidelines that were developed by Rocky Mountain Institute’s Home Energy Brief **(RMI, 2004)**, envelope design guidelines are developed as shown in **Table 6.2** for hot climates of Saudi Arabia.

Table 6.2 Envelope Design Guidelines for Residential Buildings in Hot Climates

Envelope Design	Guidelines
Walls and Roof Thermal Characteristics	**Thermal Mass Requirements:** • A thermal mass or heat capacity of > 200 kJ/m^2.C and > 500 kJ/m^2.C should be at least provided in the design of walls and roof respectively especially for poorly insulated buildings. • Thermal mass should be located to the interior side of the building envelope (i.e. walls and Roofs) (in the space) as it is found that the heating energy is significantly reduced. • In transition and summer months, the indoor thermal mass should be shaded from direct solar radiation.
	Thermal Insulation Requirements: • For poorly insulated roof buildings (R-value <1.69 m^2.°C/W; RSI-10), the wall R-value should be greater than 2.44 m^2.°C/W (RSI-14). • For poorly insulated walls in residential buildings (R-value <0.83 m^2.°C/W; RSI-5), the roof R-value should be greater than 4.35 m^2.°C/W (RSI-25). • To reduce the energy consumption by more than 20% in Riyadh and Dhahran from the **I**nternational **E**nergy **C**onservation **C**ode **(IECC)** design, the wall thermal resistance (R-value) should be greater than 6.67 m^2.°C/W (R-38) and roof thermal resistance (R-value) should be 5.88 m^2.°C/W (R-35). • Thermal insulation should be placed to the exterior side of the building envelope with good moisture resistance and protection against weather conditions (rain, humidity, solar radiation). • The exterior building envelope (walls and roof) should be

Walls and Roof Thermal Characteristics	painted with smooth and light color to reflect the solar radiation. The roof systems should be painted with light-colored or installed with reflective top layers. Regular cleaning and maintenance is important to this layer.
Fenestration System	**Glazing Thermal Characteristics:** • Use double glazing as it is found that using double green glazing reduces the energy consumption by 6% in poorly insulated buildings and by 10% for well insulated buildings. • Consider low-e coated glazing which reduces the window's solar transferring characteristics, thereby saving energy consumption. Using high performance double low-e tinted glazing (U-value<1.317 W/m^2.K, SHGC=0.278)) reduces the energy consumption by more than 10% for poorly insulated buildings and by more than 20% for well insulated buildings.
	Windows Characteristics: • Frames and sashes should be designed with reasonable thermal insulated material such as vinyl, fiberglass or thermal break material should be provided with aluminum frames. • Limit the window to wall ratio (WWR) to less than 30% for the well insulated buildings as it is found that with every 10% increases in WWR there are increases of 10-15% in energy consumption in hot climates.
	General Design Considerations: **Solar Characteristics:** Solar Heat Gain Coefficient (SHGC) should be < 0.4 and the ratio of light transmittance to SHGC should be > 1 for better view and daylight utilization which reduces electrical lighting.

Fenestration System	**Shading Strategies:** • Allow solar radiation to pass in winter especially for the poorly insulated buildings to reduce heating energy. • Provide exterior shading devices to allow solar in winter and shade in summer and transitions months. Fixed or movable (manual or motorized) devices located inside or outside the glazing should be used to control direct or indirect solar gain. • Provide interior shading devices such as insulating blinds, shades, or curtains.
Total Building Envelope Design Requirements	If the above thermal resistance guidelines are not followed, then the following guidelines based on **IECC 2000** should be minimum requirements for envelope design in hot climates for residential buildings with less than or equal 20% windows area: • The wall thermal resistance (R-value) should be more than 1.94 $m^2.^oC/W$ (R-11) for light thermal mass, 1.761 $m^2.^oC/W$ (R-10) for high exterior thermal mass and 1.066 $m^2.^oC/W$ (R-6) for high interior or integral mass. • The roof thermal resistance (R-value) should be more than 3.35 $m^2.^oC/W$ (R-19). • The U-value of glazing should be less than 4.55 $W/m^2.K$ with SHGC<0.4.
Building Orientation	• Orient the building so that solar radiation in summer is minimal on side with large glass areas. South-North orientation is the best in hot climates of Saudi Arabia.

Air Leakage and Air-Conditioning Strategies	**Air Ventilation and Air-conditioning Strategies:** **<u>Poorly Insulated Envelope Designs (Wall: R-value<1.066 m^2.ºC/W & Roof: R-value <2.29 m^2.ºC/W):</u>** • Provide minimum air ventilation when air-conditioning is on (for indoor air quality) in winter months (December, January and February), cool transition month (March), in summer (June, July, August and September) and warm transition months (May and October). • In **April**, the air ventilation should be allowed at a maximum rate of 11 ACH from 19:00-7:00 when no air-conditioning is use, and minimum rate of 0.35 ACH from 08:00-18:00 with air-conditioning. • In **November**, the air ventilation should be allowed at a maximum rate of 12 ACH from 07:00-18:00 when no air-conditioning is use, and minimum rate of 0.35 ACH 19:00-06:00 with air-conditioning.
	<u>Standard Insulated Envelope Designs (Wall: 1.066 m^2.ºC/W <R-value< 5 m^2.ºC/W & Roof: 2.29 m^2.ºC/W <R-value <4.35 m^2.ºC/W):</u> Similar to above except for the following months: • In **February**, the air leakage should be allowed at a maximum rate of 3 ACH from 08:00-18:00 when no air-conditioning is use, and minimum rate of 0.35 ACH from 19:00-07:00 with air-conditioning. • In **December**, the air leakage should be allowed at a maximum rate of 2.5 ACH from 07:00-18:00 when no air-conditioning is use, and minimum rate of 0.35 ACH 19:00-06:00 with air-conditioning.

Air Leakage and Air-Conditioning Strategies	**<u>Well Insulated Envelope Designs (Wall: R-value > 5 m^2.ºC/W & Roof: R-value >2.56 m^2.ºC/W):</u>** In addition to standard insulated envelope designs, the following should be applied: • In **January**, the air leakage should be allowed at a maximum rate of 1.5 ACH from 08:00-18:00, and minimum rate of 0.35 ACH from 19:00-07:00 with air-conditioning.
	Air Infiltration Control Strategies for Envelope Designs: • An effective way to reduce the energy consumption is to reduce the air infiltration through windows and doors by applying the weather-stripping and by applying caulk (such as expanding foam sealant) through cracks and openings. • Continuous air barrier or vapor retarders should be provided for the building envelope to reduce the air leakage into or out of a building. **Notes:** It is found that with every 1 ACH increases in air infiltration in : • **Dhahran:** there is an increase of 15% and 19% in total energy consumption for poorly and well insulated buildings respectively. • **Riyadh:** there is an increase of 10% in total energy consumption for all types of buildings.

6.4 Recommendations for Future Research

This study work has highlighted many findings that lead to future potential research. The followings are potential extensions for this research:

- Thermal and energy performance of building envelopes should be evaluated under various internal loads; lighting and appliances.
- The zoning concept of daytime areas in residential buildings should be investigated to define zone allocation strategies for occupancy to achieve thermal comfort and reduce the energy consumption.
- Minimum window area that is recommended for reduced energy consumption and maximum visual comfort as a function of orientation of the window façade and geographical location should be studied.
- Shading devices and solar characteristics of glazing should also be investigated for different orientations to reach an ideal window design for residential buildings in hot climates.
- The air infiltration (ACH) should be fully investigated in hot humid climates. The CFD modeling or other air leakage identification techniques should be conducted to quantify and properly define the air infiltration characteristics in residential buildings.
- The application of smart ventilators or residential type air conditioning with economizer should be assessed in the climates of Saudi Arabia to quantify the actual and effective ventilation strategies to achieve thermal comfort at low energy consumption.

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APPENDECES

APPENDIX A: Data Collection Form

SURVEY OF ENVELOPE DESIGN PARAMETERS IN RESIDENTIAL BUILDINGS IN SAUDI ARABIA

TO DESIGN OFFICE MANAGER

SUBJECT: QUESTIONNAIRE SURVEY FOR THESIS RESEARCH

Dear Sir,

Mr. Saleh Al-Saadi is a Graduate student in the Architectural Engineering Department. He is currently collecting data for his Master thesis titled "***Envelope Design for Thermal Comfort and Reduced Energy Consumption in Residential Buildings".*** He is conducting a questionnaire survey for his thesis research. The purpose of this survey is to identify the building envelope design parameters (i.e. roof, walls and windows) that are commonly used in the design practice of residential buildings in Saudi Arabia. Please distribute the questionnaire to the appropriate persons in your design office (e.g. Architects, Architectural Engineers, Construction Documents Developers or Specification Writers).

I hope that you will extend any help you can to make his research successful. We always value your participation and appreciate your active contribution in this phase of the study.

Thanks in advance for your positive cooperation.

Dr. Ismail Budaiwi
Thesis Advisor,

Chairman, Architectural Engineering Department, KFUPM

Questionnaire Survey

INSTRUCTIONS: Please mark the answer that mostly reflects your design practice. (Respondent's information will remain anonymous and the data will be used for educational purpose only).

Section I: Respondent's General Information

Name (Optional)	
Company Name:	
Job Title:	
Telephone No.:	
Facsimile:	
E-mail Address:	
Company Address:	

1. How many years of experience does your design office have in designing single-family houses in Saudi Arabia?

a) less than 5 years	☐	b) 5-10 years	☐
c) 10-15 years	☐	d) Over 15 years	☐

2. What is the **yearly average number** of single-family houses that your design office normally designs?	Number of houses=	

Section II: Building General Information

1. **On average**, what is the **floor area** of a single-family house?	Floor Area=………..m^2

	Square Shape	Rectangular	Irregular
2. What is the **common geometrical shape** you normally use for a single-family house?	☐	☐	☐

	1-Floor	2-Floors	3-Floors
3. How **many floors** you normally design for a single-family house?	☐	☐	☐

Section III: Building Envelope Design Parameters

A) Exterior Walls Design

The followings are common exterior wall designs and locations of the insulation material that are normally used in single-family houses, **select one or more designs** according to your design practice: **(please Tick '√' the empty boxes for the selected design)**

			Location of Insulation Material Relative to the Primary Layer		
Wall Designs:	**Normally used**	**With No Insulation**	**To the Exterior**	**To the Interior**	**Bounded by Two Layers**
1. Single-Leaf Wall	☐	☐	☐	☐	
2. Double Leaf Wall	☐	☐	☐	☐	
3. Cavity wall	☐	☐	☐	☐	☐
4. Sandwich Panel Wall	☐	(e.g. Main Layer/Insul./Main Layer **or** Insul./Main Layer/Insul.**)**			
5. Others, Please Specify: ……………………………………………………………………….					

Main Building Materials normally used for Exterior Walls	**Please Tick '√'**
4. Concrete Masonry Blocks (CMU):	
a. Solid	☐
b. Hollow	☐
c. Hollow with insulation material inserts	☐
5. Aerated Concrete Blocks (e.g. Autoclaved, Siporex)	☐
6. Clay Bricks:	
a. Solid	☐
b. Hollow	☐
c. Hollow with insulation material inserts	☐
7. Reinforced Concrete:	
a. Cast-in-Place	☐
b. Pre-Cast	☐
8. Stone	☐
9. Adobe	☐
10. Others, Please Specify: ……………………………………………………………………….	
Exterior Finishing normally used for Walls	**Please Tick '√'**
1. Cement Plaster (e.g. Stucco)	☐
2. Stone Veneer	☐
3. Marble Cladding	☐
4. Others, Please Specify: ……………………………………………………………………….	

Walls' Surface Colors that <u>are normally used</u>:					**Please Tick '√'**
Light Color (white paint)	☐	Medium Color (off-white, cream)	☐	Dark Color (Brown, red or other dark colored paints)	☐

B) Roofing System Design

The followings are common roof deck types and location of insulation materials that **are normally used** in single-family houses, **<u>select one or more designs</u>** according to your design practice: **(please Tick '√' the empty boxes for the selected design)**

			Location of Insulation Material Relative to the Roof Slab		
Roofing Deck Designs:	**Normally used**	**With No Insulation**	**To the Exterior**	**To the Interior**	**Filled in hollow-Cores**
1. Reinforced Concrete Slab	☐	☐	☐	☐	
2. Hourdi Block Slab	☐	☐	☐	☐	☐
3. Pre-cast hollow-core concrete planks	☐	☐	☐	☐	☐
4. Others, Please Specify: ……………………………………………………………………………….					

Building Materials that <u>are normally used</u> for Roofs:	**Please Tick '√'**
1. Sloping Foam Concrete Screed, Thickness =…….. mm	☐
2. Sloping Plain (sand/cement) Concrete Screed, Thickness =…….. mm	☐
3. Sand Fill, Thickness =…….. mm	☐
4. Hollow Clay bricks for hourdi Slab	☐
5. Hollow CMU blocks for hourdi Slab	☐
6. Others, Please Specify: ………………………………………………………………………………	
Flooring (Exposed) Layer of the Roof Construction:	**Please Tick '√'**
1. Tiles (i.e. Terrazzo, Cement)	☐
2. Gravel layer, Thickness =…….mm	☐
3. Soil layer, Thickness =…….mm	☐
Special Features of Roofing System	**Please Tick '√'**
1. Shading (e.g. metal corrug. sheets, pergolas) is normally used to shade part of the Roof	☐
2. False Ceiling is normally used in Roofing System, Depth of plenum =………. mm	☐

Roof's Surface Colors that <u>are normally used</u>:					
Light Color (white paint)	☐	Medium Color (off-white, cream)	☐	Dark Color (roofs with gravel, red tile)	☐

C) Types of Insulation Materials in Walls and Roofing Systems

The followings are common insulation materials that **are normally used in walls and roofing systems, select one or more** according to your design practice: **(please Tick '√' the selected design for both wall and roof)**

Insulation Materials that are normally used for:	Wall	Roof
1. Rock wool	☐	☐
2. Fiber glass	☐	☐
3. Cellulose	☐	☐
4. Vermiculite	☐	☐
5. Perlite	☐	☐
6. Extruded polystyrene (XPS)	☐	☐
7. Expanded or Molded polystyrene (EPS)	☐	☐
8. Polyurethane	☐	☐
9. Polyethylene	☐	☐
10. Light-weight Concrete		☐
11. Others, Please Specify: ………………………………………………………………………….		
12. Low emissivity material (i.e. aluminum paper) is used in:	Wall Air cavity ☐	Ceiling Plenum ☐
13. Allowable air space or gap that is commonly used in your **Wall design**=…………………..mm		
14. Required Minimum R-value for insulation material **in Wall Design is** =…………………. m^2.°C / W		
15. Required Minimum R-value for insulation material **in Roof Design is** =…………………. m^2.°C / W		

D) Window Designs

The followings are common glazing types that are used in single-family houses, **select one or more** according to your design practice:

Glazing Types or Components that are normally used:	Please Tick '√'
1. Single-glazed layer:	
a. Clear	☐
b. Bronze/Gray/Green Tint	☐
2. Double-glazed layers:	
a. Clear	☐
b. Bronze/Gray/Green Tint	☐
c. Low-e with High-Solar-Gain (Pyrolitic or hard coat Low-E glass)	☐
d. Low-e with Moderate-Solar-Gain, (Sputtered or soft-coat products)	☐
e. Low-e with Low-Solar-Gain, (Spectrally Selective)	☐
3. Triple-glazed layers:	
a. Clear	☐
b. Low-e	☐
4. Others, Please specify: ………………………………………………………………....	

Exterior Shadings
1. Side Fins, Projection =……. mm
2. Overhang, Projection =……. mm
3. Others, Please specify: ……………………………………………………….…….…

Window Ratio:	
What is the Window to Wall Ratio (WWR) that is normally used in your design?	WWR= ………….

Window Types that <u>are normally used</u> in single-family houses: (Please Tick '√')	
Operable Windows ☐	Fixed Windows ☐

Section IV: Air Leakage and Lighting Requirements

The followings are general air leakage and lighting requirements in single-family houses**, <u>select one or more</u>** according to your design practice:

Air Leakage Requirements in single-family houses (Please Tick '√')			
1. Buildings are designed to be:	Air Tight ☐	Average Tight ☐	Air Loose ☐
2. Measures that are **<u>normally used in your design</u>** to reduce air leakage in single-family houses:			**Please Tick '√'**
a. Air barrier are installed in walls and roofs			☐
b. Weather-stripping is used in windows and doors			☐
c. Caulking and gaskets are used in windows and doors			☐
d. None is used			☐
Lighting Requirements in single-family houses			**Please Tick '√'**
3. Lighting sources that are **<u>normally used</u>** :			
a. Fluorescent lamps			☐
b. Incandescent lamps			☐
c. Energy efficient lamps			☐
4. Lighting Power Density (LPD) used for residential buildings is = ………..W/m^2			

Please add any additional information about **<u>your building envelope design practice</u>** that you think is important:

APPENDIX B: Thermal Characteristics of Developed Wall and Roof Designs

Table A.1 Thermal Characteristics of Common Building Materials Used in Envelope Design of Residential Buildings in Saudi Arabia

Building Material	Conductivity, k (W/m.°C)	Heat Capacity (J/m^2.°C)	Density (kg/m^3)	Reference
Rock Wool	0.0461	834	16	**Al-Mujahid, 1996**
Expanded Polystyrene	0.036	1210	20	**Said et al., 1997**
Polyurethane	0.023	1590	32	**Al-Mujahid, 1996**
Extruded Polystyrene	0.029	1213	35	**Al-Sanea, 2002**
200 mm Hollow CMU Block	1.389	840	1984	**RI/KFUPM, 1990**
200 mm Hollow Clay Bricks	0.65	840	1419	**RI/KFUPM, 1989**
245 mm Siprox Block	0.383	840	633	**RI/KFUPM, 1994**
100 mm Hollow CMU Block	0.96	840	2324	**RI/KFUPM, 1990**
100 mm Hollow Clay Bricks	0.44	840	1634	**RI/KFUPM, 1990**
100 mm Precast Concrete Panel	1.355	840	2245	**RI/KFUPM, 1994**
Fiber Glass	0.035	1210	32	**Said et al., 1997**
Reinforced Concrete Slab	1.803	840	2243	
200 mm CMU Hourdi Slab	1.092	840	2303	**RI/KFUPM, 1990**
200 mm Clay Hourdi Slab	0.603	840	1449	**RI/KFUPM, 1990**
200 mm Siporex Hourdi Slab	0.144	840	550	**RI/KFUPM, 1994**
200 mm Precast Hollow Core Slab	1.018	529	1289	**Calculated based on equivalent area**
50 mm Gravel	1.436	1670	881	**Hand. of ASHRAE Fundamental 1997**
4 mm Water Membrane	0.190	1675	1121	**Al-Sanea, 2002**
20 mm Mortar Bed	0.720	840	1858	**Al-Sanea, 2002**
Cement Paving Tiles	1.730	920	2243	**Al-Sanea, 2002**
50 mm Sand Fill	0.330	800	1515	**Al-Sanea, 2002**

Table A.2 Thermal Characteristics of Generic Wall Types in the Design Practices of Residential Buildings in Saudi Arabia

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
Single Leaf Walls								
1	Single Hollow CMU Block	none	cement plaster	cement plaster	3.06	0.33	2	347.14
2	Single Hollow Clay Bricks	none	cement plaster	cement plaster	2.04	0.49	3	252.22
3	Single Siprox Block	none	cement plaster	cement plaster	1.22	0.82	5	144.1
4	Single Hollow CMU Block	50 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.71	1.41	8	347.81
5	Single Hollow CMU Block	75 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.51	1.96	11	348.15
6	Single Hollow CMU Block	100 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.4	2.50	14	348.48
7	Single Hollow CMU Block	50 mm Rock Wool Insulation (internal)	cement plaster	cement plaster	0.71	1.41	8	347.81
8	Single Hollow CMU Block	75 mm Rock Wool Insulation (Internal)	cement plaster	cement plaster	0.51	1.96	11	348.15
9	Single Hollow CMU Block	100 mm Rock Wool Insulation (Internal)	cement plaster	cement plaster	0.4	2.50	14	348.48
10	Single Hollow CMU Block	50 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.58	1.72	10	348.35
11	Single Hollow CMU Block	75 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.42	2.38	14	348.96
12	Single Hollow CMU Block	100 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.32	3.13	18	349.56
13	Single Hollow CMU Block	50 mm Expanded Polysterene (Internal)	cement plaster	cement plaster	0.58	1.72	10	348.35
14	Single Hollow CMU Block	75 mm Expanded Polysterene (Internal)	cement plaster	cement plaster	0.42	2.38	14	348.96
15	Single Hollow CMU Block	100 mm Expanded Polysterene (Internal)	cement plaster	cement plaster	0.32	3.13	18	349.56
16	Single Hollow CMU Block	50 mm Polyurethane (external)	cement plaster	cement plaster	0.4	2.50	14	349.69
17	Single Hollow CMU Block	75 mm Polyurethane	cement	cement	0.28	3.57	20	350.96

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
		(external)	plaster	plaster				
18	Single Hollow CMU Block	100 mm Polyurethane (external)	cement plaster	cement plaster	0.21	4.76	27	352.23
19	Single Hollow CMU Block	50 mm Polyurethane (Internal)	cement plaster	cement plaster	0.4	2.50	14	349.69
20	Single Hollow CMU Block	75 mm Polyurethane (Internal)	cement plaster	cement plaster	0.28	3.57	20	350.96
21	Single Hollow CMU Block	100 mm Polyurethane (Internal)	cement plaster	cement plaster	0.21	4.76	27	352.23
22	Single Hollow CMU Block	50 mm Extruded Polystyrene (external)	cement plaster	cement plaster	0.49	2.04	12	349.26
23	Single Hollow CMU Block	75 mm Extruded Polystyrene (external)	cement plaster	cement plaster	0.34	2.94	17	350.33
24	Single Hollow CMU Block	100 mm Extruded Polystyrene (external)	cement plaster	cement plaster	0.26	3.85	22	351.39
25	Single Hollow CMU Block	50 mm Extruded Polystyrene (Internal)	cement plaster	cement plaster	0.49	2.04	12	349.26
26	Single Hollow CMU Block	75 mm Extruded Polystyrene (Internal)	cement plaster	cement plaster	0.34	2.94	17	350.33
27	Single Hollow CMU Block	100 mm Extruded Polystyrene (Internal)	cement plaster	cement plaster	0.26	3.85	22	351.39
28	Single Hollow Clay Bricks	50 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.63	1.59	9	252.89
29	Single Hollow Clay Bricks	75 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.47	2.13	12	253.23
30	Single Hollow Clay Bricks	100 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.38	2.63	15	253.56
31	Single Hollow Clay Bricks	50 mm Rock Wool Insulation (internal)	cement plaster	cement plaster	0.63	1.59	9	252.89
32	Single Hollow Clay Bricks	75 mm Rock Wool Insulation (Internal)	cement plaster	cement plaster	0.47	2.13	12	253.23
33	Single Hollow Clay Bricks	100 mm Rock Wool Insulation (Internal)	cement plaster	cement plaster	0.38	2.63	15	253.56
34	Single Hollow Clay Bricks	50 mm Expanded Polystyrene (external)	cement plaster	cement plaster	0.53	1.89	11	253.43
35	Single Hollow Clay Bricks	75 mm Expanded	cement	cement	0.39	2.56	15	254.04

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
		Polystyrene (external)	plaster	plaster				
36	Single Hollow Clay Bricks	100 mm Expanded Polystyrene (external)	cement plaster	cement plaster	0.31	3.23	18	254.64
37	Single Hollow Clay Bricks	50 mm Expanded Polystyrene (Internal)	cement plaster	cement plaster	0.53	1.89	11	253.43
38	Single Hollow Clay Bricks	75 mm Expanded Polystyrene (Internal)	cement plaster	cement plaster	0.39	2.56	15	254.04
39	Single Hollow Clay Bricks	100 mm Expanded Polystyrene (Internal)	cement plaster	cement plaster	0.31	3.23	18	254.64
40	Single Hollow Clay Bricks	50 mm Polyurethane (external)	cement plaster	cement plaster	0.38	2.63	15	254.76
41	Single Hollow Clay Bricks	75 mm Polyurethane (external)	cement plaster	cement plaster	0.27	3.70	21	256.04
42	Single Hollow Clay Bricks	100 mm Polyurethane (external)	cement plaster	cement plaster	0.21	4.76	27	257.31
43	Single Hollow Clay Bricks	50 mm Polyurethane (Internal)	cement plaster	cement plaster	0.38	2.63	15	254.76
44	Single Hollow Clay Bricks	75 mm Polyurethane (Internal)	cement plaster	cement plaster	0.27	3.70	21	256.04
45	Single Hollow Clay Bricks	100 mm Polyurethane (Internal)	cement plaster	cement plaster	0.21	4.76	27	257.31
46	Single Hollow Clay Bricks	50 mm Extruded Polystyrene (external)	cement plaster	cement plaster	0.45	2.22	13	254.34
47	Single Hollow Clay Bricks	75 mm Extruded Polystyrene (external)	cement plaster	cement plaster	0.32	3.13	18	255.4
48	Single Hollow Clay Bricks	100 mm Extruded Polystyrene (external)	cement plaster	cement plaster	0.25	4.00	23	256.47
49	Single Hollow Clay Bricks	50 mm Extruded Polystyrene (Internal)	cement plaster	cement plaster	0.45	2.22	13	254.34
50	Single Hollow Clay Bricks	75 mm Extruded Polystyrene (Internal)	cement plaster	cement plaster	0.32	3.13	18	255.4
51	Single Hollow Clay Bricks	100 mm Extruded Polystyrene (Internal)	cement plaster	cement plaster	0.25	4.00	23	256.47

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value (W/m^2.°C)	R-Value (m^2.°C/W)	R-Value (RSI)	Heat Capacity (KJ/m^2.°C)
Double Leaf Walls								
52	Double Hollow CMU Block	none	cement plaster	cement plaster	2.56	0.39	2	404.26
53	Double Hollow Clay Bricks	none	cement plaster	cement plaster	1.57	0.64	4	288.34
54	Double Hollow CMU Block	50 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.68	1.47	8	404.93
55	Double Hollow CMU Block	75 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.5	2.00	11	405.27
56	Double Hollow CMU Block	100 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.39	2.56	15	405.6
57	Double Hollow CMU Block	50 mm Rock Wool Insulation (internal)	cement plaster	cement plaster	0.68	1.47	8	404.93
58	Double Hollow CMU Block	75 mm Rock Wool Insulation (Internal)	cement plaster	cement plaster	0.5	2.00	11	405.27
59	Double Hollow CMU Block	100 mm Rock Wool Insulation (Internal)	cement plaster	cement plaster	0.39	2.56	15	405.6
60	Double Hollow CMU Block	50 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.56	1.79	10	405.47
61	Double Hollow CMU Block	75 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.4	2.50	14	406.08
62	Double Hollow CMU Block	100 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.32	3.13	18	406.68
63	Double Hollow CMU Block	50 mm Expanded Polysterene (Internal)	cement plaster	cement plaster	0.56	1.79	10	405.47
64	Double Hollow CMU Block	75 mm Expanded Polysterene (Internal)	cement plaster	cement plaster	0.4	2.50	14	406.08
65	Double Hollow CMU Block	100 mm Expanded Polysterene (Internal)	cement plaster	cement plaster	0.32	3.13	18	406.68
66	Double Hollow CMU Block	50 mm Polyurethane (external)	cement plaster	cement plaster	0.39	2.56	15	406.81
67	Double Hollow CMU Block	75 mm Polyurethane (external)	cement plaster	cement plaster	0.27	3.70	21	408.08
68	Double Hollow CMU Block	100 mm Polyurethane (external)	cement plaster	cement plaster	0.21	4.76	27	409.35
69	Double Hollow CMU	50 mm Polyurethane	cement	cement	0.39	2.56	15	406.81

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
	Block	(Internal)	plaster	plaster				
70	Double Hollow CMU Block	75 mm Polyurethane (Internal)	cement plaster	cement plaster	0.27	3.70	21	408.08
71	Double Hollow CMU Block	100 mm Polyurethane (Internal)	cement plaster	cement plaster	0.21	4.76	27	409.35
72	Double Hollow CMU Block	50 mm Extruded Polysterene (external)	cement plaster	cement plaster	0.47	2.13	12	407.45
73	Double Hollow CMU Block	75 mm Extruded Polysterene (external)	cement plaster	cement plaster	0.34	2.94	17	407.45
74	Double Hollow CMU Block	100 mm Extruded Polysterene (external)	cement plaster	cement plaster	0.26	3.85	22	408.51
75	Double Hollow CMU Block	50 mm Extruded Polysterene (Internal)	cement plaster	cement plaster	0.47	2.13	12	407.45
76	Double Hollow CMU Block	75 mm Extruded Polysterene (Internal)	cement plaster	cement plaster	0.34	2.94	17	407.45
77	Double Hollow CMU Block	100 mm Extruded Polysterene (Internal)	cement plaster	cement plaster	0.26	3.85	22	408.51
78	Double Hollow Clay Bricks	50 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.58	1.72	10	289.01
79	Double Hollow Clay Bricks	75 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.44	2.27	13	289.35
80	Double Hollow Clay Bricks	100 mm Rock Wool Insulation (external)	cement plaster	cement plaster	0.36	2.78	16	289.68
81	Double Hollow Clay Bricks	50 mm Rock Wool Insulation (internal)	cement plaster	cement plaster	0.58	1.72	10	289.01
82	Double Hollow Clay Bricks	75 mm Rock Wool Insulation (Internal)	cement plaster	cement plaster	0.44	2.27	13	289.35
83	Double Hollow Clay Bricks	100 mm Rock Wool Insulation (Internal)	cement plaster	cement plaster	0.36	2.78	16	289.68
84	Double Hollow Clay Bricks	50 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.49	2.04	12	289.55
85	Double Hollow Clay Bricks	75 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.37	2.70	15	290.16
86	Double Hollow Clay Bricks	100 mm Expanded Polysterene (external)	cement plaster	cement plaster	0.29	3.45	20	290.76
87	Double Hollow Clay	50 mm Expanded	cement	cement	0.49	2.04	12	289.55

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
	Bricks	Polysterene (Internal)	plaster	plaster				
88	Double Hollow Clay Bricks	75 mm Expanded Polysterene (Internal)	cement plaster	cement plaster	0.37	2.70	15	290.16
89	Double Hollow Clay Bricks	100 mm Expanded Polysterene (Internal)	cement plaster	cement plaster	0.29	3.45	20	290.76
90	Double Hollow Clay Bricks	50 mm Polyurethane (external)	cement plaster	cement plaster	0.36	2.78	16	290.89
91	Double Hollow Clay Bricks	75 mm Polyurethane (external)	cement plaster	cement plaster	0.26	3.85	22	292.16
92	Double Hollow Clay Bricks	100 mm Polyurethane (external)	cement plaster	cement plaster	0.2	5.00	28	293.43
93	Double Hollow Clay Bricks	50 mm Polyurethane (Internal)	cement plaster	cement plaster	0.36	2.78	16	290.89
94	Double Hollow Clay Bricks	75 mm Polyurethane (Internal)	cement plaster	cement plaster	0.26	3.85	22	292.16
95	Double Hollow Clay Bricks	100 mm Polyurethane (Internal)	cement plaster	cement plaster	0.2	5.00	28	293.43
96	Double Hollow Clay Bricks	50 mm Extruded Polysterene (external)	cement plaster	cement plaster	0.42	2.38	14	290.46
97	Double Hollow Clay Bricks	75 mm Extruded Polysterene (external)	cement plaster	cement plaster	0.31	3.23	18	291.53
98	Double Hollow Clay Bricks	100 mm Extruded Polysterene (external)	cement plaster	cement plaster	0.24	4.17	24	292.59
99	Double Hollow Clay Bricks	50 mm Extruded Polysterene (Internal)	cement plaster	cement plaster	0.42	2.38	14	290.46
100	Double Hollow Clay Bricks	75 mm Extruded Polysterene (Internal)	cement plaster	cement plaster	0.31	3.23	18	291.53
101	Double Hollow Clay Bricks	100 mm Extruded Polysterene (Internal)	cement plaster	cement plaster	0.24	4.17	24	292.59

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
Cavity Walls								
102	Cavity Hollow CMU Block	50 mm Air Space	cement plaster	cement plaster	1.8	0.56	3	404.26
103	Cavity Hollow CMU Block	50 mm Air Space	cement plaster	cement plaster	1.24	0.81	5	288.34
104	Cavity Hollow CMU Block	50 mm Air Space+ 50 mm Rock Wool Insulation	cement plaster	cement plaster	0.61	1.64	9	404.93
105	Cavity Hollow CMU Block	50 mm Air Space+75 mm Rock Wool Insulation	cement plaster	cement plaster	0.46	2.17	12	405.27
106	Cavity Hollow CMU Block	50 mm Air Space+100 mm Rock Wool Insulation	cement plaster	cement plaster	0.37	2.70	15	405.6
107	Cavity Hollow CMU Block	50 mm Air Space+50 mm Expanded Polysterene	cement plaster	cement plaster	0.51	1.96	11	405.47
108	Cavity Hollow CMU Block	50 mm Air Space+75 mm Expanded Polysterene	cement plaster	cement plaster	0.38	2.63	15	406.08
109	Cavity Hollow CMU Block	50 mm Air Space+100 mm Expanded Polysterene	cement plaster	cement plaster	0.3	3.33	19	406.68
110	Cavity Hollow CMU Block	50 mm Air Space+50 mm Polyurethane	cement plaster	cement plaster	0.37	2.70	15	406.81
111	Cavity Hollow CMU Block	50 mm Air Space+75 mm Polyurethane	cement plaster	cement plaster	0.26	3.85	22	408.08
112	Cavity Hollow CMU Block	50 mm Air Space+100 mm Polyurethane	cement plaster	cement plaster	0.2	5.00	28	409.35
113	Cavity Hollow CMU Block	50 mm Air Space+50 mm Extruded Polysterene	cement plaster	cement plaster	0.44	2.27	13	406.4
114	Cavity Hollow CMU Block	50 mm Air Space+75 mm Extruded Polysterene	cement plaster	cement plaster	0.32	3.13	18	407.45
115	Cavity Hollow CMU Block	50 mm Air Space+100	cement	cement	0.25	4.00	23	408.51

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value (W/m².°C)	R-Value (m².°C/W)	R-Value (RSI)	Heat Capacity (KJ/m².°C)
		mm Extruded Polystyrene	plaster	plaster				
116	Cavity Hollow Clay Bricks	50 mm Air Space+ 50 mm Rock Wool Insulation	cement plaster	cement plaster	0.53	1.89	11	289.01
117	Cavity Hollow Clay Bricks	50 mm Air Space+75 mm Rock Wool Insulation	cement plaster	cement plaster	0.41	2.44	14	289.35
118	Cavity Hollow Clay Bricks	50 mm Air Space+100 mm Rock Wool Insulation	cement plaster	cement plaster	0.34	2.94	17	289.68
119	Cavity Hollow Clay Bricks	50 mm Air Space+50 mm Expanded Polystyrene	cement plaster	cement plaster	0.46	2.17	12	289.55
120	Cavity Hollow Clay Bricks	50 mm Air Space+75 mm Expanded Polystyrene	cement plaster	cement plaster	0.35	2.86	16	290.16
121	Cavity Hollow Clay Bricks	50 mm Air Space+100 mm Expanded Polystyrene	cement plaster	cement plaster	0.28	3.57	20	290.76
122	Cavity Hollow Clay Bricks	50 mm Air Space+50 mm Polyurethane	cement plaster	cement plaster	0.34	2.94	17	290.89
123	Cavity Hollow Clay Bricks	50 mm Air Space+75 mm Polyurethane	cement plaster	cement plaster	0.25	4.00	23	292.16
124	Cavity Hollow Clay Bricks	50 mm Air Space+100 mm Polyurethane	cement plaster	cement plaster	0.19	5.26	30	293.43
125	Cavity Hollow Clay Bricks	50 mm Air Space+50 mm Extruded Polystyrene	cement plaster	cement plaster	0.4	2.50	14	290.46
126	Cavity Hollow Clay Bricks	50 mm Air Space+75 mm Extruded Polystyrene	cement plaster	cement plaster	0.29	3.45	20	291.53
127	Cavity Hollow Clay Bricks	50 mm Air Space+100 mm Extruded Polystyrene	cement plaster	cement plaster	0.24	4.17	24	292.59

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
Sandwich Wall								
128	Sandwich Hollow CMU Block	50 mm Rock Wool Insulation	cement plaster	cement plaster	0.68	1.47	8	404.93
129	Sandwich Hollow CMU Block	75 mm Rock Wool Insulation	cement plaster	cement plaster	0.5	2.00	11	405.27
130	Sandwich Hollow CMU Block	100 mm Rock Wool Insulation	cement plaster	cement plaster	0.39	2.56	15	405.6
131	Sandwich Hollow CMU Block	50 mm Expanded Polysterene	cement plaster	cement plaster	0.56	1.79	10	405.47
132	Sandwich Hollow CMU Block	75 mm Expanded Polysterene	cement plaster	cement plaster	0.4	2.50	14	406.08
133	Sandwich Hollow CMU Block	100 mm Expanded Polysterene	cement plaster	cement plaster	0.32	3.13	18	406.68
134	Sandwich Hollow CMU Block	50 mm Polyurethane	cement plaster	cement plaster	0.39	2.56	15	406.81
135	Sandwich Hollow CMU Block	75 mm Polyurethane	cement plaster	cement plaster	0.27	3.70	21	408.08
136	Sandwich Hollow CMU Block	100 mm Polyurethane	cement plaster	cement plaster	0.21	4.76	27	409.35
137	Sandwich Hollow CMU Block	50 mm Extruded Polysterene	cement plaster	cement plaster	0.47	2.13	12	406.39
138	Sandwich Hollow CMU Block	75 mm Extruded Polysterene	cement plaster	cement plaster	0.34	2.94	17	407.45
139	Sandwich Hollow CMU Block	100 mm Extruded Polysterene	cement plaster	cement plaster	0.26	3.85	22	408.51
140	Sandwich Hollow Clay Bricks	50 mm Rock Wool Insulation	cement plaster	cement plaster	0.58	1.72	10	289.01
141	Sandwich Hollow Clay Bricks	75 mm Rock Wool Insulation	cement plaster	cement plaster	0.44	2.27	13	289.35
142	Sandwich Hollow Clay Bricks	100 mm Rock Wool Insulation	cement plaster	cement plaster	0.36	2.78	16	289.68
143	Sandwich Hollow Clay Bricks	50 mm Expanded Polysterene	cement plaster	cement plaster	0.49	2.04	12	289.55
144	Sandwich Hollow Clay Bricks	75 mm Expanded Polysterene	cement plaster	cement plaster	0.37	2.70	15	290.16
145	Sandwich Hollow Clay	100 mm Expanded	cement	cement	0.29	3.45	20	290.76

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
	Bricks	Polystere	plaster	plaster				
146	Sandwich Hollow Clay Bricks	50 mm Polyurethane	cement plaster	cement plaster	0.36	2.78	16	290.89
147	Sandwich Hollow Clay Bricks	75 mm Polyurethane	cement plaster	cement plaster	0.26	3.85	22	292.16
148	Sandwich Hollow Clay Bricks	100 mm Polyurethane	cement plaster	cement plaster	0.2	5.00	28	293.43
149	Sandwich Hollow Clay Bricks	50 mm Extruded Polystere	cement plaster	cement plaster	0.42	2.38	14	290.46
150	Sandwich Hollow Clay Bricks	75 mm Extruded Polystere	cement plaster	cement plaster	0.31	3.23	18	291.53
151	Sandwich Hollow Clay Bricks	100 mm Extruded Polystere	cement plaster	cement plaster	0.24	4.17	24	292.59
152	Sandwich 25 mm Rock Wool Insulation	Single Hollow CMU Block	cement plaster	cement plaster	0.71	1.41	8	348.4
153	Sandwich 50 mm Rock Wool Insulation	Single Hollow CMU Block	cement plaster	cement plaster	0.4	2.50	14	347.81
154	Sandwich 25 mm Expanded Polystere	Single Hollow CMU Block	cement plaster	cement plaster	0.58	1.72	10	348.35
155	Sandwich 50 mm Expanded Polystere	Single Hollow CMU Block	cement plaster	cement plaster	0.32	3.13	18	349.56
156	Sandwich 25 mm Polyurethane	Single Hollow CMU Block	cement plaster	cement plaster	0.4	2.50	14	349.69
157	Sandwich 50 mm Polyurethane	Single Hollow CMU Block	cement plaster	cement plaster	0.21	4.76	27	352.23
158	Sandwich 25 mm Extruded Polystere	Single Hollow CMU Block	cement plaster	cement plaster	0.49	2.04	12	349.26
159	Sandwich 50 mm Extruded Polystere	Single Hollow CMU Block	cement plaster	cement plaster	0.26	3.85	22	351.39
160	Sandwich 25 mm Rock Wool Insulation	Single Hollow Clay Brick	cement plaster	cement plaster	0.63	1.59	9	252.89
161	Sandwich 50 mm Rock Wool Insulation	Single Hollow Clay Brick	cement plaster	cement plaster	0.38	2.63	15	253.56
162	Sandwich 25 mm Expanded Polystere	Single Hollow Clay Brick	cement plaster	cement plaster	0.53	1.89	11	253.43
163	Sandwich 50 mm	Single Hollow Clay	cement	cement	0.31	3.23	18	254.64

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value ($W/m^2.°C$)	R-Value ($m^2.°C/W$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
	Expanded Polysterene	Brick	plaster	plaster				
164	Sandwich 25 mm Polyurethane	Single Hollow Clay Brick	cement plaster	cement plaster	0.38	2.63	15	254.76
165	Sandwich 50 mm Polyurethane	Single Hollow Clay Brick	cement plaster	cement plaster	0.21	4.76	27	257.31
166	Sandwich 25 mm Extruded Polysterene	Single Hollow Clay Brick	cement plaster	cement plaster	0.45	2.22	13	254.34
167	Sandwich 50 mm Extruded Polysterene	Single Hollow Clay Brick	cement plaster	cement plaster	0.25	4.00	23	256.47
168	Sandwich Precast Concrete (100mm)	50 mm Rock Wool Insulation	cement plaster	cement plaster	0.71	1.41	8	391.66
169	Sandwich Precast Concrete (100mm)	75 mm Rock Wool Insulation	cement plaster	cement plaster	0.51	1.96	11	392
170	Sandwich Precast Concrete (100mm)	100 mm Rock Wool Insulation	cement plaster	cement plaster	0.4	2.50	14	392.33
171	Sandwich Precast Concrete (100mm)	50 mm Expanded Polysterene	cement plaster	cement plaster	0.58	1.72	10	392.2
172	Sandwich Precast Concrete (100mm)	75 mm Expanded Polysterene	cement plaster	cement plaster	0.42	2.38	14	392.81
173	Sandwich Precast Concrete (100mm)	100 mm Expanded Polysterene	cement plaster	cement plaster	0.32	3.13	18	393.41
174	Sandwich Precast Concrete (100mm)	50 mm Polyurethane	cement plaster	cement plaster	0.4	2.50	14	393.53
175	Sandwich Precast Concrete (100mm)	75 mm Polyurethane	cement plaster	cement plaster	0.28	3.57	20	394.81
176	Sandwich Precast Concrete (100mm)	100 mm Polyurethane	cement plaster	cement plaster	0.21	4.76	27	396.08
177	Sandwich Precast Concrete (50mm)	50 mm Expanded Polysterene	cement plaster	cement plaster	0.61	1.64	9	203.62
178	Sandwich Precast Concrete (50mm)	75 mm Expanded Polysterene	cement plaster	cement plaster	0.43	2.33	13	204.22
179	Sandwich Precast Concrete (50mm)	100 mm Expanded Polysterene	cement plaster	cement plaster	0.33	3.03	17	204.83
180	Sandwich Precast Concrete (50mm)	50 mm Polyurethane	cement plaster	cement plaster	0.41	2.44	14	204.95
181	Sandwich Precast	75 mm Polyurethane	cement	cement	0.28	3.57	20	206.22

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value (W/m^2.°C)	R-Value (m^2.°C/W)	R-Value (RSI)	Heat Capacity (KJ/m^2.°C)
	Concrete (50mm)		plaster	plaster				
182	Sandwich Precast Concrete (50mm)	100 mm Polyurethane	cement plaster	cement plaster	0.22	4.55	26	207.5
183	Sandwich 50 mm Expanded Polysterene	Sandwich Precast Concrete (100mm)	cement plaster	cement plaster	0.33	3.03	17	110.54
184	Sandwich 75 mm Expanded Polysterene	Sandwich Precast Concrete (100mm)	cement plaster	cement plaster	0.23	4.35	25	110.75
185	Sandwich 50 mm Polyurethane	Sandwich Precast Concrete (100mm)	cement plaster	cement plaster	0.23	4.35	25	113.2
186	Sandwich 75 mm Polyurethane	Sandwich Precast Concrete (100mm)	cement plaster	cement plaster	0.15	6.67	38	115.75
187	Sandwich 50 mm Expanded Polysterene	Sandwich Precast Concrete (50mm)	cement plaster	cement plaster	0.33	3.03	17	204.83
188	Sandwich 75 mm Expanded Polysterene	Sandwich Precast Concrete (50mm)	cement plaster	cement plaster	0.23	4.35	25	206.04
189	Sandwich 50 mm Polyurethane	Sandwich Precast Concrete (50mm)	cement plaster	cement plaster	0.22	4.55	26	207.5
190	Sandwich 75 mm Polyurethane	Sandwich Precast Concrete (50mm)	cement plaster	cement plaster	0.15	6.67	38	210.04
191	Sandwich Siporex Panel (50mm)	50 mm Expanded Polysterene	cement plaster	cement plaster	0.44	2.27	13	61.24
192	Sandwich Siporex Panel (50mm)	75 mm Expanded Polysterene	cement plaster	cement plaster	0.34	2.94	17	61.84
193	Sandwich Siporex Panel (50mm)	100 mm Expanded Polysterene	cement plaster	cement plaster	0.23	4.35	25	64.27
194	Sandwich Siporex Panel (50mm)	50 mm Polyurethane	cement plaster	cement plaster	0.33	3.03	17	62.57
195	Sandwich Siporex Panel (50mm)	75 mm Polyurethane	cement plaster	cement plaster	0.24	4.17	24	63.84
196	Sandwich Siporex Panel (50mm)	100 mm Polyurethane	cement plaster	cement plaster	0.19	5.26	30	65.11
197	Sandwich 50 mm Expanded Polysterene	Sandwich Siporex Panel (50mm)	cement plaster	cement plaster	0.3	3.33	19	39.35
198	Sandwich 75 mm Expanded Polysterene	Sandwich Siporex Panel (50mm)	cement plaster	cement plaster	0.21	4.76	27	40.56
199	Sandwich 100 mm	Sandwich Siporex	cement	cement	0.16	6.25	36	41.77

Wall No.	Main Building Material	Insulation	Exterior Finish	Interior Finish	U-Value (W/m^2.°C)	R-Value (m^2.°C/W)	R-Value (RSI)	Heat Capacity (KJ/m^2.°C)
	Expanded Polysterene	Panel (50mm)	plaster	plaster				
200	Sandwich 50 mm Polyurethane	Sandwich Siporex Panel (50mm)	cement plaster	cement plaster	0.2	5.00	28	42
201	Sandwich 75 mm Polyurethane	Sandwich Siporex Panel (50mm)	cement plaster	cement plaster	0.14	7.14	41	44.56
202	Sandwich 100 mm Polyurethane	Sandwich Siporex Panel (50mm)	cement plaster	cement plaster	0.11	9.09	52	47.1

Table A.3 Thermal Characteristics of Generic Roof Types in the Design Practices of Residential Buildings in Saudi Arabia

Roof No.	Main Building Material	Insulation	Roof Components	U-Value (W/m^2.°C)	R-Value (W/m^2.°C)	R-Value (RSI)	Heat Capacity (KJ/m^2.°C)
Reinforced Concrete Slab							
1	200 mm RC Slab	none	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	1.57	0.64	4	745
2	200 mm RC Slab	50 mm Gravel	Built up Roof (Gravel+Waterproofing Membrane+Plain Concrete Screed)	1.51	0.66	4	787
3	200 mm RC Slab	100 mm Light Weight Concrete	Built up Roof (Tilesl+Waterproofing Membrane+LWC Concrete Screed)	0.61	1.64	9	667
4	200 mm RC Slab	50 mm Fiber Glass (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.48	2.08	12	747
5	200 mm RC Slab	75 mm Fiber Glass (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.36	2.78	16	748
6	200 mm RC Slab	100 mm Fiber Glass (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.29	3.45	20	749
7	200 mm RC Slab	50 mm Fiber Glass (internal)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.48	2.08	12	747
8	200 mm RC Slab	75 mm Fiber Glass (internal)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.36	2.78	16	748
9	200 mm RC Slab	100 mm Fiber Glass (internal)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.29	3.45	20	749
10	200 mm RC Slab	50 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.49	2.04	12	746
11	200 mm RC Slab	75 mm Expanded	Built up Roof (Tiles+Waterproofing	0.37	2.70	15	747

Roof No.	Main Building Material	Insulation	Roof Components	U-Value ($W/m^2.°C$)	R-Value ($W/m^2.°C$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
		Polystyrene (external)	Membrane+ Plain Concrete Screed)				
12	200 mm RC Slab	100 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.29	3.45	20	747
13	200 mm RC Slab	50 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.36	2.78	16	747
14	200 mm RC Slab	75 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.26	3.85	22	749
15	200 mm RC Slab	100 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.2	5.00	28	750
16	200 mm RC Slab	50 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.42	2.38	14	747
17	200 mm RC Slab	75 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.31	3.23	18	748
18	200 mm RC Slab	100 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	0.24	4.17	24	749
CMU Hourdi Block Slab							
19	200 mm CMU Hourdi Slab	none	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	1.4	0.71	4	708
20	200 mm CMU Hourdi Slab	500 mm False Ceiling	Built up Roof (Tiles+Waterproofing Membrane+ Plain Concrete Screed)	1.06	0.94	5	692
21	200 mm CMU Hourdi Slab	50 mm Gravel	Built up Roof (Gravel+Waterproofing Membrane+Plain Concrete Screed)	1.36	0.74	4	750
22	200 mm CMU Hourdi Slab	100 mm Light Weight Concrete	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.59	1.69	10	630
23	200 mm CMU Hourdi Slab	50 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.32	3.13	18	631
24	200 mm CMU Hourdi Slab	75 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.26	3.85	22	631
25	200 mm CMU Hourdi Slab	100 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.22	4.55	26	632
26	200 mm CMU Hourdi Slab	50 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.26	3.85	22	632
27	200 mm CMU Hourdi Slab	75 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.2	5.00	28	632
28	200 mm CMU Hourdi Slab	100 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.17	5.88	33	635

Roof No.	Main Building Material	Insulation	Roof Components	U-Value ($W/m^2.°C$)	R-Value ($W/m^2.°C$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
Clay Hourdi Block Slab							
29	200 mm Clay Hourdi Slab	none	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	1.16	0.86	5	565
30	200 mm Clay Hourdi Slab	100 mm Light Weight Concrete	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.54	1.85	11	487
31	200 mm Clay Hourdi Slab	50 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.31	3.23	18	488
32	200 mm Clay Hourdi Slab	75 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.25	4.00	23	489
33	200 mm Clay Hourdi Slab	100 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.22	4.55	26	489
34	200 mm Clay Hourdi Slab	50 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.35	2.86	16	566
35	200 mm Clay Hourdi Slab	75 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.24	4.17	24	569
36	200 mm Clay Hourdi Slab	100 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.19	5.26	30	570
37	200 mm Clay Hourdi Slab	50 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.39	2.56	15	567
38	200 mm Clay Hourdi Slab	75 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.29	3.45	20	568
39	200 mm Clay Hourdi Slab	100 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.23	4.35	25	569
Siporex Hourdi Block Slab							
40	200 mm Siporex Hourdi Slab	none	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.52	1.92	11	414
41	200 mm Sip. Hourdi Slab	500 mm False Ceiling	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.46	2.17	12	399
42	200 mm Sip. Hourdi Slab	50 mm Gravel	Built up Roof (Gravel+Waterproofing Membrane+Plain Concrete Screed)	0.51	1.96	11	456
43	200 mm Sip. Hourdi Slab	100 mm Light Weight Concrete	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.34	2.94	17	336
44	200 mm Sip. Hourdi Slab	50 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.23	4.35	25	337
45	200 mm Sip.	75 mm Expanded	Built up Roof (Tiles+Waterproofing	0.2	5.00	28	338

Roof No.	Main Building Material	Insulation	Roof Components	U-Value ($W/m^2.°C$)	R-Value ($W/m^2.°C$)	R-Value (RSI)	Heat Capacity ($KJ/m^2.°C$)
	Hourdi Slab	Polysterene (external)	Membrane+LWC Concrete Screed)				
46	200 mm Sip. Hourdi Slab	100 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.18	5.56	32	338
47	200 mm Sip. Hourdi Slab	50 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.2	5.00	28	338
48	200 mm Sip. Hourdi Slab	75 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.16	6.25	36	340
49	200 mm Sip. Hourdi Slab	100 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+LWC Concrete Screed)	0.14	7.14	41	341
50	200 mm Sip. Hourdi Slab	50 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.27	3.70	21	416
51	200 mm Sip. Hourdi Slab	75 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.22	4.55	26	417
52	200 mm Sip. Hourdi Slab	100 mm Extruded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.14	7.14	41	418
Precast Hollow Core Slab							
53	200 mm Precast Hollow Core Slab	none	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	1.38	0.72	4	458
54	200 mm Precast Hollow Core Slab	500 mm False Ceiling	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	1.04	0.96	5	443
55	200 mm Precast Hollow Core Slab	50 mm Gravel	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	1.33	0.75	4	499
56	200 mm Precast Hollow Core Slab	100 mm Light Weight Concrete	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.58	1.72	10	380
57	200 mm Precast Hollow Core Slab	50 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.47	2.13	12	459
58	200 mm Precast Hollow Core Slab	75 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.36	2.78	16	460
59	200 mm Precast Hollow Core Slab	100 mm Expanded Polysterene (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.29	3.45	20	460
60	200 mm Precast Hollow Core Slab	50 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.34	2.94	17	460
61	200 mm Precast Hollow Core Slab	75 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.25	4.00	23	462
62	200 mm Precast Hollow Core Slab	100 mm Polyurethane (external)	Built up Roof (Tiles+Waterproofing Membrane+Plain Concrete Screed)	0.2	5.00	28	463

APPENDIX C: Entered Ventilation Strategies in VisualDOE in Dhahran

Table C.1 Entered Values in VisualDOE for Combined Ventilation Strategy in Transition Months for a Window Less R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Naturally Ventilated Buildings

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*2 ACH 08:00-18:00, 0.5 ACH 19:00-07:00*	*3 ACH 16:00-9:00, 0.5 ACH 10:00-15:00*	*15 ACH 20:00-6:00, 0.5 ACH 7:00-19:00*	*30 ACH 20:00-6:00, 0.5 ACH 7:00-19:00*	*3 ACH 07:00-18:00, 0.5 ACH 19:00-06:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

Table C.2 Entered Values in VisualDOE for Combined Ventilation Strategy in Transition Months for a Window Less R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Mechanically Operated Buildings

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*2 ACH 08:00-18:00, 0.5 ACH 19:00-07:00*	*5 ACH 16:00-9:00, 0.5 ACH 10:00-15:00*	*0.5 ACH (24 h)*	*0.5 ACH (24 h)*	*3 ACH 07:00-18:00, 0.5 ACH 19:00-06:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

Table C.3 Entered Values in VisualDOE for Combined Ventilation Strategy in Transition Months for a 10 % window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Naturally Ventilated Buildings

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*5 ACH 08:00-18:00, 0.5 ACH 19:00-7:00*	*20 ACH 16:00-9:00, 0.5 ACH 10:00-15:00*	*20 ACH 20:00-6:00, 0.5 ACH 7:00-19:00*	*20 ACH 20:00-6:00, 0.5 ACH 7:00-19:00*	*6 ACH 07:00-18:00, 0.5 ACH 19:00-6:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

Table C.4 Entered Values in VisualDOE for Combined Ventilation Strategy in Transition Months for a 10 % window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Mechanically Operated Buildings

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*10 ACH 08:00-18:00, 0.5 ACH 19:00-07:00*	*20 ACH 16:00-9:00, 0.5 ACH 10:00-15:00*	*0.5 ACH (24 h)*	*0.5 ACH (24 h)*	*6 ACH 07:00-18:00, 0.5 ACH 19:00-6:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

Table C.5 Entered Values in VisualDOE for Combined Ventilation Strategy in Winter Months for a 10 % Window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Naturally Ventilated Buildings

Month / Design Alternative	December	February
Design #1: W#1, R#1 (Base Case)	*0.50 ACH (24 h)*	*0.50 ACH (24 h)*
Design #4: W#1, R#7		
Design #6:W#2, R#5		
Design #7:W#3, R#1		
Design #9:W#3, R#7	*1 ACH 7:00-18:00, 0.50 ACH 19:00-6:00*	*0.50 ACH (24 h)*
Design #10:W#4, R#1		
Design #13:W#5, R#3		*1 ACH 8:00-18:00, 0.5 ACH 19:00-7:00*
Design #15:W#5, R#7		

Table C.6 Entered Values in VisualDOE for Combined Ventilation Strategy in Winter Months for a 10 % Window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Mechanically Operated Buildings

Month / Design Alternative	December	February
Design #1: W#1, R#1 (Base Case)	*0.50 ACH (24 h)*	*0.50 ACH (24 h)*
Design #4: W#1, R#7		
Design #6:W#2, R#5		
Design #7:W#3, R#1		
Design #9:W#3, R#7	*1 ACH 7:00-18:00, 0.50 ACH 19:00-6:00*	*1 ACH 7:00-18:00, 0.50 ACH 19:00-6:00*
Design #10:W#4, R#1		
Design #13:W#5, R#3		
Design #15:W#5, R#7		

Table C.7 Entered Values in VisualDOE for Combined Ventilation Strategy in Transition Months for a 20 % Window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Naturally Ventilated Buildings

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*10 ACH 08:00-18:00, 0.5 ACH 19:00-07:00*	**Single Glazing:** *10 ACH 16:00-9:00,* ***Double Glazing:*** *20 ACH 16:00-9:00, 0.5 ACH 10:00-15:00*	*30 ACH 20:00-6:00, 0.5 ACH 7:00-19:00*	*30 ACH 20:00-6:00, 0.5 ACH 7:00-19:00*	*10 ACH 07:00-18:00, 0.5 ACH 19:00-06:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3		*20 ACH 16:00-9:00, 0.5 ACH 10:00-15:00*			
Design #15:W#5, R#7					

Table C.8 Entered Values in VisualDOE for Combined Ventilation Strategy in Transition Months for a 20 % Window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Mechanically Operated Buildings

Month / Design Alternative	March	April	May	October	November
Design #1: W#1, R#1 (Base Case)	*10 ACH 08:00-18:00, 0.5 ACH 19:00-07:00*	*20 ACH 16:00-9:00, 0.5 ACH 10:00-15:00*	*0.5 ACH (24 h)*	*0.5 ACH (24 h)*	*20 ACH 07:00-18:00, 0.5 ACH 19:00-06:00*
Design #4: W#1, R#7					
Design #6:W#2, R#5					
Design #7:W#3, R#1					
Design #9:W#3, R#7					
Design #10:W#4, R#1					
Design #13:W#5, R#3					
Design #15:W#5, R#7					

Table C.9 Entered Values in VisualDOE for Combined Ventilation Strategy in Winter Months for a 20 % Window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Naturally Ventilated Buildings

<table>
<tr><th>Month / Design Alternative</th><th>December</th><th>January</th><th>February</th></tr>
<tr><td>Design #1: W#1, R#1 (Base Case)</td><td rowspan="2">Single Glazing:
4 ACH 08:00-17:00,
0.5 ACH 18:00-07:00
Double Glazing: 0. 5 ACH(24 h)</td><td rowspan="2">0.50 ACH (24 h)</td><td rowspan="2">0.50 ACH (24 h)</td></tr>
<tr><td>Design #4: W#1, R#7</td></tr>
<tr><td>Design #6:W#2, R#5</td><td rowspan="6">4 ACH 07:00-18:00,
0.5 ACH 19:00-06:00</td><td rowspan="3">0.50 ACH (24 h)</td><td rowspan="6">4 ACH 08:00-18:00,
0.5 ACH 19:00-07:00</td></tr>
<tr><td>Design #7:W#3, R#1</td></tr>
<tr><td>Design #9:W#3, R#7</td></tr>
<tr><td>Design #10:W#4, R#1</td><td>Single Glazing:
2 ACH 08:00-18:00,
0.5 ACH 19:00-07:00
Double Glazing: 0.5 ACH(24 h)</td></tr>
<tr><td>Design #13:W#5, R#3</td><td rowspan="2">2 ACH 08:00-18:00, 0.50 ACH 19:00-07:00</td></tr>
<tr><td>Design #15:W#5, R#7</td></tr>
</table>

Table C.10 Entered Values in VisualDOE for Combined Ventilation Strategy in Winter Months for a 20 % Window R.B. in Dhahran Based on ASHRAE Thermal Comfort Criteria for Mechanically Operated Buildings

<table>
<tr><th>Month / Design Alternative</th><th>December</th><th>January</th><th>February</th></tr>
<tr><td>Design #1: W#1, R#1 (Base Case)</td><td rowspan="2">Single Glazing:
4 ACH 08:00-17:00,
0.5 ACH 18:00-07:00
Double Glazing: 0. 5 ACH(24 h)</td><td rowspan="2">0.50 ACH (24 h)</td><td rowspan="2">Single Glazing:
4 ACH 08:00-18:00,
0.50 ACH 19:00-07:00
Double Glazing: 0.5 ACH (24h)</td></tr>
<tr><td>Design #4: W#1, R#7</td></tr>
<tr><td>Design #6:W#2, R#5</td><td rowspan="6">4 ACH 07:00-18:00,
0.5 ACH 19:00-06:00</td><td rowspan="4">0.50 ACH (24 h)</td><td rowspan="6">4 ACH 08:00-18:00,
0.5 ACH 19:00-07:00</td></tr>
<tr><td>Design #7:W#3, R#1</td></tr>
<tr><td>Design #9:W#3, R#7</td></tr>
<tr><td>Design #10:W#4, R#1</td></tr>
<tr><td>Design #13:W#5, R#3</td><td rowspan="2">2 ACH 08:00-18:00, 0.50 ACH 19:00-07:00</td></tr>
<tr><td>Design #15:W#5, R#7</td></tr>
</table>

VITAE

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Professional Experience Saleh worked in Petroleum Development Oman (PDO) in different engineering departments for 5.1/2 years. Then he joined KFUPM as a Research Assistant in Architectural Engineering Department for 2.1/2 years. He is currently working as a **M**echanical, **E**lectrical and **P**lumbing (**MEP**) Coordinator in SAAD Health Science Center in AlKhobar.