RESIDENTIAL HOUSE WALL THERMAL PERFORMANCE

A thesis submitted in accordance with the regulations for the degree of Doctor of Philosophy

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DECLARATION OF ORIGINALITY

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any other degree at RMIT or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at RMIT or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

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Fayez Gurmallh Aldawi

Date: 30 September 2014

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NOMENCLATURE

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h_{i}	Convective heat transfer coefficient inside (W/m^2.°C)
h_{out}	Convective heat transfer coefficient outside (W/m^2.°C)
h_{total}	Total convective heat transfer coefficient (W/m^2.°C)
x	Thickness of wall material(m)
x_{total}	Total wall thickness (m)
$T_{wall.\ in}$	Surface wall temperature inside (°C)
$T_{wall.\ out}$	Surface wall temperature outside (°C)
$T_{air.\ in}$	Air temperature inside (°C)
$T_{air.\ out}$	Air temperature outside (°C)
A	Wall surface area (m^2)
K	Material thermal conductivity (W/m.°C)
K_{total}	Total material thermal conductivity (W/m.°C)
Q	Rate of heat transfer (W/m^2)
$Q_{gain/loss}$	Heat transfer rate gain or loss (W/m^2)
Q_{total}	Total heat transfer rate by convection & conduction (W/m^2)
$Q_{rad.}$	Total heat transfer rate by radiation (W/m^2)
σ	Stefan-Boltzmann constant (5.6703×10^{-8})
R	Thermal resistance of material (°C/W)
R_{total}	Total thermal resistance of materials (°C/W)
β	Coefficient of volume expansion (K^{-1})
g	Gravity acceleration (m/s^2)
δ	Characteristic length of wall geometry (m)
U	Overall heat transfer coefficient (W/m^2. °C)
ν	Kinematic viscosity of the air (m/s^2)
Pr	Prandtl number

Ra_{in}	Rayleigh number inside house
Ra_{out}	Rayleigh number outside house
Nu_{in}	Nusselt number inside house
Nu_{out}	Nusselt number outside house
ε	Emissivity of the material
T_{out}	Hourly main temperature (°C)
T_{base}	Temperature inside house, human comfort (°C)
$Q_{sensible}$	Absorbs heat during a temperature change (KJ)
Q_{latent}	Heat exchanged during melting ice (KJ)
M_{ice}	Mass of ice(kg)
$Q_{model\ avg.}$	Average rate of heat transfer for scale model (W/m^2)
$Q_{new\ wall\ avg.}$	Average rate of heat transfer for new wall (W/m^2)
h_{ice}	Latent heat of melting ice (kJ/kg)
T_{film}	Arithmetic average of the air inner surface and outer temperature (°C)

LIST OF ABBREVIATIONS AND ACRONYMS

AGO	Australian Greenhouse Office
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	Australian Standard Test Method for Surface Burning Characteristics of Building
BCA	Building Code of Australian
CBD	Central Business District
CDHs	Cooling Degree Hours
CDIAC	Dioxide Information Analysis Center
CFD	Computational Fluid Dynamics
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DCLG	Department for Communities and Local Government
DECC	Department of Environment and Climate Change
DHs	Degree Hours
GHGs	Green House Gases
HDHs	Heating Degree Hours
HVAC	Heating, Ventilation and Air Conditioning
NatHERS	National wide House Energy Rating Scheme
NES-713	Naval Engineering Standards-713
NZBC	New Zealand Building Code
PCMs	Phase Change Materials
RMIT	Royal Melbourne Institute of Technology
TIM	Transparent Insulation Materials
VIP	Vacuum Insulation Panels
ZEH	Zero Energy Homes

ABSTRACT

Rapid urbanisation due to global economic development and population growth necessitate the expansion of cities and towns with new buildings and associated energy requirements. The floor space area and volumetric dimension of modern residential houses are increasing at a constant rate in most developed countries including Australia. Therefore, the energy consumption for ongoing heating and cooling is also increasing. The increasing energy consumption leads to greater greenhouse gas emissions. In household consumption, around 40% of the total energy is used for space heating and cooling. Hence, the reduction of energy use for space heating and cooling is paramount for energy conservation, energy security and reduction of greenhouse gas emissions. A substantial amount of energy required for heating and cooling is lost through the house wall systems. Despite the importance of house wall systems for energy efficiency, little research has been undertaken on energy efficient house wall systems made of combined thermal masses and insulation materials that can be used and adapted for variable climate conditions with minimal design changes and cost. Therefore, the main objective of this research is to undertake a thermal performance study of two house wall systems (one conventional and the other a new design) with single and double glazed windows for variable climate conditions in order to develop an optimal energy efficient house wall system with minimal material modification and cost. Additionally, a thermal performance model for the optimal house wall systems is also to be developed for use in variable climate conditions.

In order to address these research objectives, a comprehensive study using computational modelling, experimental measurements and analytical computation has been undertaken. For this purpose, 15 new house wall systems and a currently used conventional house wall system have been selected and studied. A range of synthetic and natural insulation materials, thermal mass, single and double glazed windows was considered. All house wall systems have been studied for multi-climate conditions, ranging from cool to hot and humid climates. The computational modelling was undertaken using AccuRate software. The experimental measurements were undertaken using a scale model house with variable wall systems made of brick veneer, reinforced concretes, synthetic and natural insulation materials to examine the in-situ thermal behaviour. The analytical computation of thermal performance was undertaken by developing a spread sheet (Excel) based thermal performance model using basic equations and principles of three modes of heat transfer: conduction, convection and radiation. A cost benefit analysis was also undertaken for the optimal new house wall system. Data obtained through computational modelling, experimental measurements and analytical computation were thoroughly analysed and major findings were determined.

The major findings of this research include: a) the development of an optimally designed house wall system that can provide energy savings up to 37% for ongoing heating and cooling compared to currently used conventional house wall systems for variable climate conditions; b) a theoretical thermal performance model that can be used for any climate conditions; c) determination of the optimal position of insulation materials within house wall systems for different climate conditions which allows reducing further ongoing heating and cooling energy; and d) economic viability, fire resistance and environmental sustainability, can be enhanced if natural insulation materials are used in residential house wall systems.

The major practical implications of the research findings are multi-fold. The building communities (consumers, builders, regulatory authorities, policy makers, building materials manufacturing/production industry) can use scientifically proven findings in residential building sector and other relevant sectors. New insulation materials can be used in main stream building construction as detailed data are now available through this research. The building construction method can be more optimised for enhancing further energy savings.

Based on major findings and limitation of this study, some future studies have been identified. These recommendations include: i) undertaking a thermal performance study using a full-scale model house with conventional and new house wall systems; ii) exploring a new concept for the roof system, since a significant portion of heat gain/loss is occurred through the roof; and iii) carrying out investigation on the effects of humidity and dynamic heating/cooling loads.

CHAPTER 1 INTRODUCTION AND LITERATURE REVIEW

1.1 Motivation and Introduction

Rapid urbanisation and population growth necessitate the expansion of cities and towns with new buildings and associated energy needs. The residential sector is a great contributor to greenhouse gas emissions (~ 30%) due to the use of primarily fossil fuel energy (~35-40%) (AGO, 2011; Olivier et al., 2012; Alam et al., 2009; Zhao & Magoules, 2012; Howard et al., 2012).The number of residential houses in Australia is expected to be around 10 million in 2020 compared to 6 million in 1990 (Alam et al., 2009). The floor space area and volumetric dimension of modern residential houses are increasing at a constant rate in most developed countries including Australia (Alam et al., 2010). Figure 1.1 illustrates the increment of living space in residential houses in Australia.

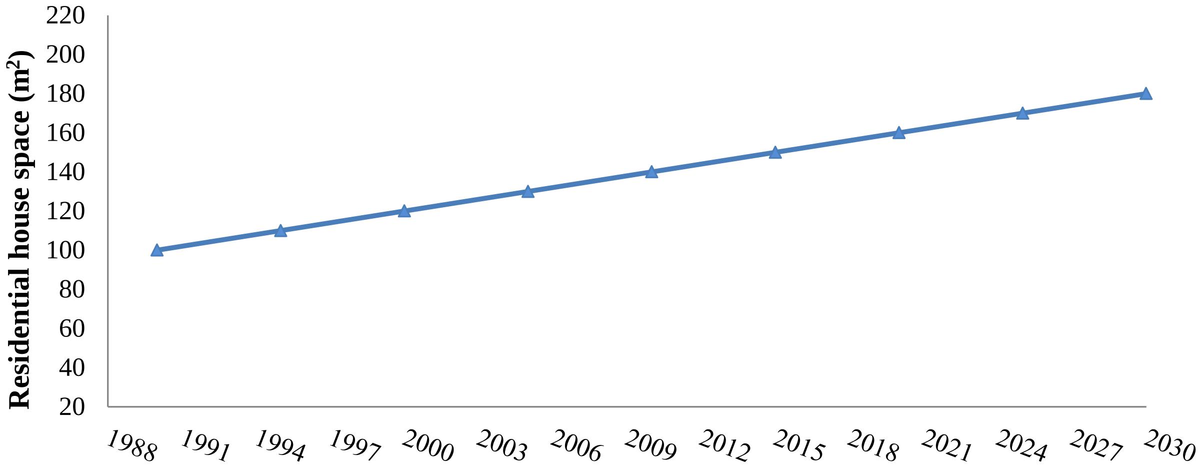


Figure 1.1: Average living space in residential houses in Australia (Alam et al., 2009)

According to a recently published Australian government report, the energy consumption in the residential housing sector will be around 467 PJ in 2020 compared to 299 PJ in 1990, which means that energy demand will increase by over 50%. Figure 1.2 shows a continuous upward energy consumption trend in the Australian housing sector in coming years. The increasing energy consumption leads to greater greenhouse gas emissions (Report on energy use in the Australian residential sector, 2011; Alam et al., 2009; Chowdhury et al., 2010; Mick, 2007).

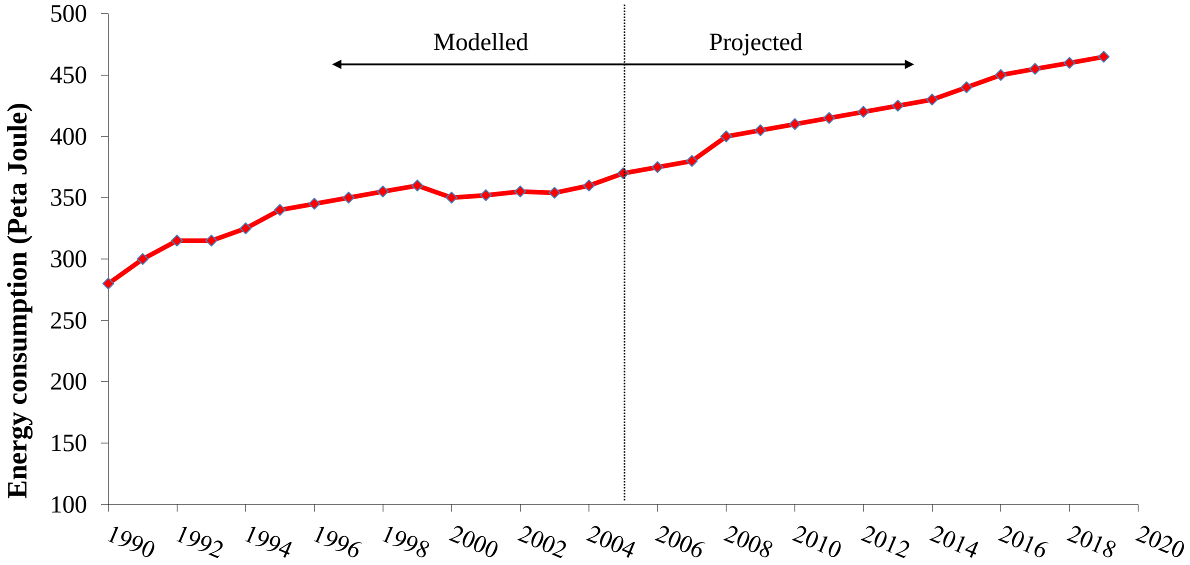


Figure 1.2: Energy consumption in Australian housing sector

Figure 1.3 shows the top three countries (Australia, United States and Canada) generating over 18 tonnes CO_2 emission per capita, which is significantly higher than India and China (CDIAC, 2010). The Australian per capita CO_2 emission has been contributed largely by coal-based power generation and inefficient use of energy in the housing sector, which led to around 15% of greenhouse gas emissions emitted from the Australian residential building sector in 2006 (AGO, 2011). The government of Australia formulated policies and took actions to reduce the growth of energy; however, some technical work still needs to be developed to improve the thermal performance of residential building and decrease energy consumption (Turton, 2004; Tucker et al., 2002; Olivier it al., 2012; Jeong, Lee & Huh, 2010).

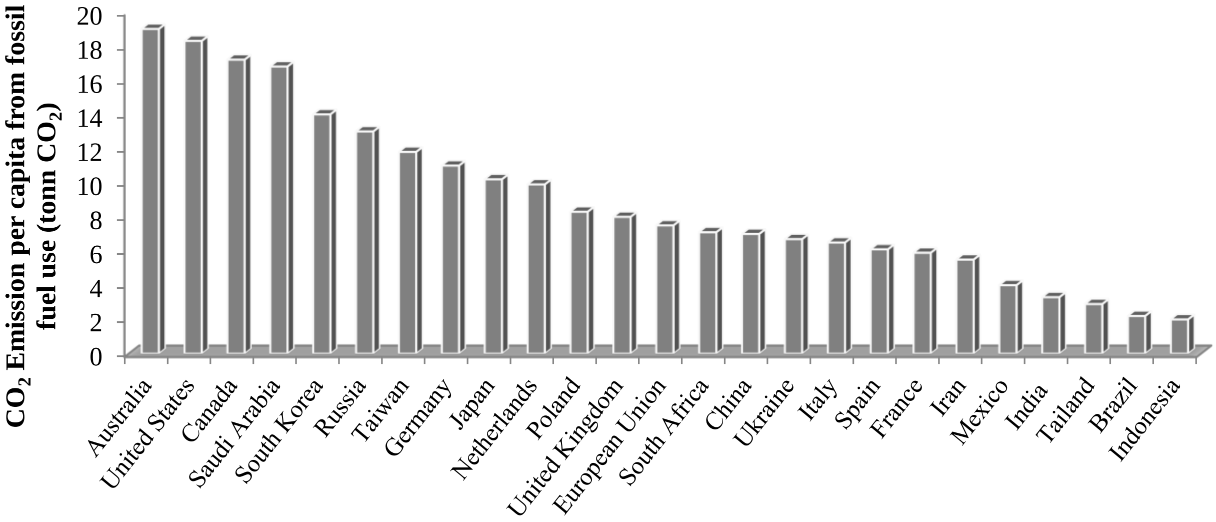


Figure 1.3: Per capita greenhouse gas emission for top 19 countries in 2010,(CDIAC)

Saidur et al. (2007) conducted a study on energy and the associated greenhouse gases (GHGs) from household appliances in Malaysia. The study found that refrigerators-freezers consumed considerable energy, meaning that more fossil fuels were used, thus leading to more emission of GHGs, and this means that cooling and heating systems in households consume considerable energy. With the use of insulation, this energy saving can be realized and thus would lead to less release of GHGs. Kaynakli (2011) presents the effects of hot water consumption through the use of electricity. The data evidenced the emission of carbon oxides extensively. Using electricity to heat or cool buildings will lead to emission of more greenhouse gases and thus insulation of buildings is necessary. According to Kaynakli (2011), building energy consumption accounts for approximately 40% of global energy demands. In Australia, Korea, Turkey and China, each household consumes around 40% of the total energy used for space heating and cooling (Gregory et al., 2008, Chowdhury et al., 2010; Korea Ministry of Environment, 2003; Ekici, Gulten & Aksoy, 2012; Li, et al. 2010; Ma & Wang, 2000). The second highest energy consumption component is for hot water systems, as shown in Figure 1.4.

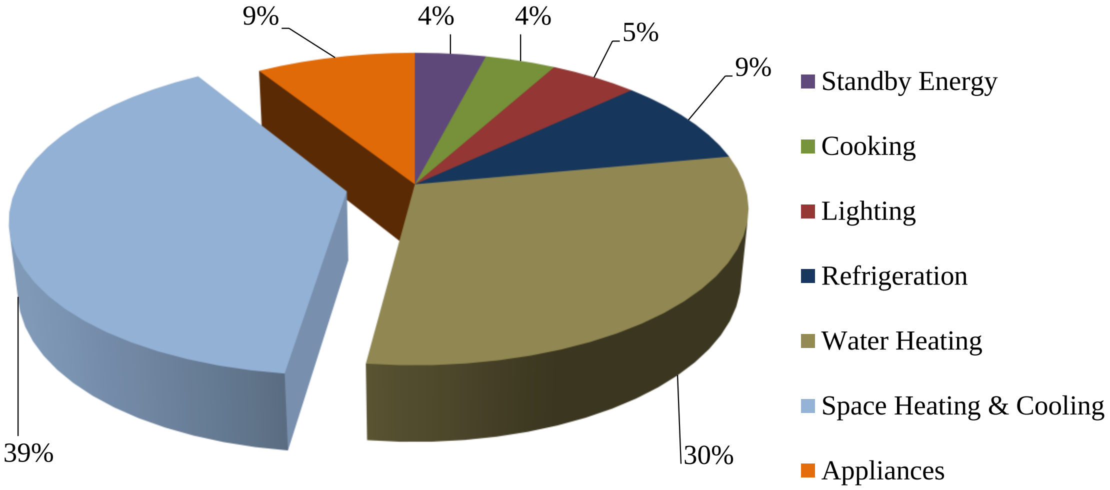


Figure 1.4: Australian household energy usages (Report on energy use in the Australian residential sector, 2011; Aldawi et al., 2013)

The use of insulation materials has increased, both in terms of buildings' insulation and in the minimum values of insulation required by national regulations. Insulation materials are not independent energy production or conservation systems, but part of the complex structural elements which form a building's shell. Optimization of wall thermal performance in buildings is mandatory for cost savings and energy conservation. Thermal insulation is required for the improvement of thermal performance of a building. It is defined by the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) as a material or combination of materials, that, when properly applied, retard the heat flow by conduction, convection, and radiation. Insulation retards heat flow into or out of a building because of its thermal resistance. In addition, insulation in buildings facilitates personal comfort because of excessive heat transferred to the inside of the building due to factors such as time lag, which creates an unpleasant environment. Insulators also reduce temperature fluctuations and variations, prevent corrosions and condensation, provide freezing protection in storage vessels and pipes, and reduce vibrations and noise from the outside. To maintain comfort, heat gained during summer should be taken care of by cooling systems while the heat lost in winter should be replaced by heating systems. There are many insulators that can be used in building insulations. This is by way of selection of effective and efficient thermal insulators. Reducing the energy consumption in buildings is important because of environmental and energy resources concerns (Ozel, 2011; Ekici, Gulten & Aksoy, 2012; Ballarini & Corrado, 2012; Budaiwi & Abdou, 2013; Jelle, 2011; Al-Homoud, 2005).

1.2 International Responses to Housing Energy Performance

A literature review of advanced economies on international housing energy performance reveals that there are an increasing number of countries encouraging stricter energy performance standards for new housing, particularly zero net energy homes (ZEH) standard (DCLG, 2006a; Horne & Hayles, 2008; Míguez, et al., 2006; Osmani & O'Reilly, 2009; Zhu, et al., 2009).Typically, these standards are either performance-based or prescriptive. Prescriptive guidelines involve a detailed requirement for each element such as length, width and height whereas performance-based guidelines provide furthering of energy requirement such as residential buildings shall be equipped with certain amount of energy in cooling or heating (Kordjamshidi, 2011; May, 2003; Oleszkiewicz, 1994).

1.3 Heat Escape through House Components

Studies indicate that around 30 to 40% of heat escapes or are lost through the un-insulated house wall, as illustrated in Figure 1.5 (Berkeley, 1996; Oral & Yilmaz, 2002; Alam & Theose, 2008; Northwest National Laboratory, 2010; Mick, 2007; Zhao & Magoulès, 2012; Howard et al. 2012). Hence, a reduction of energy use for space heating and cooling not only enhances energy conservation, but also reduces greenhouse gas emissions and enhances energy security. Therefore, proper design and selection of the house envelope assist in reducing space heating-cooling loads (Alam et al., 2008; Gregory et al., 2008, Wakefield, He & Dowling, 2009; Haapio &Viitaniemi, 2008; Tommerup, et al., 2007; Ozel, 2011; Ekici, Gulten, & Aksoy, 2012; Ballarini & Corrado, 2012).

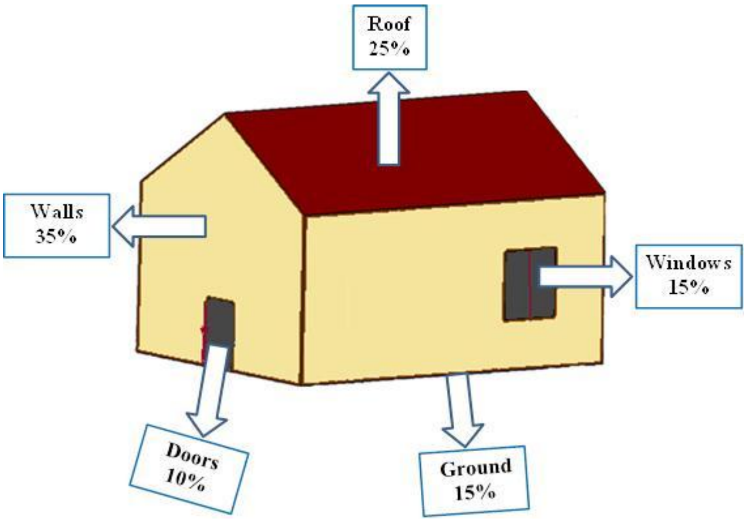


Figure 1.5: Schematic of heat escape through un-insulated house elements (Gregory et al., 2008)

Some of the insulating materials used include: inorganic fibrous materials, glass wool and stone wool, organic foamy materials expanded and extruded polystyrene and to a lesser extent polyurethane, combined material that is silicon calcium, gypsum foam and wood-wool and new technology materials, that is, transparent materials and dynamic materials. Advanced insulation material is a prerequisite for cost-effective construction and rehabilitation of buildings. The material chosen should be least hazardous to the environment, adaptive and friendly to construction personnel (Papadopoulos, 2005). Cellulose can also be used as an insulation material, but its thermal performance is significantly lower than that of stone wool batts and therefore can still be used as an insulating material (Nicolajsen, 2005). Moistened insulation triggers increased values of effective thermal conductivity according to Ochs et al. (2008).

In the European Union’s residential housing sector, around 57% energy is used for space heating, 25% for domestic hot water and 11% for electricity, out of the total energy consumed. However, some North European countries’ residential houses consume over 70% of used energy only for space heating (Berkeley, 1996). Thus, the energy saving potential of the house envelope must be maximised during the operational phase of residential houses. In addition to the traditional energy-saving measures (e.g., modernisation of heat sources and ventilation, introduction of automation and heat metering, and improvement of installed equipment), a smart house envelope is urgently required to achieve significant energy reductions in the building sector. In order to achieve ultimate sustainable-energy buildings/houses, research work should be undertaken focussing on energy conservation and environmental protection in buildings. The first and foremost focus should be on energy-efficient house envelopes, the second focus on environmental-friendliness, and, finally, the third focus should on sustainability. The first focus should deal with construction materials and methods for energy efficiency and economic feasibility, the second focus with energy-savings measures that are beneficial to the environment, and the third focus should find a balance between present and future energy needs and environmental requirements, whilst saving energy resources and keeping a clean environment for future generations (Nicolajsen, 2005).

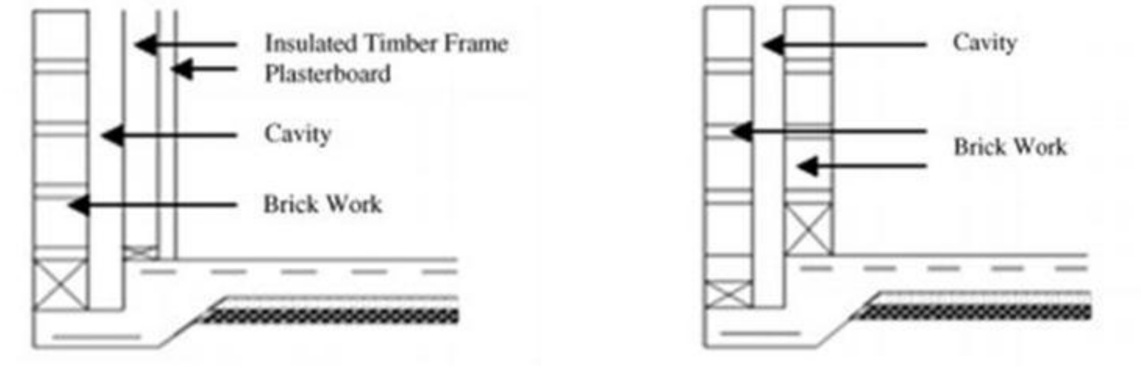
Therefore, an energy efficient building envelope with smart thermal mass and insulation is the first necessary and fundamental step towards sustainable-energy buildings for residential as well as commercial sectors.

Thermal mass minimises thermal fluctuations by absorbing and releasing both internal and external excessive heat in areas with large thermal fluctuations. Khalifa (1998) investigated concrete thermal mass with variable thicknesses in order to understand thermal storage capacity using analytical methods for hot climate condition. His findings indicate that a concrete wall can be used as a thermal mass for the buildings to minimise the thermal fluctuations. He also concluded that the variable heat transfer coefficients would be useful to estimate heat loss/gain. The study was restricted to a particular type of climate condition and no insulation materials were used in his study. A similar study was undertaken by Kosny and Kossecka (2002), who examined heat transfer through two building envelopes made of timber and reinforced concretes in a moderate climate condition. The study was undertaken using ENERGY PLUS software. One-dimensional heat transfer analysis was conducted. They reported that concrete has a higher thermal storage capacity than that of a timber frame wall. They did not look at the effect of variable climate conditions on thermal storage capacity of concrete and timber walls.

Zhu et al. (2009) looked at the energy saving potential of two thermal masses (weatherboard/brick veneer and concrete wall systems) for zero energy houses. The experimental houses were built at the same location in hot climate condition of suburban Las Vegas, USA. Thermal performance was monitored and documented. The measured data showed that the concrete house wall envelope saved and stored more energy than the brick veneer house wall system. They did not use any insulation materials and look at the variable climate effects on both house wall systems.

Bellamy and Mackenzie (2001) investigated a small weight and a heavy weight one-room house made of brick veneer and insulated reinforced concrete, respectively, for a relatively cool climate in Lincoln, South Island, New Zealand. Both houses were monitored for their thermal performance for two years. The analysed data showed that the insulated concrete house required less energy consumption for heating and cooling compared to the brick veneer house. The study was primarily based on experimental measurements. No computational modelling or analytical analysis was employed. Additionally, no multi-climate effects were considered.

Gregory et al. (2008) conducted a comparative study of the energy impact of thermal masses of four houses made of brick veneer (BV), cavity brick (CB), reverse brick veneer (RBV) and weatherboard (WB), as shown in Figure 1.6. The study was undertaken using AccuRate software. Based on modelling results, Gregory et al. (2008) concluded that thermal mass has the ability to significantly reduce energy usage in residential buildings by maintaining a comfortable internal temperature with no heating or cooling. They also reported that the cavity brick and reverse brick veneer house wall systems have greater thermal storage capacity than simple brick veneer and weatherboard house wall systems. However, the study did not include any alternative building and insulation materials. Additionally, the effect of variable climate conditions on house wall thermal performance was not included in the study.



a) Brick veneer (BV)

b) Cavity brick (CB)

c) Reverse brick veneer (RBV)

d) Light weight (LW)

Figure 1.6: Schematic of cross section of construction type (Gregory et al., 2008)

The importance of using insulation materials in buildings to reduce heat gain/loss is emphasised by various researchers (Al-Sanea & Zedan, 2011; Cabeza et al., 2010, Pierquet, Bowyer & Huelman, 1998).

Kalogirou, Florides and Tassou (2002) undertook computational simulation of thermal performance of brick made houses for Mediterranean climate conditions in the Turkish republic of Cyprus, using TRNSYS software. The modelling findings indicated that thermal mass with no windows facing the sun provides better thermal performance and thermal storage capacity.

Cabeza et al. (2010) compared the performance of three different insulating materials (polyurethane, polystyrene and mineral wool with 50mm thicknesses) with brick veneer house wall systems. Their study was based on experimental investigation in the sub-tropical climate condition of Spain. A significant energy saving for cooling/heating was achieved by all three insulation materials in comparison with the brick veneer wall system. They also concluded that the performance of polystyrene insulation was the best. However, they did not consider any natural insulation materials. Their study was limited to experimental investigation only and did not consider multiple climate effects.

Pierquet, Bowyer and Huelman (1998) undertook a computational study using HOT-2000 software on thermal performance of house wall systems. They used polystyrene, cordwood masonry and plastered straw bale insulation materials in their computational modelling for cold climate condition in the USA. Their study revealed that concrete with polystyrene insulation materials provided better energy savings compared to other materials. However, no experimental validation of their findings was provided.

Yesilata, Bulut and Turgut (2011) investigated experimentally the thermal behaviour of two house wall systems (brick wall and concrete wall), where the insulation material was scrapped tyre rubber, in Turkey. The concrete house wall with tyre rubber required up to 14% less energy for heating and cooling. However, no fire hazard and toxicity effects were included in their study.

Al-Sanea and Zedan (2011) studied the thermal effect of single and multilayer insulation materials for hot climate conditions in Saudi Arabia. The investigation was undertaken analytically. They concluded that multilayer insulation is better than a single layer. However, the study lacks experimental validation.

Arslan and Kose (2006) have studied the optimization of insulation thickness, considering condensed vapour in buildings. The study was undertaken in Turkey, which experiences variable climate conditions. Most external walls of houses in Turkey are made of timber structure, brick veneer and no insulation. The study revealed that using polystyrene insulation can reduce heat loss through the house wall by 70%. However, the findings were not experimentally validated.

Mahlia and Iqbal (2010) studied the cost benefit analysis of insulation materials for building walls in Maldives. The climatic condition in Maldives is hot, dry and humid, with minimum and maximum temperatures ranging between 25°C and 37°C, respectively. They analysed different insulation materials such as fibreglass, urethane, polystyrene and perlite. They found that the cost of insulation materials increases linearly with increasing insulation thickness. They also reported that insulation thickness is directly proportional to cost; however, after reaching optimum insulation thickness, further energy saving is minimal. They did not study the economic effect of any natural insulation materials for other climate conditions.

Kaynakli (2008) examined the heating energy requirements for various insulation materials for residential houses in Turkey. He estimated the heating energy requirement by using the degree-hour (DHs) concept. The study revealed that there is a notable variation in heat transfer depending on the type of insulation used. The study also reported that the heating energy requirement is at least 20% more for single glass windows compared to double glass windows. Kaynakli did not consider any natural insulation materials, variable climate effect or economic viability of materials.

Kumar, Ashok and Suman (2013) carried out an experimental investigation of house wall systems made of clay bricks and concretes with insulation materials (polystyrene, polyurethane, fibreglass) for two climate conditions experienced in India. They found that polyurethane insulation material provided better thermal insulation. However, the study did not look at any natural insulation materials and materials cost analysis.

Tummu et al. (2013) undertook thermal performance analysis of a house wall system for humid climate conditions in Thailand, using experimental and computational methods. They used polyurethane insulation material. The main finding of this study was the effect of insulation positioning in wall systems to maximise energy conservation. Unfortunately, the effects of other synthetic and natural insulation materials on thermal performance were not considered in this study. The finding was also limited to one climate condition.

Budaiwi and Abdou (2013) carried out an experimental study on moisture effect of a typical synthetic insulation material (fibre glass) for humid and hot climate condition in Saudi Arabia. They found that the thermal resistance of the insulation material could be affected by the moisture inside the house wall system. However, the study was limited to one type of insulation material and climate condition.

Kolaitis et al. (2013) studied the thermal performance of a brick veneer residential house wall system, using numerical simulation for moderate climate condition in Greece. They used one insulation material (polystyrene). The study reported that the external insulation was better. However, no further details were revealed. Again, the study was limited to one insulation material. Furthermore, no experimental validation was included in the study.

Ucar and Balo (2009) studied three insulation materials (foam board, fibreglass and polystyrene) for Turkish climate condition. They also undertook economic cost analysis of these insulation materials. Their results showed that energy cost savings were directly proportional to the cost of fuel, insulation material and climatic conditions. The input energy source such as natural gas and liquidified petroleum gas (LPG) provides a better payback period than other fuels. The study did not include cost effectiveness analysis of other insulation materials.

Liang and Ho (2006) conducted an experimental study to determine toxicity levels of commercially manufactured insulation materials such as fibreglass, rock wool, polyurethane and polyethylene, using UK Naval Engineering Standards 713 (NES-713). They calculated the toxicity index in order to evaluate the specimen’s combustible characteristics and analysing their toxic constituents and contents. They reported that polyethylene had the highest toxicity level and that fibreglass insulation has the lowest level of toxicity. However, the toxicity effect of polystyrene insulation material was not considered in this study.

Stec and Hull (2011) assessed toxicity levels of insulating materials such as rock wool, polystyrene, phenolic foam, glass wool, polyisocyanurate foam, and polyurethane. These materials were investigated under a range of fire conditions. Wool and glass failed to ignite and gave low yields of toxic products. The study revealed that polyisocyanurate and polyurethane emitted the highest level of toxicity and that polystyrene generated the lowest level. Unfortunately, they did not study the effect of toxicity of natural insulation materials.

It may be noted that currently there are no standards for insulation materials’ toxicity in building applications. However, ASTM standards has set forth environmental toxicology standards providing proper procedures to evaluate, assess and identify potential synthetic and natural pollutants. The pollution measure is based on what toxins are released to the atmosphere and thus insulation materials are considered in these standards. The fire rating of insulation materials should be determined in order to use them safely in residential house buildings (Lazko et al., 2013; Chow & Leung, 2001). According to Hart (2008), numerous codes and standards are used for fire safety, including ASTM E84, ASTM E119, ASTM 136, AS 1851, AS2444, AS 3837, BS 5839-8, BS EN 1021-1&2, EN 1363-1:2012. The fire resistance and toxicity of a range of insulation materials based on various widely used national standards have been reviewed and compiled in Table 1.1.

Table 1.1: Fire resistance time and toxicity of insulation materials

No.	Insulation Material	Toxicity	Fire resistance time (min.)	Fire rate standard
1	Particleboard	Non toxic	13-15	Euro-Class classification E rating
2	Cellulose fibre	Very low toxic	40-60	AS 3837 BCA Class 1
3	Straw board	Eco-friendly	25-35	AS1530 Part 4
4	Sheep wool	Non-toxic eco-friendly	15-25	Euro Class E EN 13501-1: 2002
6	Polyurethane	Mid.- high level	35-90	AS1530 Part 4, AS4072 Part 1
7	Rock wool	Min. toxicity	60-85	Euro-class B-S1-d0
8	Fibreglass	Low level	45-55	GB8624 1997 B1 C-Class
9	Polystyrene	Low level	60-75	AS 3837 BCA Class 1

1.3.1 Summary from Prior Studies

Table 1.2shows a brief summary of reviewed literature related to residential buildings. From this literature, it is evident that current residential house wall systems are not energy efficient for their ongoing heating and cooling, since a significant amount of energy is wasted through the wall systems. There are no appropriate uses of thermal mass and insulation materials in residential houses. The suitability of various synthetic and natural insulation materials has not been well studied and explored. The position and sequence of insulation materials in house wall systems for variable climate conditions have also not been thoroughly studied. Additionally, scant information is available on a smart house wall design that can be adapted for variable climate zones with minimal wall structure and materials modification. Furthermore, no thermal model for a residential house wall system is currently available that can be used to determine an optimal house wall system based on available local building materials, their thermal properties and weather data.

Table 1.2: Summary of related published research work

Author	Thermal mass	Insulation materials	Climate region	Insulation thickness	Economic benefits	Thermal performance	Toxicity/ fire rate
Zhu et al. (2009)	Yes	Polystyrene	US	25mm	No	Yes	No
Bellamy & Mackenzie (2001)	Yes	-	New Zealand	No	No	Yes	No
Gregory et al. (2008)	Yes	-	Australia	No	No	Yes	No
Khalifa (1998)	Yes	-	-	No	No	Yes	No
Kosny & Kossecka (2002)	Yes	-	-	No	No	Yes	No
Kalogirou, Florides &Tassou (2002)	Yes	-	Turkey	No	No	Yes	No
Al-Sanea & Zedan (2011)	Yes	-	-	Yes	Yes	Yes	No
Yesilata, Bulut &Turgut (2011)	Yes	Scrap-tire rubber	-	No	No	Yes	No
Pierquet, Bowyer & Huelman(1998)	No	Polystyrene	-	No	No	Yes	No
Arslan & Kose (2006)	No	Polystyrene	Turkey	60, 65, 75mm	Yes	No	No
Mahlia & Iqbal (2010)	No	Polystyrene Fibreglass	Maldives	Yes	Yes	No	No
Kaynakli (2008)	No	No	Turkey	53-124mm	No	Yes	No
Liang & Ho (2006)	No	-	Taiwan	Yes	No	No	Yes
Hart (2008)	No	Cement board	-	No	No	No	Yes
Ucar & Balo (2009)	No	Fibreglass Polystyrene Foam board	-	10-76mm	Yes	No	No
Capila, Uson & Bribian (2010)	No	No	-	No	Yes	No	No
Stec& Hull (2011)	No	Glass-wool Polyurethane Polystyrene	-	No	No	No	Yes
Kumar, Ashok, &Suman (2013)	Yes	Fibreglass Polyurethane Polystyrene	India	No	No	Yes	No
Tummu et al.(2013)	No	Polyurethane	Thailand	59mm	No	Yes	No
Budaiwi & Abdou (2013)	No	Fibreglass	Saudi Arabia	50mm	No	Yes	No
Kolaitis et al. (2013)	No	Polystyrene	Greece	80mm	No	Yes	No

1.4 Objectives and Scope of this Work

From an examination of the prior work undertaken in this area, one may conclude that there are significant knowledge gaps in designing an energy efficient residential house wall system for on-going heating and cooling that can be adapted for multi-climate conditions with minimal modification and cost. Therefore, the following research objectives will be addressed by this research project:

- Investigate the thermal performance of conventional and alternative house wall systems for on-going heating and cooling energy savings;
- Develop a thermal performance model for house wall systems for multi-climate zones;
- Devise an optimal house wall system for mainstream housing in multi-climate zones;
- Determine building materials for residential house wall systems based on thermal performance, cost benefit, fire resistance and toxicity.

The following key research questions have been formulated to address the aforementioned research objectives:

1. What types of thermal mass and insulation construction materials can be used to reduce the heat gain/loss for residential house wall systems?
2. What will be the optimal combination of construction materials and methods that can be used to minimise the heat gain/loss through house wall systems?
3. Can a thermal performance model be developed to determine the appropriate house wall design for variable climate conditions?
4. What insulation and thermal mass materials will provide higher energy saving and thermal comfort?
5. How much benefit can be attained using single and double glazed windows?
6. Will the new house wall design be economically viable and can it be utilised for main stream housing?

Several factors such as the following can affect the thermal performance of a residential house:

- Thermal mass;
- Thermal insulation;
- Climate condition;
- Availability of building materials;

- Toxicity and fire resistance;
- Cost effectiveness; and
- Sustainability and environmental impact.

There is sufficient scope in this important human basic need to research and develop a house wall system which will provide energy savings for on-going heating and cooling, reduction of CO_2 emissions and improved thermal comfort. This research will be undertaken by a combination of analytical, computational and experimental investigations.

1.5 Thesis Overview

The layout of the thesis has been formulated in the following chapters to address all research questions and objectives in detail.

Chapter 1 provides an introduction, background and review of current literature available in the field. The chapter also includes the research questions and objectives.

Chapter 2 describes the properties of building insulation materials. These materials include mineral wool, cellulose, fibreglass, plastic fibre, cotton, natural fibre, sheep's wool, straw, polystyrene, polyisocyanurate, polyurethane, vermiculite, perlite, urea-formaldehyde, cementations foam, phenolic foam, and insulation facings insulation.The thermal properties such as thermal insulation, lag time and thermal masses of those insulation materials are discussed.

Chapter 3 illustrates the typical Australian residential houses and alternative (new) house wall system designs. The chapter also includes a detailed physical description of the new house wall systems and its modelling parameters.

Chapter 4 discusses various computational energy modelling software and the justification of selected computational modelling software (i.e., AccuRate). Australian climate conditions, residential house thermal comfort, and star energy rating have also been discussed in this chapter. This chapter also includes the thermal performance (heating and cooling) results for conventional and new house wall systems obtained through computational modelling.

Chapter 5 provides the detail of the theoretical analysis based on the application of heat transfer theory and equations used in this study. Three modes of heat transfer (conduction, convection and radiation) are used to determine the overall heat loss or gain. In addition, this chapter also includes the 'degree-hour' data and their analysis.

Chapter 6 outlines the experimental scale test house models, equipment, facilities, test procedure, acquired data and their results. This Chapter assist to understand the thermal performance of building materials and its insulation. A scale model house of dimensions 0.5m × 0.5m × 0.5m was made without windows, doors and natural ventilation for this investigation.

Chapter 7 presents general discussion of results for conventional and new house wall designs. A comparison of results obtained through computational modelling, theoretical analysis and experimental measurements. The economic analysis of house wall systems is also included in this chapter. The implications of the results from this work are also described here.

Chapter 8 contains the major and minor conclusions from this research and outlines the recommendations for future work.

Appendixes (A to D) are attached at the end of references, bibliography and the list of publications arising from this work.

CHAPTER 2 BUILDING MATERIAL THERMAL PROPERTIES

2.1 Introduction

To achieve a significant reduction in energy uses for residential houses, the existing house envelope needs to be improved with better buildings materials. The construction materials used in residential house must have low thermal energy requirements.

2.2 Thermal Properties of Building Materials

A primary consideration must be undertaking when choosing thermal properties of building insulation materials. The following glossaries are used to define the thermal properties of selected materials:

a. Thermal conductance (C): thermal conductance refers to the time rate of steady state heat transfer per unit area of a material or construction system by a temperature unit difference between the surfaces and body.
b. Thermal conductivity (K): thermal conductivity refers to the time rate of steady state heat transfer through unit area of homogeneous material results by unit temperature tendency in a direction vertical to that unit area.
c. Emissivity (ε): material emissivity refers to the ability of its surface to emit energy by radiation. It is a ratio of the energy released by a specific material to the emitted energy.
d. Thermal resistance (R): thermal resistance refers to the ability of material to resist the flow of heat.
e. Thermal transmittance (U): thermal transmittance refers to the overall conductance of heat transfer through a material.

The material thermal properties used in this study are shown in Table 2.1. The properties include materials thickness, thermal conductivity and density.

Table 2.1: Building materials thermal properties

	Material	Thermal conductivity W/m.K	Density kg/m^3
Insulation materials	Polyurethane rigid board	0.02	29.0
	Sarking	0.10	25.0
	Cellulose fibre-R1.5	0.041	56.0
	Sheep wool-R1.5	0.04	25.0
	Rock wool batt	0.034	60.0
	Polystyrene	0.033	20.0
	Glass fibre-R1.5	0.04	12.0
	Straw board (wheat)	0.06	160.0
	Straw board rendered	0.06	160.0
	Wood chip board (particle board)	0.12	630.0
Construction materials	Brick	1.0	1500.0
	Re-inforced concrete	1.13	2300.0
	Hard timber (structure)	0.18	850.0
	Soft timber (plywood)	0.16	550.0
	External rendering	0.25	1100.0
	Tile concrete	0.84	1900.0
	Cast concrete slab	1.13	2300.0
	Timber flooring	0.14	650.0
	Plasterboard	0.25	950.0
	Single glass window	0.90	2500.0
	Aluminium frame	200.0	2600.0

2.2.1 Thermal Comfort

Thermal comfort is very difficult to define due to variable needs. Clearly it can be defined as the conditioned temperature satisfying the person feeling the temperature in his/her place of living. ANSI/ASHRAE standard 55 defined thermal comfort as the condition of the human body that expresses satisfaction with the thermal environment assessed by subjective evaluation. Heating and cooling plays significant roles in thermal comfort (Wong et al., 2002). One of the design goals of HVAC is to maintain a standard thermal comfort for houses residents (ANSI/ASHRAE standard 55).

2.2.2 Thermal Insulation

Thermal insulation is generally used by the construction industry to prevent heat loss or gain through the external walls. Thermal insulation creates thermal comfort inside the houses by keeping the temperature in suitable condition. It also creates a barrier between the warm air inside the house and the cold air outside. The better this barrier is the less energy house needs for cooling and heating. Therefore, using insulation materials can assist to reduce energy consumption and increase thermal comfort (Dear, Brager, & Cooper, 1997). This Chapter discusses the properties of various building construction and insulation materials.

2.2.3 Lag Time

Lag time can be defined as the time taken by a periodic time wave to penetrate the wall of a building from the outside to the inside. This time is directly proportional to the thickness and resistivity of materials. The more resistive and thicker the material is, the longer it will take for heat waves to penetrate. The reduction of cyclical temperature on the inside surface compared to the outside is termed the decrement factor. Asan (1998) conducted a study on the effects of wall insulation thickness and position on the time lag and the decrement factor. The investigations included numerical and one-dimensional transient heat conduction equations, using the Crank Nicolson scheme under convection boundary conditions. The time lag is proportional to the thickness of the material, as is the decrement factor. These factors should be considered in the design of buildings. For instance, buildings in desert climates should be constructed with material with a time lag of 10 to 12 hours, since during the day temperatures can reach 40 to 50 degrees and it is expected that the night may be freezing. If 10-12 hour time lag insulation materials are used, then low night temperatures will reach the inside of the building around midday, thus cooling the air inside, and high temperature during the day will reach the inside at night, thus warming the inside.

2.2.4 R-Value

The R-value refers to the ability of insulation material to resist heat flow. This term is mostly used as commercial identification when buying insulation. R-values can vary depending on the heat flow direction through the product. Insulation with higher R-value is the better for thermal performance. However, it does not mean higher thickness has a higher R-value. For example, 50mm thick polystyrene and 80mm thick glass wool both have similar R-value (approximately 1.5). R-values are expressed in metric units (m^2.K/W). The R-value of building components (wall, floor, ceiling and roof) can be calculated. The R-values used in this study for walls, ceilings and floors are R1.5, R2.5, R2.5, respectively. Based on house location and climate condition, different R-values are recommended (BCA). The recommended minimum R-value for residential houses located in different cities and territories is shown Table 2.2.

Table 2.2: Recommended R-value for residential houses in Australia

Climate type	City, State	Roof/Ceiling	Wall
Cool Temperate and Alpine	Melbourne, VIC	2.5-3.0	1.5
	Canberra, ACT	3.0	1.5-2.0
	Hobart, TAS	3.5	1.5-2.0
	Mt Gambier, SA	3.5	1.5-2.0
	Ballarat, VIC	3.5	1.5-2.0
	Thredbo, NSW	4.0	1.5-2.0
Hot humid and hot dry	Darwin, NT	0-4.0	0-2.0
	Cairns, QLD	0-3.5	0-1.5
	Broome, WA	0-4.0	0-2.0
	Townsville, QLD	0-3.5	0-1.5
Warm/Mild Warm/Humid	Brisbane, QLD	1.5-2.5	1.0
	Perth, WA	1.5-3.0	1.5
	Alice Springs, NT	1.5-4.0	1.5-2.0
	Bourke, NSW	1.5-4.0	1.5-2.0
	Sydney, NSW	1.5-3.0	1.5
	Adelaide, SA	2.0-3.0	1.5

2.2.5 Thermal Masses

Materials such as concrete and bricks have higher thermal masses as they have higher specific density. A large amount of heat energy can be stored by high density materials. High thermal mass materials also take a longer time to release the heat content once the heat source is removed. Conversely, lightweight materials such as timber have low thermal mass, requiring a lower time to release the heat content (Gregory et al., 2008). Figure 2.1 illustrates the time taken to release the heat through different house thermal masses. Materials with high thermal mass such as double brick layer can absorb and keep heat during the day or night and release it gradually over 6-8 hours. However, materials with lightweight and low thermal mass such as timber or weatherboard takes less time to store or release heat over 2-3 hours, and will also lose heat faster (Wakefield, He & Dowling, 2009). Therefore, the optimal use of thermal masses for the house wall systems can provide a comfortable house environment and reduce energy consumption for heating and cooling. In this study, two types of houses are used: conventional (brick veneer) and new house design. In order to understand the volumetric heat capacity of various thermal masses of conventional and new design house wall systems, the total volumetric heat capacity of materials has been estimated in this study. The volumetric heat capacity of the conventional wall system and new house wall system are shown in Table 2.3 and Table 2.4 respectively. The tables show that the new house wall system has higher volumetric heat capacity (17%) compared to the conventional house wall system. This higher heat capacity enables the new wall system to store heat for longer periods as it has higher thermal mass (reinforced concrete).

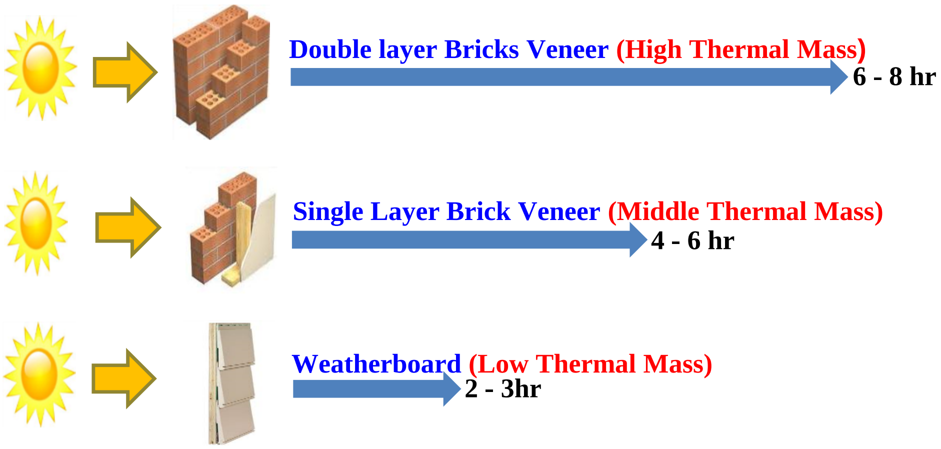


Figure 2.1: Heat flow-delay through different thermal mass house wall systems (Aldawi et al., 2013)

Table 2.3: Volumetric heat capacity of conventional house wall system

Material	Volume / unit area of wall surface	Volumetric heat capacity kJ/m^3.K	Specific heat per layer kJ/m^2.K
Brick veneer	0.110	1400.0	154.000
Air cavity	0.050	0.001	0.00005
Sarking	0.005	10.6	0.053
Timber	0.090	1057.0	95.130
Plaster board	0.010	924.0	9.240
Total	0.265		258.420
Volumetric heat capacity of conventional wall system = 258.420 / 0.265 = 975.17 kJ/m^3.K			

Table 2.4: Volumetric heat capacity of new house wall system

Material	Volume / unit area of wall surface	Volumetric heat capacity kJ/m^3.K	Specific heat per layer kJ/m^2.K
Render	0.010	1200.0	12.00
Polystyrene	0.059	5.5	0.32
Reinforced concrete	0.150	2112.0	316.80
Polystyrene	0.059	5.5	0.32
Plaster board	0.010	924.0	9.24
Total	0.288		338.68
Volumetric heat capacity of new wall system = 338.68 / 0.288 = 1176 kJ/m^3.K			

2.3 Traditional Insulation Materialsof Buildings

The building insulation materials are generally defined as those materials or combinations of materials that can retard the flow of heat. The insulation materials in a building are used to reduce heat transfer by conduction, convection or radiation in order to achieve the desired thermal comfort. This reduction of energy has a direct impact on the environment and health (Daouas, Hassen & Aissia, 2010). There are four types of insulation materials widely used in the building industry:

a) Bulk insulation (batts and blanket)

Bulk insulation materials are batts and blanket that have small pockets embedded within the material. Bulk insulation must not be compressed, since it contains air pockets which provide the material insulating effect. Bulk insulation is placed by hand into the area needing to be insulated. Bulk insulation is available as boards, blankets, batts, and/or as loose fill. Examples of bulk flexible insulators are fibreglass, glass wool or rock wool and polyester. Bulk insulation also comes in spray foam. Spray foam is blown into small areas to block air leaks around doors and windows. It has a lower density comparing to rigid foam insulation.

b) Loose-fill insulation

Loose fill insulation is made of granulated material and is usually installed by the manufacturer. It needs to be installed correctly to provide insulation cover. Loose fill insulation is usually used in roof ceilings at the slope of 25° pitch. An example of loose fill insulation is cellulose fibre and natural wool.

c) Reflective foil laminated

Reflective insulation is a similar material to bulk insulation. The only difference here is that the external layer is covered by reflective foil. The material used in reflection foil is aluminum in order to prevent heat flow inside the buildings or houses. Reflective foil insulation is mostly used in residential and commercial building to increase their thermal performance. It is typically used in roof and wall insulation. Double-sided foil can increase the insulation’s effectiveness by around 10%. Sisalation foil is an example of reflective foil.

d) Boards and rigid foam panels

The density of these materials is very high and has higher R-value per unit of thickness. Board insulation is a particularly used for wall insulation in houses built of reinforced concrete, bricks and other materials. Polystyrene and polyurethane are rigid foam insulation.

e) Spray foam

Spray foam insulation is used to seal the leakage of air around doors and windows. The essential benefit of spray foam is providing a quick insulation solution for small areas. The spray foam is useful to block air leakage in the ceiling, roof and ground for residential houses. Spray foam insulation made of polyurethane material generally provides higher thermal insulation performance.

2.3.1 Mineral Wool

The Mineral wool includes glass wool (fibreglass) and rock wool, which is usually produced as mats and boards, but sometimes produced as filling material. Light and soft mineral wool products are applied in frame houses and other structures with cavities. Heavier and harder mineral wool boards with high mass densities are used when the thermal insulation is intended for carrying loads, e.g., on floors or roofs. Mineral wool may sometimes be utilized as a filler material to fill various cavities and spaces. Mineral wool is manufactured from borosilicate glass at a temperature of approximately 1400°C, where the heated mass is pulled through turning nozzles, thus creating fibres. Rock wool is fashioned from melting stone at about 1500°C, where the heated mass is hurled out from a wheel or disk, enabling the creation of fibres. In both glass wool and rock wool, dust abatement oil and phenolic resin is added to consolidate the fibres and enhance the product properties. In most cases, thermal conductivity figures for mineral wool are between 0.030 and 0.040 (W/m.K). However, the thermal conductivity of mineral wool depends on temperature, moisture content and mass density. For instance, the thermal conductivity of mineral wool may rise from 0.037 to 0.055 (W/m.K) when moisture content rises from 0 vol% to 10 vol%, correspondingly. Mineral wool products can be perforated, cut and accustomed at the building site without any loss of thermal resistance (Salyer & Sirca, 1990; Baetens, Jelle & Gustavsen, 2010).

2.3.1.1 Rock Wool Insulation

Rock wool insulation is made from natural minerals or recycled construction and slag waste. Rock wool is durable insulation and comes in different forms such as rigid batts, flexible blankets, and semi-rigid batts. Rock wool has density ranging between 60 to 150 kg/m^3. Rockwool has large thermal properties and thermal resistance. It also has higher fire resistant properties as well as sound insulation. In industrial application, rock wool is used to resist temperatures of up to 820°C. Rock wool can be used in all types of building elements, including roofs, walls, floors and foundations (Baetens, Jelle & Gustavsen, 2010). Examples of rock wool are shown in Figure 2.2.

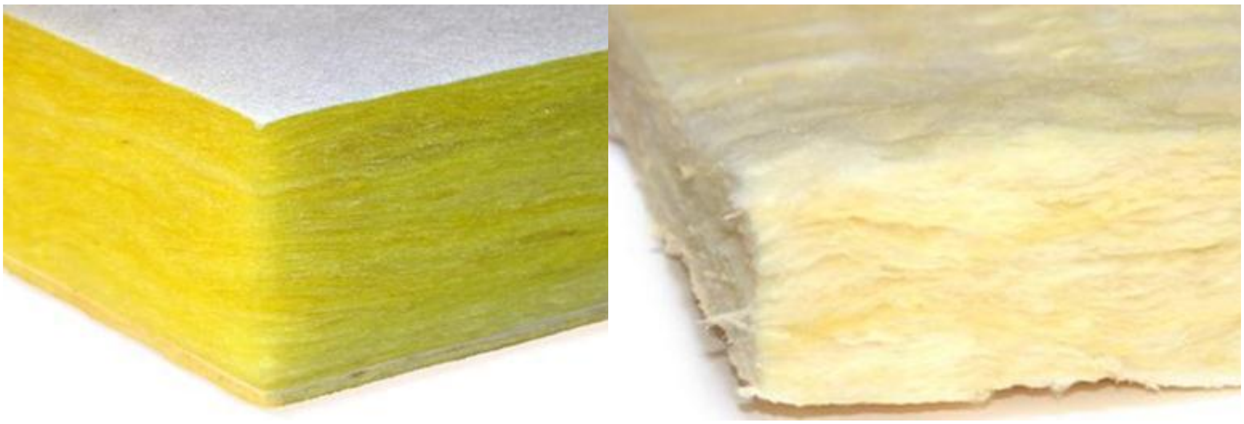
a) Reflective

b) Non-reflective

Figure 2.2: Rockwool insulation (http://www.archiexpo.com)

2.3.1.2 Glass Wool or Fibreglass Insulation

Glass wool insulation is made of fibers arranged into a textile which similar to wool. Glass wool has higher thermal insulation due to intertwined and glass fibers. This feature can delay the transition of heat flow due to its lower density. Glass fibre sheets and panels can be utilized in walls and ceiling tiles, as well as in piping insulation and for soundproofing. Glass wool comes in batts, blankets and rolls. Fibreglass has higher fire resistance and less impact on the environment. However, fibreglass has a health issue because of its potential irritant effects on eyes and the skin (Boonyartikarn & Spiezle, 1990). Figure 2.3 shows glass wool insulation



a) Reflective b) Non-reflective

Figure 2.3: Glass wool insulation (http://steelroofing.com)

2.3.2 Wood Chipboard or Particleboard Insulation

Chipboard insulation is a reconstituted wood panel. It is made of wood particles or flakes wood. Chipboard insulation is used for different internal house applications and insulation purposes. Chipboard insulation has low thermal performance. Chipboard has a higher density, ranging between 350 to 650 kg/m^3. It has lower fire rating and is environmentally friendly. (Leslie, 2009). Figure 2.4 illustrates typical chipboard.

Figure 2.4: Chipboard insulation(http://www.selcobw.com)

2.3.3 Straw Board Insulation

Straw board insulation has lower specific density of 80-160 (kg/m^3) and thermal conductivity of 0.036-0.048 (W/m.K). Straw board has excellent thermal insulating and acoustic properties. Straw board is made of natured wheat or rice straws. It is compressed for durable and fire resistance. Compressed straw board is usually used for wall and ceiling insulation for residential and commercial buildings. During the manufacturing process, a dry extrusion process and heat are applied to make a solid panel. Straw board does not contain any chemical or toxic substances. Thus, straw board is environmentally friendly. Figure 2.5 shows straw board insulation.

Figure 2.5: Straw board insulation (http://epdmrubber.wordpress.com)

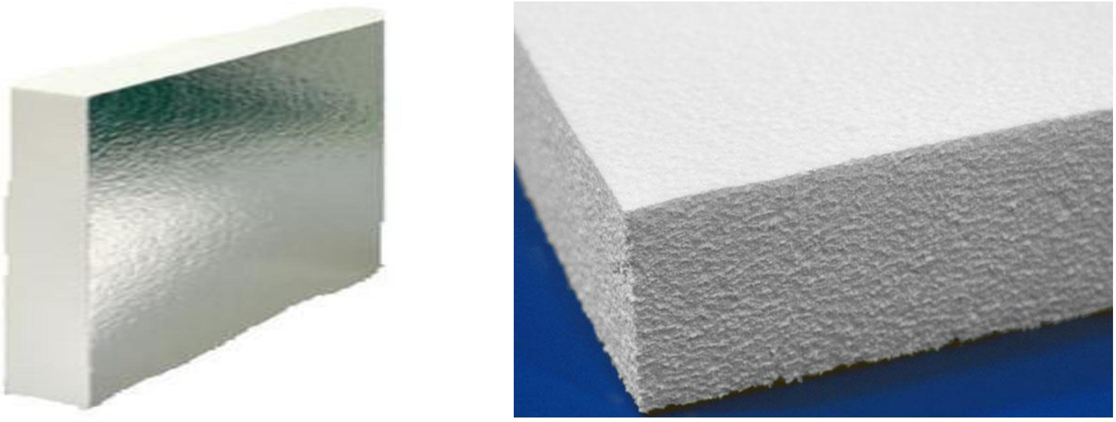
2.3.4 Cellulose Fibre Insulation

Cellulose fibre insulation consists of 85% recycled paper (newspapers and magazines mixed with acid). Cellulose (polysaccharide, ($C_6H_{10}O_5$) n) consists of thermal insulation that is created from recycled paper or wood fibre mass. The production procedure ensures that the insulation material is able to resemble wool. Boric acid (H_3BO_3) and borax (sodium borates, Na_2B_4) are added to enhance the product properties. Cellulose insulation is used as a filler material to fill a variety of cavities and spaces. However, cellulose insulation boards and mats are also produced in this process. Characteristic thermal conductivity values for cellulose insulation range from between 0.04 and 0.05 (W/m.K). The thermal conductivity of cellulose insulation differs, depending on temperature, moisture content and mass density. In a particular case, the thermal conductivity of cellulose insulation may increase from 0.04 to 0.06 (W/m.K), with rising moisture content from 0 vol% to 5 vol%, respectively. Cellulose insulation products may be perforated, cut and attuned at the construction site, without any noticeable loss of thermal resistance. The disadvantage of cellulose fibre is that it is very dusty during the installation process (Wilkes, 1991; Boonyartikarn & Spiezle, 1990). Figure 2.6 illustrates cellulose fibre insulation).

Figure 2.6: Cellulose fibre insulation (http://www.archiexpo.com)

2.3.5 Expanded Polystyrene Insulation (EPS)

Expanded polystyrene (EPS) is manufactured from tiny spheres of polystyrene (a substance that emanates from crude oil). This polystyrene has an expansion agent, (e.g. pentane C6 H12) which inflates by heating it with water vapour. The expanding spheres are attached together at their contact areas. The insulation material is cast as boards or in continuous form on a production line. EPS has a partly open pore structure. Conventional thermal conductivity values for EPS normally range from 0.03 to 0.04 (W/m.K). The thermal conductivity of EPS varies with temperature, moisture content and mass density. For instance, the thermal conductivity of EPS may increase from 0.036 to 0.054 (W/m.K), when the moisture content rises from 0 vol% to 10 vol%, respectively. EPS products may be perforated, sliced and attuned at the building location, without any loss of thermal resistance. Polystyrene has high thermal insulation and can achieve high R-value ratings. Polystyrene insulation is more efficient due to its more dense structure and excellent moisture resistance. Polystyrene can be found in foam or rigid board and has a low density of 30 kg/m^3. Polystyrene is lightweight and can be used to prevent heat loss/gain through the wall, ceiling roof and ground. Polystyrene has a range of R-values from R1.5 to R4.0. Without any environmental hazard, around 80% of polystyrene insulation can be recycled. Polystyrene insulation can resist heat from room temperature up to 100°C. Polystyrene provides high thermal comfort in a house due to less heating and cooling loss (Arslan & Kose, 2006; Zhu et al., 2009. Polystyrene insulation is highly recommended by the BCA. Figure 2.7shows some typical polystyrene insulation).



a) Reflective b) Non reflective

Figure 2.7: Polystyrene insulation (http://www.thefoamfactory.com)

2.3.6 Sheep Wool Insulation

Sheep wool is the textile fibre obtained from sheep or like animals. The sheep wool insulation comes in a roll which is suitable for use in internal and external walls, ceiling and floors. In conventional houses, power consumption improves when batts of sheep wool are used in a timber-frame structure. The standard sizes of sheep wool insulation are 50mm, 75mm and 100mm. Sheep wool has active fibre that provides high resistance to heat transfer. Sheep wool insulation is renewable, natural and sustainable. It also has good resistance to fire due to added chemical improvements. The embodied energy of sheep wool is considered one of the lowest in comparison with all other insulating materials. In terms of moisture, sheep wool insulation can absorb up to 40% of its weight without becoming wet. Sheep wool insulation has zero global warming with no environmental impact and does not have any health issues (Department of Health and Human Services of Australia, 2011). Figure 2.8 illustrates some sheep wool insulation.

a) Blanket b) Board

Figure 2.8: Sheep wool insulation(http://www.romansolutions.com)

2.3.7 Polyurethane Rigid Foam Insulation (PUR)

Polyurethane (PUR) is created through the reaction of two chemicals, isocyanates and polyols (alcohols containing multiple hydroxyl groups). During the expansion process, the closed pores are filled with an expansion gas. The gas used in this process can be HFC, CO2 or C6 H12. The insulation material is produced as boards or as continuous material on a production line. PUR may also be used as expanding foam at the construction site, i.e., to fasten around windows and doors and to fill various cavities. The thermal conductivity values for PUR range from 0.02 to 0.03 (W/m.K). This is considerably lower than mineral wool, polystyrene and cellulose products. The thermal conductivity of PUR fluctuates in relation to temperature, moisture content and mass density. Generally, the thermal conductivity of PUR may rise from 0.025 to 0.046 (W/m.K), with mounting moisture content from 0 vol% to 10 vol%, respectively. PUR products can also be enhanced at the building site, without any thermal loss. It should be acknowledged that, although PUR is safe in its projected use, it raises serious health concerns and hazards, specifically in any outbreak of fire. The burning of PUR releases hydrogen cyanide (HCN) and isocyanates, which are very toxic substances. The toxicity of HCN emanates from the cyanide anion (CN^-), which inhibits cellular respiration (David & Steve, 2002;Gunter, 1985). In general, hydrogen cyanide may be found in smoke from nitrogen (N) containing plastics. Figure 2.9 shows polyurethane rigid foam insulation material.

a) Reflective b) Non-reflective (section view)

Figure 2.9: Polyurethane rigid board insulation (http://sake.co.kr/eng)

2.3.8 Cork Insulation

Cork thermal insulation is largely made from the cork oak, and can be produced either as a filler material or as boards. The normal thermal conductivity values for cork range from 0.04 to 0.05 W/m.K. Cork insulation products may be conditioned at the building site with no apparent loss of thermal resistance. Figure 2.10 shows cork insulation.

Figure 2.10: Cork insulation (http://www.archiproducts.com)

2.4 New Concepts of Insulation

2.4.1 Vacuum Insulation Panels (VIP)

Vacuum insulation panels (VIP) consist of an open porous core of fumed silica envelopes of numerous metalized polymer laminate layers. VIPs represent present day state-of the-art thermal insulation, with thermal conductivities varying from 0.003 to 0.004 (W/m.K) in new condition to typically 0.008 (W/m.K) after 25 years. The difference arises from water vapour and air diffusing through the VIP envelope and into the VIP core material, which has an open pore structure. Depending on the type of VIP envelope used, old material's thermal conductivity will differ greatly after 50 to 100 years. This predictable increase of thermal conductivity characterizes a major problem of all VIPs. Perforation of the VIP envelope might be caused by nails and other similar tools, causing an increase in the thermal conductivity to about 0.02 (W/m.K). Consequently, VIPs cannot be cut for alteration at the construction site or perforated without losing a great part of their thermal insulation performance. A gas insulation material (GIM), also used as vacuum insulation panel, is essentially a homogeneous material with a closed small pore structure that is full of a low-conductance gas like argon (Ar), krypton (Kr) or xenon (Xe).The gas used must have an overall thermal conductivity of not more than 0.004 (W/m.K) in its pristine condition. The vacuum inside the closed pore structure is replaced with a low-conductance gas (Jelle, Gustavsen & Baetens, 2010). This application of insulation has advantages and disadvantages. However, air leakage and sealing efficiency is one of the main disadvantages.

2.4.2 Phase Change Materials (PCMS)

Phase change materials (PCM) are not thermal insulation materials, but are interesting for thermal building applications. This is why they are mentioned in this context. PCMs change phase from solid to liquid when heated, and therefore absorb energy in the endothermic process. When the ambient temperature falls again, the liquid PCMs will return to a solid state, while releasing the previously absorbed heat in an exothermic process. Such a phase change stage stabilizes the interior building temperature and reduces the heating and cooling loads. Various paraffins are classic examples of PCMs, although low thermal conductivity and large volume change during phase transition limits their building application (Farid et al., 2004; Hasnain, 1998). A synopsis of the major PCMs has been provided by Demirbas (2006), but other evaluations of PCMs can be found in works by Griffith, Arashteh and Türler (1995), and Baetens, Jelle and Gustavsen (2010). An appropriate phase change temperature range that depends on climatic conditions and preferred comfort temperatures, as well as the capability to absorb and release large amounts of heat, is significant for the selection of a specific PCM for building applications. The work by Dieckmann (2008) configures subsequent melting enthalpies and melting temperatures for various groups of PCMs.

2.5 Summary

Various types of insulation materials are often hastily incorporated into conventional construction. They may provide good performance by increasing the energy efficiency in building and houses. However, it is necessary to reassess the current construction method and insulation approach. Alternative houses with higher thermal masses and efficient insulation materials can solve the problem of heat loss/gain through house envelopes. Insulation materials should be compared in order to specify the most efficient and effective insulating material. These materials include mineral wool, cellulose, fibreglass, plastic fibre, cotton, natural fibre, sheep’s wool, straw, polystyrene, polyisocyanurate, polyurethane, vermiculite, perlite, urea-formaldehyde, cementations foam, phenolic foam, and insulation facings insulation. The R-value of an insulating material is the thermal resistance to conductive heat flow. The greater the R-value, the greater the insulating effectiveness and depends on its thickness, density and type of insulation.

CHAPTER 3 SIMULATED HOUSE WALLSFOR CONVENTIONAL AND NEW HOUSE DESIGNS

3.1 Design Patterns of Australian Houses

Over several centuries, Australia’s residential landscape has contained a rich mix of different architectural styles. Building in Australia can be divided into two main categories: residential and non-residential or commercial buildings. For Australian residential houses, there are four types of external house walls in use. They are: a) timber weatherboard b) fibro cement weatherboard c) single brick veneer and d) double brick veneer house wall.

a) Timber Weatherboard House

Timber weatherboard houses were a general housing choice in the 19th and early 20th centuries. The external wall is made of cladding timber with plasterboard for internal walls as shown in Figure 3.1. Today, timber weatherboard houses are a rarely built due to their energy performance and fire hazard.

a) Schematic of timber weatherboard house wall b) Typical timber weatherboard house

Figure 3.1: Timber weatherboard house

b) Fibre Cement Weatherboard House

Fibro cement cladding house construction is quite similar to that of weatherboard houses. Fibro cement made of composite material (cement, cellulose fibres and ground sand).Nowadays this house wall is becoming a replacement for timber weatherboard. The use of fibro cement as an external facade material has grown for both commercial and residential buildings. The advantage of this construction is that it is lightweight and easier to build, as shown in Figure 3.2.


a) Schematic of fibro cement house wall b) Typical fibro cement weatherboard house

Figure 3.2: Fibro cement weatherboard house

c) Double Brick Veneer House

In the 1900s, the Australian state of Victoria introduced the first identifiable brick veneer house wall, built in Geelong. By 1950, double brick construction had almost been replaced by brick veneer in Victoria. Currently, brick veneer walls have become one of the most common house construction types in Australia (Abdou & Budaiwi, 2005). The double brick house is illustrated in Figure 3.3.


a) Schematic of double-brick house wall b) Double-brick house

Figure 3.3: Double brick house

d) Single Brick Veneer House (Conventional House)

A brick veneer wall requires less construction materials compared to a double brick wall. The single brick veneer wall is also less expensive. A brick veneer wall is thus lighter, and it can reduce the labor costs and materials transport costs (Alo, 2010). The maintenance costs are minimal for a single brick veneer house wall. Brick veneer also has a lesser tendency to shift or crack compared to a double brick wall (Alo, 2010). A typical single brick house is illustrated in Figure 3.4.

a) Schematic of single-brick house wall

b) Typical single-brick house

Figure 3.4: Single brick house (conventional house)

The brick veneer wall does not increase the structural integrity of a house because it is installed as a separate outer layer. When cracks or openings develop over time, brick veneer can suffer potential water damage. Water can enter through the cracks or openings between the bricks. Most of the brick veneer is installed on the outside of a timber frame. The timber may become rotted by water which is trapped between the brick and timber frame. In extreme cases, the rotting timber frame can cause structural failure to the house (Reneckis & LaFave, 2012; Abdou & Budaiwi, 2005). As most residential houses are made of single brick veneer, it is the largest energy consumer in developed nations, including Australia. More than 35% of total heat escapes through un-insulated house wall systems (Abdou & Budaiwi, 2005). The brick wall is decorative and non-structural because it is applied to the outside of pre-existing walls (Leslie, 2009). Therefore, this study will focus on external house wall systems to find alternative wall envelopes to improve their energy performance. The new house wall system with appropriate insulation materials will result in reducing heating and cooling loads and thus reduce energy consumption (Alam et al., 2009).

3.2 Description of Simulated House

3.2.1 House Plan View and Dimensions

In this study, a 3-bedroom house with a conventional house wall system and a new house wall system were selected. The average floor area is 100.2m² and the total physical volume is approximately 460m^3. The house consists of a living or dining area, kitchen, three bedrooms, bathroom and toilet, as shown in Figure 3.5. Many forms and construction materials are included in Australian residential practices. The construction materials used in this study were selected based on the standard of Building Code of Australia (BCA). The breakdown of the house flooring area is shown in

Table 3.1.

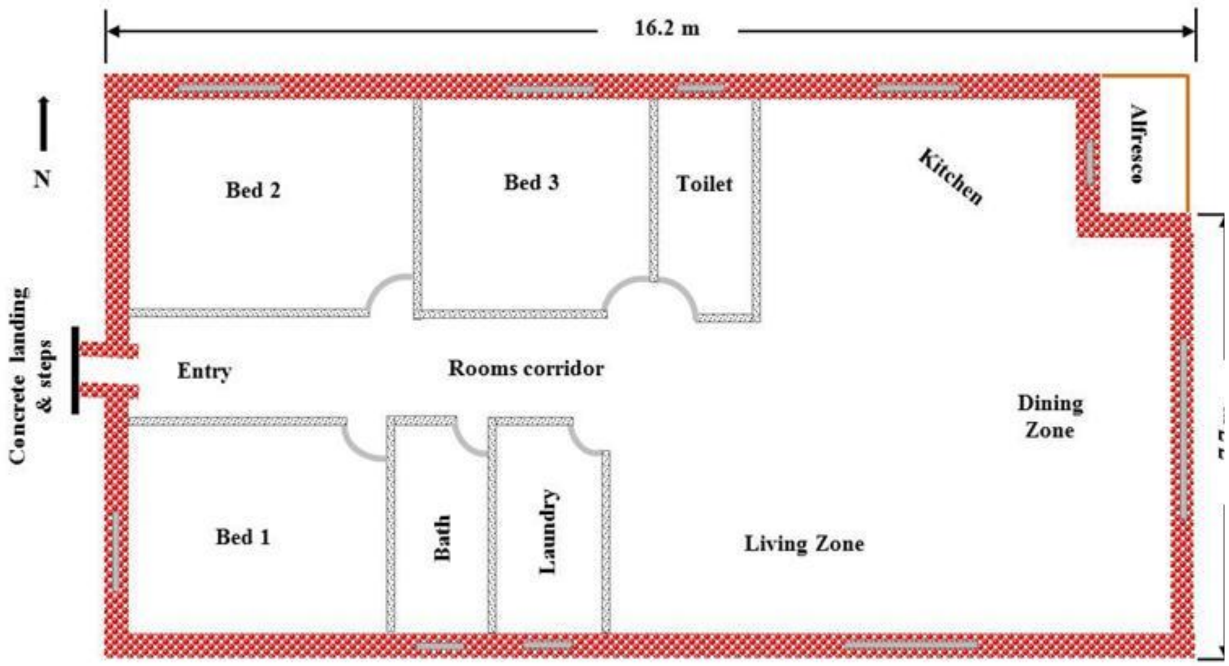


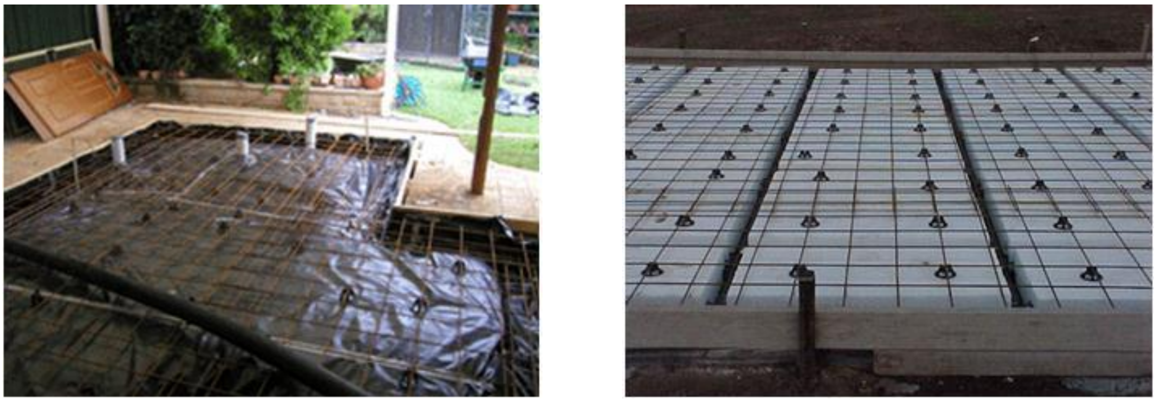
Figure 3.5: A plan view of typical residential 3 bedrooms house, (Aldawi et al., 2013)

Table 3.1: House area details

House description	Dimension	Unit	House description	Dimension	Unit
Entry area	3.8	m^2	Total tiled roof area	125.0	m^2
Rooms corridor area	3.6	m^2	Total steel deck roof area	23.0	m^2
Kitchen area	14.2	m^2	Windows area	32.9	m^2
Bed 1 area	9.1	m^2	External wall perimeter length	47.0	m
Bed 2 area	10.0	m^2	External walls area (total)	112.0	m^2
Bed 3 area	10.2	m^2	Internal walls area	78.5	m^2
Bath area	6.2	m^2	External door area	1.8	m^2
Toilet area	3.8	m^2	Wall height	2.4	m
Laundry area	5.5	m^2	Roof space volume	143.0	m^3
Dining & living area	36.5	m^2	Condition floor area	80.0	m^2
Landing and steps area	2.5	m^2	Total tiled roof area	125.0	m^2
Alfresco area	7.2	m^2	Total area	110.0	m^2
Total floor area excluding alfresco, landing	100.2	m^2	External walls area (excludes windows)	80.7	m^2

3.2.2 Floor Structure

A reinforced concrete slab-on-ground has been used in many states and territories of Australia for residential building. For more than a half century, reinforced concrete has progressively been replacing the suspended timber methods that had been used traditionally. The concrete slab foundation with thermal insulation properties generally assists in improving the thermal performance of houses. The concrete slab foundation is supported by reinforced steel beams. It is required that a minimum of 40mm of concrete covers the reinforcement steel beams (BCA). There are two general types of concrete foundations widely used in Australia: H-class concrete slabs, which mean a highly reactive clay site with high ground movement, and a trench full of reinforced concrete with 100mm thickness; the other type is the waffle concrete foundation, which is become more popular due to its better insulation properties and lower construction costs (Standards Australia, 1996). However, the floor foundation used in this study is an H-class reinforced concrete slab with a 110mm thickness concrete slab. In this study, the foundation is kept the same for all house wall systems. Figure 3.6 illustrates both typical reinforced concrete foundation used in Australia. Table 3.2 shows the built elements for the foundation used in the study.



a) H-class reinforced concrete slab

b) Waffle concrete foundation

Figure 3.6: Common type of reinforced concrete foundation used in Australia

Table 3.2: Foundation built elements details

Zone	Floor	Construction	Area (m)^2	Under floor	Edge insulation
Bed 1	1	Concrete slab 100 mm; bare/bare	9.10	Ground	None
Bed 2	1	Concrete slab 100 mm; bare/bare	9.97	Ground	None
Bed 3	1	Concrete slab 100 mm; bare/bare	10.18	Ground	None

Bath	1	Concrete slab 100 mm; bare/bare	6.04	Ground	None
kitchen	1	Concrete slab 100 mm; bare/bare	11.57	Ground	None
Living	1	Concrete slab 100 mm; bare/bare	35.74	Ground	None
Laundry	1	Concrete slab 100 mm; bare/bare	5.28	Ground	None
Rooms corridor	1	Concrete slab 100 mm; bare/bare	6.10	Ground	None
Entry	1	Concrete slab 100 mm; bare/bare	3.60	Ground	None
Toilet	1	Concrete slab 100 mm; bare/bare	2.62	Ground	None

3.2.3 House Structure

The traditional house structure most commonly used in Australia is timber construction. There are two kinds of structural timber materials predominantly used: hardwood and softwood. Softwood structural timbers are manufactured from kiln-dried Radiata Pine. Structural Pine is lightweight and easy to install. Structural Pine is strong, and it has stable dimensions. Hardwoods are made of angiosperm trees, which have a more complex structure than softwoods. Softwood is much widely used in Australia residential houses to make house wall studs or wall frames because it is widely available in Australia. The wall studs are typically spaced 400mm or 500mm from centre to the centre and are the vertical support frame from top to bottom. Solid steel frames are used to support base and top wall studs. Most new homes have a brick veneer wall construction, with an external skin of brickwork and an internal wall frame made of plaster board. In this study, a reinforced concrete structure is used as an alternative design for a new house wall. Further details about house wall configurations are given in Section 3.3. Figure 3.7 illustrates a typical timber house structure of conventional house used in Australia.

Figure 3.7: A typical house timber structure for a conventional house used in Australia

3.2.4 Wall Insulation

For a thermally efficient house, insulation is the most significant aspect. There are two main categories of insulation products. These are bulk and reflective or/and combination between them. All types of bulk insulation are produced from one material with R-value for a given thickness. In insulation terms, the ‘R’ value is used to measure the product’s resistance to heat transfer and it is a guide to house wall performance. The higher ‘R’ values indicate efficient insulation to reduce heat flow. For houses built in Melbourne, and in order to achieve a 5-star energy rating, the minimum recommended ‘R’ value is R2.5 to R3.0 for ceilings and R1.5 for external walls. In conventional houses, reflective and non-reflective insulation materials are used (Lstiburek, 2004). Bulk insulation mainly resists heat transfer for two modes: conduction and convection. For heat transfer in radiation mode, it is appropriate to use reflective insulation due to low emissivity (ability to re-radiate heat). Aluminum laminated foil is usually used in reflective insulation. The insulation materials used in this study, based on the literature review, are expanded polystyrene, cellulose fibre, rock wool, sheep wool, straw board, glass fibre and woodchip board.

3.2.5 Doors

The house has two external doors (front and rear). The main front door is made of solid wood, while the interior doors are made of hollow wood panels. The dimensions of the main door are 2040mm high × 820mm wide × 0.035mm thick. The inner doors are made of two layers (10mm) of plaster board and an air gap in between (90mm). In this study, the outer door structure is kept the same for all house configurations.

3.2.6 Roof and Ceiling Structure

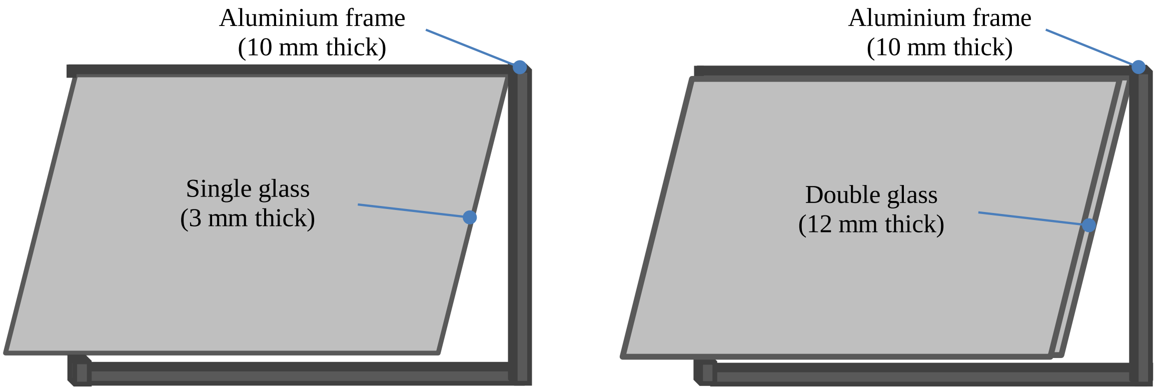
The new residential construction incorporates the use of timber in roof structures with terracotta/concrete tiles. The roof slope angle is 20°, in accordance with the Building Code of Australia (BCA).The minimum BCA requirement for roof insulation is R2.5, as shown in Table 3.3. In Australia, the most commonly insulation material used for roof insulation is glass wool batts. After installing the insulation material, a 10mm plaster board is used for ceiling the roof. To have equal compression for all simulated houses, the roof and its ceiling structure has not been changed.

Table 3.3: Roof and ceiling built elements details

Zone	Ceiling	Construction	Area $(m)^2$	Above ceiling	Opening area
Bed 1	1	Plasterboard 13 mm + R2.5 bulk insulation	9.10	Roof	0.00
Bed 2	1	Plasterboard 13 mm + R2.5 bulk insulation	9.97	Roof	0.00
Bed 3	1	Plasterboard 13 mm + R2.5 bulk insulation	10.18	Roof	0.00
Bath	1	Plasterboard 13 mm + R2.5 bulk insulation	6.04	Roof	0.00
kitchen	1	Plasterboard 13 mm + R2.5 bulk insulation	11.57	Roof	0.00
Living	1	Plasterboard 13 mm + R2.5 bulk insulation	35.74	Roof	0.00
Landry	1	Plasterboard 13 mm + R2.5 bulk insulation	5.28	Roof	0.00
Rooms corridor	1	Plasterboard 13 mm + R2.5 bulk insulation	6.10	Roof	0.00
Entry	1	Plasterboard 13 mm + R2.5 bulk insulation	3.60	Roof	0.00
Toilet	1	Plasterboard 13 mm + R2.5 bulk insulation	2.62	Roof	0.00

3.2.7 Window and Shading

Standard size windows were used in this study as outlined in the BCA. This window is single glazed with a base frame made of aluminium. The standard size of the window is 1800mm × 1200mm and 3mm thickness. In this study, single glazed windows were used for most house wall analysis. However, double glazed windows were used for some simulated houses. Figure 3.8 illustrates a schematic of single and double glazed window used in this study. The overall heat transfer coefficients (U) of single and double glazed windows are 6.35W/m^2.°C and 4.95W/m^2.°C, respectively. No shading effects due to trees and other surrounding buildings are included in this study. Table 3.4 shows windows opening types and sizes used in this study. The windows structure is kept the same for all simulated house wall systems.



a) Single glazed b) Double glazed

Figure 3.8: Schematic of single and glazed window

Table 3.4: Open type and size of windows used in this study (Aldawi et al., 2013)

House description	Window open type	Window size (m^2)	House description	Window open type	Window size (m^2)
Bed 1	Awing	1.8 × 1.2	Living/Dining	Sliding	2.1 × 2.4
Bed 2	Awing	1.8 × 1.2	Living/Dining	Sliding	1.8 × 2.4
Bed 2	Awing	1.8 × 1.2	Living/Dining	Sliding	1.8 × 2.4
Bed 3	Awing	1.8 × 1.2	Living/Dining	Sliding	1.2 × 1.2
Bath	Awing	1.8 × 1.2	Living/Dining	Sliding	2.1 × 2.4
Landry	Awing	1.8 × 1.2			

3.3 House Wall Configuration

As mentioned previously, two house wall systems were selected for this study: a) the brick veneer house wall system as standard and b) the new house wall system. Both house wall systems (conventional and new house) consist of the same internal walls, roof, foundation and windows. The change was only in the external wall configuration. The standard height of house walls is 2.5m in accordance with the BCA.

3.3.1 Conventional House Wall

The external wall of the conventional house consists of 110mm external brick, 40mm air gap and 90mm timber frame structure. The sarking material is attached around the external structure of the timber with a 2mm thickness. Fibreglass insulation with thickness of 59mm is inserted in between the external timber structure and the internal plaster board (10mm thick.) The schematic of the brick veneer house wall used in this study is shown Figure 3.9. Figure 3.10shows a typical conventional house used in Australia. The conventional house wall construction and dimensions are shown in Table 3.5.

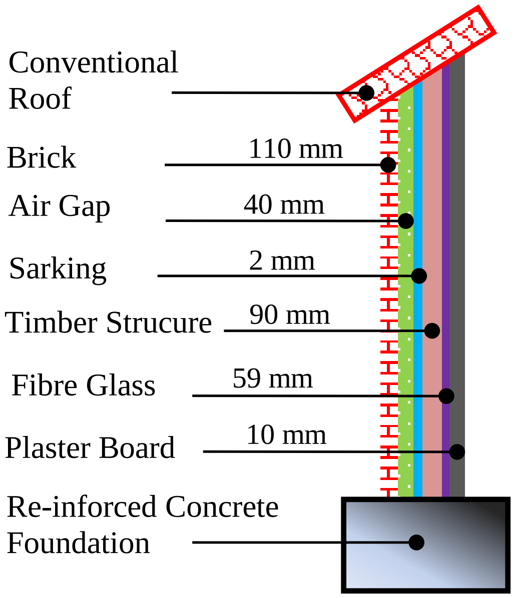


Figure 3.9: Schematic of conventional house wall configuration

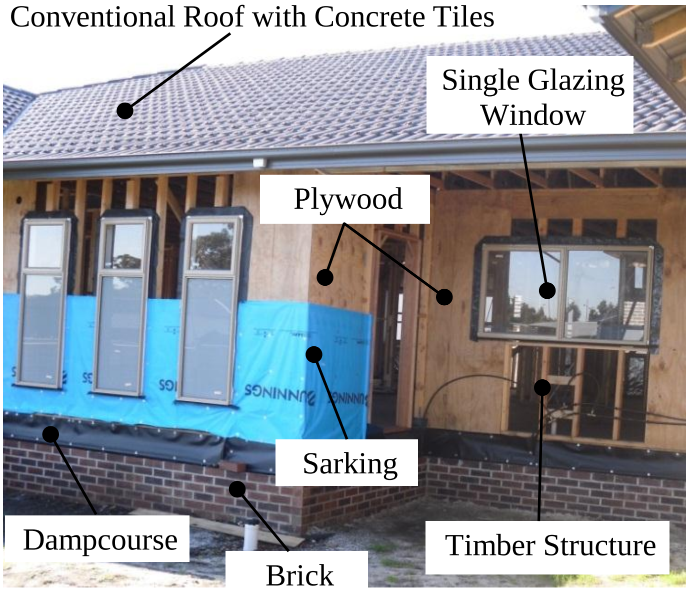


Figure 3.10: Typical conventional house wall system under construction, Australia

Table 3.5: Conventional house construction and dimensions

Layer	Construction type	Construction description	Thickness (mm)
1	External wall	Brick veneer: extrude clay brick (typical density)	110
2	External wall	Air gap vertical 31-65mm (40 nominal)	40
3	External wall	Timber (softwood)	90
4	External wall	Plywood	10

4	External wall	Insulation batt, fibreglass (R1.5)	59
5	External wall	Plaster board	10
1	Roof	Tiles (concrete)	20
1	Window	Single glass	3
1	External door	Timber (hardwood)	50
1	Floor	Concrete slab: bare/bare	100
2	Floor	Polyester/wool blanket (R1.5)	68
1	Ceiling	Plaster board	10
1	Internal door	Particleboard	10
2	Internal door	Air gap vertical > 66 mm, unventilated	86
3	Internal door	Particleboard	10
1	Skylight and roof window	Nil	Nil

In this study, the major change in the simulated house was in external walls, whereas other house elements were kept unchanged. With the new house wall, different construction methods and insulation materials are used to investigate the house wall thermal performance in order to achieve an optimum house wall design. The following section explains different designs for a new house wall. Further detail of house wall materials and specifications is shown in Appendix A.

3.3.2 Design 1: New House Wall with Two Panels of Polystyrene Insulation (Outer and Inner)

Design 1 consists of reinforced concrete with double-sided insulation panels. The wall is made of 10mm thick render, 118mm (59mm and 59mm) polystyrene as insulation materials, 150mm reinforced concrete panel, and 10mm plaster board on the inside. The schematic of the new wall system is shown in Figure 3.11.

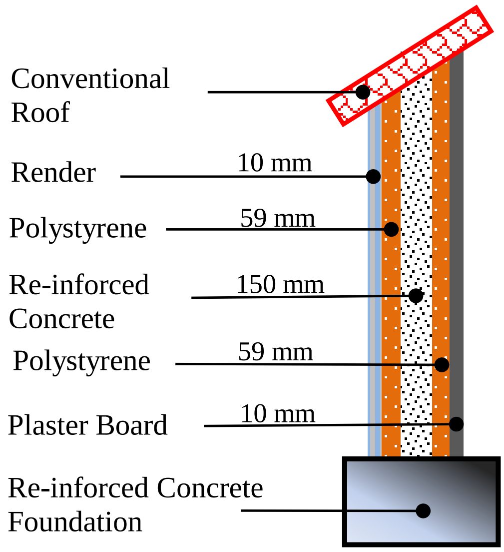


Figure 3.11: Schematic of new house wall configuration (Design 1)

3.3.3 Design 2: New House Wall with One Panel of Polystyrene Insulation – (Outer Position)

Design 2 consists of reinforced concrete and single side insulation panel. The insulation panel is polystyrene, placed on the outside of the house wall. The system is made of 10mm exterior render put on the outside of the wall, 59mm polystyrene, 150mm reinforced concrete and 10mm plaster board placed on the inside of the house wall. The schematic of this system is shown in Figure 3.12.

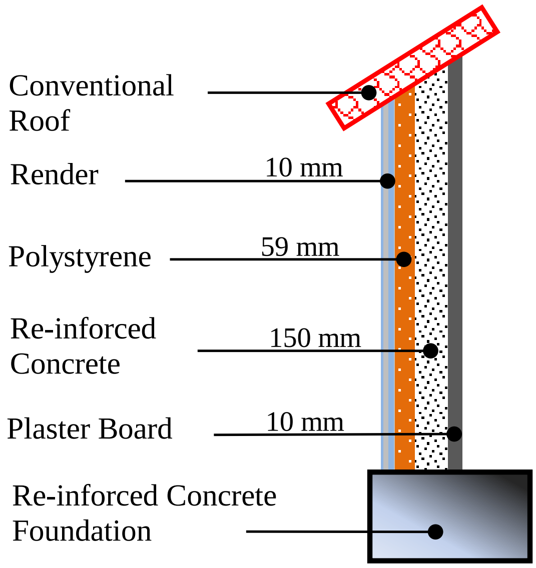


Figure 3.12: Schematic of new house wall configuration (Design 2)

3.3.4 Design 3: New House Wall with One Panel of Polystyrene Insulation – (Inner Position)

This design has similar construction materials as Design 2 with a change in construction material sequence only. The insulation panel is polystyrene, placed on the inside of the house wall. The system is made of 10mm exterior render, 150mm reinforced concrete, 59mm polystyrene and 10mm plaster board placed on the inside of the house wall. The schematic of this system is shown in Figure 3.13.

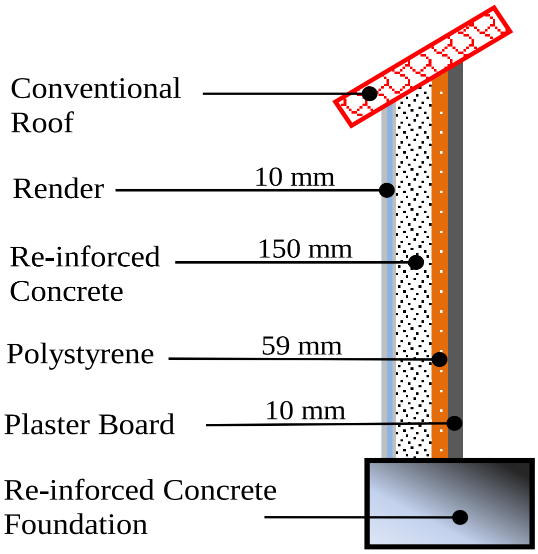


Figure 3.13: Schematic of new house wall configuration (Design 3)

3.3.5 Design 4: New House Wall with Two Half Concrete Panels and One Panel of Polystyrene Insulation in-between

Design 4 consists of single insulation with double-sided reinforced concrete panels. The insulation panel is polystyrene, placed in between reinforced concrete panels. The wall is made of 10mm render, 150mm (75mm and 75mm) reinforced concrete panel, 59mm polystyrene as insulation materials and 10mm plaster board placed on the inside of the house wall. The schematic of Design 4 is shown in shown in Figure 3.14.

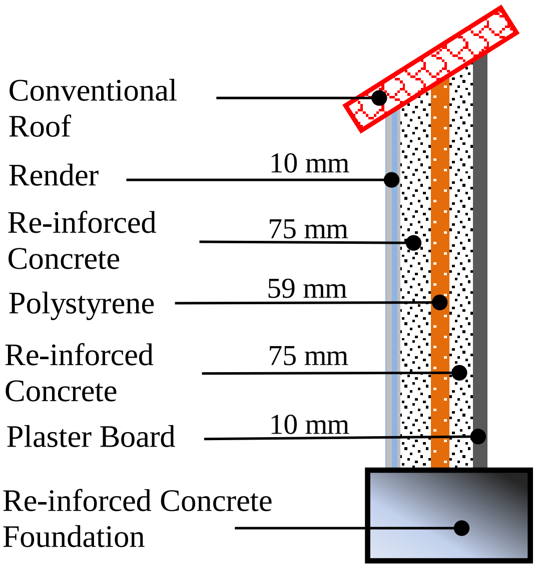


Figure 3.14: Schematic of new house wall configuration (Design 4)

3.3.6 Design 5: New House Wall with Two Half Concrete Panels and Two Panels of Polystyrene Insulation in-between

Design 5 has a similar construction material as Design 4; the difference is only in the insulation layer. The insulation panels are double polystyrene placed in between reinforced concrete panels. The wall is made of 10mm render, 150mm (75mm and 75mm) reinforced concrete panel, 118mm (59mm and 59mm) polystyrene and 10mm plaster board placed on the inside of the house wall. The schematic of Design 5 is shown Figure 3.15.

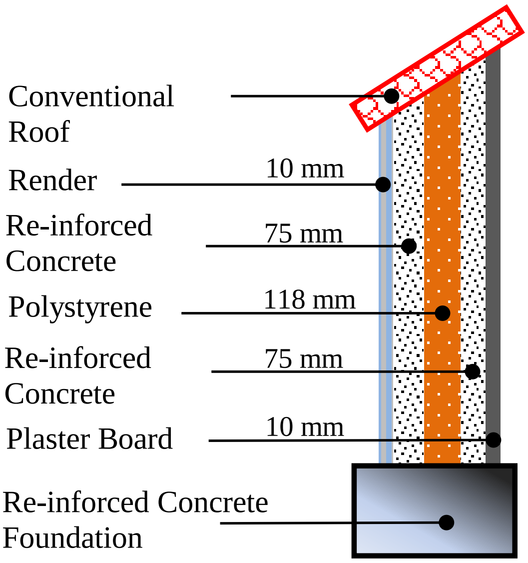


Figure 3.15: Schematic of new house wall configuration (Design 5)

3.3.7 Design 6: New House Wall with Two Half Concrete Panels and One Panel of Polyurethane Insulation in-between

Design 6 also has similar construction materials as Design 4; it differs only in the type of insulation material used. The insulation material is single polyurethane placed in between reinforced concrete panels. The wall is made of 10mm render, 150mm (75mm and 75mm) reinforced concrete panel, 59mm polyurethane and 10mm plaster board placed on the inside of the house wall. The schematic of Design 6 is shown in Figure 3.16.

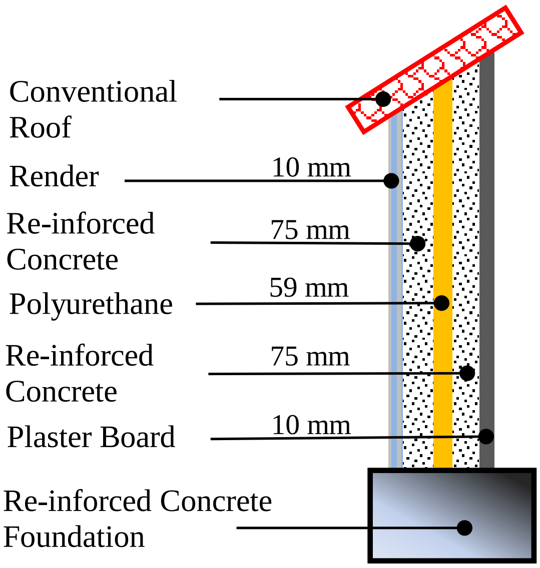


Figure 3.16: Schematic of new house wall configuration (Design 6)

3.3.8 Design 7: New House Wall with Two Half Concrete Panels and Two Panels of Polyurethane Insulation in-between

Design 7 has similar construction material as Design 6, but is different only in the insulation layer. The insulation panels are double polyurethane placed in between reinforced concrete panels. The wall is made of 10mm render, 150mm (75mm and 75mm) reinforced concrete panels, 118mm (59mm and 59mm) polyurethane and 10mm plaster board placed on the inside of the house wall. The schematic of Design 7 is shown in Figure 3.17.

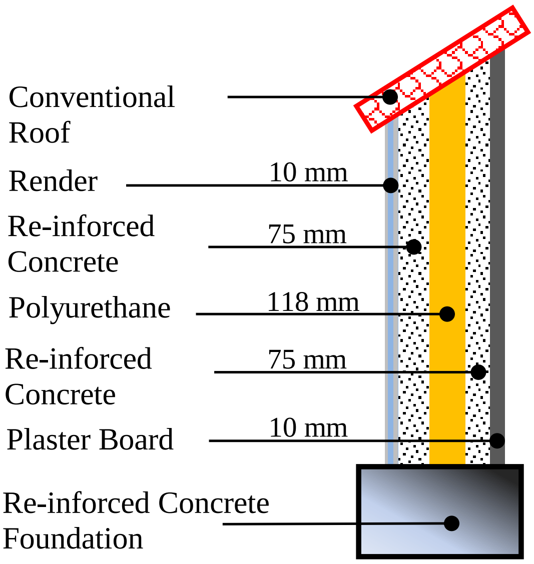


Figure 3.17: Schematic of new house wall configuration (Design 7)

3.3.9 Design 8: New House Wall with Air Gap and One Panel of Polystyrene Insulation

Design 8 consists of single insulation with single side reinforced concrete panel. Design 8 is made of 10mm external cladding (render), 150mm reinforced concrete, 40mm air gap, 59mm polystyrene insulation and 10mm plasterboard placed on the inside of the house wall. The schematic of Design 8 is shown in Figure 3.18 .

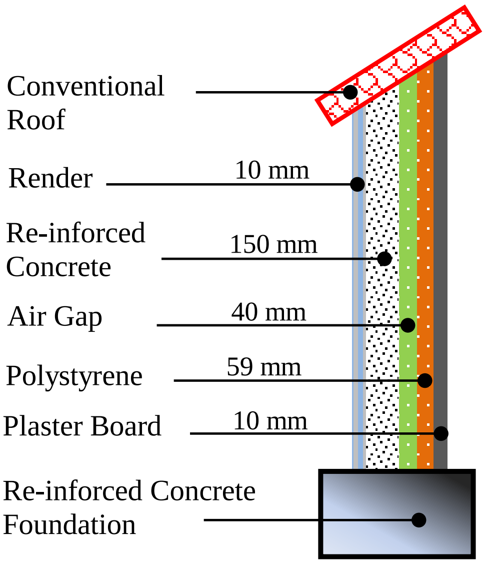


Figure 3.18: Schematic of new house wall configuration (Design 8)

3.3.10 Design 9: New House Wall with One Panel of Polystyrene Insulation and Air Gap

Design 9 has similar construction material as Design 8, differing only in material sequences. Design 9 consists of 10mm render, a layer of reinforced concrete panel with 150mm thickness and standard 59mm polystyrene insulation. Then 40mm of the air cavity is left before installing the interior part, which is made of 10mm plasterboard. The schematic of a new wall is shown in Figure 3.19.

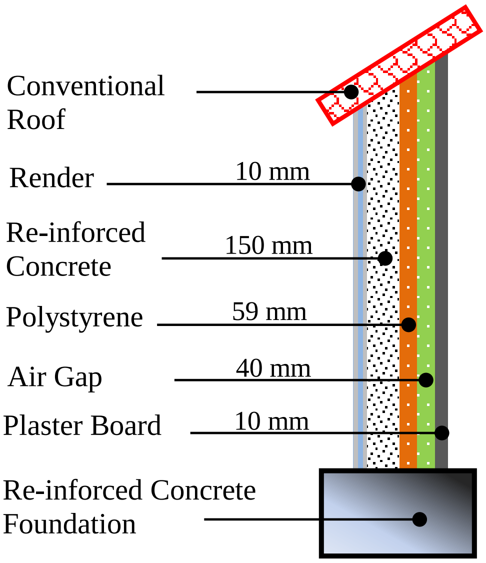


Figure 3.19: Schematic of new house wall configuration (Design 9)

3.3.11 Design 10: New House Wall with One Panel of Polystyrene Insulation (Outer) and Air Gap (Inner)

Design 10 consists of single insulation with single side reinforced concrete panel. Design 10 is made of 10mm render, standard 59mm polystyrene insulation, a layer of reinforced concrete panel with 150mm thickness. Then, 40mm of the air cavity is left before installing the interior part which is made of 10mm plasterboard. The schematic of a new wall is shown Figure 3.20.

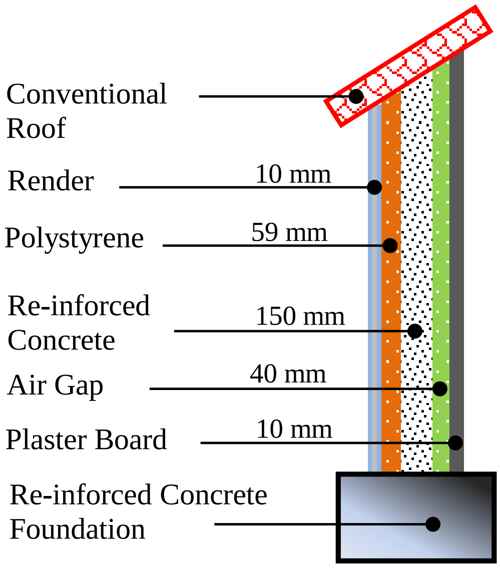


Figure 3.20: Schematic of new house wall configuration (Design10)

3.3.12 Design 11: New House Wall with One Panel of Polystyrene Insulation (Inner) and Air Gap (Outer)

Design 11 has similar construction material as Design 10 but differs in material sequences. Design 11 consists of 10mm render, 40mm of the air cavity, a layer of reinforced concrete panel with 150mm thickness. Then, come standard 59mm polystyrene insulation and the interior part, which is made of 10mm plaster board. The schematic of a new wall is shown in Figure 3.21.

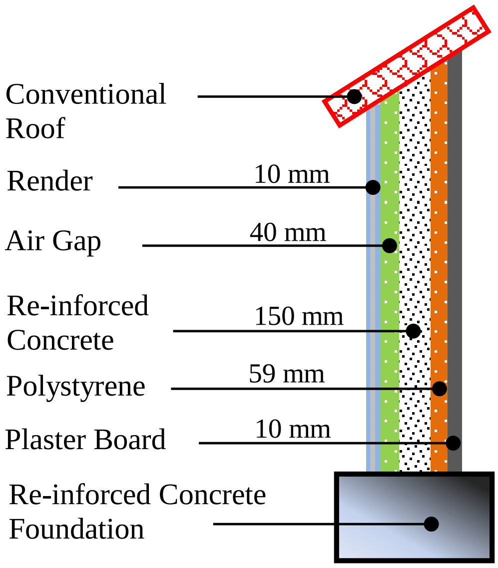


Figure 3.21: Schematic of new house wall configuration (Design 11)

3.3.13 Design 12: New House Wall with Two Panels of Rockwool Insulation – (Outer and Inner Positions)

Design12 consists of reinforced concrete with double sided insulation panels. The wall is made of 10mm render, 118mm (59mm and 59mm) rock wool as insulation material, 150mm reinforced concrete panel, and 10mm plaster board on the inside. The schematic of the new wall system is shown in Figure 3.22.

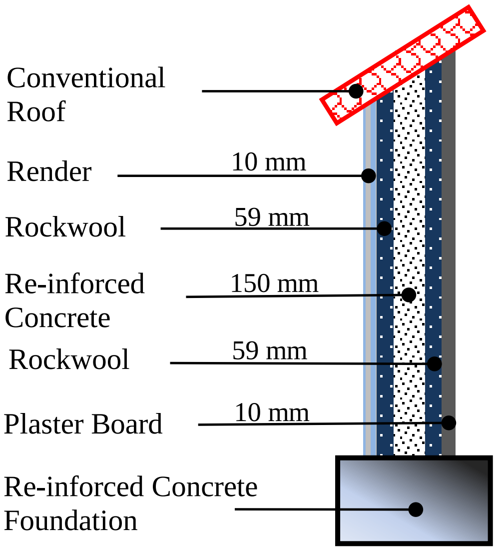


Figure 3.22: Schematic of new house wall configuration (Design 12)

3.3.14 Design 13: New House Wall with Two Panels of Sheep Wool Insulation – (Outer and Inner Positions)

Design 13 has similar construction material as Design 12 but differs in insulation material. Design13 consists of reinforced concrete with double-sided insulation panels. The wall is made of 10mm render, 118mm (59mm and 59mm) sheep wool as insulation materials, 150mm reinforced concrete panel, and 10mm plasterboard on the inside. The schematic of the new wall system is shown in Figure 3.23.

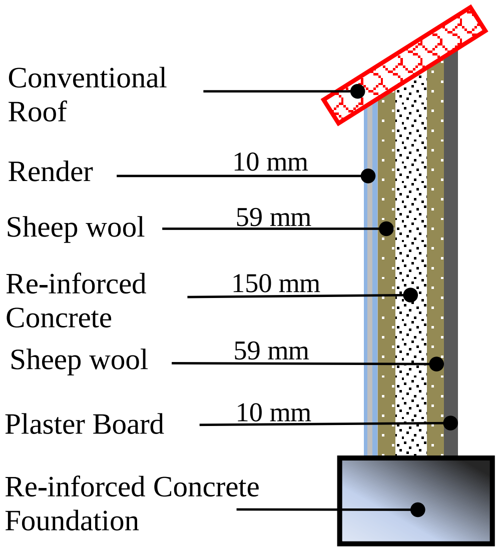


Figure 3.23: Schematic of new house wall configuration (Design 13)

3.3.15 Design 14: New House Wall with Two Half Concrete Panels and Two Panels of Rockwool Insulation in-between

Design 14 has similar construction material as Design 7 but with different type of insulation material. Design 14 consists of double insulation with double sided reinforced concrete panels. The wall is made of 10mm render, 150mm (75mm and 75mm) reinforced concrete panel, 118mm (59mm and 59mm) rock wool and 10mm plaster board on the inside. The schematic of Design 14 is shown in Figure 3.24.

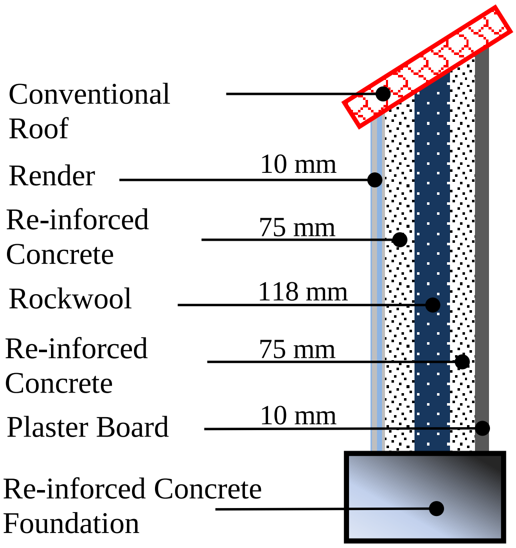


Figure 3.24: Schematic of new house wall configuration (Design 14)

3.3.16 Design 15: New House Wall with Two Half Concrete Panels and Two Panels of Sheep Wool Insulation in-between

Design 15 has similar construction material as Design 14 but with different insulation material. Design 15 consists of double insulation with double sided reinforced concrete panels. The wall is a made of 10mm render, 150mm (75mm and 75mm) reinforced concrete panel, 118mm (59mm and 59mm) sheep wool and 10mm plaster board on the inside. The schematic of Design 15 is shown in Figure 3.25.

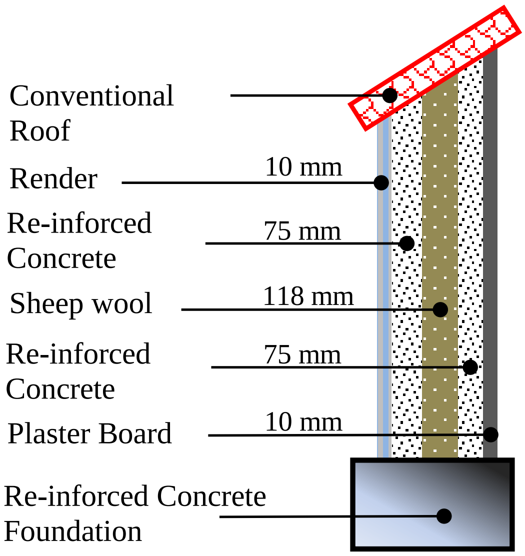


Figure 3.25: Schematic of new house wall configuration (Design 15)

In this study, different house wall designs were used. All new house wall construction materials and dimensions are shown in Table 3.6.

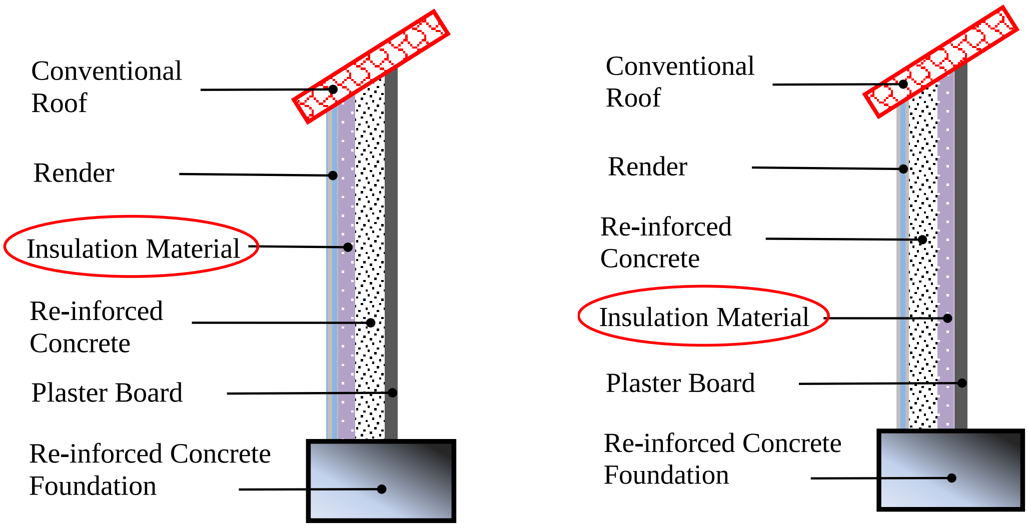
Table 3.6: New house construction materials & dimensions for all designs

Layer	Construction type	Construction description	Thickness (mm)
1	External wall	Render	10
3	External wall	Reinforced concrete panel	150
5	External wall	Insulation (different materials, R1.5)	59
1	Roof	Tiles (concrete)	20
1	Window	Single glass	3
1	External door	Timber (mountain ash)	50
1	Floor	Concrete slab: bare/bare	100
2	Floor	Polyester/wool blanket (R1.5)	68
1	Ceiling	Particleboard	10

1	Internal door	Particleboard	10
2	Internal door	Air gap vertical > 66 mm, unventilated	90
3	Internal door	Plaster board	10
1	Skylight and roof window	Nil	nil
1	Insulation	Each house wall has different insulation	59

3.4 Inner and Outer Insulation Position

High thermally resistant wall envelope insulation system significantly can reduce the heat gain/ loss. An external wall insulation system is thermally insulated to protect a house from excessive exterior heating or cooling by using insulation materials such as expanded polystyrene, cellulose fibre-R1.5, rock wool batt, sheep wool, straw board, glass fibre-R1.5 and wood chip board. The internal and external insulation positions are illustrated in Figure 3.26.



a) External insulation b) Internal insulation

Figure 3.26: Schematic of inner and outer installation position

Different sequences of concrete and insulation are modelled via AccuRate. The analysis shows that the interior and exterior insulation position with the wall configurations can significantly affect the annual heating and cooling thermal performance of the whole building. The result shows that there is variation in energy demand for cooling and heating between different wall sequences and configurations.

When the source of heating is shut off, the temperature starts to decrease gradually. In this case, if the insulation materials is installed from outside, the concrete plays a major role in keeping the lag time of inside building heat release slow due to the high thermal capacity of concrete. This allows the heat to fall gradually and escape through the roof, as shown in Figure 3.27.

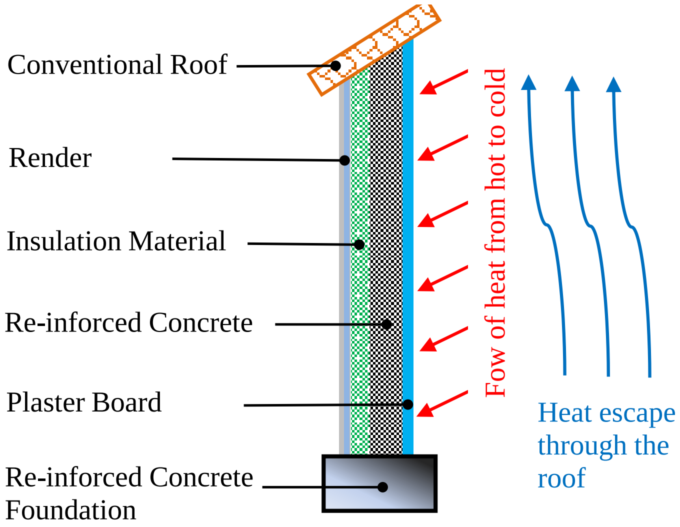


Figure 3.27: Schematic of heat flow when outer insulation position are used

3.5 Summary

A 15 house wall designs were developed in this study to evaluate their thermal performance compared with the current conventional wall system. The 15 designs were selected based on lower energy consumption for heating and cooling that explained in computational simulation (see Chapter 4). The simulation allows the use of easy change in material types, dimensions and thicknesses for all house components (roof, ground and walls). This assists in manipulating house wall materials and construction in order to find the optimum wall design.

CHAPTER 4 COMPUTATIONAL METHOD

4.1 Introduction

The Australian government's National Greenhouse Strategy established a range of measures to calculate and reduce future greenhouse gas emissions (AGO, 2011). In order to reduce the energy required in cooling or heating in residential houses, the house envelopes of house walls should be improved. As mentioned previously, around 40% of the total energy used in Australian residential houses is consumed in space heating and/or cooling. The use of heating and cooling is considered by the Australian government in order to reduce the excessive use of energy. A range of measures has been developed by governments to achieve a reduction in residential greenhouse gas emissions. This reduction can be achieved by finding alternative house envelope designs. The government of Australia has introduced a star-ratings energy system for new Australian residential housing for space heating and cooling (Drogemuller et al., 1999). Several energy simulation software packages have been developed to estimate energy required for space heating and/or cooling. This Chapter discusses the context of energy needs for space heating and/or cooling for Australian residential houses.

4.2 Energy Rating Tools in Australia

The first thermal performance requirements for residential houses were introduced by the Building Code of Australia (BCA). In 2003, rating methods were approved for a minimum thermal performance of 4 Stars. In 2006, the performance requirement increased to 5 Stars and progressively increased to 6 Stars in 2010. This move from 4 to 6 stars has presented a challenge for the building sector to find ways to reduce house heating and cooling energy. There are several commercially developed energy simulation software packages currently available in Australia. The first generation simulation energy rating tools in Australia were Green Star, ABGR, NatHERS, FirstRate, BASIX, BERS Pro, NABERS and AccuRate. However, these software packages cannot be used universally for all climate conditions due to the unavailability of data for local climates, construction materials and house design patterns. Brief detail about this software is provided in the following section.

4.2.1 FirstRate5

FirstRate5 was developed by the Department of Sustainability of the Victorian Government. This software assists in completing and improving the energy efficiency of a house. In FirstRate5, the user is required to enter the house plan at the sketch design stage to provide a simple and quick method to estimate energy need. This quick method provides various design features such as building materials, windows, insulation materials and house orientation to help measure the energy efficiency of the house. FirstRate5 is the improved version and its second generation rating software was released in 2007. FirstRate5 can be used in Victoria as well as in different states and territories, such as the ACT, Western Australia and South Australia. The output of selected house materials and designs provides an overall rating of 0 to 10 stars and energy required for cooling and heating in MJ/m^2.annum. Figure 4.1 shows the house plan view used in this study.

Name | Value
Name | Level 1

North offset (degrees) 0,0

Note: Data has been entered via the Zoning tables. This may affect the rating.

Figure 4.1: House plan view used in this study drawing by FirstRate5

4.2.2 Nationwide House Energy Rating Scheme (NatHERS)

NatHERS software is an energy rating tool developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO).Lists of guidelines were set by the NatHERS scheme that must be followed by all energy rating tools. The NatHERS scheme helps to ensure that houses in all regions are treated fairly in their energy rating. The NatHERS scheme is widely used in different climatic conditions. The input data to this software must include house information such as construction and insulation materials, window size and type, house orientation, ventilation and shading, etc. The software provides information on the house’s thermal performance month by month. It also provides the amount of heating and cooling energy needed to keep the house in high thermal comfort. The energy thermal performance is shown in a star rating ranging between 1 and 5 stars. NatHERS software is controlled by the Australian Greenhouse Office (AGO). In 2006, a major revision to the

NatHERS was introduced by AGO to develop an advanced second generation of energy rating software called AccuRate software.

4.2.3 Building Energy Rating Scheme (BERS Pro)

Generally BERS Pro software uses the same mathematical engine as NatHERS. BERS Pro software needs the same house level of information and details as NatHERS software but the entry data is in a graphical interface. It is used to estimate the energy level required for heating and cooling. This software is more widely used in Queensland due to that state's hot humid climate. BERS was developed in Brisbane by Solar Logic. Solar Logic provides training courses to recognised BERS users. BERS Pro is the professional version and the advanced second generation of BERS.

4.2.4 National Australian Built Environment Rating System (NABERS)

The NABERS is a rating tool used to calculate existing buildings energy needs for office and residential buildings based on their operation, users and environmental impact. NABERS is used to estimate energy required, including refrigeration, appliances, hot water systems, rainwater, pollution and sewage water. NABERS is used for a whole life approach, which covers a wide range of issues such as landscape, transportation systems, indoor air quality, waste and toxic materials. NABERS cannot be used at the design stage. NABERS was developed by the NSW Department of Environment and Climate Change (DECC) in 2008. NABERS has two versions: home and office. It provides a star scale rating of 1 to 5.

4.2.5 Building Sustainability Index (BASIX)

In 2005, BASIX software was created and introduced by the Government of New South Wales to study the thermal performance of new residential houses and to examine the impact of new house materials on the environment. The Government introduced BASIX into the approval process and development to save power consumption and water. It is designed to evaluate the energy required for new houses against thermal performance, including thermal comfort, water and range of sustainability. The architects and property developers can enter details of their property designs using BASIX software. The new house envelopes must meet energy requirements relating to the thermal performance of those houses based on heating and cooling energy needs. BASIX software can be used with single or multi-level floors of residential houses. To run the simulation, the user must answer several questions about the houses development, such as house location, size and landscape. When all questions are answered, the user is able to obtain a certificate to meet the target of house thermal performance (Eckstein, 2006)

4.2.6 Green Building Council of Australia (GBCA)

The Green Building Council of Australia (GBCA) is developing the Green Star program to be used for rating commercial offices and buildings. A wide range of environmental features were input into Green Star such as indoor air quality, energy performance, transport system, water, construction materials, land organization and use. The Green Star tool integrates another rating tool ABGR in its calculation. The Green Star tool provides an energy rating from 0 to 6 stars, 5 stars mean the commercial building is in the best practice and 6 stars is excellent. For example, the Council House 2 of Melbourne achieved 6 star energy raying. The Green Star tool made in Microsoft Excel and it is free to download. It can be used and downloaded from the GBCA website (www.gbcaus.com.au).

4.2.7 Australian Building Greenhouse Rating (ABGR)

The New South Wales Department of Environment and Climate Change (DECC) developed this energy rating tool. The ABGR scheme is an energy rating tool used in commercial offices and buildings. It is based on data and performance of commercial building for 12 months of greenhouse gas emissions. It can be used by other states such as Victoria and Queensland. The website, www.abgr.com.au, has further information for ABGR software.

4.3 AccuRate Software

AccuRate version 1.1.4.1 is the updated and second generation software of NatHERS. AccuRate was developed by the CSIRO and was released in 2005. It is a rating tool that assigns a star rating to a residential building based on its calculated annual heating and cooling energy requirements. The efficiency of heating and cooling equipment is not taken into account. The software can be used with all house designs, whether detached or semi-detached, a unit, townhouse or apartment. In the software, the whole house can be subdivided into a number of zones, each of which includes multiple elements, such as floor, roof, ceiling, walls and windows. Each house element is considered to be composed of a series of homogeneous structures (Walsh & Delsante, 1983). The software has an in-built library of commonly used building materials, their thermal properties, and the climate data for Australia (e.g., 69 micro-climate zones). The AccuRate data library is mainly classified into three sections: construction materials, insulation materials and air gap insulation. The construction materials include timber, brick, steel and reinforced concrete. The insulation materials include polystyrene, cellulose fibre, rock wool batt, sheep wool, straw board, rendered straw bale, glass fibre, wood chipboard and polyurethane rigid foam. The air gap properties are given for ranges of thicknesses (13-16, 17-30, 31-65 and > 65mm), emissivity and inclinations. With respect to emissivity, the key parameter is the effective emissivity (E). All materials used in AccuRate are fully described by a thermal resistance and thermal capacitance. The units of thermal resistance are m^2.K/W. The thermal capacitance is the product of the density and specific heat, and its units in the material tables are kJ/m^3.K.

The following aspects of occupant behaviour are taken into account:

- Heating and cooling operation hours
- Thermostat settings of heating and cooling
- Window operation and other openings to increase ventilation
- Adjustable house elements (walls, roof, ground, window, shading and ceiling).

All the limitations in NatHERS software were considered in the AccuRate version. The BCA accredited AccuRate software as the benchmark for other House Energy Rating Scheme (HERS) software used in the Australian housing sector's energy performance. Other software packages are required to offer results consistent with AccuRate's reliability (Hearne Scientific Software, 2011). AccuRate is widely used and accepted for the simulation of house energy performances in all Australian states and territories (AccuRate Manual, 2013). It calculates the heating and cooling energy requirements hourly over a period of one year, using one year of typical weather data appropriate for the location. The software requires detailed information about the house, such as orientation, construction type, insulation levels, window size and type, window orientation, shading, overshadowing and ventilation (AccuRate Manual, 2013). In this study, AccuRate computational modelling is used to investigate the thermal performance of house wall systems.

4.3.1 AccuRate Standard and Non-Standard Input Data

The AccuRate software requires building specification, including a range of defaults that can be controlled by the user and nonstandard modification (NatHERS 2000). The standard input data that can be modified by users are as follows:

- Thermal simulation can be run by defining the climate file of the selected city by entering the postcode of that city.

- The definition of construction elements of roof, ceiling, walls, floor, doors and windows.
- The definition of built fabric for zone types within all volumes of that fabric.
- The external shading features and the elements definition.
- The built elements details and their relationships to all building elements.
- The building orientation for infiltration calculations.

In this study the non-standard inputs which cannot be modified by users were:

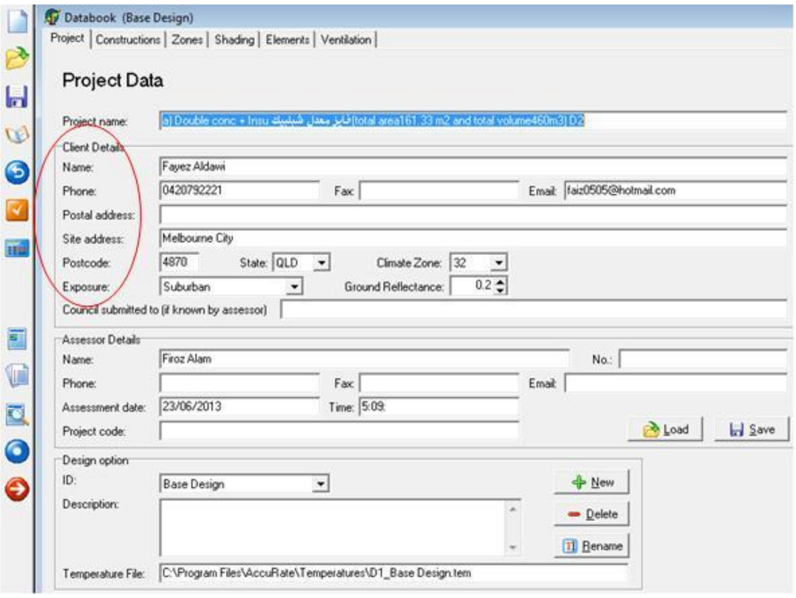
- The fabric ingathering modification to account for framing factors.
- The sensible internal heat gains modification considered for free-running operation.
- The heating and cooling thermostat controls modification considered for free-running operation.
- The sensible internal heat gains modification considered for free-running operation.
- The setting, development and use of a location observed climate file.

4.3.2 Project Input Data

The first page of the screen project requests detail about the project name, city of project, post code, owner contact information, and design options as displayed in Figure 4.2. The project location is specified by entering the postcode of the selected city as a reference. In the project, the user must identify the house exposure type. Exposure describes the type of terrain and obstructions surrounding the building. It sets a factor that multiplies the wind speed read from the weather data file, and another factor that reduces the air flow rates through openings. The definitions of house exposure in AccuRate are:

- Exposed: open and flat country with few or no trees and buildings.
- Open: countryside at a normal area with some trees and dispersed buildings.
- Suburban: buildings that are low rise in suburbs of towns and cities. (This choice is selected in this study.)
- Protected: inside the city with high-density or CBD, close to tall buildings. (AccuRate Manual, 2013)

Design options in AccuRate can be used to keep different versions of the same building within one project file, instead of creating a separate project file for each variation: for example, ‘keep the same external wall construction materials but with different insulation materials or glazing type’. All design options have the same postcode, climate zone, exposure and ground reflectance.



Project Data

Project name: a) Double conc + Insu فايز معدل شبابيك (total area161.33 m2 and total volume460m3) D2

Client Details
Name: Fayez Aldawi
Phone: 0420792221
Fax:
Email: faiz0505@hotmail.com
Postal address:
Site address: Melbourne City
Postcode: 4870
State: QLD
Climate Zone: 32
Exposure: Suburban
Ground Reflectance: 0.2
Council submitted to (if known by assessor)

Assessor Details
Name: Firoz Alam
No.:
Phone:
Fax:
Email:
Assessment date: 23/06/2013
Time: 5:09
Project code:

Design option
ID: Base Design
Description:
Temperature File: C:\Program Files\AccuRate\Temperatures\D1_Base Design.tem

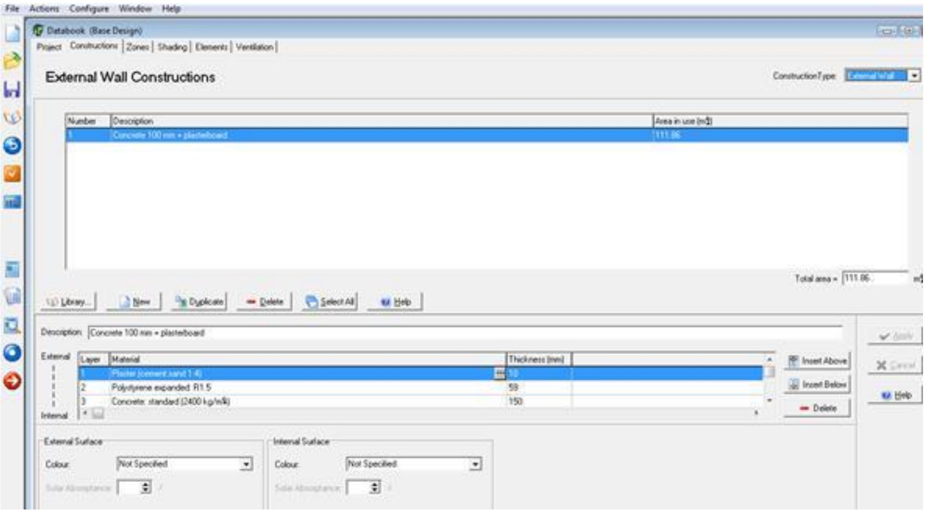
Figure 4.2: The project name and information

4.3.3 Key Input Data in AccuRate

Five key groups of input data are required by AccuRate in order to run the simulation. Those normally are: construction fabric information, zone type, shading scheme feature, built element, ventilation data and house orientation.

4.3.3.1 Construction Fabric Information

The construction details are the second data entry tab in the software. The construction part contains fabric elements for the external walls, doors, floors, ceilings and roofs. It requires selecting the inbuilt materials from the library for all of the house elements to create an assemblage of built fabric matrices. The construction fabrics were selected according to the instructions of BCA. Figure 4.3 shows the construction fabric information input data screen in AccuRate.



ConstructionType: External Wall

Number	Description	Area in use (m²)
1	Concrete 100 mm + plasterboard	111.86

Total area = 111.86 m²

Description: Concrete 100 mm + plasterboard

Layer	Material	Thickness (mm)
1	Plaster (cement:sand 1:4)	10
2	Polystyrene expanded: R1.5	59
3	Concrete: standard (2400 kg/m³)	150

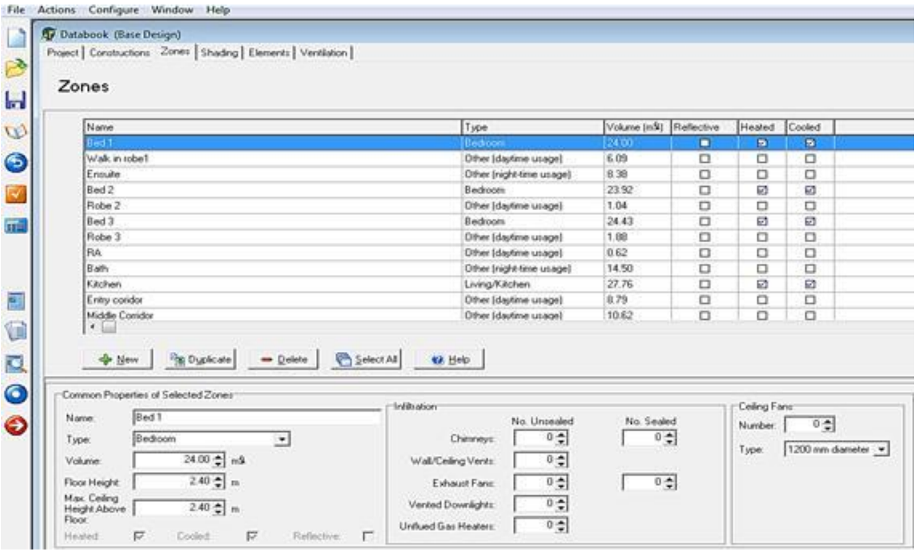
External Surface
Colour: Not Specified

Internal Surface
Colour: Not Specified

Figure 4.3: Input data screen for house construction fabric in AccuRate

4.3.3.2 Zones Type

In this section, the thermal performance test cells of the zone types were entered within the volumes of zone definition. The data entry in this section contains zone name, zone volume, height of floor and ceiling. Each zone is enclosed by elements of house fabric. Each zone gives values for internal heat gains based on human activity, purpose and perceived usage patterns. Heating and cooling parameters are selected based on zone type and ventilation profiles. The house wall resistance value, air change value and air losses or gains through windows could affect the house thermal performance. Figure 4.4shows the screen of zone type in AccuRate software.



Name	Type	Volume (m³)	Reflective	Heated	Cooled
Bed 1	Bedroom	24.00	☐	☑	☑
Walk in robe1	Other (daytime usage)	6.09	☐	☐	☐
Ensuite	Other (night-time usage)	8.38	☐	☐	☐
Bed 2	Bedroom	23.92	☐	☑	☑
Robe 2	Other (daytime usage)	1.04	☐	☐	☐
Bed 3	Bedroom	24.43	☐	☑	☑
Robe 3	Other (daytime usage)	1.88	☐	☐	☐
RA	Other (daytime usage)	0.62	☐	☐	☐
Bath	Other (night-time usage)	14.50	☐	☐	☐
Kitchen	Living/Kitchen	27.76	☐	☑	☑
Entry corridor	Other (daytime usage)	8.79	☐	☐	☐
Middle Corridor	Other (daytime usage)	10.62	☐	☐	☐

Name: Bed 1
Type: Bedroom
Volume: 24.00 m³
Floor Height: 2.40 m
Max. Ceiling Height Above Floor: 2.40 m
Heated: ☑ Cooled: ☑ Reflective: ☐

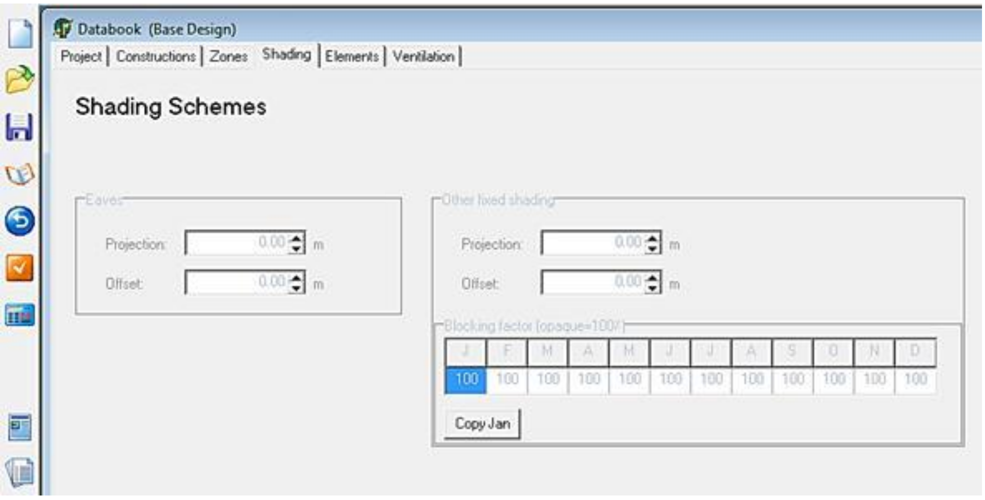
	No. Unsealed	No. Sealed
Chimneys:	0	0
Wall/Ceiling Vents:	0	
Exhaust Fans:	0	0
Vented Downlights:	0	
Unflued Gas Heaters:	0	

Number: 0
Type: 1200 mm diameter

Figure 4.4: The input data screen for zone types in AccuRate

4.3.3.3 *Window Shading Feature*

There was an option to state the shading features when inputting data for window elements. The shading feature for the window is defined when selecting this tab. This tab is connected with the thermal performance test cells for the house built elements in AccuRate. The window shading feature lets the user select different height and depth for each window. The shading features provide a lower solar access to the house in summer. In this study, shading features have not been used. Figure 4.5illustrates the screen input data screen of the window shading scheme in AccuRate.



Eaves

Projection: 0.00 m

Offset: 0.00 m

Other fixed shading

Projection: 0.00 m

Offset: 0.00 m

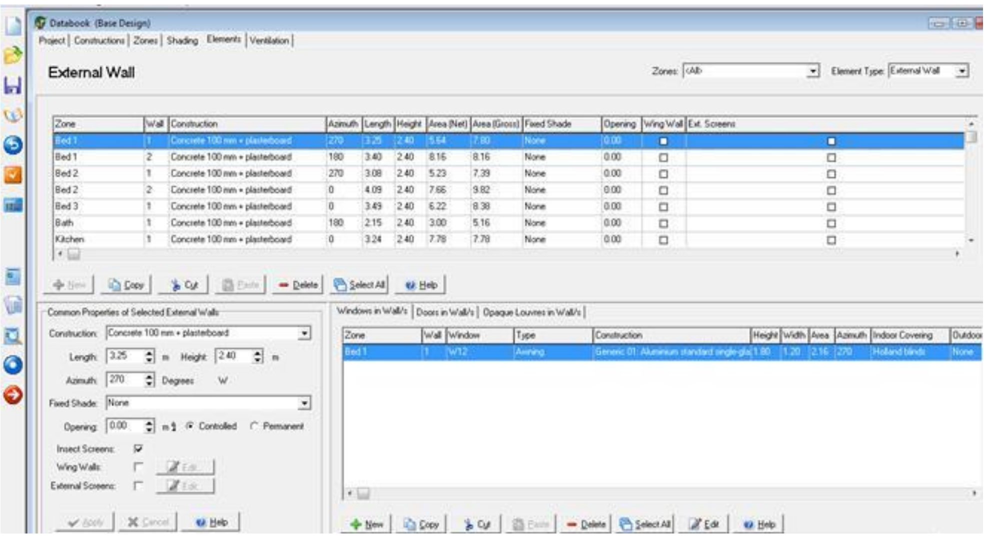
Blocking factor (opaque=100%)

J	F	M	A	M	J	J	A	S	O	N	D
100	100	100	100	100	100	100	100	100	100	100	100

Figure 4.5: The window shading scheme input data screen in AccuRate

4.3.3.4 *Built Elements*

The most complex stage of the data entry process is the data input of the built elements tab. This process of data input requires linking the element materials and its relationships with the three dimensional object for the thermal simulation. Each of the tab zones enclosed with elements was defined within the construction information tab of built elements. The ground, floor, wall, ceiling and roof were the perimeter elements of a zone defined with the width, height and area of each plane. Figure 4.6 shows the built elements input data screen in AccuRate.



External Wall

Zones: <All>
Element Type: External Wall

Zone	Wall	Construction	Azimuth	Length	Height	Area (Net)	Area (Gross)	Fixed Shade	Opening	Wing Wall	Ext. Screens
Bed 1	1	Concrete 100 mm + plasterboard	270	3.25	2.40	5.64	7.80	None	0.00	☐	☐
Bed 1	2	Concrete 100 mm + plasterboard	180	3.40	2.40	8.16	8.16	None	0.00	☐	☐
Bed 2	1	Concrete 100 mm + plasterboard	270	3.08	2.40	5.23	7.39	None	0.00	☐	☐
Bed 2	2	Concrete 100 mm + plasterboard	0	4.09	2.40	7.66	9.82	None	0.00	☐	☐
Bed 3	1	Concrete 100 mm + plasterboard	0	3.49	2.40	6.22	8.38	None	0.00	☐	☐
Bath	1	Concrete 100 mm + plasterboard	180	2.15	2.40	3.00	5.16	None	0.00	☐	☐
Kitchen	1	Concrete 100 mm + plasterboard	0	3.24	2.40	7.78	7.78	None	0.00	☐	☐

Common Properties of Selected External Walls

Construction: Concrete 100 mm + plasterboard
Length: 3.25 m Height: 2.40 m
Azimuth: 270 Degrees W
Fixed Shade: None
Opening: 0.00 m² ● Controlled ○ Permanent
Insect Screens: ☑
Wing Walls: ☐
External Screens: ☐

Zone	Wall	Window	Type	Construction	Height	Width	Area	Azimuth	Indoor Covering	Outdoo
Bed 1	1	W12	Awning	Generic 01: Aluminium standard single-gla	1.80	1.20	2.16	270	Holland blinds	None

Figure 4.6: The built element input data screen in AccuRate

4.3.3.5 Ventilation and House Orientation

The ventilation tab is the final tab which requires standard data entry. The simplified inbuilt natural ventilation model was the data input and its application to this tab. When applying ventilation features to the house, the house elements will depend on the sun altitude and azimuth. The azimuths of the house were defined for calculation of solar gain and wind speed. This calculation is used by the AccuRate simulation to model the fluid dynamics of external air pressure on the house. The house orientation simplified perimeter size was confirmed a square shape and facing true north. The orientation of the house used in the study is north facing due to Australia's geographical location in the southern hemisphere. The AccuRate software allows incorporation of the effect of natural ventilation caused by the indoor air movement (AccuRate software manual, 2004). In this study, the effect of natural ventilation was incorporated in thermal modelling for all houses wall systems. However, the variation of thermal energy with and without natural ventilation was found to be negligible. The ventilation data input screen of AccuRate is shown in Figure 4.7.

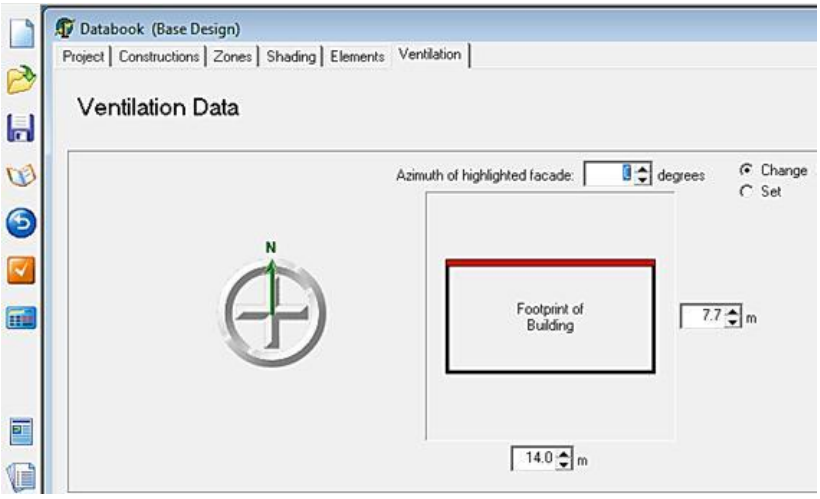


Figure 4.7: The Ventilation input data screen in AccuRate library

4.3.3.6 AccuRate Climate Data

The climate data used in AccuRate is based on data collected by the Bureau of Meteorology, (BOM) Australia for 20 years. This data has the external house influences, including ambient air temperatures, external humidity, wind patterns and solar radiation (Boland, 1995; Stokes, 2007). A particular climate data set applies to the house once a postcode is selected. There is currently a proposal to increase the number of climate zones to 80. The latitude and longitude of climate zones used in this study are described in Table 4.1.

Table 4.1: The latitude and longitude of climate zones for selected cities

Climate zone no.	Location	State	Latitude	Longitude
21	Melbourne	VIC	37.8 S	145.0 E
10	Brisbane	QLD	27.4 S	153.1 E
1	Darwin	NT	12.4 S	130.9 E
26	Hobart	TAS	42.8 S	147.5 E
16	Adelaide	SA	34.9 S	138.6 E
17	Sydney	NSW	33.9 S	151.2 E
24	Canberra	ACT	35.3 S	149.2 E
7	Rockhampton	QLD	23.4 S	150.5 E
13	Perth	WA	31.9 S	115.9 E
6	Alice Springs	NT	23.8 S	133.9 E
33	Broome	WA	18.0 S	122.2 E
32	Cairns	QLD	16.9 S	145.8 E
5	Townsville	QLD	19.3 S	146.8 E

4.3.3.7 Household Internal Heat Gains and Appliance Load

Internal heat gains inside the house contribute slightly to space heating and cooling. The internal heat gain is primarily obtained from household appliances and house occupants. Generally two time zones in a day (day time: 7:00-23:00 and night time: 23:00-7:00) are considered for internal heat gain. In internal heat gain estimations, 75W per person, with 60% availability during daytime and 100% during night time, is considered. Equipment gains are generally 16 W/m^2, with 25% available during the day and 5% during the night. Lighting gains are usually 8.5 W/m^2, with 15% available during the day and 0% during the night. A constant value for hot water and other systems is also taken into account. Appliance heat produced is taken into account, because it strongly affects the heating and cooling energy calculated. However, because AccuRate is a rating tool, it does not allow the user to modify the assumptions made regarding occupant behaviour. The house used in this work is an average family house for two adults and two children. In this study, the effect of internal heat gains on heating and cooling performance is not considered due to computational modelling limitation (Aldawi et al., 2013).

4.3.3.8 Thermostat Setting and Conditioned Hours

The thermostat setting depends on local climate conditions. The conditioned temperature settings were selected as per the recommendations of the (BCA. The conditioned temperature was selected according to the Bureau of Meteorology Australia and the user cannot set the thermostat and conditions hours. The rooms have conditioned operating hours regulated by the thermostat setting. Heating is applied if the temperature of the room without heating is below the thermostat setting and the cooling is applied if the temperature rises above the thermostat setting (Wakefield, He & Dowling, 2009). In this study, only bedrooms and living rooms are considered to be conditioned (heated or cooled). Heating or cooling for living rooms was made available from 7:00 to 24:00 hours with a thermostat setting of 22°C. As bedrooms have different conditioned hours for heating and cooling, we have selected a lower temperature (15°C) between 1:00 to 7:00 hours and a higher temperature (18°C) between 8:00 to 9:00 and 16:00 to 24:00 hours (Aldawi et al., 2013). House zone divisions used in this study are illustrated in Table 4.2.

Table 4.2: Conventional and new house zone divisionsfor conditioned setting (AccuRate)

Zone type	Volume	Conditioned setting	Input variable	Occupancy assumption
Bed1	24.0	Conditioned from 0100-0700 (15°C) Conditioned from 0800-0900 (18°C) Conditioned from 1600-2400 (18°C)	Volume Floor height Ceiling height Heating & cooling	Day-time/ Night-time No light heat gains
Bed 2	23.9	Conditioned from 0100-0700 (15°C) Conditioned from 0800-0900 (18°C) Conditioned from 1600-2400 (18°C)	Volume Floor height Ceiling height Heating & cooling	Day-time/Night-time No light heat gains
Bed 3	24.43	Conditioned from 0100-0700 (15°C) Conditioned from 0800-0900 (18°C) Conditioned from 1600-2400 (18°C)	Volume Floor height Ceiling height Heating & cooling	Day-time/Night-time No light heat gains
Bath	11.5	No conditioned- no heat gains	Volume Floor height Ceiling height	Day-time/Night-time No light heat gains
Living/ Dining	35.24	Conditioned from 0700-2400 (22°C)	Volume Floor height Ceiling height	Day-time No light heat gains Night-time occupancy Light heat gains include
Kitchen	27.76	Conditioned from 0700-2400 (22°C) Day-time occupancy	Volume Floor height Ceiling height	Day-time No cooking heat gains Night-time Cooking heat gains include
Rooms Corridor	10.62	No conditioned- no heat gains	Volume Floor height Ceiling height	Day-time/ Night-time No light heat gains
Roof space	143.0	No conditioned- no heat gains No roof space vents	Volume	Day-time/Night-time No light heat gains
Entry	8.63	Conditioned as part of living space	Volume Floor height Ceiling height	Day-time/Night-time No light heat gains
Landry	12.6	No conditioned- no heat gains No roof space vents	Volume	Day-time/Night-time No light heat gains

4.3.3.9 Star Rate

AccuRate provides an energy rating on a scale of 0 to 10.A star value ranging from 0 to 10 stars is calculated on the estimated annual energy load for each climate zone and their thermal dwelling properties. The higher scale rate is better for energy saving and consumption. Table 4.3 shows the total energy required against the star rating value.

Table 4.3: Total energy required vs. star rate

	Total energy required (MJ/m^2.annum) vs. stars rate																			
City	**0.5**	**1**	**1.5**	**2**	**2.5**	**3**	**3.5**	**4**	**4.5**	**5**	**5.5**	**6**	**6.5**	**7**	**7.5**	**8**	**8.5**	**9**	**9.5**	**10**
Melbourne	676	559	462	384	321	271	230	198	171	149	131	114	98	83	68	54	39	25	13	2
Brisbane	245	203	167	139	116	97	83	71	62	55	48	43	38	34	30	25	21	17	13	10
Darwin	853	773	706	648	598	555	516	480	446	413	381	349	317	285	253	222	192	164	140	119
Hobart	876	723	598	498	417	354	303	262	229	202	177	155	134	113	92	71	51	31	14	0
Adelaide	584	480	394	325	270	227	192	165	143	125	109	96	83	70	58	46	33	22	11	3
Sydney	286	230	184	148	120	98	81	68	58	50	44	39	35	30	26	22	17	13	9	6
Canberra	957	792	657	547	458	387	330	284	247	216	189	165	142	120	99	77	56	35	17	2
Rockhampton	344	295	255	222	194	171	152	136	122	110	99	90	80	71	63	54	46	38	31	24
Perth	483	387	311	251	204	167	139	118	102	89	79	70	61	52	44	34	25	17	9	4
Alice Springs	681	562	464	385	321	269	228	196	170	148	130	113	99	84	70	56	43	29	17	7
Broome	732	652	585	531	486	448	416	387	360	335	310	285	260	234	208	182	157	134	115	99
Cairns	330	302	276	253	232	214	197	181	167	153	140	128	117	105	94	84	74	64	56	48
Townsville	337	309	283	259	238	218	200	183	168	153	140	127	114	103	92	81	71	61	52	44

4.3.3.10 Household Heating and Cooling Energy Load

According to Australian state and territory government regulations since 2008, all new houses must comply with certain minimum energy requirements on a scale of 0 to 10 stars for heating and cooling (Alam et al., 2009). For example, houses in Melbourne are to be rated for 6 stars, so they should not consume more energy than 114 MJ/m^2 per year for ongoing space heating and cooling. A higher star rating indicates more efficient energy consumption for heating and cooling. Figure 4.8 illustrates the star energy rating against energy consumption for ongoing heating and cooling of houses located in major Australian cities and towns.

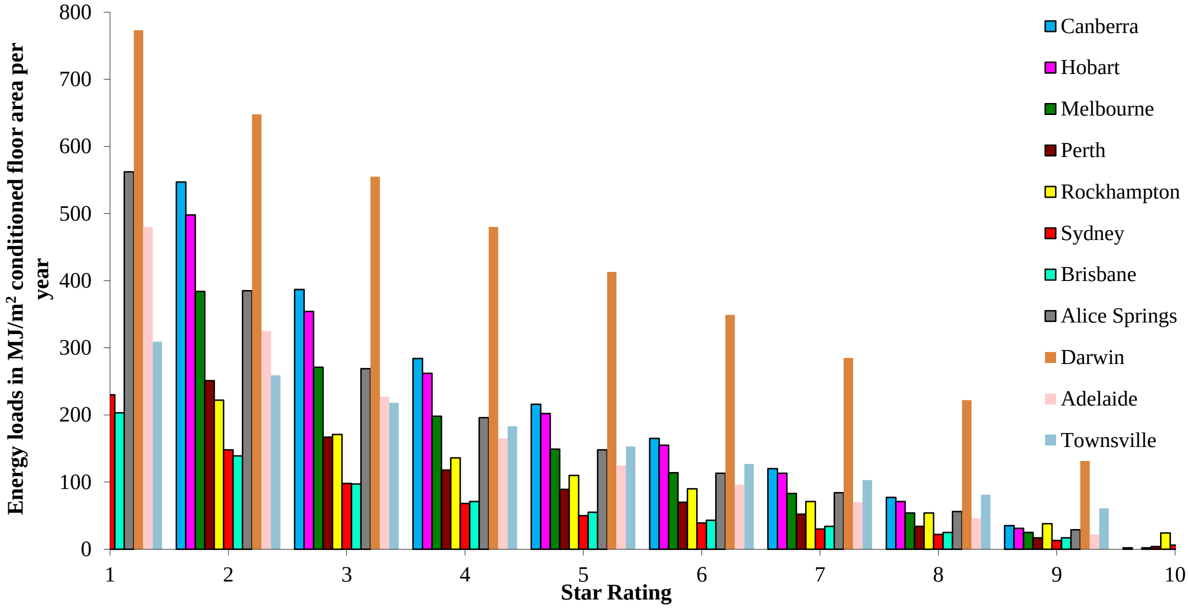
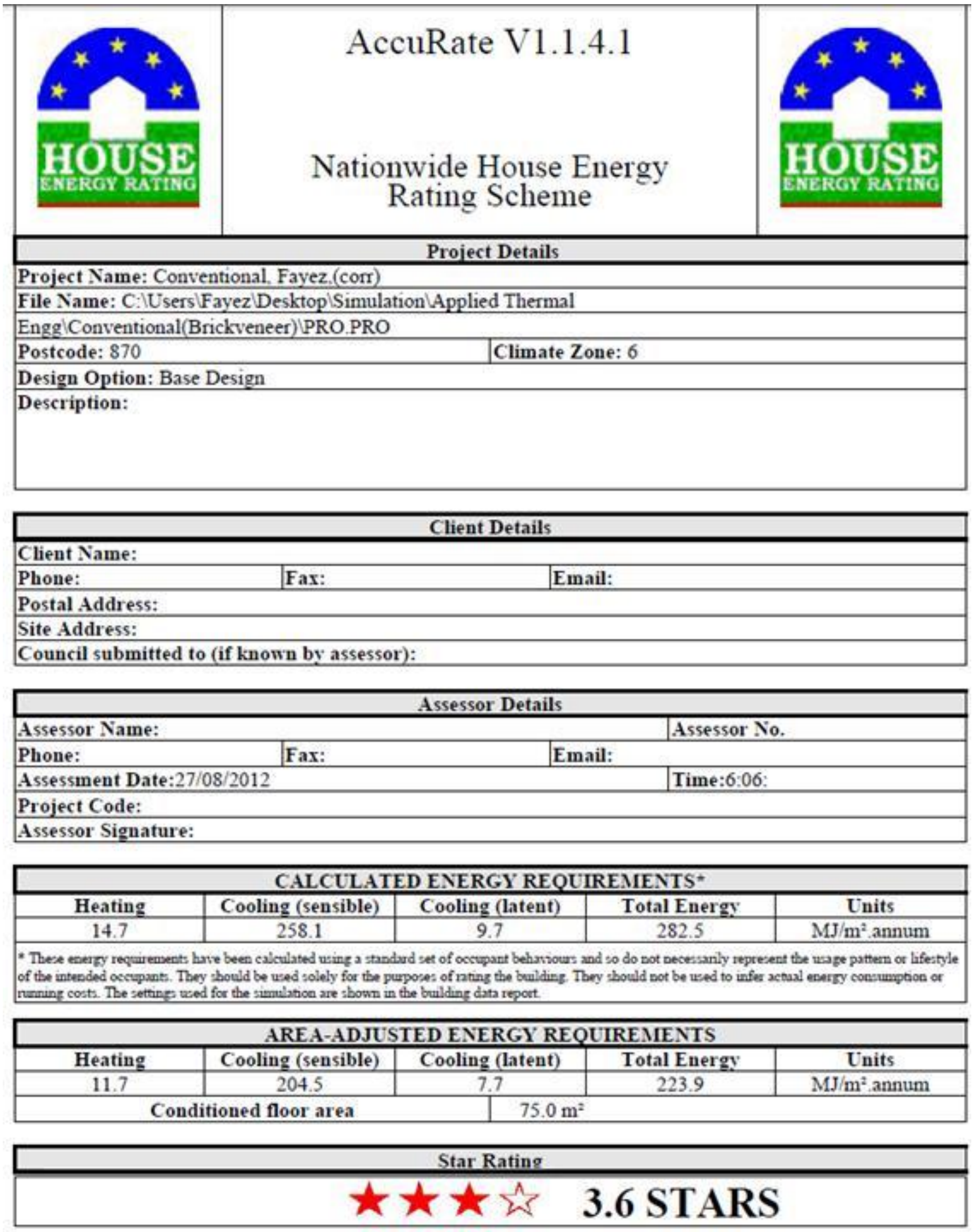


Figure 4.8: Star energy ratings vs. energy consumption for selected cites

4.3.3.11 AccuRate Final Report

The modeling outcome-report provides the estimation of energy required for space heating and/ or cooling to maintain a particular house within conditioned comfort zones. The energy unit used in the simulated report is (MJ/m^2.annum). It also provides a star energy rating on a scale of 0 to 10.Figure 4.9 shows the energy report produced by AccuRate software.



AccuRate V1.1.4.1

Nationwide House Energy Rating Scheme

Project Details

Project Name: Conventional, Fayez,(corr)
File Name: C:\Users\Fayez\Desktop\Simulation\Applied Thermal Engg\Conventional(Brickveneer)\PRO.PRO
Postcode: 870 **Climate Zone:** 6
Design Option: Base Design
Description:

Client Details

Client Name:
Phone: **Fax:** **Email:**
Postal Address:
Site Address:
Council submitted to (if known by assessor):

Assessor Details

Assessor Name: **Assessor No.**
Phone: **Fax:** **Email:**
Assessment Date:27/08/2012 **Time:**6:06:
Project Code:
Assessor Signature:

CALCULATED ENERGY REQUIREMENTS*

Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units
14.7	258.1	9.7	282.5	MJ/m².annum

* These energy requirements have been calculated using a standard set of occupant behaviours and so do not necessarily represent the usage pattern or lifestyle of the intended occupants. They should be used solely for the purposes of rating the building. They should not be used to infer actual energy consumption or running costs. The settings used for the simulation are shown in the building data report.

AREA-ADJUSTED ENERGY REQUIREMENTS

Heating	Cooling (sensible)	Cooling (latent)	Total Energy	Units
11.7	204.5	7.7	223.9	MJ/m².annum
Conditioned floor area	75.0 m²			

Star Rating

★★★☆ **3.6 STARS**

Figure 4.9: The energy report produced by AccuRate software

4.4 Australian Climate Conditions

The climate in Australia varies significantly, including arid, middle, tropical, subtropical and temperate zones. The Australian climate is classified into six main zones based on weather patterns and conditions, meteorological data, and solar radiation, as shown Figure 4.10. In order to distinguish microclimates throughout Australia, the entire continent has been subdivided into 69 micro climate zones with a certain amount of energy required for ongoing heating and cooling. As mentioned earlier, major cities are located in varied climate conditions. Thirteen major cities and towns, representing all major climate zones, have been selected for this study. These are Melbourne, Brisbane, Darwin, Hobart, Adelaide, Sydney, Canberra, Rockhampton, Perth, Alice Springs, Broome, Townsville and Cairns. For example, the city of Melbourne experiences mostly cool temperatures, whereas Brisbane has warm humid summers and mild winters, Darwin has high humid summers and warm winters, and Adelaide has warm temperatures. The average overall ambient temperature in the Melbourne metropolitan area ranges between 0°C and 16°C in winter and 18°C and 30°C in summer (Zmeureanu & Renaud, 2008; Climate Action Network Australia, 2005). Table 4.4shows the climate of Australia with examples of selected major cities.

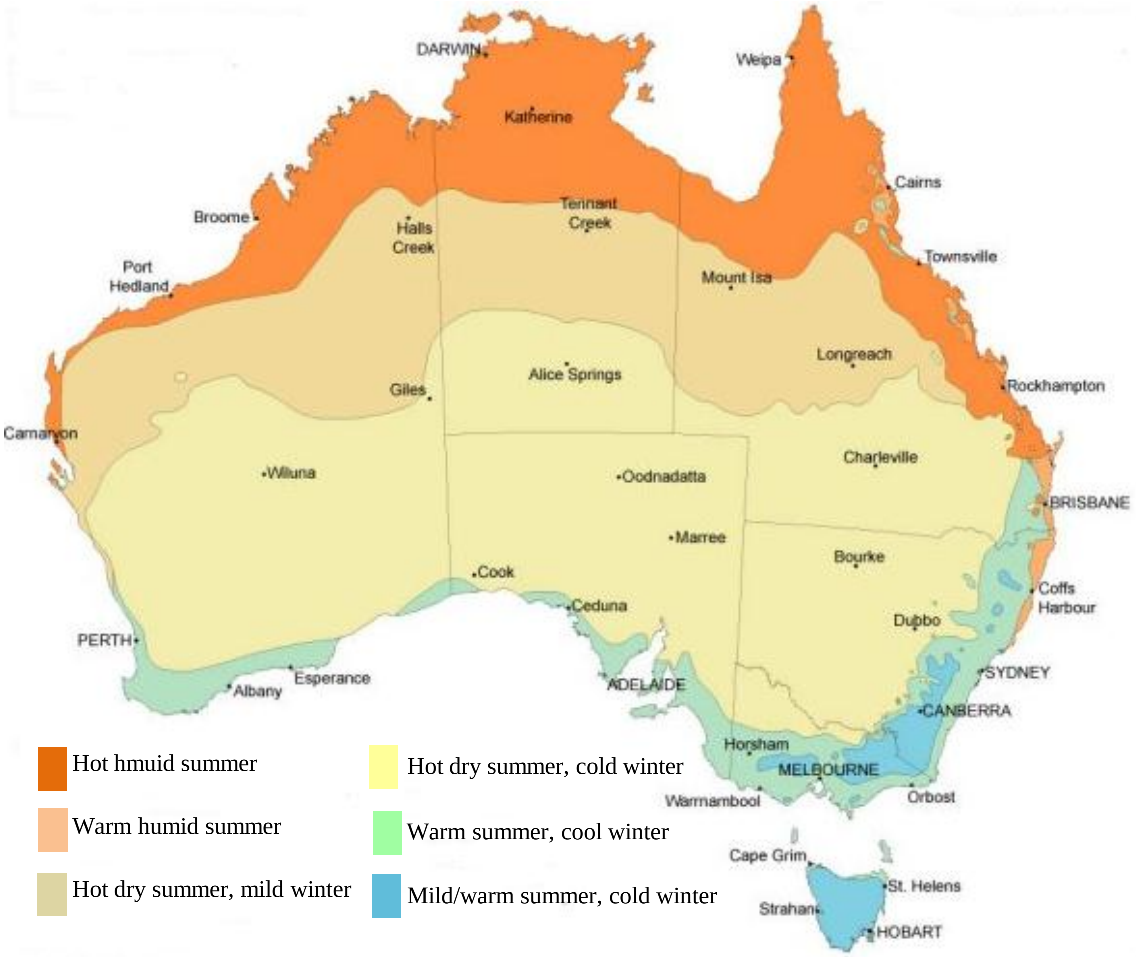


Figure 4.10: Climatic zones in Australia (local harvest org., 2012)

Table 4.4: Climatic zones for different cities and states in Australia

Weather description	Example of city	State
Hot humid summer	Townsville, Darwin	QLD, NT
Warm humid summer	Brisbane, Rockhampton	QLD
Hot dry summer, mild winter	Halls Creek	WA
Hot dry summer, cold winter	Alice Springs, Darwin	NT
Warm summer, cool winter	Perth, Adelaide	WA, SA
Mild/ warm summer, cold winter	Melbourne, Canberra	VIC, ACT

4.5 Results and Discussions

Using AccuRate thermal modelling software, the thermal performances for all house wall systems (conventional and new designs) were investigated. The results show the total energy requirement as well as the energy star rating for conventional and new house wall systems. In this study, all major cities located in different states and territories of Australia were used. The findings are discussed in the following sub-sections.

4.5.1 Conventional House Wall (Benchmark)

The energy requirements for ongoing heating and cooling, star energy ratings and relative improvements for single and double glazed window are illustrated in Table 4.5 and Figure 4.11.For single and double glazed windows, the conventional house wall system of Darwin and Broome requires the highest energy for on-going heating and cooling (MJ/m^2/year), while Brisbane and Sydney require the lowest energy for this purpose. A similar energy requirement for heating and cooling is also noted for Cairns, Alice Springs, Townsville, Hobart and Canberra. The energy needs for Melbourne and Rockhampton are in-between. The conventional house wall system with double glazed windows requires less energy for all 13 cities and towns. The improvement of double glazed window is between 9 and 16.5%.

Table 4.5: Conventional house energy required for selected cities

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy MJ/m^2. annum		Star rating 0-10		Impro--vement
			Single	***Double***	***Single***	***Double***	***Single***	***Double***	***Single***	***Double***	***%***
1	Melbourne	VIC	112.5	107.0	38.1	30.1	150.6	137.1	4.9	5.3	**9.0**
2	Brisbane	QLD	7.9	7.6	63.4	53.1	71.3	60.7	3.9	4.6	**14.9**
3	Darwin	NT	0.0	0.0	630.4	575.0	630.4	575.0	2.2	2.8	**8.8**
4	Hobart	TAS	186.9	180.0	4.8	3.1	191.7	183.1	5.2	5.4	**4.5**
5	Adelaide	SA	53.6	51.6	85.0	72.1	138.6	123.7	4.6	5.0	**10.8**
6	Sydney	NSW	13.1	12.7	60.4	48.7	73.5	61.4	3.8	4.3	**16.5**
7	Canberra	ACT	176.1	170.8	40.3	30.8	216.4	201.6	4.9	5.3	**6.8**
8	Rockhampton	QLD	0.7	0.6	165.0	142.3	165.7	143.0	3.1	3.8	**13.7**
9	Perth	WA	26.2	25.7	95.7	78.3	121.9	104.0	3.9	4.4	**14.7**
10	Alice Springs	NT	17.3	16.3	201.2	169.3	218.5	185.6	3.6	4.2	**15.1**
11	Broome	WA	0.0	0.0	467.0	420.0	467.0	420.0	2.4	3.0	**10.1**
12	Cairns	QLD	0.0	0.0	231.7	205.0	231.7	205.0	2.5	3.2	**11.5**
13	Townsville	QLD	0.0	0.0	252.5	225.3	252.5	225.5	2.2	2.8	**10.7**
					Average improvement (%)						**11.3**

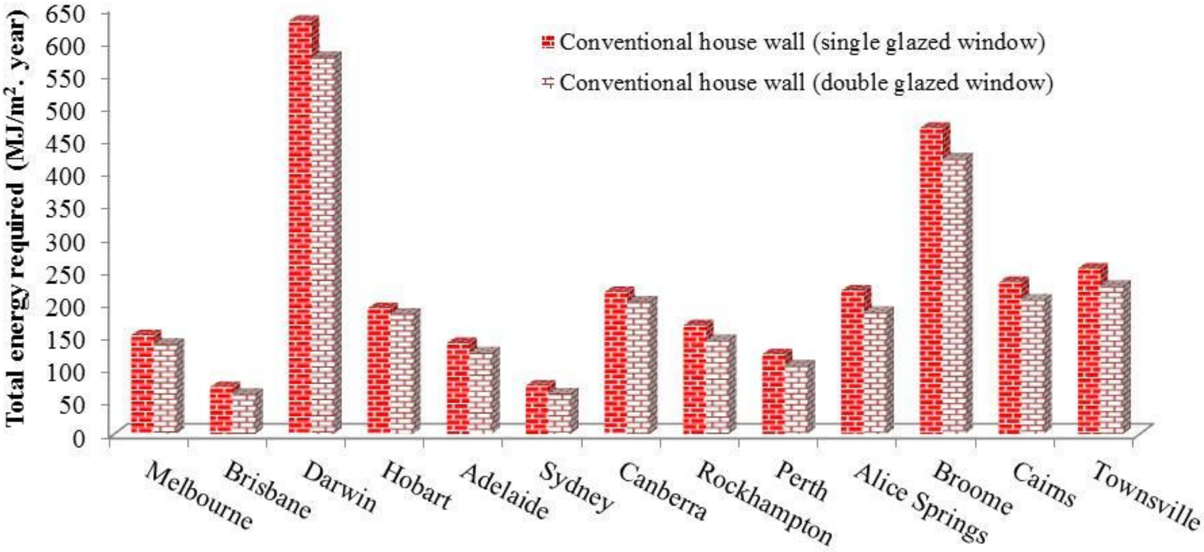


Figure 4.11: Total energy required for on-going heating and cooling for selected cities, conventional house wall

4.5.2 Design 1: New House Wall with Two Panels of Polystyrene Insulation – (Outer and Inner Positions)

4.5.2.1 Single glazed window

The energy requirements for ongoing heating and cooling, star energy ratings and relative improvements for Design 1 are illustrated in Table 4.6. Design 1 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (45.9%) is noted for Perth, followed by Adelaide (43.9%) and Alice Springs (43.2%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.12.

Table 4.6: New house wall energy required for selected cities (Design 1 with single glazed window)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***Des.1***	***Conv.***	***Des.1***	***Conv.***	***Des.1***	***Conv.***	***Des.1***	***%***
1	Melbourne	VIC	112.5	65.8	38.1	43.2	150.6	97.8	4.9	6.5	**35.1**
2	Brisbane	QLD	7.9	0.9	63.4	52.8	71.3	53.7	3.9	5.1	**24.7**
3	Darwin	NT	0.0	0.0	630.4	395.3	630.4	395.3	2.2	5.3	**37.3**
4	Hobart	TAS	186.9	127.6	4.8	18.7	191.7	146.3	5.2	6.2	**23.7**
5	Adelaide	SA	53.6	23.4	85.0	54.3	138.6	77.7	4.6	6.7	**43.9**
6	Sydney	NSW	13.1	1.9	60.4	46.9	73.5	48.8	3.8	5.1	**33.6**
7	Canberra	ACT	176.1	134.4	40.3	33.3	216.4	167.7	4.9	5.9	**22.5**
8	Rockhampton	QLD	0.7	0.0	165.0	116.3	165.7	116.3	3.1	4.7	**29.8**
9	Perth	WA	26.2	6.3	95.7	59.7	121.9	66.0	3.9	6.2	**45.9**
10	Alice Springs	NT	17.3	4.6	201.2	119.6	218.5	124.2	3.6	5.7	**43.2**
11	Broome	WA	0.0	0.0	467.0	302.8	467.0	302.8	2.4	5.1	**35.2**
12	Cairns	QLD	0.0	0.0	231.7	147.6	231.7	147.6	2.5	5.2	**36.3**
13	Townsville	QLD	0.0	0.0	252.5	172.6	252.5	172.6	2.2	4.3	**31.6**
					Average improvement (%)						**34.1**

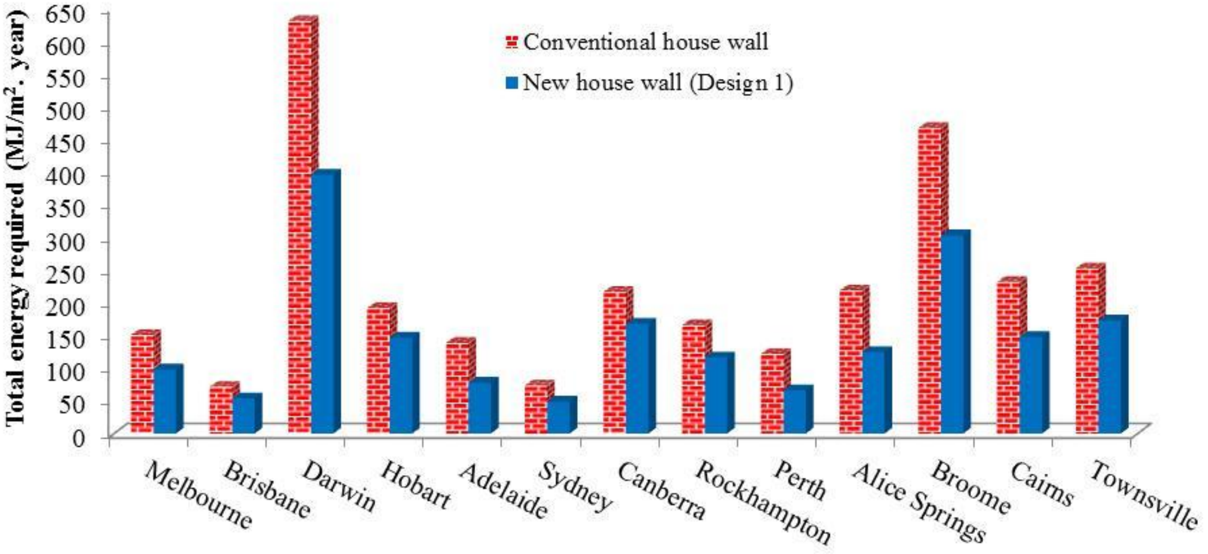


Figure 4.12: Total energy required for on-going heating and cooling for selected cities,(Design 1) with single glazed window

4.5.2.2 Double glazed window

The energy requirements for ongoing heating and cooling, star energy ratings and relative improvements for Design 1 are illustrated in Table 4.7. Design 1 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (45.3%) is noted for Adelaide, followed by Perth (43.3%) and Alice Springs (41.6%), while the lowest reduction was for Brisbane (16.5%). The cities of Melbourne, Darwin, Hobart, Broom, Townsville and Cairns have achieved energy savings of 30-40%, while Sydney, Canberra and Rockhampton are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.12.

Table 4.7: New house wall energy required for selected cities (Design 1 with double glazed window)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***Des.1***	***Conv.***	***Des.1***	***Conv.***	***Des.1***	***Conv.***	***Des.1***	***%***
1	Melbourne	VIC	107.0	54.8	30.1	29.6	137.1	84.4	5.3	6.9	**38.4**
2	Brisbane	QLD	7.6	0.5	53.1	50.2	60.7	50.7	4.6	5.3	**16.5**
3	Darwin	NT	0.0	0.0	575.0	382.7	575.0	382.7	2.8	5.6	**33.4**
4	Hobart	TAS	180.0	108.4	3.1	18.6	183.1	127.0	5.4	6.7	**30.6**
5	Adelaide	SA	51.6	18.2	72.1	49.5	123.7	67.7	5.0	7.1	**45.3**
6	Sydney	NSW	12.7	1.1	48.7	43.9	61.4	45.0	4.3	5.4	**26.7**
7	Canberra	ACT	170.8	114.4	30.8	31.2	201.6	145.6	5.3	6.4	**27.8**
8	Rockhampton	QLD	0.6	0.0	142.3	108.6	143.0	108.6	3.8	5.1	**24.1**
9	Perth	WA	25.7	4.1	78.3	54.9	104.0	59.0	4.4	6.6	**43.3**
10	Alice Springs	NT	16.3	2.6	169.3	105.7	185.6	108.3	4.2	6.2	**41.6**
11	Broome	WA	0.0	0.0	420.0	287.5	420.0	287.5	3.0	5.5	**31.5**
12	Cairns	QLD	0.0	0.0	205.0	134	205.0	134.0	3.2	5.5	**34.6**
13	Townsville	QLD	0.0	0.0	225.3	153.2	225.5	153.2	2.8	4.9	**32.1**
				Average improvement (%)							**32.8**

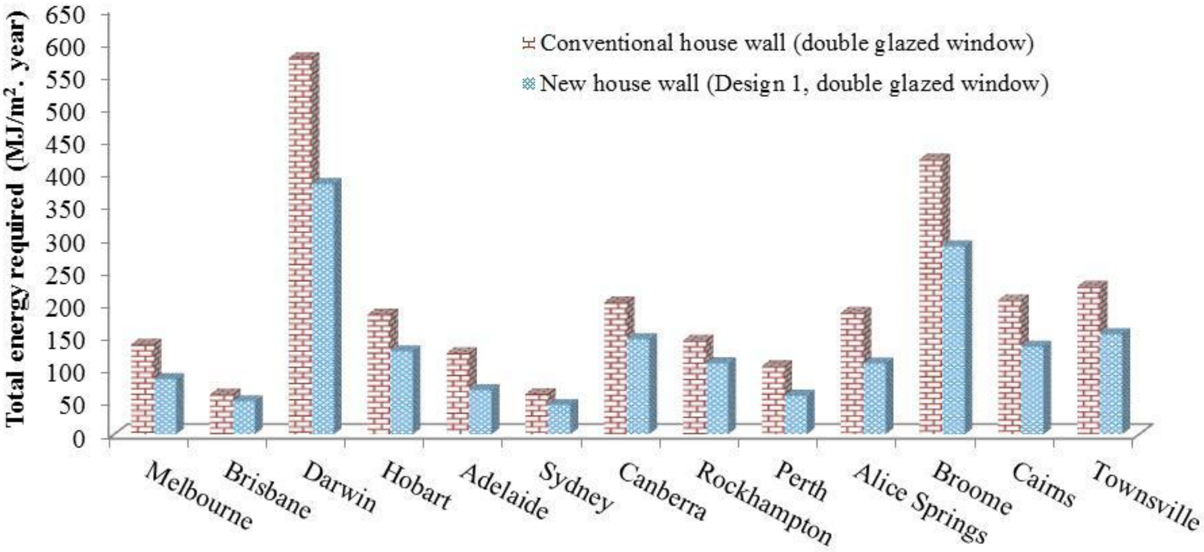


Figure 4.13: Total energy required for on-going heating and cooling for selected cities (Design 1) with double glazed window

An average improvement between single and double glazed windows for the conventional and new design is around 11.3% and 9.6%, respectively. However, compared to the conventional and new design house wall systems with double glazed windows, the average energy saving is around 32.8%. Therefore, the new design with single and double glazed windows has superior thermal performances (34.1% & 32.8%) compared to the conventional house with the same window configurations.

Table 4.8:Double glazed improvement

City	Total energy MJ/m^2.annum		Improve	Total energy MJ/m^2.annum		Improve	Single glazed Conv-D1	Double glazed Conv-D1
	Conv. Single glazed	Conv. Double glazed	%	D1 Single glazed	D1 double glazed	%		
Melbourne	150.6	137.1	9.0	97.8	84.4	13.7	35.1	38.4
Brisbane	71.3	60.7	14.9	53.7	50.7	5.6	24.7	16.5
Darwin	630.4	575.0	8.8	395.3	382.7	3.2	37.3	33.4
Hobart	191.7	183.1	4.5	146.3	127.0	13.2	23.7	30.6
Adelaide	138.6	123.7	10.8	77.7	67.7	12.9	43.9	45.3
Sydney	73.5	61.4	16.5	48.8	45.0	7.8	33.6	26.7
Canberra	216.4	201.6	6.8	167.7	145.6	13.2	22.5	27.8
Rockhampton	165.7	143.0	13.7	116.3	108.6	6.6	29.8	24.1
Perth	121.9	104.0	14.7	66.0	59.0	10.6	45.9	43.3
Alice Springs	218.5	185.6	15.1	124.2	108.3	12.8	43.2	41.6
Broome	467.0	420.0	10.1	302.8	287.5	5.1	35.2	31.5
Cairns	231.7	205.0	11.5	147.6	134.0	9.2	36.3	34.6
Townsville	252.5	225.5	10.7	172.6	153.2	11.2	31.6	32.1
Average improvement			**11.3**			**9.6**	**34.1**	**32.8**

4.5.3 Design 2: New House Wall with One Panel of Polystyrene Insulation – (Outer Position)

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 2 are illustrated in Table 4.9. Design 2 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (54.3%) is noted for Perth, followed by Alice Springs (48.5%) and Adelaide (47.9). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.14.

Table 4.9: New house wall energy required for selected cities (Design 2)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro--vement
			Conv.	***Des.2***	***Conv.***	***Des.2***	***Conv.***	***Des.2***	***Conv.***	***Des.2***	*%*
1	Melbourne	VIC	112.5	69.0	38.1	28.5	150.6	97.5	4.9	6.5	**35.3**
2	Brisbane	QLD	7.9	0.3	63.4	52.0	71.3	52.3	3.9	5.2	**26.6**
3	Darwin	NT	0.0	0.0	630.4	428.3	630.4	428.3	2.2	4.8	**32.1**
4	Hobart	TAS	186.9	131.3	4.8	17.4	191.7	148.7	5.2	6.2	**22.4**
5	Adelaide	SA	53.6	21.7	85.0	50.5	138.6	72.2	4.6	6.9	**47.9**
6	Sydney	NSW	13.1	1.1	60.4	45.8	73.5	46.9	3.8	5.3	**36.2**
7	Canberra	ACT	176.1	135.8	40.3	28.5	216.4	164.3	4.9	6.0	**24.1**
8	Rockhampton	QLD	0.7	0.0	165.0	117.4	165.7	117.4	3.1	4.7	**29.1**
9	Perth	WA	26.2	3.0	95.7	52.7	121.9	55.7	3.9	6.8	**54.3**
10	Alice Springs	NT	17.3	1.4	201.2	111.2	218.5	112.6	3.6	6.0	**48.5**
11	Broome	WA	0.0	0.0	467.0	313.1	467.0	313.1	2.4	4.7	**33.0**
12	Cairns	QLD	0.0	0.0	231.7	154.9	231.7	154.9	2.5	4.9	**33.1**
13	Townsville	QLD	0.0	0.0	252.5	162.4	252.5	162.4	2.2	4.7	**35.7**
					Average improvement (%)						**35.3**

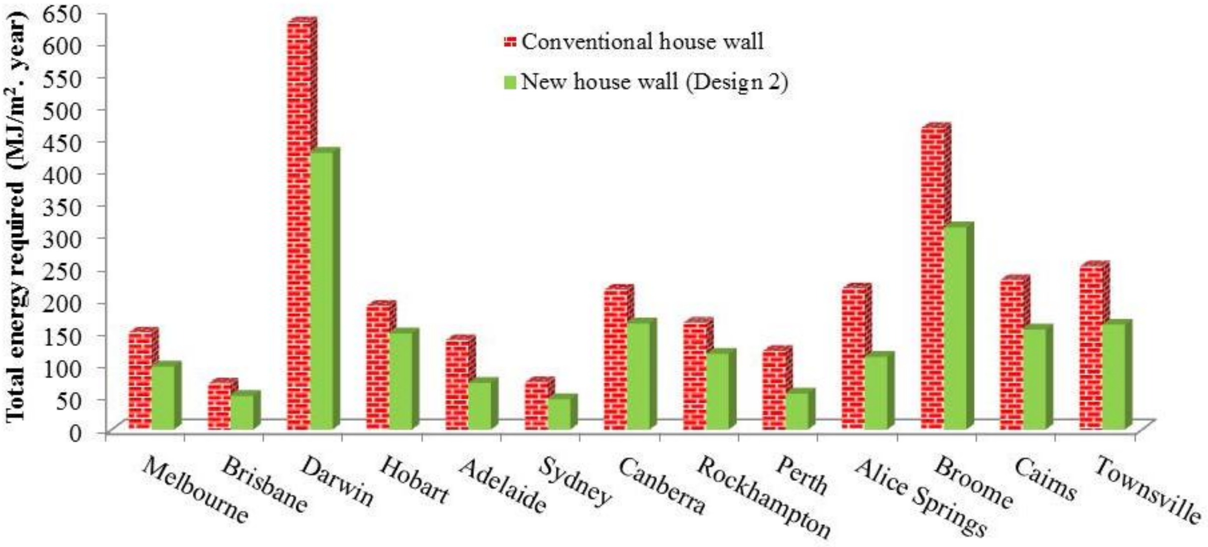


Figure 4.14: Total energy required for on-going heating and cooling for selected cities (Design 2)

4.5.4 Design 3: New House Wall with One Panel of Polystyrene Insulation – (Inner Position)

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 3 are illustrated in Table 4.10. Design 3 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (40.8%) is noted for Perth, followed by Alice Springs (38.4%) and Adelaide (37%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.15.

Table 4.10: New house wall energy required for selected cities (Design 3)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***Des.3***	***Conv.***	***Des.3***	***Conv.***	***Des.3***	***Conv.***	***Des.3***	***%***
1	Melbourne	VIC	112.5	75.4	38.1	33.8	150.6	109.2	4.9	6.2	**27.5**
2	Brisbane	QLD	7.9	1.6	63.4	54.0	71.3	55.6	3.9	4.9	**22.0**
3	Darwin	NT	0.0	0.0	630.4	407.2	630.4	407.2	2.2	5.1	**35.4**
4	Hobart	TAS	186.9	143.0	4.8	19.0	191.7	162.0	5.2	5.8	**15.5**
5	Adelaide	SA	53.6	28.7	85.0	58.6	138.6	87.3	4.6	6.3	**37.0**
6	Sydney	NSW	13.1	3.1	60.4	47.8	73.5	50.9	3.8	4.9	**30.7**
7	Canberra	ACT	176.1	151.0	40.3	34.2	216.4	185.2	4.9	5.6	**14.4**
8	Rockhampton	QLD	0.7	0.0	165.0	120.5	165.7	120.5	3.1	4.6	**27.3**
9	Perth	WA	26.2	8.8	95.7	63.4	121.9	72.2	3.9	5.9	**40.8**
10	Alice Springs	NT	17.3	7.1	201.2	127.5	218.5	134.6	3.6	5.4	**38.4**
11	Broome	WA	0.0	0.0	467.0	304.5	467.0	304.5	2.4	4.8	**34.8**
12	Cairns	QLD	0.0	0.0	231.7	151.8	231.7	151.8	2.5	5.0	**34.5**
13	Townsville	QLD	0.0	0.0	252.5	165.8	252.5	165.8	2.2	4.6	**34.3**
					Average improvement (%)						**30.2**

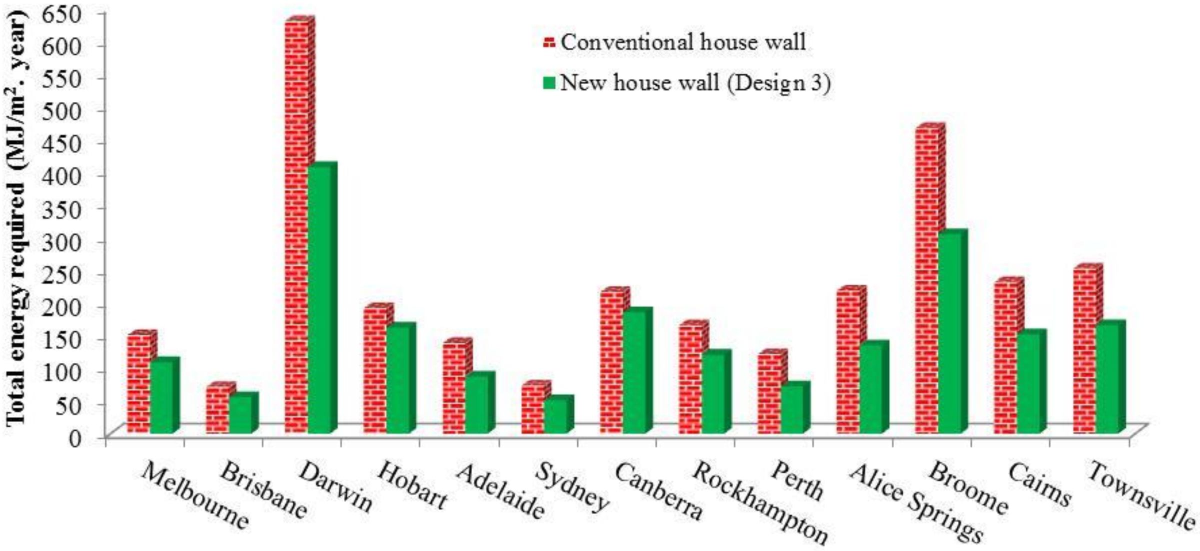


Figure 4.15: Total energy required for on-going heating and cooling for selected cities (Design 3)

4.5.5 Design 4: New House Wall with Two Half Concrete Panels and One Panel of Polystyrene Insulation in-between

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 4 are indicated in Table 4.11.Design 4 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (51.8%) is noted for Perth, followed by Alice Springs (46.7%) and Adelaide (45.7%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The energy requirements for these cities are illustrated in Figure 4.16.

Table 4.11: New house wall energy required for selected cities (Design 4)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro--vement
			Conv.	***Des.4***	***Conv.***	***Des.4***	***Conv.***	***Des.4***	***Conv.***	***Des.4***	*%*
1	Melbourne	VIC	112.5	69.3	38.1	30.3	150.6	99.6	4.9	6.4	**33.9**
2	Brisbane	QLD	7.9	0.4	63.4	53.0	71.3	53.4	3.9	5.1	**25.1**
3	Darwin	NT	0.0	0.0	630.4	432.3	630.4	432.3	2.2	4.7	**31.4**
4	Hobart	TAS	186.9	131.7	4.8	17.6	191.7	149.3	5.2	6.1	**22.1**
5	Adelaide	SA	53.6	22.4	85.0	52.9	138.6	75.3	4.6	6.8	**45.7**
6	Sydney	NSW	13.1	1.4	60.4	46.6	73.5	48.0	3.8	5.2	**34.7**
7	Canberra	ACT	176.1	135.9	40.3	28.8	216.4	164.7	4.9	6.0	**23.9**
8	Rockhampton	QLD	0.7	0.0	165.0	119.7	165.7	119.7	3.1	4.6	**27.8**
9	Perth	WA	26.2	3.5	95.7	55.3	121.9	58.8	3.9	6.6	**51.8**
10	Alice Springs	NT	17.3	1.9	201.2	114.5	218.5	116.4	3.6	5.9	**46.7**
11	Broome	WA	0.0	0.0	467.0	316.1	467.0	316.1	2.4	4.6	**32.3**
12	Cairns	QLD	0.0	0.0	231.7	157.3	231.7	157.3	2.5	4.8	**32.1**
13	Townsville	QLD	0.0	0.0	252.5	175.7	252.5	175.7	2.2	4.2	**30.4**
					Average improvement (%)						**33.7**

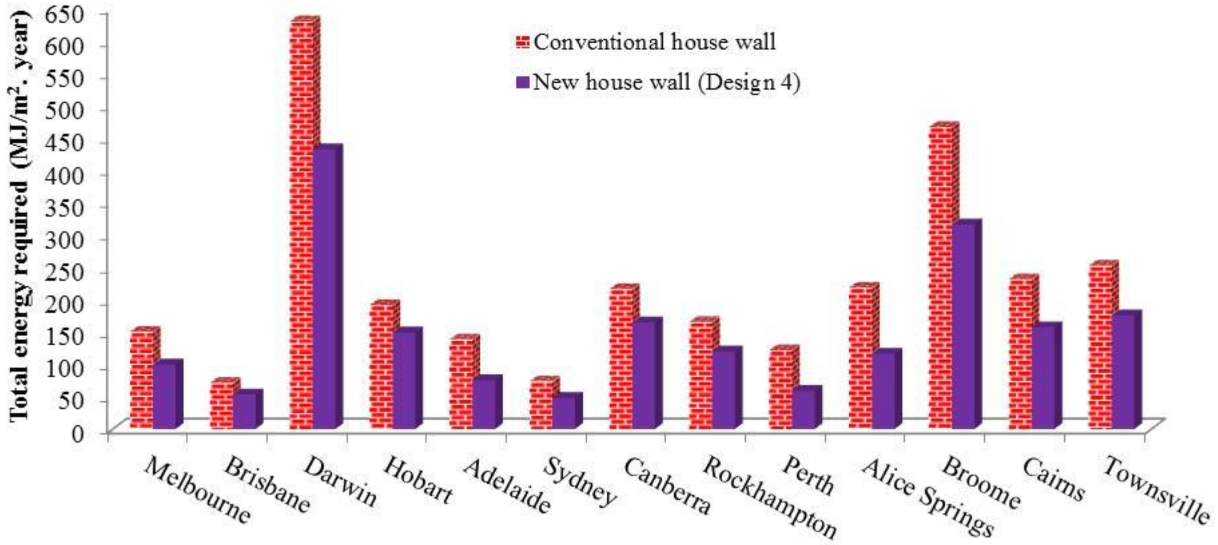


Figure 4.16: Total energy required for on-going heating and cooling for selected cities(Design 4)

4.5.6 Design 5: New House Wall with Two Half Concrete Panels and Two Panels of Polystyrene Insulation in-between

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 5 are illustrated in Table 4.12. Design 5 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (50.0%) is noted for Adelaide, followed by Alice Springs (49.0%) and Perth (46.3%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The energy requirements for these cities are illustrated in Figure 4.17.

Table 4.12: New house wall energy requirements for selected cities (Design 5)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro--vement
			Conv.	***Des.5***	***Conv.***	***Des.5***	***Conv.***	***Des.5***	***Conv.***	***Des.5***	***%***
1	Melbourne	VIC	112.5	61.2	38.1	29.9	150.6	91.1	4.9	6.7	**39.5**
2	Brisbane	QLD	7.9	0.3	63.4	52.5	71.3	52.8	3.9	5.2	**25.9**
3	Darwin	NT	0.0	0.0	630.4	422.7	630.4	422.7	2.2	4.9	**32.9**
4	Hobart	TAS	186.9	117.9	4.8	17.9	191.7	135.8	5.2	6.4	**29.2**
5	Adelaide	SA	53.6	18.1	85.0	51.2	138.6	69.3	4.6	7.0	**50.0**
6	Sydney	NSW	13.1	0.9	60.4	45.9	73.5	46.8	3.8	5.3	**36.3**
7	Canberra	ACT	176.1	120.4	40.3	29.1	216.4	149.5	4.9	6.3	**30.9**
8	Rockhampton	QLD	0.7	0.0	165.0	117.3	165.7	117.3	3.1	4.7	**29.2**
9	Perth	WA	26.2	2.3	95.7	63.1	121.9	65.4	3.9	6.8	**46.3**
10	Alice Springs	NT	17.3	1.1	201.2	110.4	218.5	111.5	3.6	6.1	**49.0**
11	Broome	WA	0.0	0.0	467.0	307.2	467.0	307.2	2.4	4.8	**34.2**
12	Cairns	QLD	0.0	0.0	231.7	154.6	231.7	154.6	2.5	4.9	**33.3**
13	Townsville	QLD	0.0	0.0	252.5	172.0	252.5	172.0	2.2	4.4	**31.9**
					Average improvement (%)						**36.1**

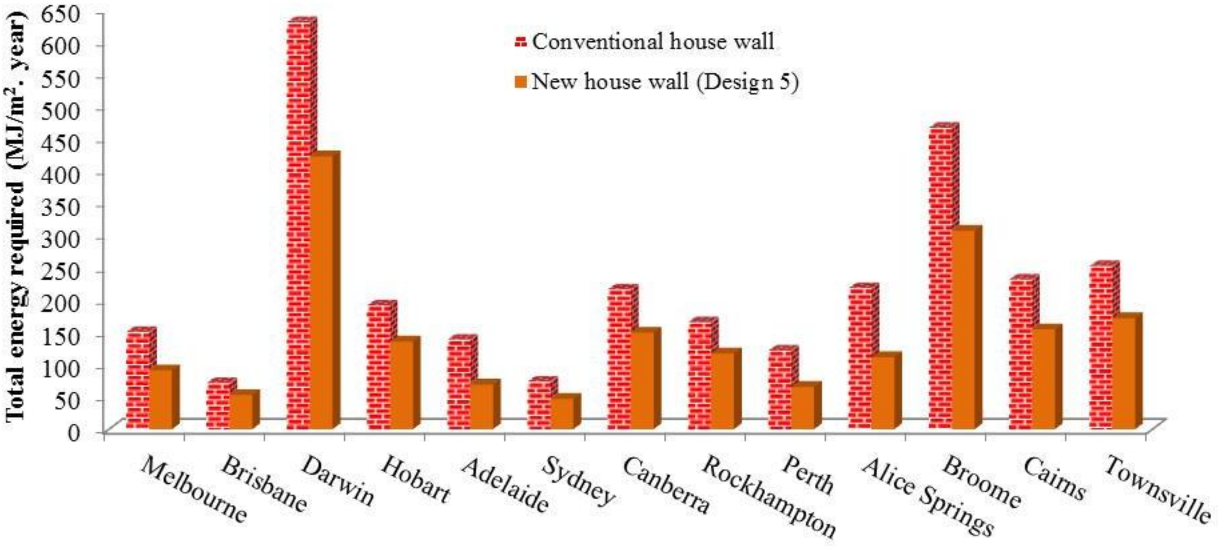


Figure 4.17: Total energy required for on-going heating and cooling for selected cities(Design 5)

4.5.7 Design 6: New House Wall with Two Half Concrete Panels and One Panel of Polyurethane Insulation in-between

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 6 are illustrated in Table 4.13. Design 6 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (52.9%) is noted for Perth, followed by Adelaide (48.1%) and Alice Springs (48.0%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.18.

Table 4.13: New house wall energy requirements for selected cities (Design 6)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro--vement
			Conv.	***Des.6***	***Conv.***	***Des.6***	***Conv.***	***Des.6***	***Conv.***	***Des.6***	*%*
1	Melbourne	VIC	112.5	65.0	38.1	29.8	150.6	94.8	4.9	6.6	**37.1**
2	Brisbane	QLD	7.9	0.3	63.4	52.7	71.3	53.0	3.9	5.1	**25.7**
3	Darwin	NT	0.0	0.0	630.4	426.6	630.4	426.6	2.2	4.8	**32.3**
4	Hobart	TAS	186.9	124.2	4.8	17.7	191.7	141.9	5.2	6.3	**26.0**
5	Adelaide	SA	53.6	20.0	85.0	52.0	138.6	72.0	4.6	6.9	**48.1**
6	Sydney	NSW	13.1	1.1	60.4	46.2	73.5	47.3	3.8	5.2	**35.6**
7	Canberra	ACT	176.1	127.5	40.3	28.9	216.4	156.4	4.9	6.2	**27.7**
8	Rockhampton	QLD	0.7	0.0	165.0	118.4	165.7	118.4	3.1	4.7	**28.5**
9	Perth	WA	26.2	2.9	95.7	54.5	121.9	57.4	3.9	6.7	**52.9**
10	Alice Springs	NT	17.3	1.4	201.2	112.3	218.5	113.7	3.6	5.9	**48.0**
11	Broome	WA	0.0	0.0	467.0	311.5	467.0	311.5	2.4	4.7	**33.3**
12	Cairns	QLD	0.0	0.0	231.7	156.0	231.7	156.0	2.5	4.9	**32.7**
13	Townsville	QLD	0.0	0.0	252.5	173.6	252.5	173.6	2.2	4.3	**31.2**
					Average improvement (%)						**35.3**

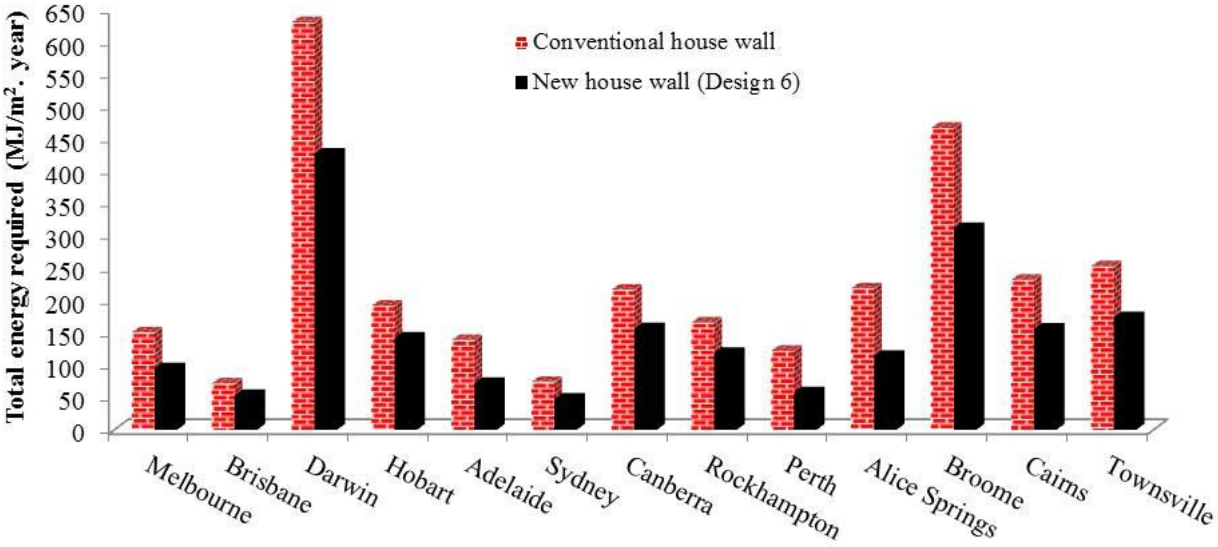


Figure 4.18: Total energy required for on-going heating and cooling for selected cities(Design 6)

4.5.8 Design 7: New House Wall with Two Half Concrete Panels and Two Panels of Polyurethane Insulation in-between

The energy requirements for on-going heating and, cooling, star energy ratings and relative improvements for Design 7 are illustrated in Table 4.14. Design 7 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (54.2%) is noted for Perth, followed by Adelaide (51.2%) and Alice Springs (49.6%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.19.

Table 4.14: New house wall energy requirements for selected cities (Design 7)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro--vement
			Conv.	***Des.7***	***Conv.***	***Des.7***	***Conv.***	***Des.7***	***Conv.***	***Des.7***	***%***
1	Melbourne	VIC	112.5	58.5	38.1	29.8	150.6	88.3	4.9	6.8	**41.4**
2	Brisbane	QLD	7.9	0.3	63.4	52.3	71.3	52.6	3.9	5.2	**26.2**
3	Darwin	NT	0.0	0.0	630.4	419.5	630.4	419.5	2.2	4.9	**33.5**
4	Hobart	TAS	186.9	113.6	4.8	18.0	191.7	131.6	5.2	6.6	**31.4**
5	Adelaide	SA	53.6	16.7	85.0	50.9	138.6	67.6	4.6	7.1	**51.2**
6	Sydney	NSW	13.1	0.8	60.4	46.0	73.5	46.8	3.8	5.3	**36.3**
7	Canberra	ACT	176.1	115.6	40.3	29.2	216.4	144.8	4.9	6.4	**33.1**
8	Rockhampton	QLD	0.7	0.0	165.0	116.5	165.7	116.5	3.1	4.7	**29.7**
9	Perth	WA	26.2	2.0	95.7	53.8	121.9	55.8	3.9	6.8	**54.2**
10	Alice Springs	NT	17.3	0.9	201.2	109.3	218.5	110.2	3.6	6.1	**49.6**
11	Broome	WA	0.0	0.0	467.0	304.6	467.0	304.6	2.4	4.8	**34.8**
12	Cairns	QLD	0.0	0.0	231.7	153.8	231.7	153.8	2.5	4.9	**33.6**
13	Townsville	QLD	0.0	0.0	252.5	170.8	252.5	170.8	2.2	4.4	**32.4**
					Average improvement (%)						**37.5**

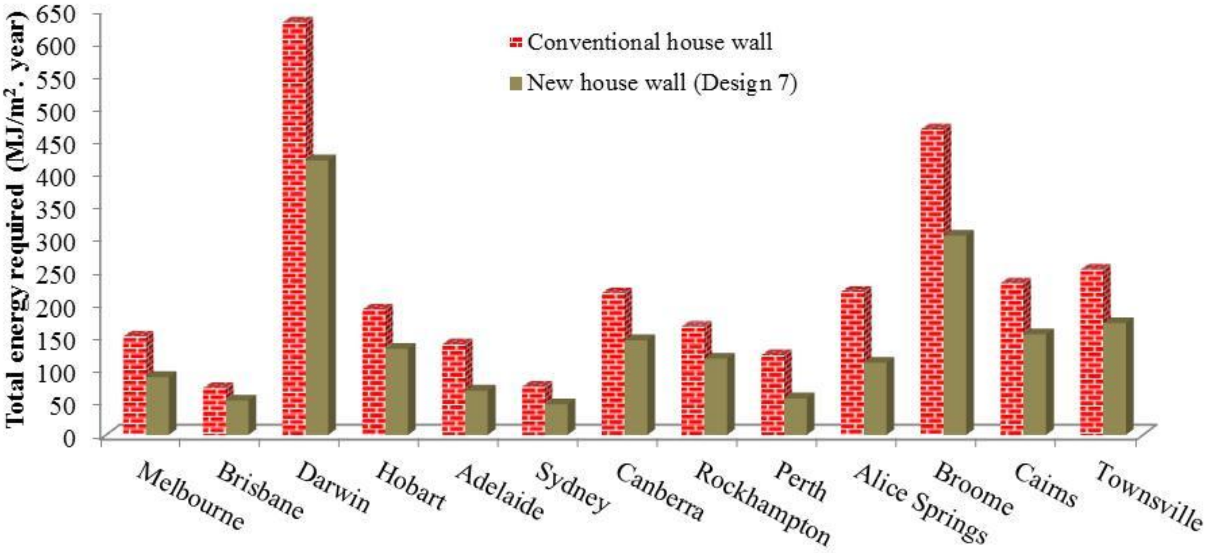


Figure 4.19: Total energy required for on-going heating and cooling for selected cities (Design 7)

4.5.9 Design 8: New House Wall with Air gap and One Panel of Polystyrene Insulation

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 8 are illustrated in Table 4.15. Design 8 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (41.0%) is noted for Perth. The cities of Alice Springs, Adelaide, Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.20.

Table 4.15: New house wall energy requirements for selected cities (Design 8)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***Des.8***	***Conv.***	***Des.8***	***Conv.***	***Des.8***	***Conv.***	***Des.8***	*%*
1	Melbourne	VIC	112.5	73.9	38.1	33.8	150.6	107.7	4.9	6.2	**28.5**
2	Brisbane	QLD	7.9	1.5	63.4	54.1	71.3	55.6	3.9	4.9	**22.0**
3	Darwin	NT	0.0	0.0	630.4	405.4	630.4	405.4	2.2	5.1	**35.7**
4	Hobart	TAS	186.9	140.5	4.8	19.1	191.7	159.6	5.2	5.9	**16.7**
5	Adelaide	SA	53.6	28.0	85.0	58.3	138.6	86.3	4.6	6.4	**37.7**
6	Sydney	NSW	13.1	3.0	60.4	47.8	73.5	50.8	3.8	4.9	**30.9**
7	Canberra	ACT	176.1	148.3	40.3	34.2	216.4	182.5	4.9	5.6	**15.7**
8	Rockhampton	QLD	0.7	0.0	165.0	119.9	165.7	119.9	3.1	4.6	**27.6**
9	Perth	WA	26.2	8.5	95.7	63.4	121.9	71.9	3.9	5.9	**41.0**
10	Alice Springs	NT	17.3	6.8	201.2	126.8	218.5	133.6	3.6	5.4	**38.9**
11	Broome	WA	0.0	0.0	467.0	302.9	467.0	302.9	2.4	4.9	**35.1**
12	Cairns	QLD	0.0	0.0	231.7	151.6	231.7	151.6	2.5	5.1	**34.6**
13	Townsville	QLD	0.0	0.0	252.5	166.0	252.5	166.0	2.2	4.6	**34.3**
					Average improvement (%)						**30.7**

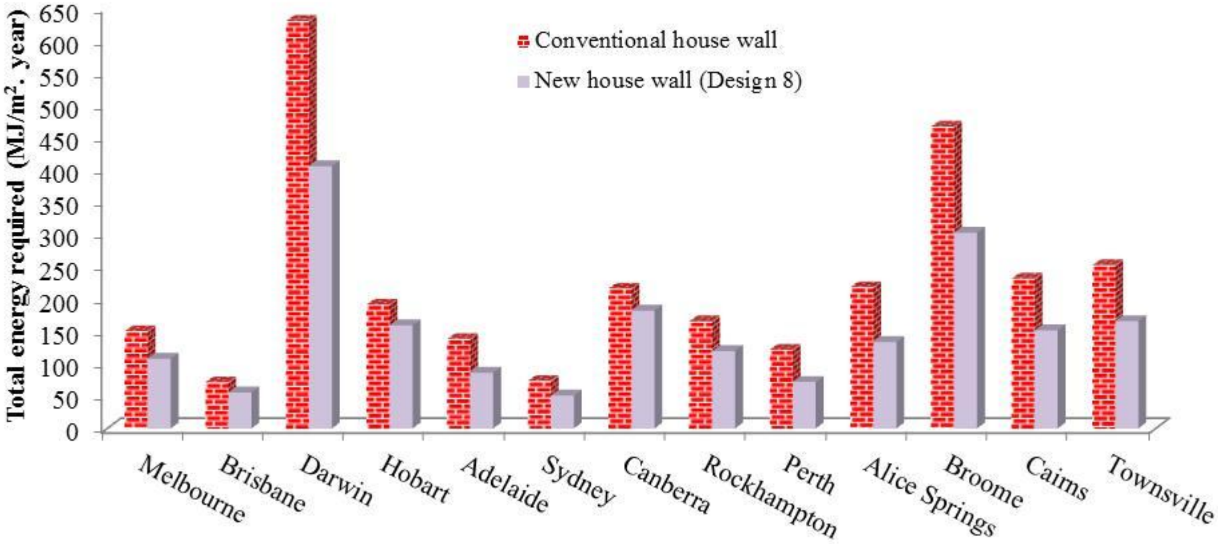


Figure 4.20: Total energy required for on-going heating and cooling for selected cities(Design 8)

4.5.10 Design 9: New House Wall with One Panel of Polystyrene Insulation and Air Gap

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 9 are illustrated in Table 4.16. Design 9 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (41.2%) is noted for Perth. The cities of Alice Springs, Adelaide, Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.21.

Table 4.16: New house wall energy requirements for selected cities (Design 9)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***Des.9***	***Conv.***	***Des.9***	***Conv.***	***Des.9***	***Conv.***	***Des.9***	***%***
1	Melbourne	VIC	112.5	73.9	38.1	33.8	150.6	107.7	4.9	6.2	**28.5**
2	Brisbane	QLD	7.9	1.5	63.4	54.0	71.3	55.5	3.9	4.9	**22.2**
3	Darwin	NT	0.0	0.0	630.4	405.4	630.4	405.4	2.2	5.1	**35.7**
4	Hobart	TAS	186.9	140.5	4.8	19.1	191.7	159.6	5.2	5.9	**16.7**
5	Adelaide	SA	53.6	28.0	85.0	58.3	138.6	86.3	4.6	6.4	**37.7**
6	Sydney	NSW	13.1	3.0	60.4	47.8	73.5	50.8	3.8	4.9	**30.9**
7	Canberra	ACT	176.1	148.3	40.3	34.2	216.4	182.5	4.9	5.6	**15.7**
8	Rockhampton	QLD	0.7	0.0	165.0	120.0	165.7	120.0	3.1	4.6	**27.6**
9	Perth	WA	26.2	8.5	95.7	63.2	121.9	71.7	3.9	5.9	**41.2**
10	Alice Springs	NT	17.3	6.8	201.2	126.8	218.5	133.6	3.6	5.4	**38.9**
11	Broome	WA	0.0	0.0	467.0	311.9	467.0	311.9	2.4	4.9	**33.2**
12	Cairns	QLD	0.0	0.0	231.7	151.6	231.7	151.6	2.5	5.1	**34.6**
13	Townsville	QLD	0.0	0.0	252.5	166.0	252.5	166.0	2.2	4.6	**34.3**
					Average improvement (%)						**30.5**

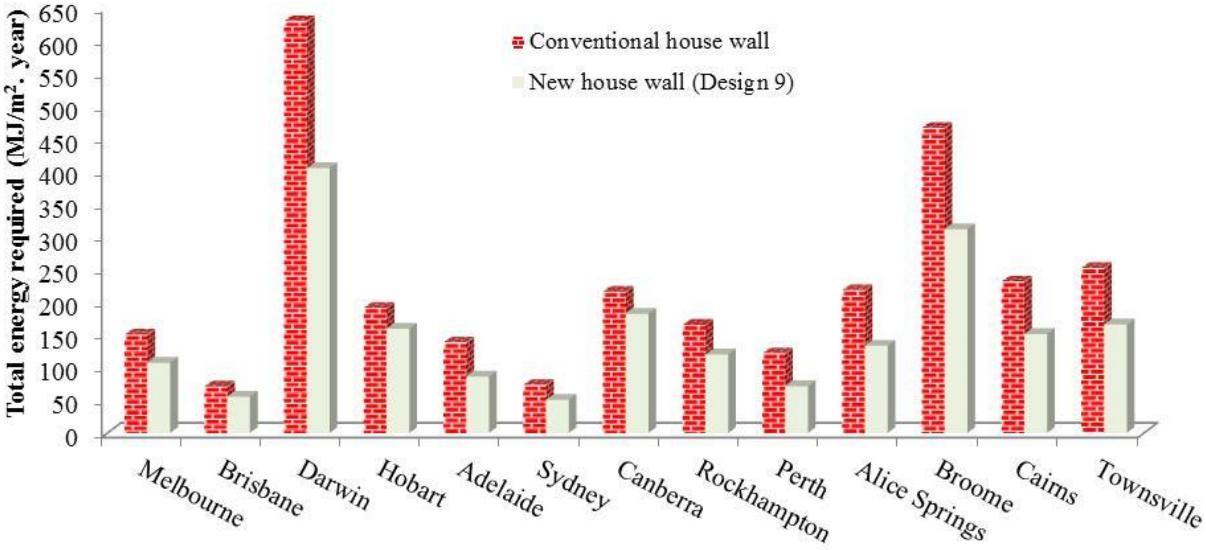


Figure 4.21: Total energy required for on-going heating and cooling for selected cities, (Design 9)

4.5.11 Design 10: New House Wall with One Panel of Polystyrene Insulation (Outer) and Air Gap (Inner)

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 10 are illustrated in Table 4.17. Design 10 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (51.0%) is noted for Perth, followed by Alice Springs (46.6%) and Adelaide (45.7%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.22.

Table 4.17: New house wall energy requirements for selected cities (Design 10)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***Des.10***	***Conv.***	***Des.10***	***Conv.***	***Des.10***	***Conv.***	***Des.10***	*%*
1	Melbourne	VIC	112.5	68.9	38.1	29.8	150.6	98.7	4.9	6.4	**34.5**
2	Brisbane	QLD	7.9	0.5	63.4	51.9	71.3	52.4	3.9	5.2	**26.5**
3	Darwin	NT	0.0	0.0	630.4	412.0	630.4	412.0	2.2	5.0	**34.6**
4	Hobart	TAS	186.9	132.3	4.8	18.1	191.7	150.4	5.2	6.1	**21.5**
5	Adelaide	SA	53.6	23.0	85.0	52.2	138.6	75.2	4.6	6.8	**45.7**
6	Sydney	NSW	13.1	1.4	60.4	45.9	73.5	47.3	3.8	5.2	**35.6**
7	Canberra	ACT	176.1	138.3	40.3	30.2	216.4	168.5	4.9	5.9	**22.1**
8	Rockhampton	QLD	0.7	0.0	165.0	115.8	165.7	115.8	3.1	4.8	**30.1**
9	Perth	WA	26.2	4.2	95.7	55.5	121.9	59.7	3.9	6.6	**51.0**
10	Alice Springs	NT	17.3	2.4	201.2	114.3	218.5	116.7	3.6	5.9	**46.6**
11	Broome	WA	0.0	304.4	467.0	0.0	467.0	304.4	2.4	4.9	**34.8**
12	Cairns	QLD	0.0	150.3	231.7	0.0	231.7	150.3	2.5	5.1	**35.1**
13	Townsville	QLD	0.0	0.0	252.5	167.4	252.5	167.4	2.2	4.5	**33.7**
					Average improvement (%)						**34.8**

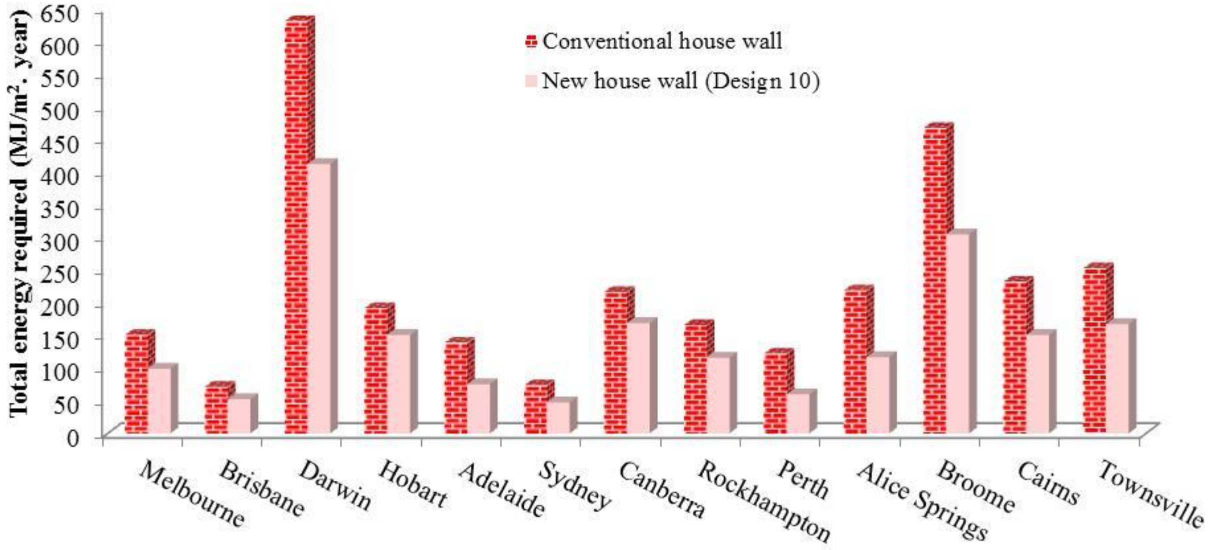


Figure 4.22: Total energy required for on-going heating and cooling for selected cities(Design 10)

4.5.12 Design 11: New House Wall with One Panel of Polystyrene Insulation (Inner) and Air Gap (Outer)

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 11 are illustrated in Table 4.18. Design 11 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (54.6%) is noted for Perth, followed by Alice Springs and Adelaide (48.8%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.23.

Table 4.18: New house wall energy requirements for selected cities (Design 11)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro--vement
			Conv.	***Des.11***	***Conv.***	***Des.11***	***Conv.***	***Des.11***	***Conv.***	***Des.11***	***%***
1	Melbourne	VIC	112.5	67.6	38.1	28.5	150.6	96.1	4.9	6.6	**36.2**
2	Brisbane	QLD	7.9	0.3	63.4	52.0	71.3	52.3	3.9	5.2	**26.6**
3	Darwin	NT	0.0	0.0	630.4	426.4	630.4	426.4	2.2	4.8	**32.4**
4	Hobart	TAS	186.9	128.8	4.8	17.4	191.7	146.2	5.2	6.2	**23.7**
5	Adelaide	SA	53.6	20.9	85.0	50.0	138.6	70.9	4.6	6.9	**48.8**
6	Sydney	NSW	13.1	1.1	60.4	45.7	73.5	46.8	3.8	5.3	**36.3**
7	Canberra	ACT	176.1	133.0	40.3	28.5	216.4	161.5	4.9	6.1	**25.4**
8	Rockhampton	QLD	0.7	0.0	165.0	117.0	165.7	117.0	3.1	4.7	**29.4**
9	Perth	WA	26.2	2.7	95.7	52.7	121.9	55.4	3.9	6.8	**54.6**
10	Alice Springs	NT	17.3	1.3	201.2	110.5	218.5	111.8	3.6	6.0	**48.8**
11	Broome	WA	0.0	0.0	467.0	311.5	467.0	311.5	2.4	4.7	**33.3**
12	Cairns	QLD	0.0	0.0	231.7	154.5	231.7	154.5	2.5	4.9	**33.3**
13	Townsville	QLD	0.0	0.0	252.5	172.1	252.5	172.1	2.2	4.4	**31.8**
					Average improvement (%)						**35.4**

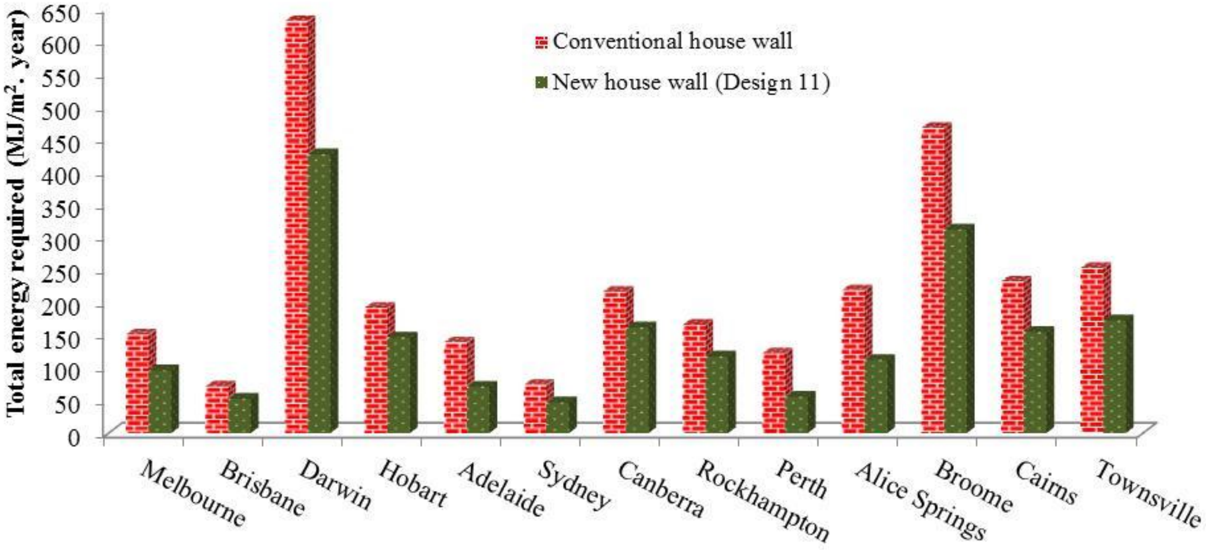


Figure 4.23: Total energy required for on-going heating and cooling for selected cities(Design 11)

4.5.13 Design 12: New House Wall with Two Panels of Rockwool Insulation – (Outer and Inner Positions)

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 12 are illustrated in Table 4.19. Design 12 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (45.9%) is noted for Perth, followed by Adelaide (44.0%) and Alice Springs (43.2%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.24.

Table 4.19: New house wall energy requirements for selected cities (Design 12)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro--vement
			Conv.	***Des.12***	***Conv.***	***Des.12***	***Conv.***	***Des.12***	***Conv.***	***Des.12***	***%***
1	Melbourne	VIC	112.5	65.8	38.1	32.0	150.6	97.8	4.9	6.5	**35.1**
2	Brisbane	QLD	7.9	0.9	63.4	52.8	71.3	53.7	3.9	5.1	**24.7**
3	Darwin	NT	0.0	0.0	630.4	395.3	630.4	395.3	2.2	5.3	**37.3**
4	Hobart	TAS	186.9	127.5	4.8	18.7	191.7	146.2	5.2	6.2	**23.7**
5	Adelaide	SA	53.6	23.4	85.0	54.2	138.6	77.6	4.6	6.7	**44.0**
6	Sydney	NSW	13.1	1.9	60.4	46.8	73.5	48.7	3.8	5.1	**33.7**
7	Canberra	ACT	176.1	134.4	40.3	33.3	216.4	167.7	4.9	5.9	**22.5**
8	Rockhampton	QLD	0.7	0.0	165.0	116.3	165.7	116.3	3.1	4.7	**29.8**
9	Perth	WA	26.2	6.3	95.7	59.6	121.9	65.9	3.9	6.2	**45.9**
10	Alice Springs	NT	17.3	4.6	201.2	119.6	218.5	124.2	3.6	5.7	**43.2**
11	Broome	WA	0.0	0.0	467.0	294.0	467.0	294.0	2.4	5.0	**37.0**
12	Cairns	QLD	0.0	0.0	231.7	147.8	231.7	147.8	2.5	5.2	**36.2**
13	Townsville	QLD	0.0	0.0	252.5	162.6	252.5	162.6	2.2	4.7	**35.6**
					Average improvement (%)						**34.4**

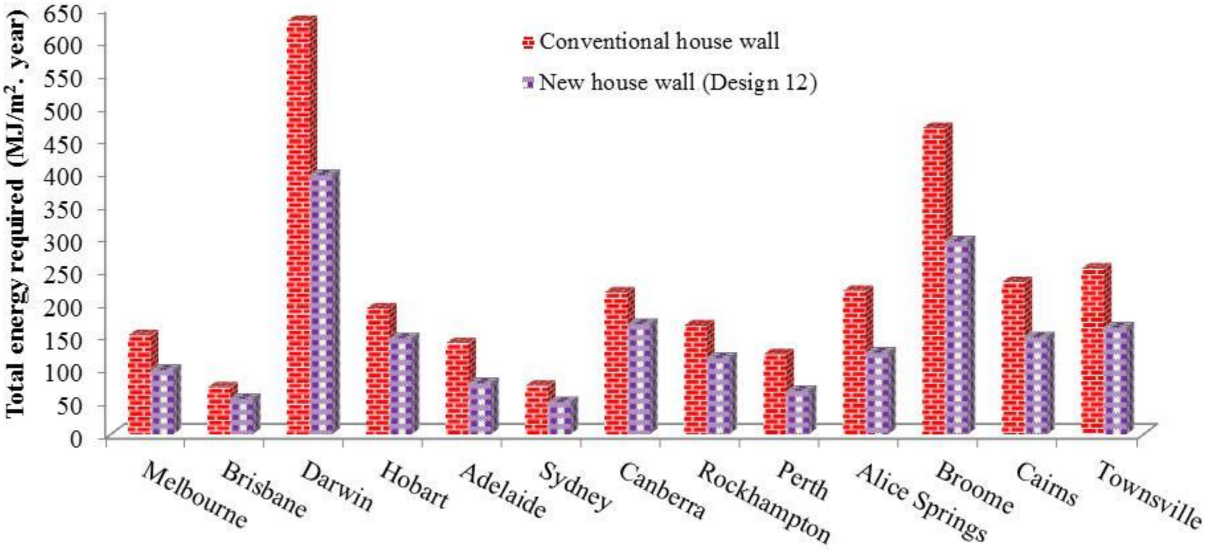


Figure 4.24: Total energy required for on-going heating and cooling for selected cities (Design 12)

4.5.14 Design 13: New House Wall with Two Panels of Sheep Wool Insulation – (Outer and Inner Positions)

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 13 are illustrated in Table 4.20. Design 13 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (45.9%) is noted for Perth, followed by Adelaide (43.9%) and Alice Springs (43.2%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.25.

Table 4.20: New house wall energy requirements for selected cities (Design 13)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***Des.13***	***Conv.***	***Des.13***	***Conv.***	***Des.13***	***Conv.***	***Des.13***	***%***
1	Melbourne	VIC	112.5	65.8	38.1	32.0	150.6	97.8	4.9	6.5	**35.1**
2	Brisbane	QLD	7.9	0.9	63.4	52.8	71.3	53.7	3.9	5.1	**24.7**
3	Darwin	NT	0.0	0.0	630.4	395.3	630.4	395.3	2.2	5.3	**37.3**
4	Hobart	TAS	186.9	127.6	4.8	18.6	191.7	146.2	5.2	6.2	**23.7**
5	Adelaide	SA	53.6	23.4	85.0	54.3	138.6	77.7	4.6	6.7	**43.9**
6	Sydney	NSW	13.1	1.9	60.4	46.9	73.5	48.8	3.8	5.1	**33.6**
7	Canberra	ACT	176.1	134.4	40.3	33.3	216.4	167.7	4.9	5.9	**22.5**
8	Rockhampton	QLD	0.7	0.0	165.0	116.2	165.7	116.2	3.1	4.7	**29.9**
9	Perth	WA	26.2	6.3	95.7	59.7	121.9	66.0	3.9	6.2	**45.9**
10	Alice Springs	NT	17.3	4.6	201.2	119.5	218.5	124.1	3.6	5.7	**43.2**
11	Broome	WA	0.0	0.0	467.0	294.0	467.0	294.0	2.4	5.0	**37.0**
12	Cairns	QLD	0.0	0.0	231.7	147.7	231.7	147.7	2.5	5.2	**36.3**
13	Townsville	QLD	0.0	0.0	252.5	162.6	252.5	162.6	2.2	4.7	**35.6**
					Average improvement (%)						**34.5**

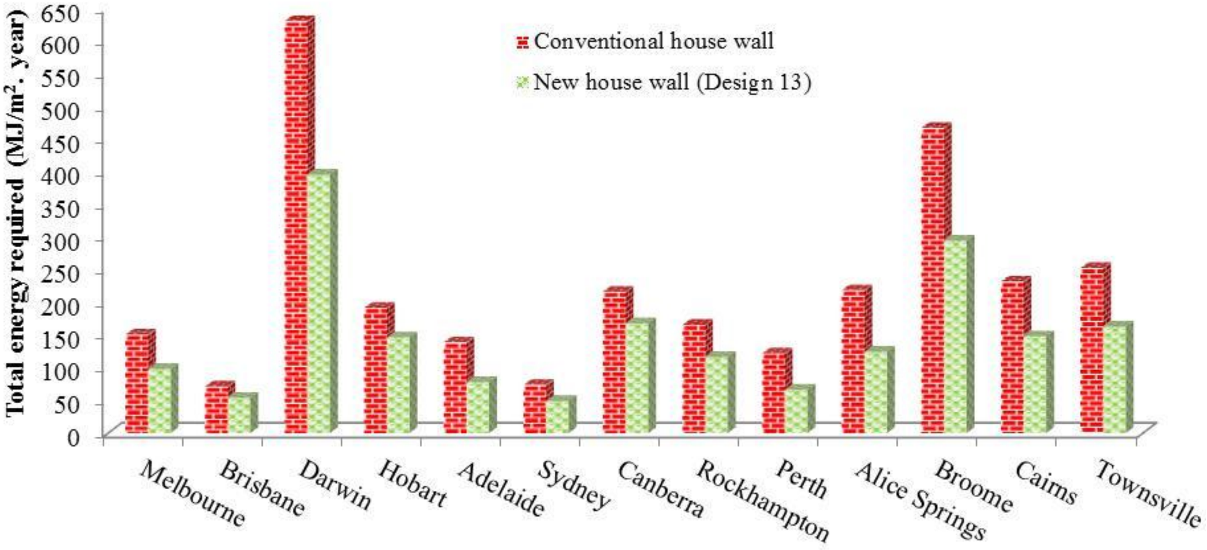


Figure 4.25: Total energy required for on-going heating and cooling for selected cities (Design 13)

4.5.15 Design 14: New House Wall with Two Half Concrete Panels and Two Panels of Rockwool Insulation in-between

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 14 are illustrated in Table 4.21. Design 14 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (53.9%) is noted for Perth, followed by Adelaide (50.1%) and Alice Springs (49.0%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.26.

Table 4.21: New house wall energy requirements for selected cities (Design 14)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro--vement
			Conv.	***Des.14***	***Conv.***	***Des.14***	***Conv.***	***Des.14***	***Conv.***	***Des.14***	***%***
1	Melbourne	VIC	112.5	61.1	38.1	29.7	150.6	90.8	4.9	6.7	**39.7**
2	Brisbane	QLD	7.9	0.3	63.4	52.5	71.3	52.8	3.9	5.2	**25.9**
3	Darwin	NT	0.0	0.0	630.4	422.5	630.4	422.5	2.2	4.9	**33.0**
4	Hobart	TAS	186.9	117.8	4.8	17.9	191.7	135.7	5.2	6.4	**29.2**
5	Adelaide	SA	53.6	18.0	85.0	51.2	138.6	69.2	4.6	7.0	**50.1**
6	Sydney	NSW	13.1	0.9	60.4	45.8	73.5	46.7	3.8	5.3	**36.5**
7	Canberra	ACT	176.1	120.3	40.3	29.1	216.4	149.4	4.9	6.3	**31.0**
8	Rockhampton	QLD	0.7	0.0	165.0	117.3	165.7	117.3	3.1	4.7	**29.2**
9	Perth	WA	26.2	2.3	95.7	53.9	121.9	56.2	3.9	6.8	**53.9**
10	Alice Springs	NT	17.3	1.1	201.2	110.3	218.5	111.4	3.6	6.1	**49.0**
11	Broome	WA	0.0	0.0	467.0	307.0	467.0	307.0	2.4	4.8	**34.3**
12	Cairns	QLD	0.0	0.0	231.7	154.7	231.7	154.7	2.5	4.9	**33.2**
13	Townsville	QLD	0.0	0.0	252.5	172.0	252.5	172.0	2.2	4.4	**31.9**
					Average improvement (%)						**37.1**

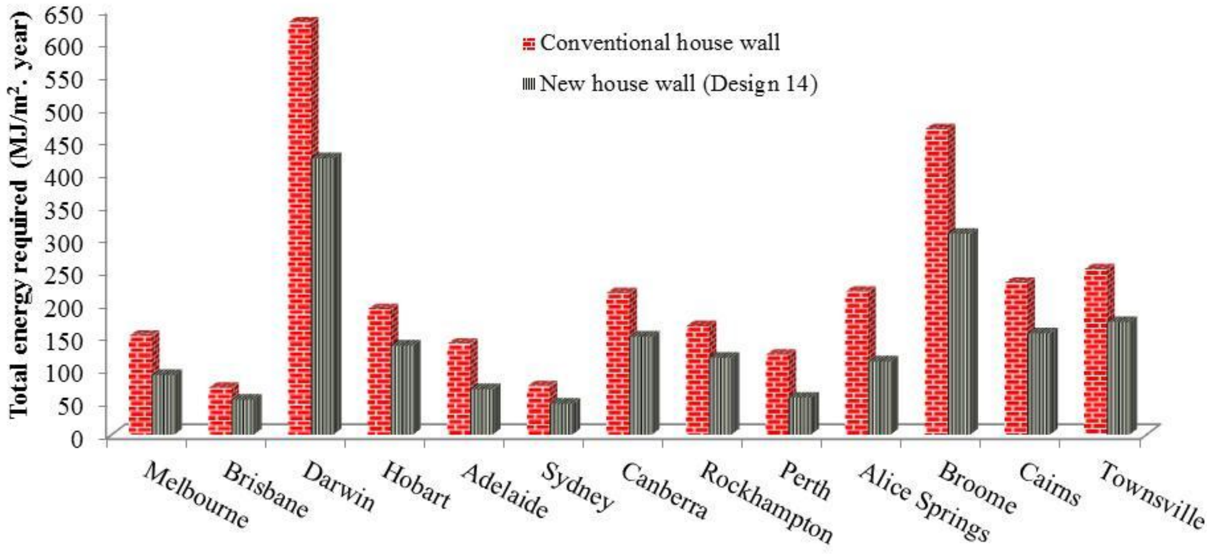


Figure 4.26: Total energy required for on-going heating and cooling for selected cities(Design 14)

4.5.16 Design 15: New House Wall with Two Half Concrete Panels and Two Panels of Sheep Wool Insulation in-between

The energy requirements for on-going heating and cooling, star energy ratings and relative improvements for Design 15 are illustrated in Table 4.22. Design 15 requires less energy for all 13 selected cities and towns. The highest reduction in energy requirement (53.9%) is noted for Perth, followed by Adelaide (50.0%) and Alice Springs (49.0%). The cities of Melbourne, Sydney, Darwin, Broome, Townsville and Cairns have achieved energy savings of 30-40%, while Brisbane, Canberra, Rockhampton and Hobart are 20-30%. The total energy requirement for all 13 cities/towns is shown separately in Figure 4.27.

Table 4.22: New house wall energy requirements for selected cities (Design 15)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy required MJ/m^2. annum		Star rating 0-10		Impro- -vement
			Conv.	***Des.15***	***Conv.***	***Des.15***	***Conv.***	***Des.15***	***Conv.***	***Des.15***	***%***
1	Melbourne	VIC	112.5	61.2	38.1	28.8	150.6	90.0	4.9	6.7	**40.2**
2	Brisbane	QLD	7.9	0.3	63.4	52.5	71.3	52.8	3.9	5.2	**25.9**
3	Darwin	NT	0.0	0.0	630.4	422.6	630.4	422.6	2.2	4.9	**33.0**
4	Hobart	TAS	186.9	117.9	4.8	17.9	191.7	135.8	5.2	6.4	**29.2**
5	Adelaide	SA	53.6	18.0	85.0	51.3	138.6	69.3	4.6	7.0	**50.0**
6	Sydney	NSW	13.1	0.9	60.4	45.9	73.5	46.8	3.8	5.3	**36.3**
7	Canberra	ACT	176.1	120.4	40.3	29.1	216.4	149.5	4.9	6.3	**30.9**
8	Rockhampton	QLD	0.7	0.0	165.0	117.3	165.7	117.3	3.1	4.7	**29.2**
9	Perth	WA	26.2	2.3	95.7	53.9	121.9	56.2	3.9	6.8	**53.9**
10	Alice Springs	NT	17.3	1.1	201.2	110.4	218.5	111.5	3.6	6.1	**49.0**
11	Broome	WA	0.0	0.0	467.0	307.3	467.0	307.3	2.4	4.8	**34.2**
12	Cairns	QLD	0.0	0.0	231.7	154.6	231.7	154.6	2.5	4.9	**33.3**
13	Townsville	QLD	0.0	0.0	252.5	171.9	252.5	171.9	2.2	4.4	**31.9**
					Average improvement (%)						**37.1**

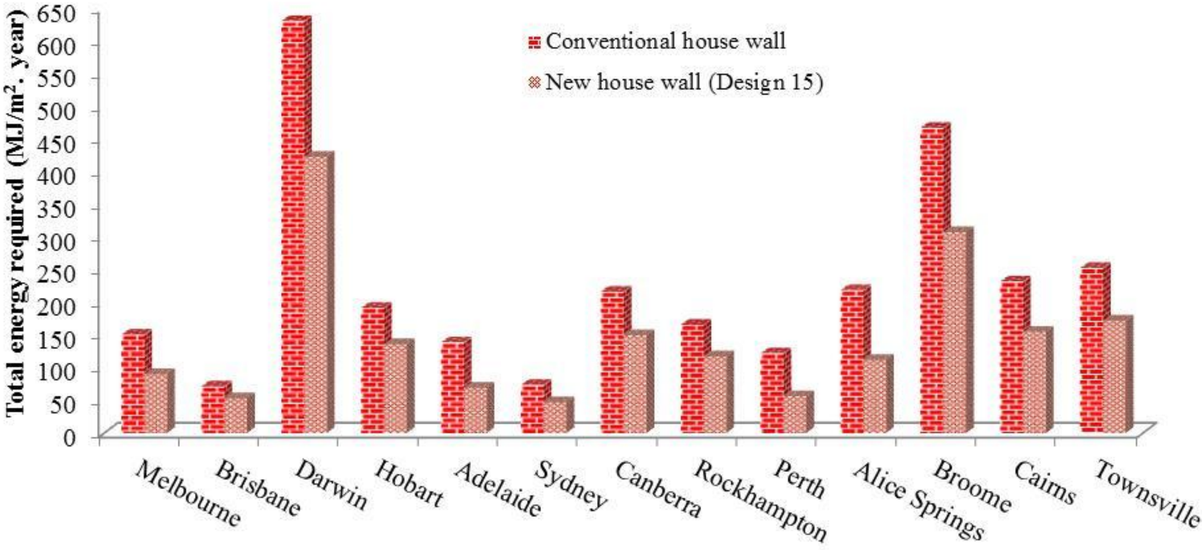


Figure 4.27: Total energy required for on-going heating and cooling for selected cities(Design 15)

4.5.17 Improvement and Optimum Design of New House Wall

All new houses wall systems require less energy for on-going heating and cooling in all 13 selected cities/towns compared to the conventional house wall system. In general, the highest reduction in energy requirement (37.5%) is noted for house Design 7 followed by house Designs 14, 15 (37.1%) and 5 (36.1%). On the other hand, the lowest reduction in energy requirement (30.2%) is noted for house Design 3, followed by house Designs 9 (30.5%) and 8 (30.7%). Table 4.23 and Figure 4.28present the obtained data from computational modeling. Each city has an optimum house design based on lower energy consumption, as shown inTable 4.23.For example, Melbourne has the lowest energy consumption for Designs 7, 15, 14 and 5.

Table 4.23: Average improvement of new house wall designs and energy saving designs

No.	City	State	D.1 %	D.2 %	D.3 %	D.4 %	D.5 %	D.6 %	D.7 %	D.8 %	D.9 %	D.10 %	D.11 %	D.12 %	D.13 %	D.14 %	D.15 %	Intensive energy saving design			
1	Melbourne	VIC	35.1	35.3	27.5	33.9	39.5	37.1	41.4	28.5	28.5	34.5	36.2	35.1	35.1	39.7	40.2	**7**	**15**	**14**	**5**
2	Brisbane	QLD	24.7	26.6	22.0	25.1	25.9	25.7	26.2	22.0	22.2	26.5	26.6	24.7	24.7	25.9	25.9	**2**	**7**	**10**	**11**
3	Darwin	NT	37.3	32.1	35.4	31.4	32.9	32.3	33.5	35.7	35.7	34.6	32.4	37.3	37.3	33.0	33.0	**1**	**12**	**13**	**8**
4	Hobart	TAS	23.7	22.4	15.5	22.1	29.2	26.0	31.4	16.7	16.7	21.5	23.7	23.7	23.7	29.2	29.2	**7**	**5**	**14**	**15**
5	Adelaide	SA	43.9	47.9	37.0	45.7	50.0	48.1	51.2	37.7	37.7	45.7	48.8	44.0	43.9	50.1	50.0	**7**	**14**	**5**	**15**
6	Sydney	NSW	33.6	36.2	30.7	34.7	36.3	35.6	36.3	30.9	30.9	35.6	36.3	33.7	33.6	36.5	36.3	**14**	**5**	**7**	**15**
7	Canberra	ACT	22.5	24.1	14.4	23.9	30.9	27.7	33.1	15.7	15.7	22.1	25.4	22.5	22.5	31.0	30.9	**7**	**14**	**5**	**15**
8	Rockhampton	QLD	29.8	29.1	27.3	27.8	29.2	28.5	29.7	27.6	27.6	30.1	29.4	29.8	29.9	29.2	29.2	**10**	**13**	**1**	**12**
9	Perth	WA	45.9	54.3	40.8	51.8	46.3	52.9	54.2	41.0	41.2	51.0	54.6	45.9	45.9	53.9	53.9	**11**	**2**	**7**	**14**
10	Alice Springs	NT	43.2	48.5	38.4	46.7	49.0	48.0	49.6	38.9	38.9	46.6	48.8	43.2	43.2	49.0	49.0	**7**	**5**	**14**	**15**
11	Broome	WA	35.2	33.0	34.8	32.3	34.2	33.3	34.8	35.1	33.2	34.8	33.3	37.0	37.0	34.3	34.2	**12**	**13**	**1**	**8**
12	Cairns	QLD	36.3	33.1	34.5	32.1	33.3	32.7	33.6	34.6	34.6	35.1	33.3	36.2	36.3	33.2	33.3	**1**	**13**	**12**	**8**
13	Townsville	QLD	31.6	35.7	34.3	30.4	31.9	31.2	32.4	34.3	34.3	33.7	31.8	35.6	35.6	31.9	31.9	**2**	**12**	**13**	**8**
Average improvement (%)			**34.1**	**35.3**	**30.2**	**33.7**	**36.1**	**35.3**	**37.5**	**30.7**	**30.5**	**34.8**	**35.4**	**34.4**	**34.5**	**37.1**	**37.1**				

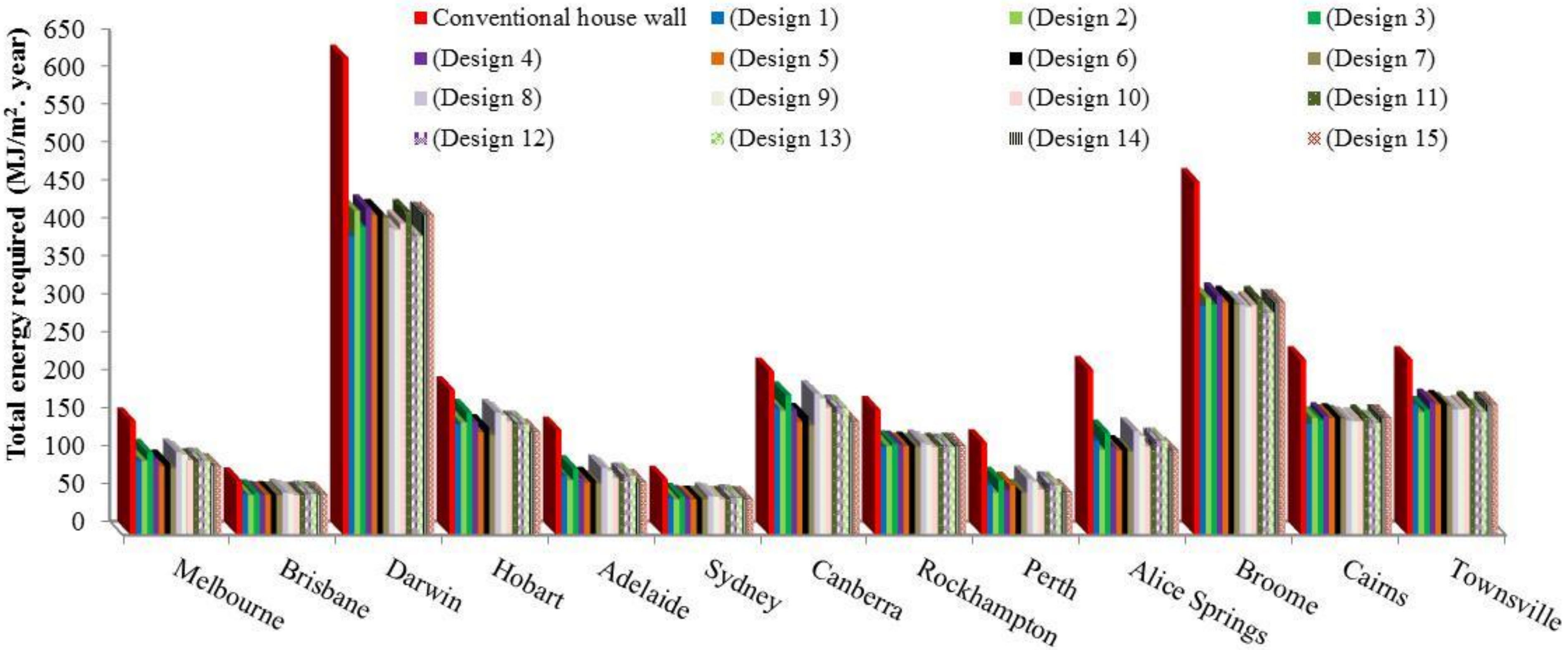


Figure 4.28: Total energy required for on-going heating and cooling for selected cities (all designs)

4.6 Inner and Outer Insulation Positions

The inner and outer insulation materials used in this study are polystyrene, cellulose fibre, rock wool batt, sheep wool, straw board, rendered straw bale, glass fibre, wood chipboard and polyurethane rigid foam. Installing those insulation materials on the house wall panels of the interior and exterior walls effectively can obstruct heat escape or transmission from the house. This keeps the temperature inside the house at a normal level and also saves the energy of the heating and cooling process.

Conventional house wall systems have the highest energy consumption. In the inner and outer insulation position of the new house wall systems, polyurethane rigid foam is noted to produce the lowest energy consumption for all houses in 13 cities/towns compared to conventional house wall system, as shown in Table 4.24 and Table 4.25.

A similar level of energy consumption has been produced by the new houses with insulation materials of polystyrene, cellulose fibre, rock wool bats, sheep wool and glass fibre. Further, the insulation of rendered straw bale, straw board and wood chipboard has also reduced energy consumption compared to the conventional house wall system. Further results for each selected insulation material are shown in Appendix B.

Table 4.24: Energy required for different inner insulation materials for selected cities (inner insulation position)

No.	City	State	**Conventional house wall**	Polyurethane rigid foam	Polystyrene	Cellulose fibre	Rock wool	Sheep wool	Glass fibre	Rendered straw bale	Straw board	Wood chip board
			Total energy required (MJ/m^2. annum)									
1	Melbourne	VIC	**150.6**	104.4	109.2	109.1	109.1	109.2	109.3	127.8	126.3	129.8
2	Brisbane	QLD	**71.3**	52.1	52.3	52.2	52.3	52.3	52.3	53.6	53.5	53.8
3	Darwin	NT	**630.4**	401.0	407.2	408.5	407.8	407.7	407.3	431.7	432.0	443.0
4	Hobart	TAS	**191.7**	154.5	162.0	161.9	161.8	161.9	162.1	190.5	188.3	194.4
5	Adelaide	SA	**138.6**	84.2	87.3	87.3	87.3	87.3	87.4	99.8	98.5	99.4
6	Sydney	NSW	**73.5**	46.5	46.9	46.9	46.9	46.9	46.9	49.8	49.6	50.3
7	Canberra	ACT	**216.4**	177.1	185.2	185.2	185.1	185.2	185.4	216.2	213.1	217.6
8	Rockhampton	QLD	**116.3**	117.4	117.4	117.4	117.4	117.4	122.9	122.5	124.0	116.3
9	Perth	WA	**121.9**	54.6	55.7	55.7	55.7	55.8	55.8	62.2	61.7	63.2
10	Alice Springs	NT	**218.5**	109.7	112.6	112.5	112.6	112.6	112.6	124.3	123.6	126.1
11	Broome	WA	**467.0**	299.5	304.6	305.0	304.6	304.6	304.7	325.0	324.8	332.6
12	Cairns	QLD	**231.7**	150.0	151.8	151.4	152.0	152.0	152.0	158.1	158.2	160.6
13	Townsville	QLD	**252.5**	164.6	162.4	166.3	166.5	166.5	165.9	173.9	174.3	177.7

Table 4.25: Energy required for different outer insulation materials for selected cities (outer insulation position)

No.	City	State	**Conventional house wall**	Polyurethane rigid foam	Polystyrene	Cellulose fibre	Rock wool	Sheep wool	Glass fibre	Rendered straw bale	Straw board	Wood chip board
			Total energy required (MJ/m^2. annum)									
1	Melbourne	VIC	**150.6**	92.9	97.7	97.8	97.6	97.7	97.8	116.7	116.1	121.2
2	Brisbane	QLD	**71.3**	55.1	55.6	55.6	55.6	55.6	55.6	57.8	57.6	57.6
3	Darwin	NT	**630.4**	423.1	428.3	428.7	428.4	428.3	428.6	448.1	447.5	453.0
4	Hobart	TAS	**191.7**	141.0	148.7	148.9	148.6	148.7	148.9	178.1	177.2	186.1
5	Adelaide	SA	**138.6**	68.6	72.2	72.2	72.1	72.2	72.3	85.5	84.9	88.4
6	Sydney	NSW	**73.5**	50.2	50.9	51.0	51.0	51.0	51.0	53.9	54.0	54.1
7	Canberra	ACT	**216.4**	155.6	164.3	164.5	164.2	164.3	164.5	197.3	196.0	205.6
8	Rockhampton	QLD	**165.7**	119.4	120.5	120.6	120.5	120.6	120.7	127.4	127.4	120.5
9	Perth	WA	**121.9**	70.7	72.2	72.1	72.2	72.2	72.2	77.8	76.3	75.8
10	Alice Springs	NT	**218.5**	130.8	134.6	134.4	134.4	134.4	134.7	146.0	143.8	143.7
11	Broome	WA	**467.0**	308.2	313.1	313.2	313.0	313.0	313.3	330.8	330.1	335.8
12	Cairns	QLD	**231.7**	153.7	154.9	155.2	155.1	155.0	155.0	160.1	159.9	162.0
13	Townsville	QLD	**252.5**	92.9	97.7	97.8	97.6	97.7	97.8	116.7	116.1	121.2

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Table 4.26: The suitable insulation position by using different insulation materials for selected cities

No.	City	State	Polyurethane rigid foam	Polystyrene	Cellulose fibre	Rock wool	Sheep wool	Glass fibre	Rendered straw bale	Straw board	Wood chip board
1	Melbourne	VIC	Outer	Outer	Outer	Outer	Outer	Outer	Outer	Outer	Outer
2	Brisbane	QLD	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner
3	Darwin	NT	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner
4	Hobart	TAS	Outer	Outer	Outer	Outer	Outer	Outer	Outer	Outer	Outer
5	Adelaide	SA	Outer	Outer	Outer	Outer	Outer	Outer	Outer	Outer	Outer
6	Sydney	NSW	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner
7	Canberra	ACT	Outer	Outer	Outer	Outer	Outer	Outer	Outer	Outer	Outer
8	Rockhampton	QLD	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner
9	Perth	WA	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner
10	Alice Springs	NT	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner
11	Broome	WA	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner
12	Cairns	QLD	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner
13	Townsville	QLD	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner	Inner

4.7 Summary on Energy Rating Tools and Computational Finding

The current energy rating tools available in the market are considered acceptable and sufficiently accurate. In the future, it expected that there will be developments in the current simulation tools and they will produce more accurate energy rating tools. However, the most advanced and widely used residential building rating tools in Australia is AccuRate.

To sum up, the energy consumption for new houses that the used inner insulation system recorded lower consumption for the cities of Darwin, Broom, Cairns and Townville. The outer insulation system has better energy performance for the cities of Melbourne, Brisbane, Hobart, Adelaide, Sydney, Canberra, Rockhampton, Perth and Alice Springs. Table 4.26 provides the analysed results for inner and outer insulation position using selected different materials. Further computational results about the inner and outer insulation materials are described in Appendix B.

CHAPTER 5 ANALYTICAL METHOD

5.1 Introduction

Heat is a form of energy which can be transferred between thermodynamic systems due to the difference in temperature. Normally heat transfers from higher to lower temperature areas (Cengel, 1998). Several material properties have effects on heat transfer between the objects, such as specific heat, material densities, thermal conductivity, fluid velocity, and surface emissivity (Liendhard, 2011). In order to understand the theory of heat transfer through the house wall system, analytical analysis was undertaken. The following sections briefly describe the approach used in this study.

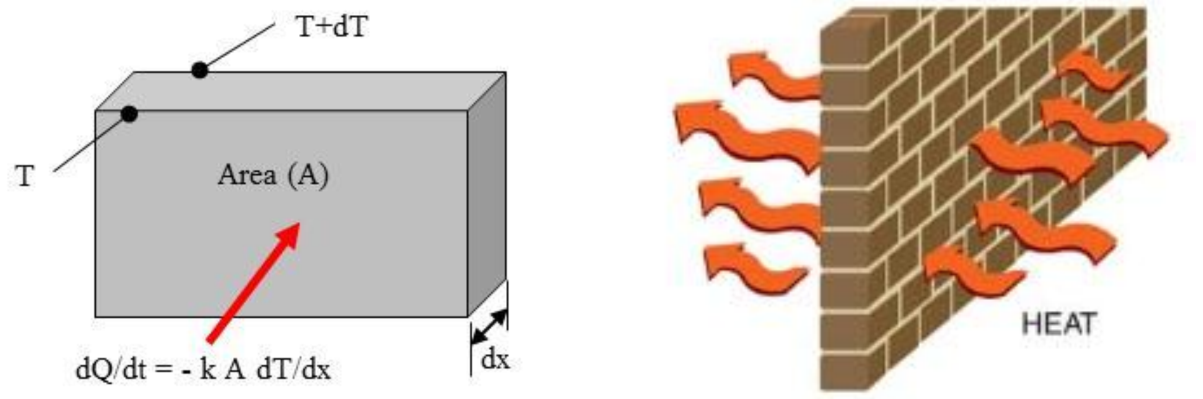
An analytical method is used to validate and benchmark the computational modelling. Heat transfer through house wall system was determined analytically. The inside air temperature is kept constant for a certain time and the outside air temperature is considered variable, based on the daytime mean and night time mean temperature for a given location, in order to estimate the total heat loss/gain through conventional and new wall systems.

5.2 Theoretical Analysis Approach

The analytical study is based on the application of heat transfer theory and equations. The energy performance of the house envelope can be determined by knowing individual building materials, thermal properties and ambient weather conditions. However, the estimated results can differ from the experimental data due to the nonlinear thermal behaviour of materials and the occupant’s energy usage pattern. Three modes of heat transfer (conduction, convection and radiation) are used to determine the overall heat loss or gain.

5.2.1 Conduction Heat Transfer

The mechanism of conduction heat transfer is based on the direct interaction between particles (atoms, molecules, electrons, phonons) and can occur in any kind of substance. Conduction heat transfer needs a medium for particle movement. Conduction can take place in solids, gases and liquids. The conduction happens due to collisions of the particles during their random motion for liquids and gases. By contrast, in solids, the atoms are bound in a lattice, and conduction is a result of vibrations of molecules described by free electron transport. The rate of conduction heat transfer through a medium depends on the medium’s geometry, its materials and thickness. An example of conduction heat transfer in the house is heat flow through the wall from the outside to inside or the opposite during the day or night time, as shown in Figure 5.1.



a) The rate of heat conduction through large plane wall of thickness Δx and Area A

b) Heat flow through the house wall by conduction (Stewart, 2004)

Figure 5.1: Conduction heat transfer

For simple geometries, according to Fourier’s law of conduction heat transfer in one-dimensional is given by:

$$Q_{cond} = -kA\frac{\Delta T}{\Delta x} \qquad [W] \tag{5.1}$$

This equation indicates that the rate of heat conduction is caused by a temperature gradient. It is in direct proportion to the temperature gradient in a specific direction. The negative sign states that heat flow is always directed towards decreasing temperatures. The surface area A of heat transfer is always normal to the direction of heat.

5.2.2 Convection Heat Transfer

Another form of heat transfer is convection and that occurs when solid surface is in contact with a fluid in motion. The term of convection refers to transfer of heat with fluid movement. Convection heat transfer includes both conduction and the effects that are connected to a bulk movement of molecules within the liquid or gas. The greater convection heat transfer results in faster fluid motion. The motion can be produced by external action or without external action. The motion of fluid with external action such as fans or wind is called forced convection. In contrast, the motion without external action is called natural or free convection and that happens due to temperature and density differences. In some cases, when the fluid is at rest, heat transfer only happens by conduction. For example, in the air gap between house wall constructions which do not have air movement, the conduction heat transfer is more dominant than convection for this case (Cengel, 1998; Liendhard, 2011). Newton's law of cooling is described the convective heat transfer, and reads:

$$Q_{conv} = hA(T_s - T_\infty) \qquad [W] \qquad (5.2)$$

Here, T_s is the temperature of the solid and for continuity reasons, T_s is equal to the temperature of the boundary layer. T_∞ is the fluid temperature at large distances from the surface, as illustrated in Figure 5.2. The heat exchange rate is proportional to the difference in temperature $\Delta T = (T_s - T_\infty)$. The convection heat transfer coefficient h is expressed by this proportionality. Therefore, h is a parameter of fluid properties like other material properties such as: dynamic viscosity μ, thermal conductivity k, density ρ and velocity v. It is an experimentally determined parameter which depends on a variable such as the geometry of the surface, the nature motion of fluid, fluid properties and the bulk fluid velocity. The convection heat transfer coefficient (h) has a relation with fluid velocity. The higher the velocity, the higher is the heat transfer coefficient. Typical values of the heat transfer coefficient are given in Table 5.1.

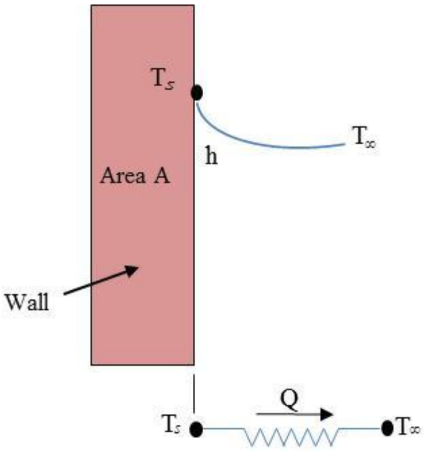


Figure 5.2: Schematic for concoction heat transfer

Table 5.1: Typical value of heat transfer coefficient

Type of convection	Heat transfer coefficient, W/(m^2.°C)
Free convection of gases	2-25
Free convection of liquids	10-1000
Forced convection of gases	25-250
Forced convection of liquids	50-20000
Boiling and condensation	2500-100000

In convection studies, it is very common to introduce non-dimensionless, governing equations and combine all variables into dimensionless numbers in order to reduce the number of total variables. The Nusselt number (Nu) introduces characteristic dimensionless numbers for mathematical fluid dynamics. The Nusselt number (Nu) is the quantity derived from the convection heat transfer coefficient, which is defined as:

$$Nu = \frac{h\delta}{k} \tag{5.3}$$

In this equation, δ is a characteristic length of the geometry of the wall, and for more complex geometries δ can be defined as the fluid volume V divided by the surface area According to the above, the heat transfer by conduction is $\div Q_{cond} = k\frac{\Delta T}{x}$ and the convective heat transport is given by$\div Q_{conv} = hA(\Delta T)$, and then, taking the ratio of convection and conduction, we obtain: $\frac{Q_{conv}}{Q_{cond}} = \frac{h\Delta T}{k\Delta T / \delta} = \frac{h\delta}{k} = Nu$ (5.4) Therefore, the Nusselt number expresses the proportion between convection and conduction caused by fluid motion. The Nusselt number, Nu = 1, for a fluid layer describes heat transfer by pure conduction.For natural convection, the Nusselt number can be described by the Rayleigh number (Ra). The exact relation Nu = f (Ra) depends on the geometry. For the geometry of the house wall considered in this study, which is similar to vertical plate geometry, the Ra can be calculated according to equation:

$$Ra = \frac{g\beta(T_s - T_\infty)\delta^3}{\nu^2}\Pr \tag{5.5}$$

5.2.3 Radiation Heat Transfer

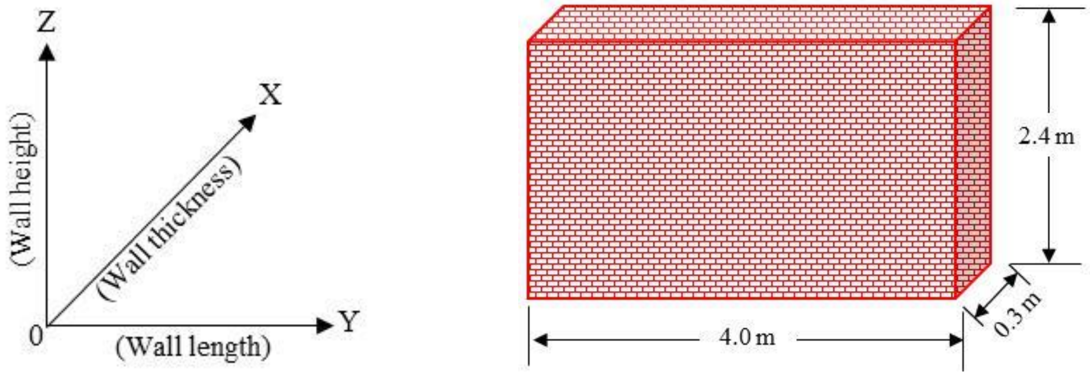
Radiation heat transfer is created on the exchange of electromagnetic waves between atoms or molecules. These modes of heat transfer can also occur in a vacuum. Unlike conduction and convection, the transfer of energy by radiation does not require a transfer medium. In fact, energy transfer by radiation is faster at the speed of light. In radiation heat transfer, the thermal radiation emitted by the body or object temperature. The blackbody radiation is the amount of emitted radiation energy, which is given by wavelength and temperature. By integration over the whole wavelength spectrum, the Stefan-Boltzmann law is obtained, which describes the total amount of irradiated power from a surface as a function of its temperature: $Q_{rad} = \varepsilon\sigma(T_s^{\ 4} - T^4{}_{surr})$ $[W]$ (5.6)

Here, $\sigma = 5.6703\times10^{-8}\ (W/m^2K^4)$ is the Stefan-Boltzmann constant and ε is emissivity. The emissivity is the total amount of radiation emitted by a given surface of temperature T_s divided by the radiation of a blackbody at the same temperature. The emissivity of a black body is equal to one.

5.3 Heat Gain or Loss Estimation through House Wall System

5.3.1 Analytical Analysis

The maximum conductive heat loss or gain is predominantly through the wall thickness (X-axis), as illustrated in Figure 5.3. There is no heat transfer through the wall from top to bottom or left to right. The only temperature difference is between the inner and outer wall surface. However, the small wall thickness causes the temperature gradient to be large in that direction. Further, if the air temperature inside and outside the house remain constant, then heat transfer through the wall of a house can be considered steady and one-dimensional. Therefore, in this study, one dimensional heat transfer equations are used to estimate the heat flow through the wall as the temperature gradient is significantly greater along the thickness of the house wall compared to the length and height (Cengel, 1998; Liendhard, 2011; Lorente, Petit & Javelas, 1996).



a) Heat transfer direction b) House wall system

Figure 5.3: Schematic of one dimensional heat transfer through house wall system

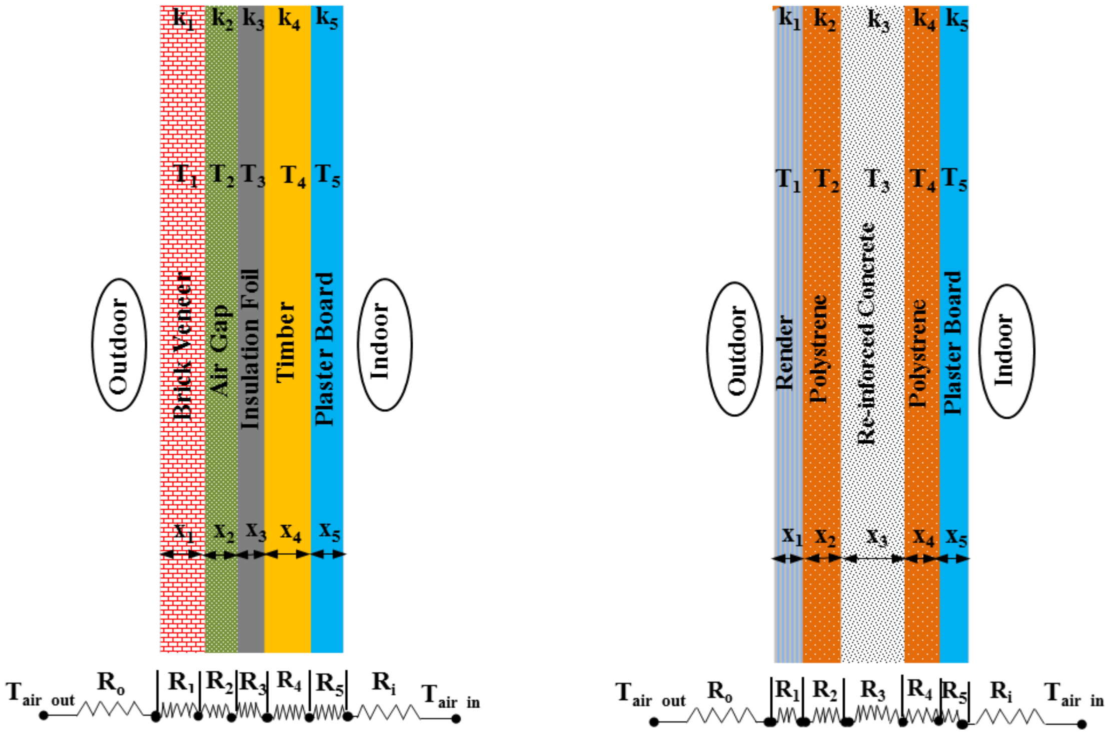
For the estimation of heat loss or gain through 1 m² multilayer conventional and new house wall systems, various insulations were used. The insulation used for the new house wall system is polystyrene (inner and outer layer of the reinforced concrete panel). For the conventional house wall system, the insulators are air gap and fibre glass, as recommended by the BCA. The thermal resistance R, thickness x and thermal conductivity k for conduction and convection heat transfer can be calculated as following:

$$R_{total} = R_{out} + R_1 + R_2 + R_3 + R_4 + R_5 + R_{in} \tag{5.7}$$

Where, $R_{out} = R_{conv,out} = \dfrac{1}{h_{out}}$, $R_1 = R_{material1} = \dfrac{x_1}{k_1 A}$, $R_2 = R_{material2} = \dfrac{x_2}{k_2 A}$, $R_3 = R_{material3} = \dfrac{x_3}{k_3 A}$,

$R_4 = R_{material4} = \dfrac{x_4}{k_4 A}$, $R_5 = R_{material5} = \dfrac{x_5}{k_5 A}$ and $R_{in} = R_{conv,in} = \dfrac{1}{h_{in}}$

$R_{out}, R_1, R_2, R_3, R_4, R_5, R_{in}$ are the thermal resistances per unit of outside convection, brick veneer, air cavity (gap), insulation foil, timber frame, plaster board and inside convection, respectively, for the conventional wall system. Similarly, $R_{out}, R_1, R_2, R_3, R_4, R_5, R_{in}$ are the thermal resistances of outside convection, render, insulation material (outer layer of the reinforced concrete panel), reinforced concrete, insulation material (inner layer of the reinforced concrete panel), plaster board and inside convection for the new wall system. The materials thermal properties for conventional and new house wall were discussed in Chapter 2. The schematics of thermal resistance network for heat transfer through conventional and new house wall systems are shown in Figure 5.4.



a) Conventional house wall system

b) New house wall system (Design 1)

Figure 5.4:Thermal resistance network for heat transfer through conventional and new house wall system

Equations 5.8 to 5.22 were used to determine the heat gain or loss through house wall composite materials. One-dimensional steady state heat transfer, based on the early work undertaken by Warner and Arpaci (1968), was used to estimate conduction, convection and radiation. In order to account for the variation of the fluid properties, the fluid properties are evaluated at film temperature. Film temperature is the arithmetic average of the surface and the free stream temperature. The fluid at this case is assumed to remain constant during the entire flow (air). Once the inside and outside temperatures are known, the film temperature is calculated as:

$$T_{film} = \frac{T_{air.in} + T_{air.out}}{2} \tag{5.8}$$

At this temperature the following can be read: Pr, k, ν and $\beta = \dfrac{1}{T_f}$

The convective and conductive heat transfers were based on house wall compositions. In natural convection heat transfer correlations are usually expressed in terms of Rayleigh number. The Rayleigh numbers inside and outside the house is:

$$Ra_{in} = \frac{g\beta\left(T_{air.in} - T_{film}\right)\delta^3}{\nu^2}\Pr \tag{5.9}$$

$$Ra_{out} = \frac{g\beta\left(T_{film} - T_{air.out}\right)\delta^3}{\nu^2}\Pr \tag{5.10}$$

The natural convection on a surface is dependent on the geometry of the surface and variation of temperature. The vertical plate geometry was used as a similar case of house wall geometry. In this case, the empirical correlation for the average Nusselt number Nu was used for natural convection over house wall inner and outer surfaces as:

$$Nu_{in} = \left[0.825 + \frac{0.387 Ra_{in}^{1/6}}{\left[1 + \left(0.492/\Pr^{9/16}\right)\right]^{8/27}}\right]^2 \tag{5.11}$$

$$Nu_{out} = \left[0.825 + \frac{0.387 Ra_{out}^{1/6}}{\left[1 + \left(0.492/\Pr^{9/16}\right)\right]^{8/27}}\right]^2 \tag{5.12}$$

Here, theNusselt number (Nu) is used to obtain convective heat transfer coefficient outside and inside the house (h_{in}, h_{out}):

$$h_{in} = \frac{k_{air}}{\delta} Nu_{in} \tag{5.13}$$

$$h_{out} = \frac{k_{air}}{\delta} Nu_{in} \tag{5.14}$$

In order to calculate the total heat gain or loss through house wall system, the following equations and relations have been used. For heat gain/loss by inner convection:

$$Q_{gain/loss} = h_{in} \times A \times (T_{air.in} - T_{wall.in}) \tag{5.15}$$

For heat gain/loss by conduction:

$$Q_{gain/loss} = \frac{k_{wall} \times A \times (T_{wall.in} - T_{wall.out})}{l} \tag{5.16}$$

For heat gain/loss by outer convection:

$$Q_{gain/loss} = h_{out} \times A \times (T_{wall.out} - T_{air.out}) \tag{5.17}$$

From equation (5.15): $T_{wall.in} = T_{air.in} - \frac{Q_{gain/loss}}{h_{in} \times A}$ (5.18)

From equation (5.16):

$$T_{wall.out} = T_{wall.in} - \frac{Q_{gain/loss} \times l}{k_{wall} \times A} \tag{5.19}$$

Substitute equation (5.18) in equation (5.19):

$$T_{wall.out} = T_{airl.in} - \frac{Q_{gain/loss}}{h_{in} \times A} - \frac{Q_{gain/loss} \times l}{k_{wall} \times A} \tag{5.20}$$

Substitute equation (5.20) in (5.17):

$$Q_{gain/loss} = h_{out} \times A \times (T_{air.in} - \frac{Q_{gain/loss}}{h_{in} \times A} - \frac{Q_{gain/loss} \times l}{k_{wall} \times A} - T_{air.out})$$

Then, the final equation used to calculate the heat gain /loss by conduction and convection (inner and outer) through the house wall can be rearranged as:

$$Q_{gain/loss} = \frac{h_{out} \times A \times (T_{air.in} - T_{air.out})}{\left(1 + \frac{h_{out} \times A}{h_{in} \times A} + \frac{h_{out} \times A \times l}{k_{wall} \times A}\right)} \qquad [W] \tag{5.21}$$

The radiation heat gain/loss between inside wall surface emissivity and its area to the surrounding surface at inner temperature can be expressed as:

$$Q_{loss/gain} = \varepsilon_{plasterboard} \times \sigma \times A \times ({T_{air.in}}^{4} - {T_{wall.in}}^{4}) \qquad [W] \tag{5.22}$$

In this analysis, the outdoor temperature (climate data) has been taken from the Bureau of Meteorology (BOM, Australia) for the years 2011, 2012 and 2013. The provided outdoor temperatures conducted in this study are for each minute for 12 major cities: Melbourne, Brisbane, Darwin, Hobart, Adelaide, Sydney, Canberra, Rockhampton, Perth, Alice Springs, Broom and Cairns. The indoor temperature used was 22°C for the months of January, February, March, October, November and December. For the months of April to September, a lower temperature setting used, which was 18°C, as explained in Chapter 4. The negative sign indicates a heating need and a positive sign a cooling need. The heat gain or loss by on-going heating and cooling for conventional and new house wall is presented in Table 5.2 and

Table 5.3.The conventional house wall system in Darwin and Broome noted the highest heat gain or loss for on-going heating and cooling by 524.84 and 432.20 MJ/m².year, respectively, while Brisbane and Sydney noted the lowest heat gain/loss for this purpose by 60.3 MJ/m².year. A similar heat gain/loss for heating and cooling is also noted for Cairns, Alice Springs, Hobart and Canberra. The heat gain/loss for Melbourne and Rockhampton is in between.

The new house wall noted less heat gain or loss for all 12 selected cities. The highest reduction in heat loss or gain (38%) is obtained for Melbourne and Darwin, followed by Cairns (36.5%), Rockhampton (35.1%), Broome (35.0%), Alice Springs (34.1%), Adelaide (33.2%) and Perth (31.9%). The cities of Canberra, Brisbane and Sydney have achieved energy savings of 25-30%, while Brisbane, Hobart and Canberra are 20-30%. An illustrated example of the estimation method is shown in Appendix C.

Table 5.2: Analytical result for conventional and new house wall (Design 1),total heat gain/loss

No.	City	State	Total heat loss/gain, MJ/m^2. annum		Improvement by new house, (Design1) %
			Conventional house wall	New house wall (Design 1)	
1	Melbourne	VIC	146.2	90.5	**38.1**
2	Brisbane	QLD	60.3	45.4	**24.7**
3	Darwin	NT	524.8	325.2	**38.0**
4	Hobart	TAS	178.6	130.0	**27.2**
5	Adelaide	SA	131.4	87.8	**33.2**
6	Sydney	NSW	69.2	50.0	**27.7**
7	Canberra	ACT	206.9	154.3	**25.4**
8	Rockhampton	QLD	151.9	98.8	**35.1**
9	Perth	WA	110.8	75.4	**31.9**
10	Alice Springs	NT	190.9	125.8	**34.1**
11	Broome	WA	432.2	281.0	**35.0**
12	Cairns	QLD	227.2	144.2	**36.5**
Average heat loss by conventional house wall (%)					**32.4**

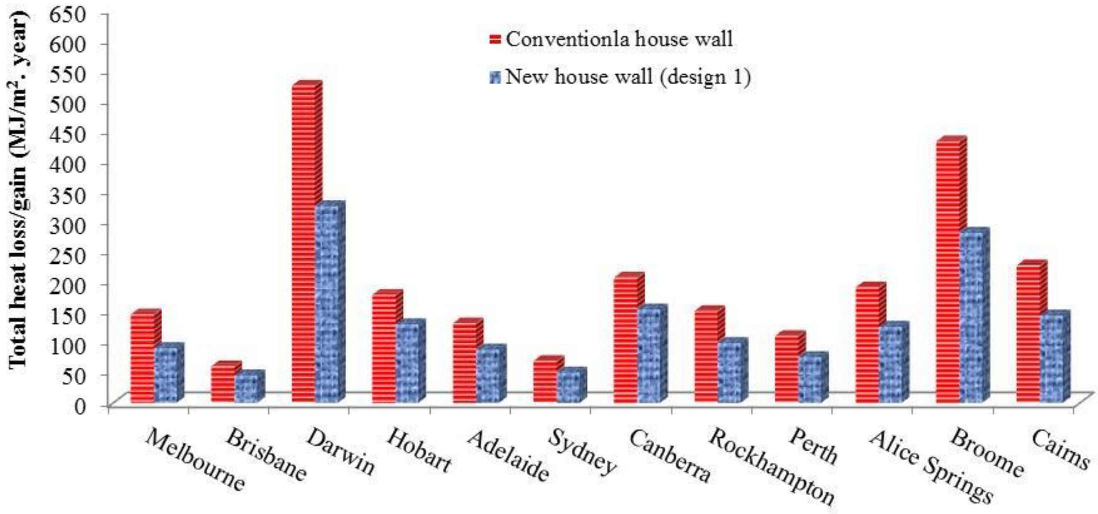


Figure 5.5: Analytical result for conventional and new house wall (Design 1), total heat gain/loss

5.3.2 Total Degree Hour (TDH)

One of the commonly used methods to estimate the amount of energy required for heating or cooling is the degree-days or degree-hours method. The difference between the base temperature and the mean outdoor air temperature is the concept method used by many researchers (Bolatturk, 2006; Wang, Huang & Heng, 2007; Bolatturk, 2008; Ozel & Pihtili, 2008; Durmayaz, Kadioglu & Sen 2008; Buyukalaca, Bulut & Yilmaz, 2001; Sisman et al., 2007; Sarak & Satman, 2003; Papakostas, Mavromatis & Kyriakis, 2010). Degree hours are necessary in calculating the building heating or cooling requirements if the monthly or yearly climate data are available. The degree hour concept is primarily a representation of the data of outside air temperature compared with the inside air temperature. It is commonly used in the power industry to know the effect of outside air temperatures on building energy consumption. Heating or cooling degree hours (HDHs or CDHs) are usually used by meteorologists. Heating degree hours (HDHs) is a measurement designed to represent the demand for energy needed to heat the building. The number of HDHs is directly proportional to the heating requirements for a given house structure at a particular location. A similar measurement, cooling degree hours (CDHs), reflects the amount of energy used to cool a house or building. The hourly values of HDHs and CDHs are the summation for a period of the month or year. Using this method requires knowing the climatic weather data and ambient temperatures for a selected place or city. The total number of annual heating and cooling degree hours (HDHs and CDHs) are calculated as:

$$HDHs = \sum_{days} = (T_{base} - T_{out})^{-} \tag{5.23}$$

$$CDHs = \sum_{days} = (T_{out} - T_{base})^{+} \tag{5.24}$$

Where, T_{out} is the hourly mean outdoor air temperature and T_{base} is the base or indoor air temperature. Only positive values are to be counted, as shown in plus sign above the parentheses. The base temperature for any particular building depends on the building adjusted temperature. Also, the base temperature is dependent on the nature of the building, including heat generating by occupants and equipment. In a previous study by Rahman in 2010, a temperature base of 18°C for HDHs and 24°C for CDHs was used.

In this study, the heating is required when the inside temperature is less than 18°C and cooling is required when the same is above 26°C as computational software adjusted (BCA). The base temperature was selected as 22°C for the months of January, February, March, October, November and December. For the months of April to September, a lower temperature setting was used: 18°C. The outside temperature was adjusted based on Australian weather data between 2011 and 2013 for 13 major cities. The estimated percentage of cooling and heating need of each selected city is shown in Table 5.3. The negative sign indicates a heating need and a positive sign a cooling need. An illustrated example on the estimation method is shown in Appendix C.

Table 5.3: Total degree hours used to obtain the percentage of cooling and heating need

No.	City	State	Need cooling	Need heating	Total degree hours	Cooling %	Heating %
1	Melbourne	VIC	4691	-27241	31932	15	85
2	Brisbane	QLD	65676	-13922	79597	83	17
3	Darwin	NT	85674	-3080	88755	97	3
4	Hobart	TAS	5096	-75905	81001	6	94
5	Adelaide	SA	11021	-34132	45153	24	76
6	Sydney	NSW	23957	-7082	31039	77	23
7	Canberra	ACT	5974	-67401	73375	8	92
8	Rockhampton	QLD	198121	-10450	208572	95	5
9	Perth	WA	56317	-22274	78591	72	28
10	Alice Springs	NT	180435	-30233	210668	86	14
11	Broome	WA	53730	-2988	56718	95	5
12	Cairns	QLD	47604	-1613	49216	97	3
13	Townsville	QLD	48167	-2300.2	50467	95	5

5.4 Summary

In order to estimate the total heat loss/gain through conventional and new wall systems, an analytical method is used to validate and benchmark the computational modelling. The analytical study is based on the application of heat transfer theory and equations. Three modes of heat transfer (conduction, convection and radiation) are used to determine the overall heat loss or gain. The energy performance of the house envelopes were differs from the experimental data due to the nonlinear thermal behaviour of materials and the occupant’s energy usage pattern.

CHAPTER 6 EXPERIMENTAL METHOD

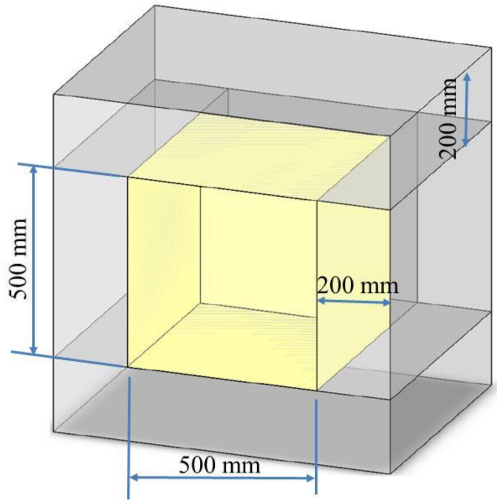
6.1 Introduction

In order to understand the thermal performance of industrial materials and thermal mass, an experimental investigation was designed and undertaken. Due to funding constraints, a scale model house of dimensions 0.5m × 0.5m × 0.5m was made without windows, doors and natural ventilation.

6.2 Experimental Set up

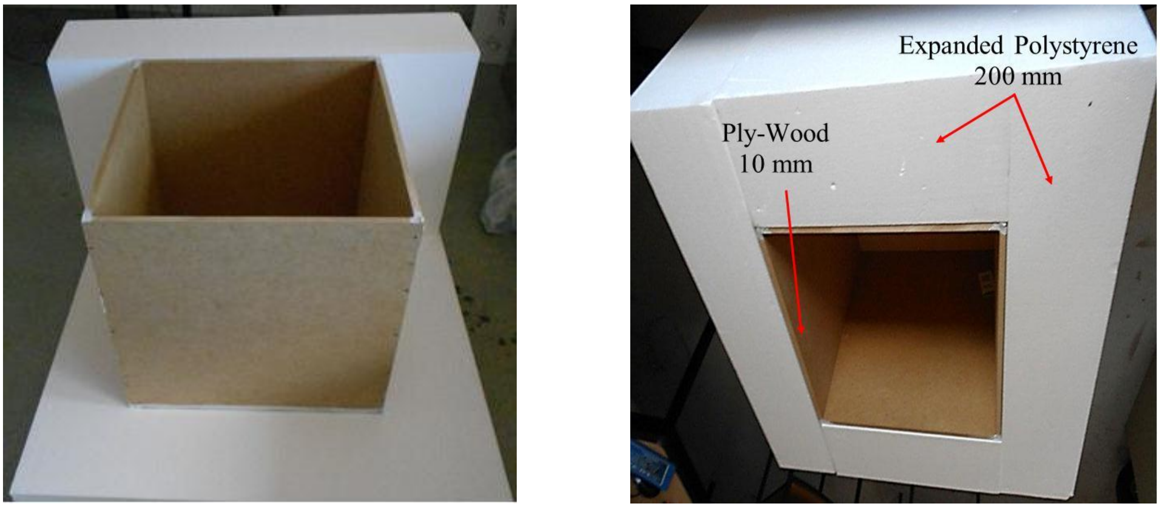
6.2.1 Scale Model Construction

The scale model was made of 10mm thick plywood and 200mm thick polystyrene insulation, and except for one vertical side all sides were fixed and highly insulated. The vertical side is the subject of experimental investigation. Appendix D shows further details about construction materials and dimensions. Figure 6.1 shows the experimental model set up at the RMIT Thermodynamics Lab.



a) CAD of scale model

b) Plywood box assembly

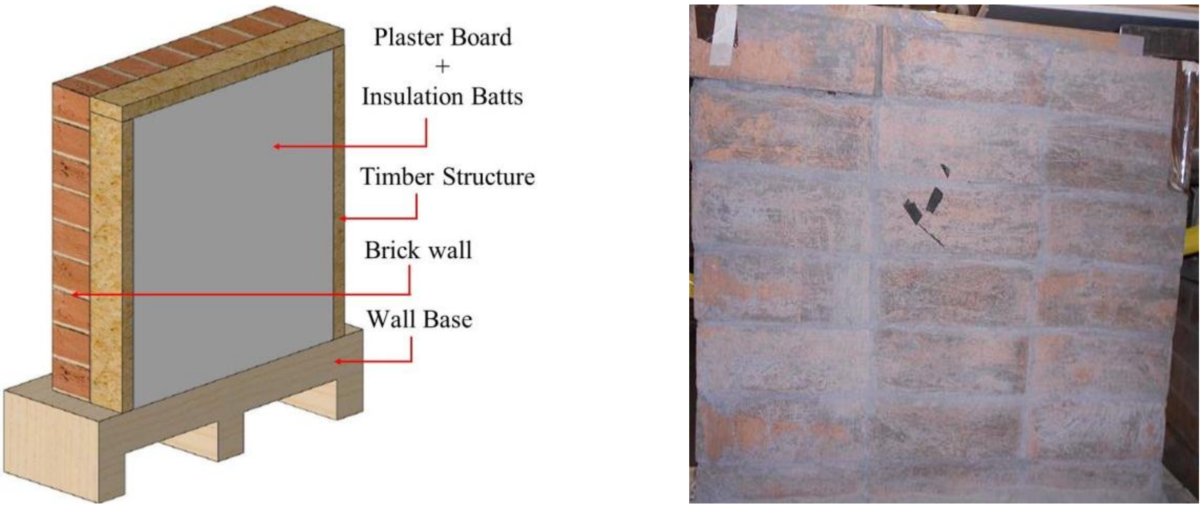


a) Plywood box insulated by polystyrene b) Physical experimental scale model

Figure 6.1: Experimental model at RMIT Thermodynamics Lab

6.2.2 Conventional Wall Construction

The conventional house wall was made of 110mm thick single brick from outside. A 40mm air gap was kept between the brick and timber frame. On the inside, a 90mm timber frame structure was built adjacent to brick. The timber frame was filled with insulation batts and covered with 10mm plasterboard on the inside. The insulation material used was glass wool (R1.5). The construction method was typically close to the real construction of a conventional house wall in Australia. Figure 6.2 shows the experimental set up for the conventional house wall system.



a) CAD of conventional wall b) Exterior brick wall (outside view)

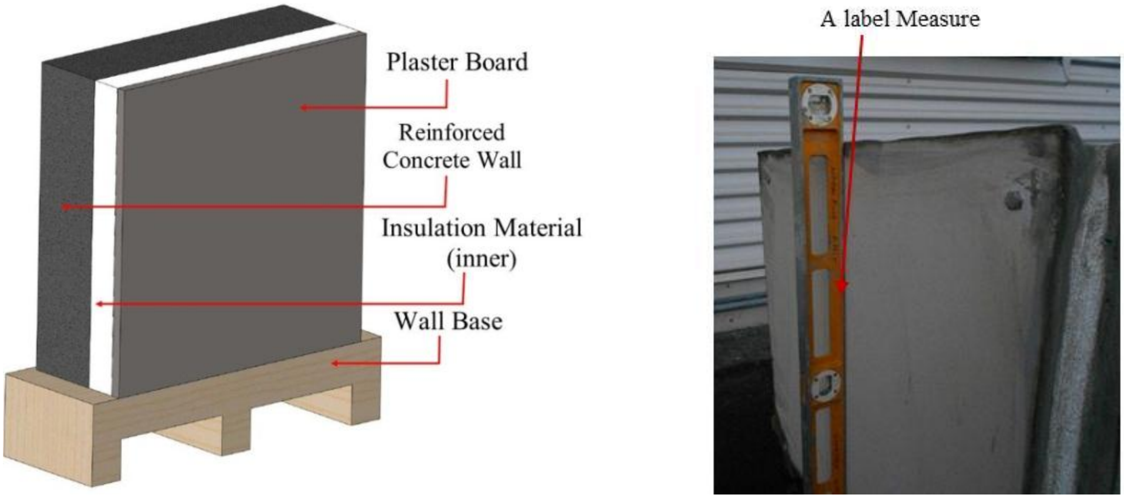
c) Timber frame with fibreglass insulation (inside view)

d) Experimental vertical wall (conventional)

Figure 6.2: Experimental house wall at RMIT Thermodynamics Lab

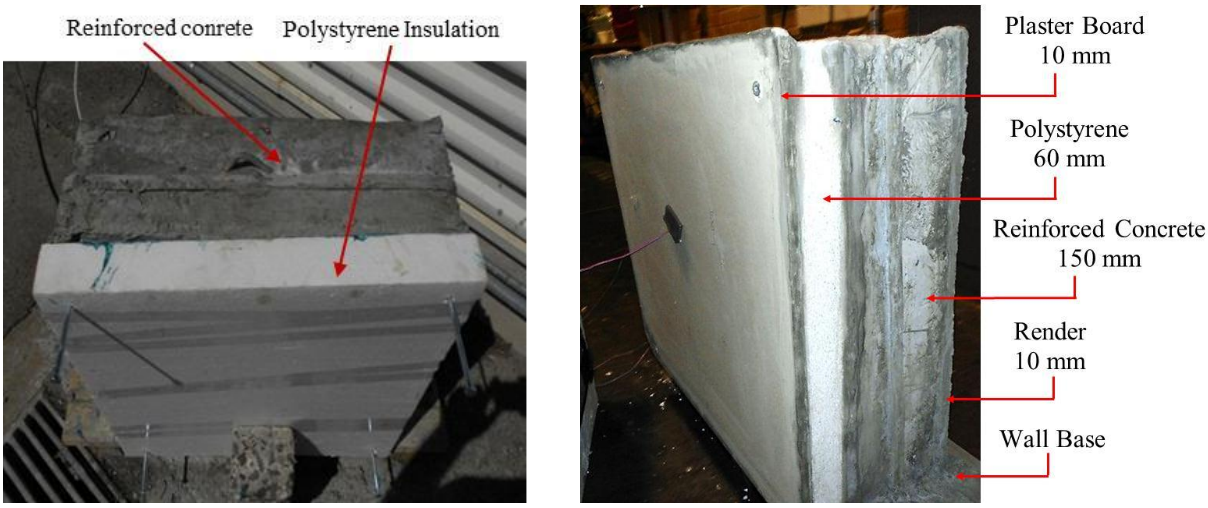
6.2.3 New Wall Construction

The new house wall is made of 150mm reinforced concrete and 10mm rendering from outside. Sixty millimetres thick polystyrene insulation (R1.5) was attached over the reinforced concrete. On the inside 10mm plaster board was used. Figure 6.3 shows the experimental set up of a new house wall system with polystyrene insulation. The same method was used to construct the other types of insulation materials: straw and polyurethane boards. In every set up for other new walls, the only change was replacing the insulation material for each wall. All insulation materials used had similar dimensions and thicknesses.



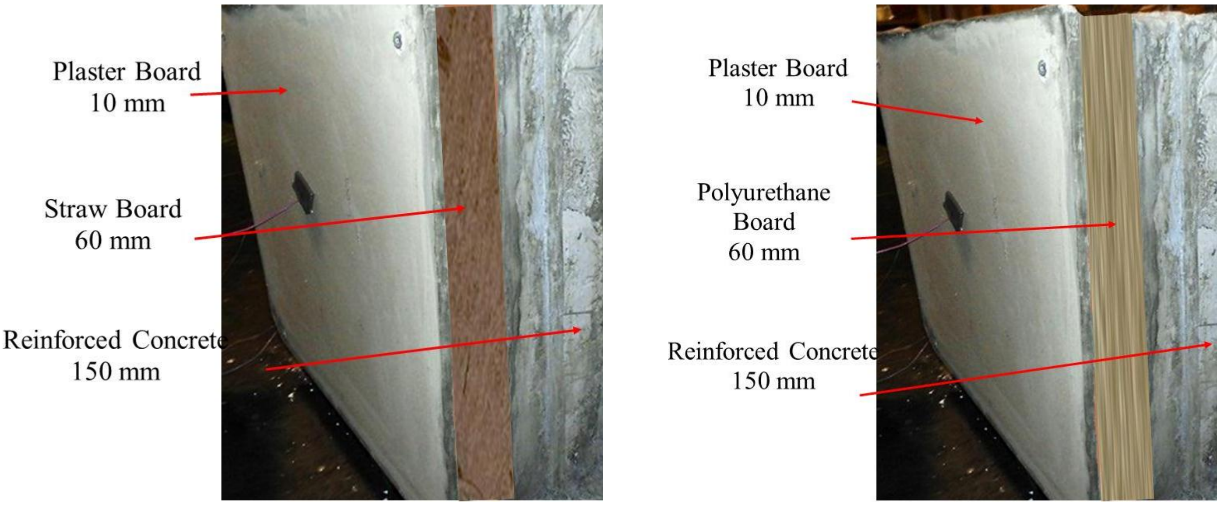
a) CAD of new wall

b) Plasterboard (inside view)



c) Reinforced concrete & polystyrene insulation (top view)

d) Experimental vertical new wall (polystyrene insulation)



a) Experimental vertical new wall (strawboard insulation)

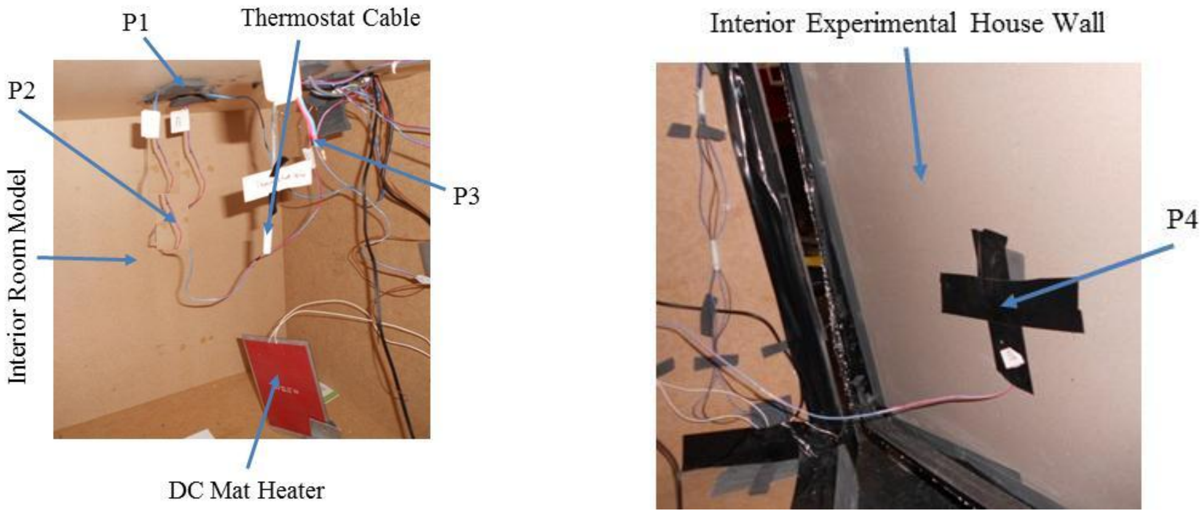
b) Experimental vertical new wall (polyurethane insulation)

Figure 6.3: Experimental setup for new house wall with different insulation materials

6.2.4 Location of Temperature Measurement and Monitoring

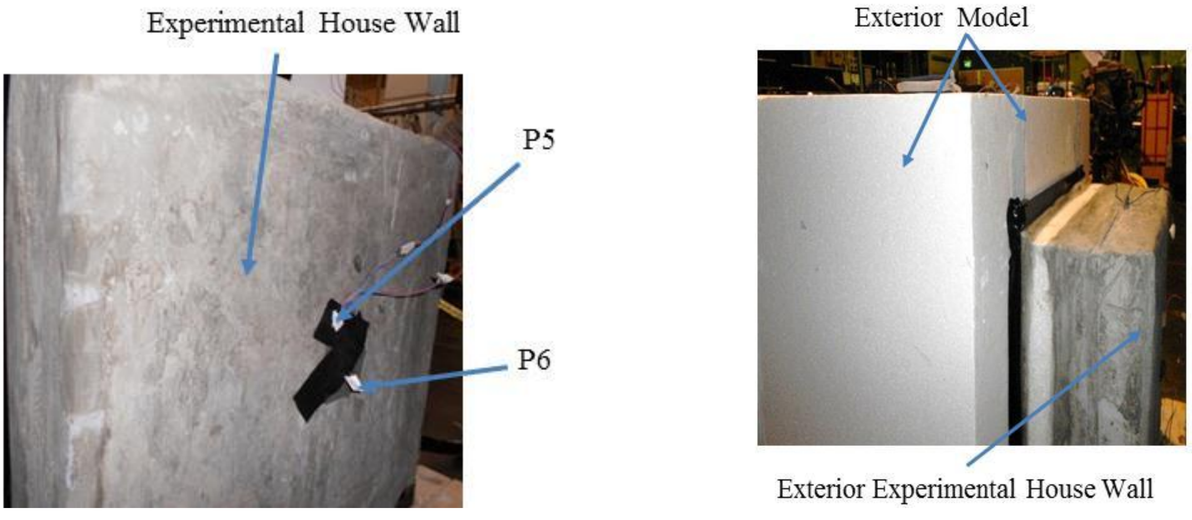
In order to estimate thermal performance, the indoor and outdoor micro temperature, humidity and weather status were measured, using a sense of thermocouples, a weather station and recording devices. The air temperature inside/outside the model house and the experimental wall system were connected to thermocouples, including Data-Taker (DT800). T-type thermocouples were placed at different measuring positions, as shown in Figure 6.4. Every measured point was recorded with different temperature values. Multiple measured points were selected to understand the variation in heat transfer value and thermal gradient.

At points P1, P2 and P3 the temperature was measured inside the scale model. Point P4 was on the experimental wall (inside) and point P5 was on the experimental wall from outside. The ambient air temperature was measured at point P6 at 20mm distance from P5. Figure 6.5 illustrates the various positions (points) where temperatures were measured and monitored. Table 6.1 shows the physical dimension of all points where temperature was measured.



a) Location of temperature measurements (inside the scale model)

b) Location of temperature measurements (inside the experimental wall)



c) Location of temperature measurements (outside the experimental wall)

d) Scale model and experimental house wall (outside)

Figure 6.4: Experimental temperature recording points

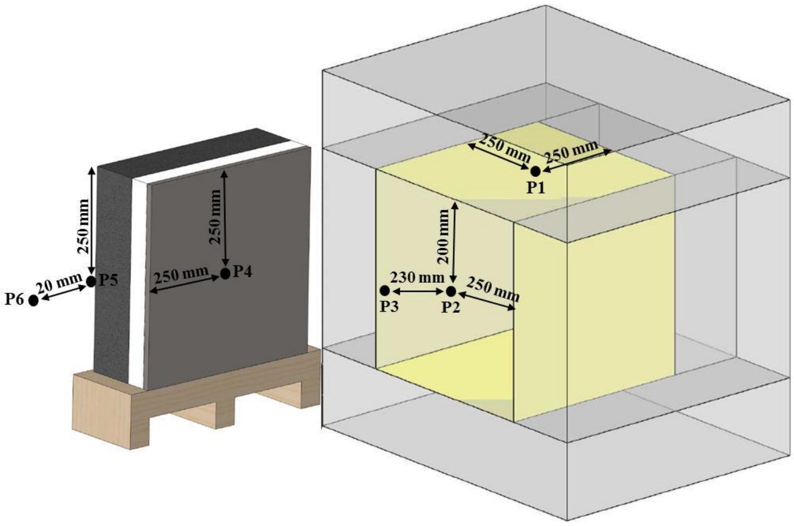


Figure 6.5: The various positions and diminution (points) were temperatures measured and monitored

Table 6.1: The physical dimension of all points where temperature was measured

Position	Description
P1	Scale model surface temperature (inside)
P2	Scale model air temperature (middle)
P3	Scale model air temperature close to interior experimental house wall by 20 mm (inside)
P4	Experimental house wall surface temperature (inside)
P5	Experimental house wall surface temperature (outside)
P6	Ambient air temperature after the outside experimental house wall by 20 mm

6.2.5 Empirical Data

The empirical data includes all data collected and obtained from the experimental measurements and recorded by instruments. As mentioned earlier, the temperature reading was monitored by using a Data-Taker (DT800) and thermocouples. The Data-Taker was connected with the computer system to record the temperature. The data (temperature and RH) was acquired and analysed in accordance with the ASHRAE standard. However, some additional environmental elements such as the following were considered:

a) Local weather, highest and lowest temperature;
b) Weather status such as sunny, cloudy or rainy;
c) Wind speed;
d) Dry and wet bulb temperature inside the experimental testing lab.

The following instrument and devices were utilised in the experimental investigation:

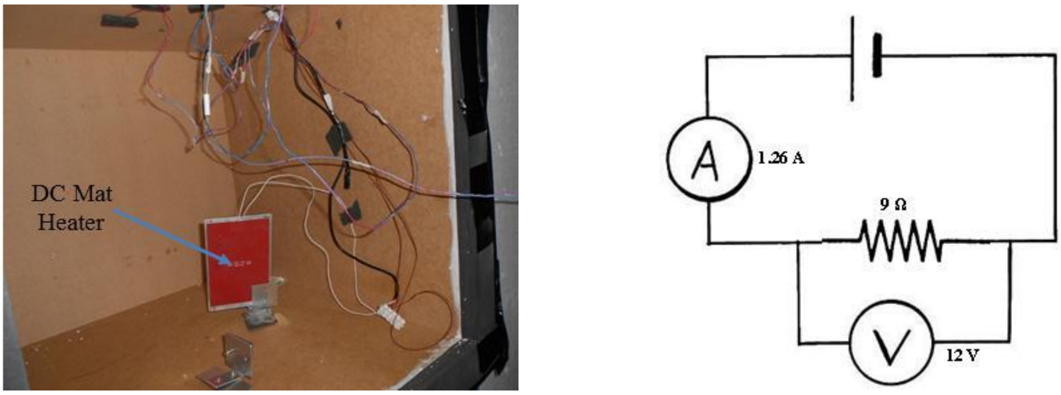
i) Digital Thermostat Meter

Thermal conditions and thermostat setting are generally required for heating and cooling temperature control. For better energy savings, the thermostat can be programmed at a specific temperature. In this experiment, the thermostat meter was used and adjusted at a setting of 29°C. Figure 6.6 shows the thermostat meter used to control temperature.

Figure 6.6: Thermostat meter

ii) DC Mat Heater

A mat plate heater was used to heat the scale model house, and it has been designed to operate at no more than 150°C. The mat heater is made of flexible silicone rubber which is attached to a 3mm thick aluminium sheet. The dimension of the aluminium sheet is 150mm x 90mm x 3mm. The mat heater plate consists of a thin aluminium anodised base plate recovered with silicone fattened glass-fibre with an embedded heating coil. Mat heater heating has the capacity to stay hot for a long period and it has a waterproof feature. It also has high thermal conversion efficiency. The resistance of the heater is 9.5Ώ, and its electrical power voltage is 12V. The mat heater and power supply circuit used in this experimental work are shown in Figure 6.7.

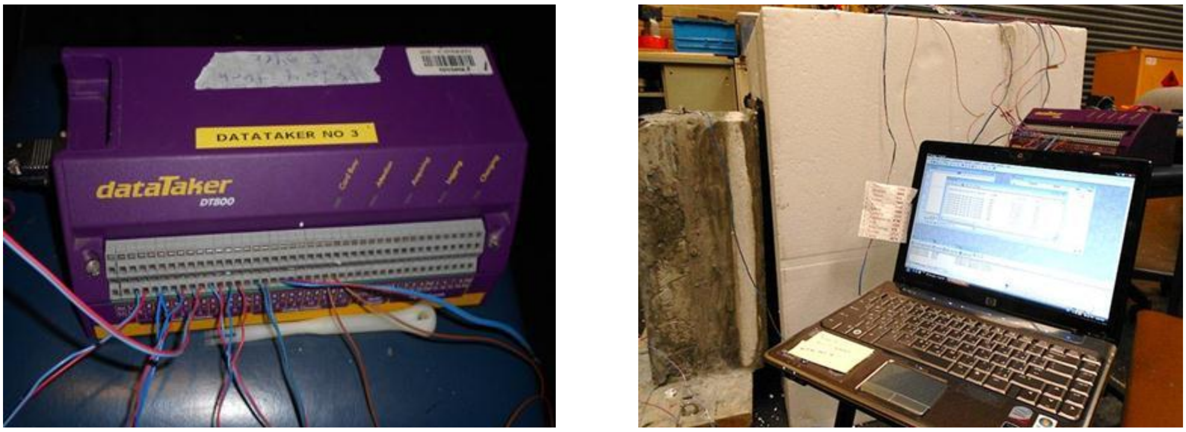


a) Mat heater used in experimental work b) DC power supply circuit

Figure 6.7: The used mat heater and power supply circuit

iii) Data-Taker

As mentioned earlier, Data-Taker (DT800) was used to record the temperature at different points connected to the thermocouples. The data obtained from the DT800 was transferred to a computer. In order to accurately measure the temperature, six channels at different locations were used. The measurement across six channels was obtained between 10mV to 13V. The DT800 can run as programmed from the internal 12V battery until the external supply is restored. The DT800 stored data into an internal or external memory card. The DT800 has correction support and error reporting capability. This includes reporting the position of an error in a program either as a text return or in the error pane. In addition, the DT800 can communicate over a local area network. Further details about the DT800 are given in Appendix D. Figure 6.8 shows the Data-Taker used to obtain temperature reading.



a) Data-Taker, DT800 b) Data-Taker connected to the computer

Figure 6.8: Data-Taker recording the temperature

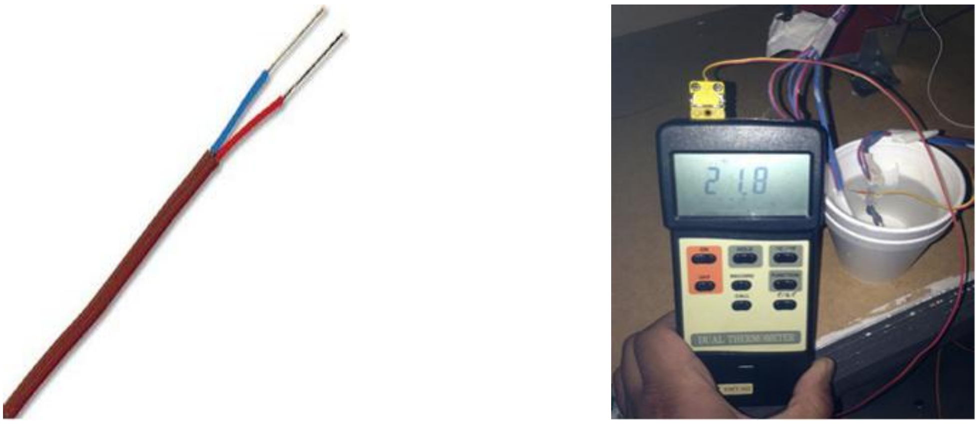
iv) Digital DC Energy Meter

The DC digital energy meter (MS6170) was used to estimate the energy consumed by the mat heater that was used to heat the space inside the scale model. The digital energy meter displays energy consumed in watt-hour and current in Amperes. The maximum current display of the Digital DC energy meter is 30A. It has an external push button switch which was used to reset the accumulated readings. The sensitivity of the DC meter is 0.001Ω. Figure 6.9 shows the digital DC energy meter used in this experiment.

Figure 6.9: Digital DC energy meter

v) Thermocouples

A wide range of thermocouples is available to measure the temperature. In this experiment, a T-type thermocouple was employed. The T-type thermocouple consists of two dissimilar metals, copper and aluminium, that are joined together at the sensing end. The maximum length for each thermocouple wire is 1.5 meters. This type of wire has high resistance and accuracy for data transfer. Before conducting the temperature measurements, the thermocouples were calibrated. One end of the thermocouple was put inside a glass of water with known temperature and the other end was connected to a digital thermometer to measure the temperature. There was a small variation in the range ±0.001°C in some thermocouples. T-type thermocouple accuracy is ±0.5°C.Figure 6.10 illustrates the type of thermocouples and the calibration.



a) ‘T’ type thermocouple b) Digital thermo meter used for calibration

Figure 6.10: Digital thermometer and ‘T’ type thermocouple

6.2.6 Accuracy of Instrument Measurement

In order to obtain accurate and reliable data from the devices used, each device was calibrated. The accuracy of each measurement device depends on the validation and regular calibration. According to Moffat (1990), the temperature accuracy is within ±0.4°C. However, the thermocouple was calibrated to an accuracy of ±0.2°C. Table 6.2 shows the accuracy range of each device used in the experiment.

Table 6.2: Measurement accuracy

Measurement devices	Model	Accuracy
Thermocouple	T-type	±0.5 °C
Data Taker	DT800	±0.2 °C
Digital DC energy meter	MS6170	±0.01V
Digital thermo meter	TC305K	±0.5 °C
Digital thermostat meter	JET-200	± 0.5 °C

6.3 Ambient Conditions

The experiment was carried out in the RMIT Thermodynamics Lab. The selection was based on the ability to control the ambient condition. The dimidiation of the RMIT Thermodynamics Lab is 9m long, 6m wide and 8m high. The testing was conducted in a controlled environment with an ambient temperature ranging between 10°C and 40°C. It is worth noting that the Lab was free from any heating or cooling source that might affect data. Figure 6.11illustrates the experimental setup details conducted at the RMIT Thermodynamics Lab.

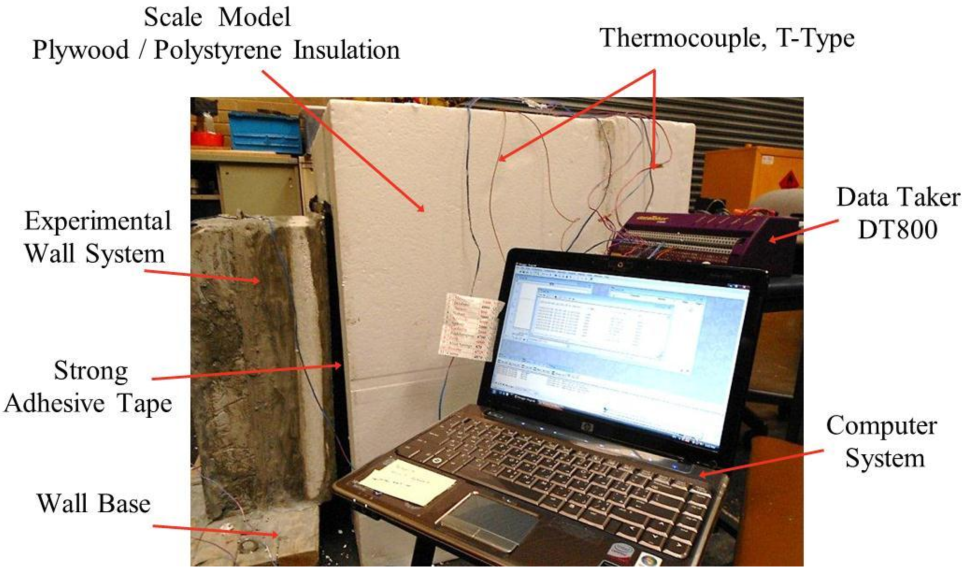


Figure 6.11: Experiment set up conducted at RMIT thermodynamic lab

6.4 Thermal Performance and Data Monitoring

To evaluate the thermal performance of the house wall system, it is essential to study the effect of cooling and heating of different building materials and construction system. To simulate the heat transfer through the wall system for summer conditions, an icing and heating system is employed in the experiment. In this experimental analysis, another important thermal performance indicator-time lag was used. Two approaches for testing the thermal performance of wall system were used. In the first approach, with the heat source in place, the temperatures were monitored and measured from the initial (starting) time till temperature reached the set temperature (29°C) and thereafter the heater only heated when the temperature dropped below 29°C. In the second approach, with the heater, the interior air was heated to 29°C, and then the heat source (the mat heater) was removed. However, the temperature drops were continuously monitored and measured. It is estimated, based on total degree hours for Melbourne city residential houses, that around 85% of total energy is required for heating only. Hence, Melbourne requires around 302 days per year for heating (i.e., less than 10 hours per day).

6.4.1 Result for Heating Experiment

6.4.1.1 Conventional Wall System

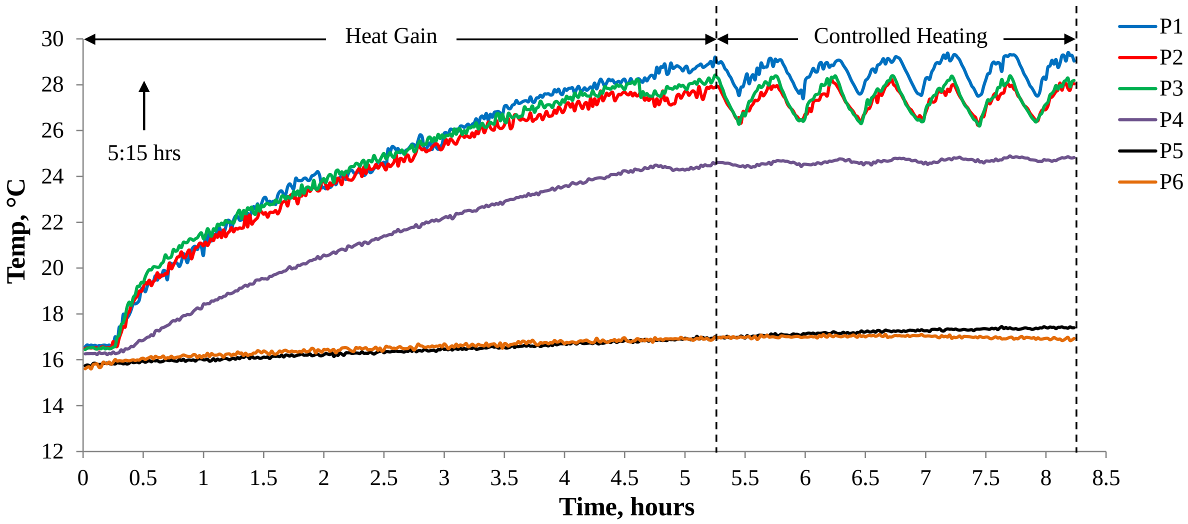
For continuous heating, the highest temperature was set at 29°C and the lowest temperature was set at 26.5°C. The thermostat allowed generating heat when the temperature dropped to

26.5°C. The thermostat switched off the heater when the interior air temperature reached 29°C. Negligible variation in temperature was noted, as shown in Figure 6.12. The measured temperatures for all six locations (P1-P2) are plotted in Figure 6.12. The figure also indicates that the outside wall temperature (P5) and ambient air temperature (P6) have minimal variation. It may be noted that the experiment was undertaken in a controlled environment which allowed less ambient air temperature variation. The interior wall temperature shows relative fluctuation (P4) as expected compared to the temperature close to the heat source in the middle of the model. Nevertheless, the Figure shows the temperature gradient drop from the highest to lowest (P1-P6).

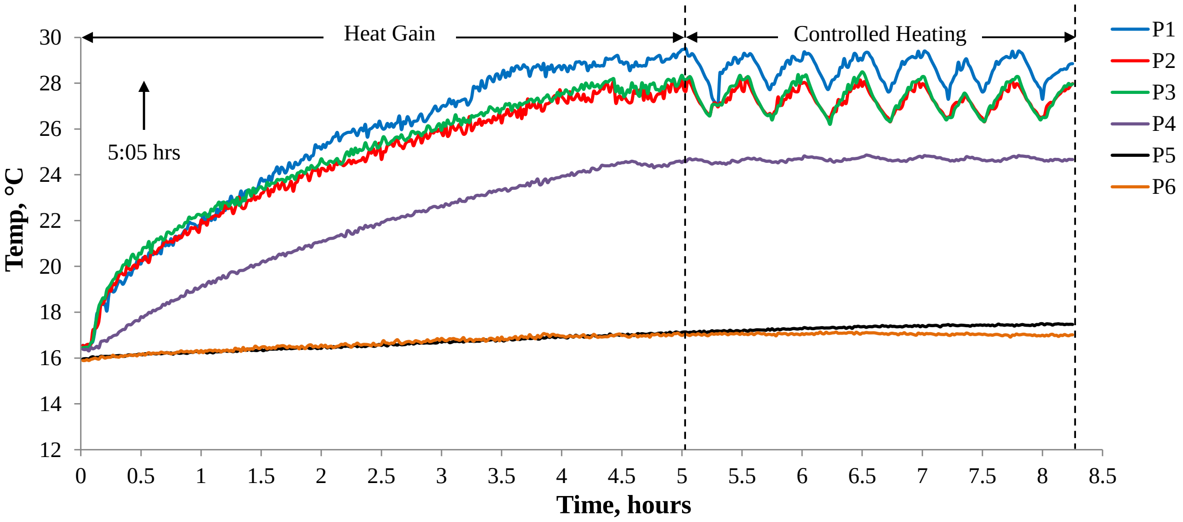
For non-continuous heating, the temperature gradient was positive until the interior air temperature reached 29°C. However, upon removal of the heat source, the interior air temperature (P1-P3) and wall temperature (P4) continuously dropped. In contrast, the exterior wall temperature (P5) and air temperature (P6) increased. Thus, the temperature gradient inside the model house was negative (P1-P3) and the outside temperature gradient remained positive (P5-P6). The temperature drop from 29°C to 26.5°C took around 3 hours, as shown in Figure 6.13. Table 6.3 shows the weather data for the conventional wall on different testing days.

Table 6.3: Weather data for conventional wall

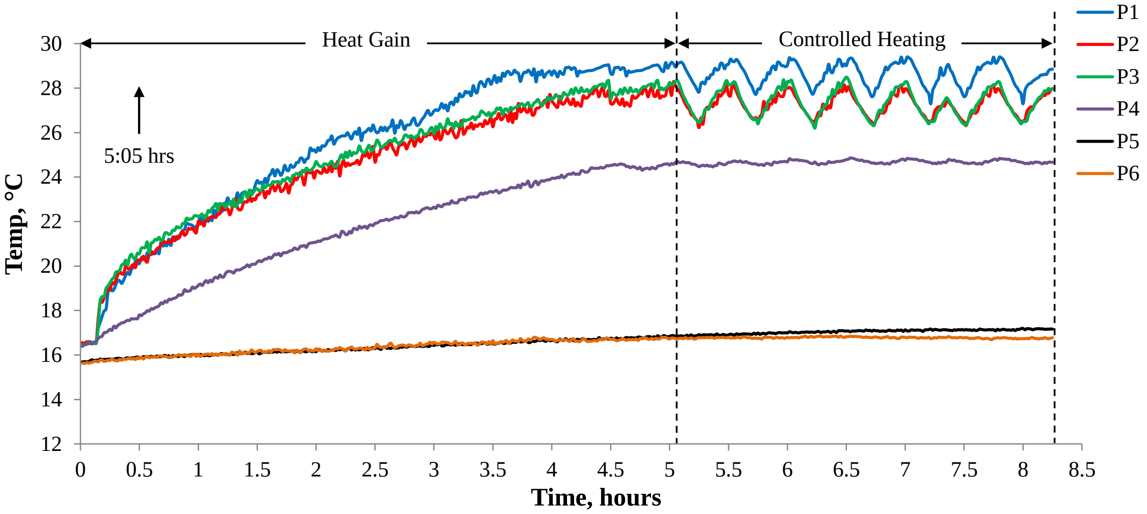
	Climate data	Continuous heating			Non-continuous heating		
		Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Indoor	Avg. temp, (°C)	15.3	15.6	16.1	15.2	14.5	14.9
	Relative humidity (RH, %)	47	46	49	49	44	42
Outdoor	High, low temp, (°C)	H= 18 L=10.8	H= 18 L= 11	H= 17 L= 10.3	H= 16 L= 9	H= 15 L= 10	H= 17 L=10
	Weather status	Sunny	Sunny	Sunny	Sunny	Sunny	Sunny
	Wind speed, (mph)	13	14	13	15	15	14



a) Day 1

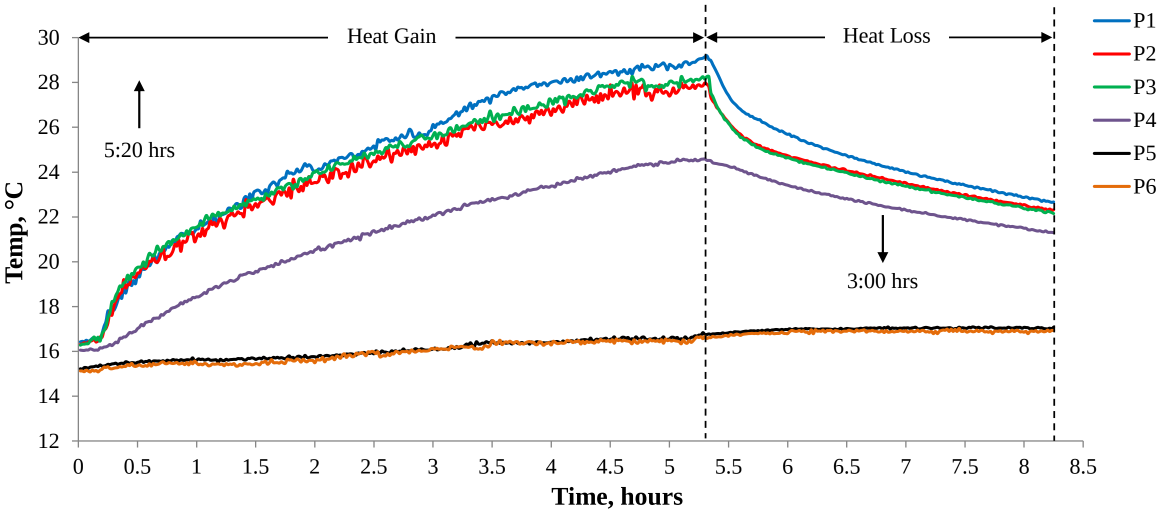


b) Day 2

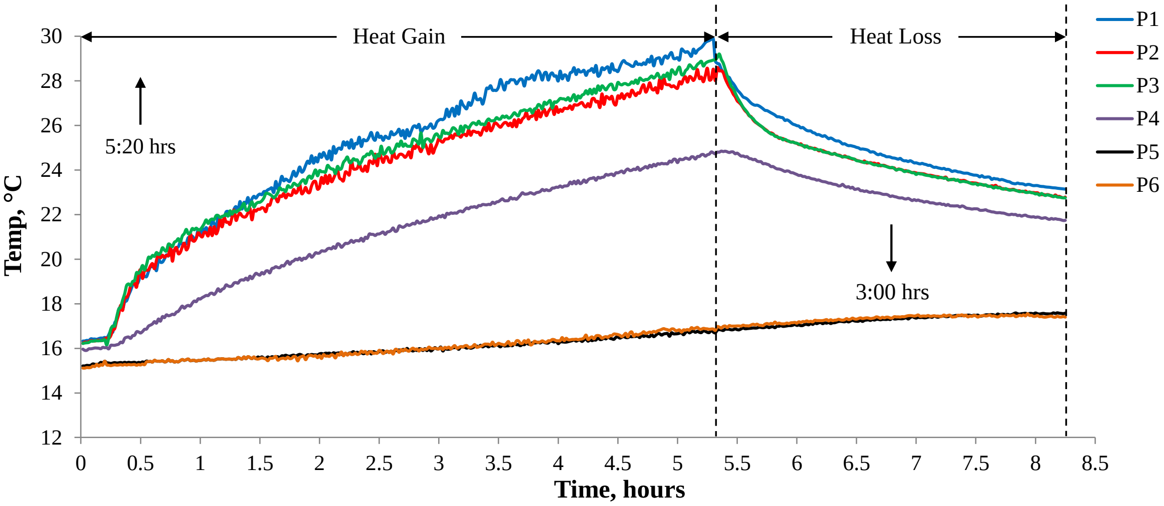


c) Day 3

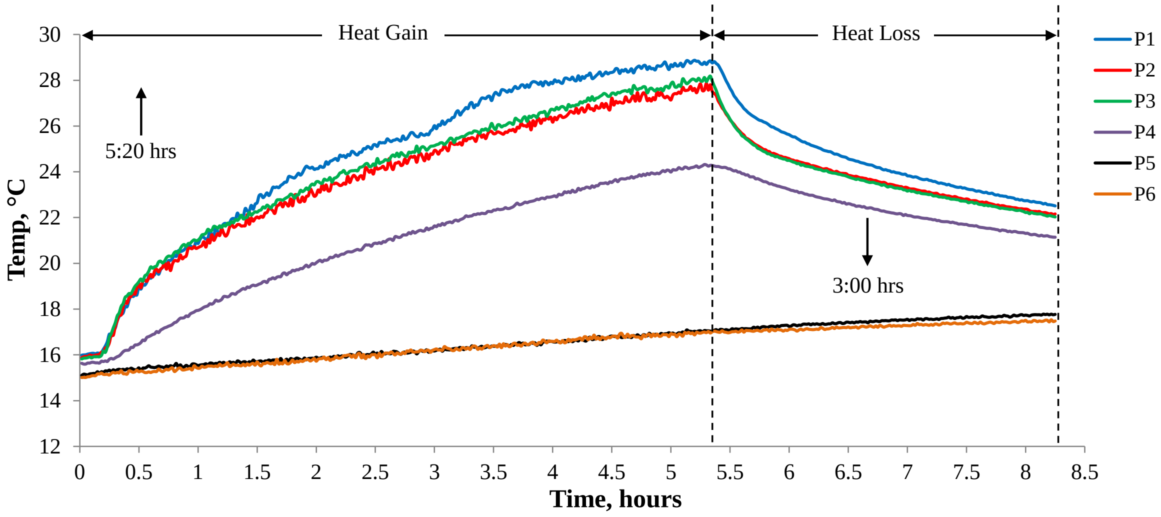
Figure 6.12: Temperature variation for conventional wall, continuous heating



a) Day 1



b) Day 2



c) Day 3

Figure 6.13:Temperature variation for conventional wall, non-continuous heating

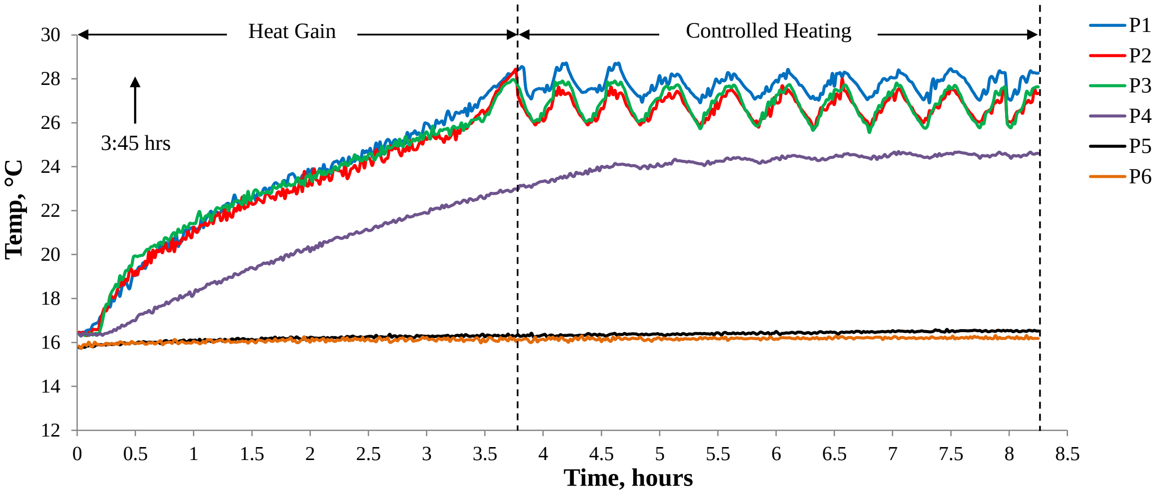
6.4.1.2 New Wall with Strawboard Insulation

For continuous heating, the highest temperature was set at 29°C and the lowest temperature was set at 26°C. The thermostat allowed generating heat when the temperature dropped to 26°C. The thermostat switched off the heater when the interior air temperature reached 29°C. Negligible variation in temperature was noted, as shown in Figure 6.14. The measured temperatures for all six locations (P1-P6) are plotted in Figure 6.14. The Figure also indicates that the outside wall temperature (P5) and ambient air temperature (P6) have minimal variation. It may be noted that the experiment was undertaken in a controlled environment which allowed less ambient air temperature variation. The interior wall temperature shows relative fluctuation (P4) as expected compared to the temperature close to the heat source in the middle of the model. Nevertheless, the Figure shows the temperature gradient drop from the highest to lowest (P1-P6).

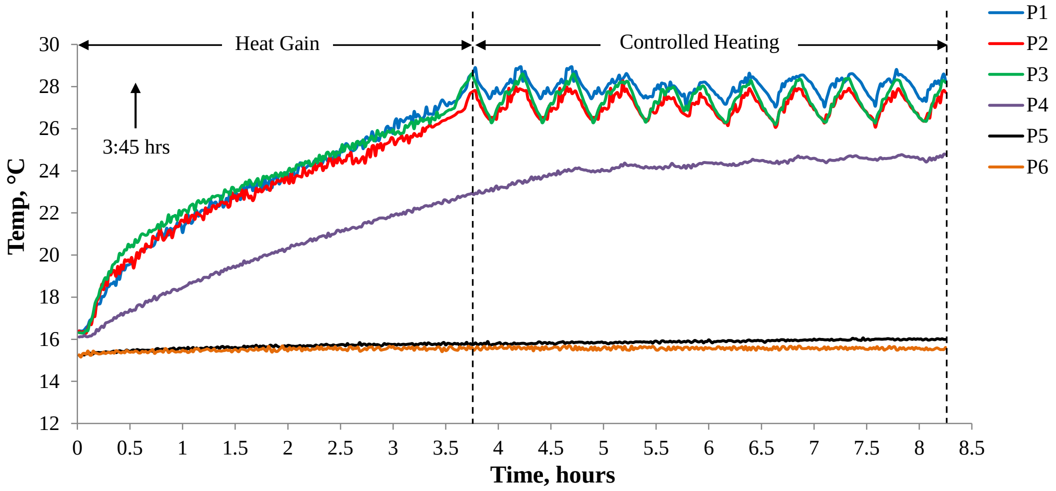
For non-continuous heating, the temperature gradient was positive until the interior air temperature reached 29°C. However, upon removal of the heat source, the interior air temperature (P1-P3) and wall temperature (P4) continuously dropped. In contrast, the exterior wall temperature (P5) and air temperature (P6) increased. Thus, the temperature gradient inside the model house was negative (P1-P3) and the outside temperature gradient remained positive (P5-P6). The temperature drop from 29°C to 22°C took around 4:40 hours, as shown in Figure 6.15. Table 6.4 shows the weather data for the new wall with strawboard insulation on different testing days.

Table 6.4: Weather data for new wall with strawboard insulation

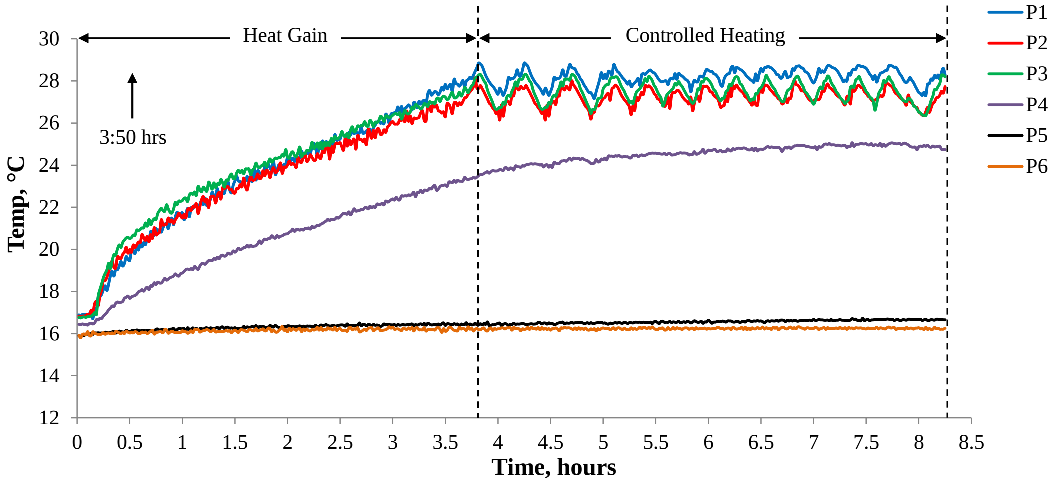
	Climate data	Continuous heating			Non-continuous heating		
		Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Indoor	Avg. temp, (°C)	15.2	15.3	15.6	16.2	15.3	14.9
	Relative humidity (RH, %)	52	51	52	44	43	42
Outdoor	High, low temp, (°C)	H= 14 L= 11	H= 16 L= 10	H= 12 L= 9	H= 16 L= 11	H=17 L=10	H=13 L=9
	Weather status	Sunny	Sunny	Cold	Sunny	Sunny	Cold
	Wind speed, (mph)	14	15	13	10	12	11



a) Day 1

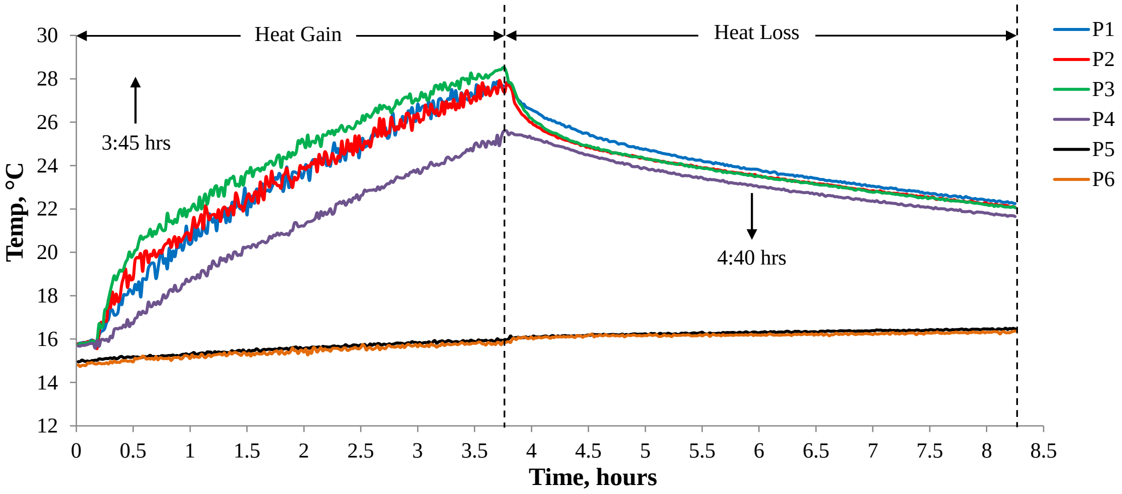


b) Day 2

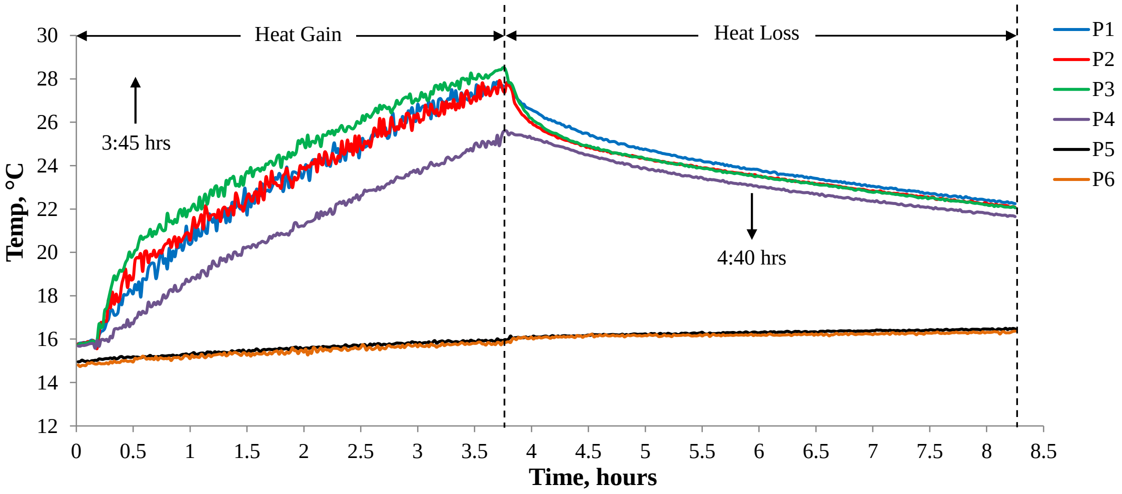


c) Day 3

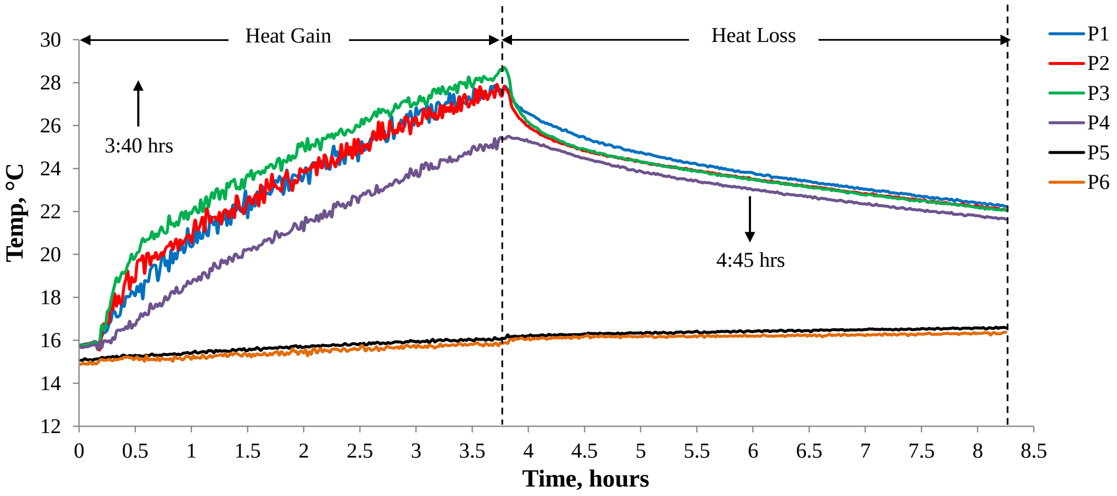
Figure 6.14: Temperature variation for new wall with strawboard insulation, continuous heating



a) Day 1



b) Day 2



c) Day 3

Figure 6.15: Temperature variation for new wall with strawboard insulation, non-continuous heating

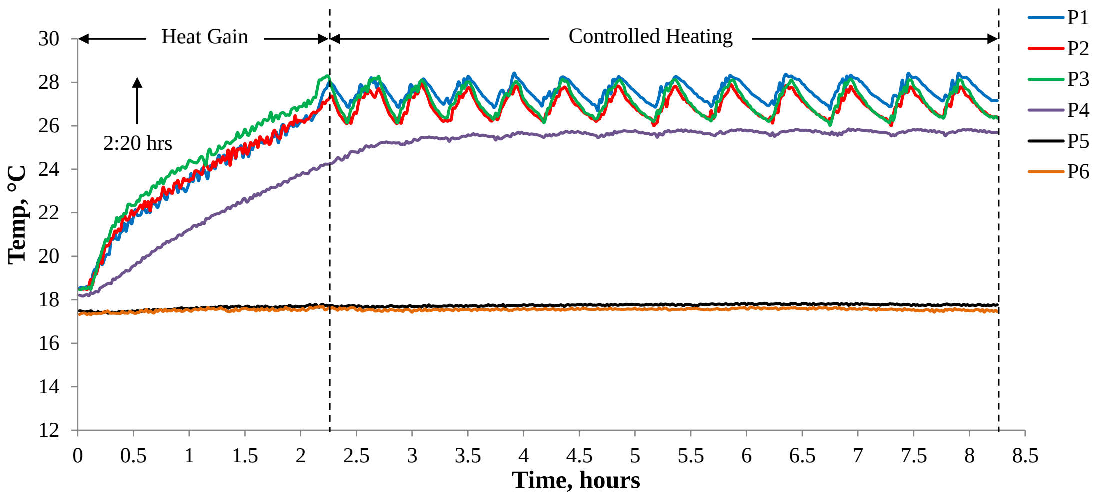
6.4.1.3 New Wall with Polystyrene Insulation

For continuous heating, the highest temperature was set at 29°C and the lowest temperature was set at 26°C. The thermostat allowed generating heat when temperature dropped to 26°C. The thermostat switched off the heater when the interior air temperature reached 29°C. Negligible variation in temperature was noted, as shown in Figure 6.16. The measured temperatures for all six locations (P1-P6) are plotted in Figure 6.16. The Figure also indicates that the outside wall temperature (P5) and ambient air temperature (P6) have minimal variation. It may be noted that the experiment was undertaken in a controlled environment which allowed less ambient air temperature variation. The interior wall temperature shows relative fluctuation (P4) as expected compared to the temperature close to the heat source in the middle of the model. Nevertheless, the Figure shows the temperature gradient drop from the highest to lowest (P1-P6).

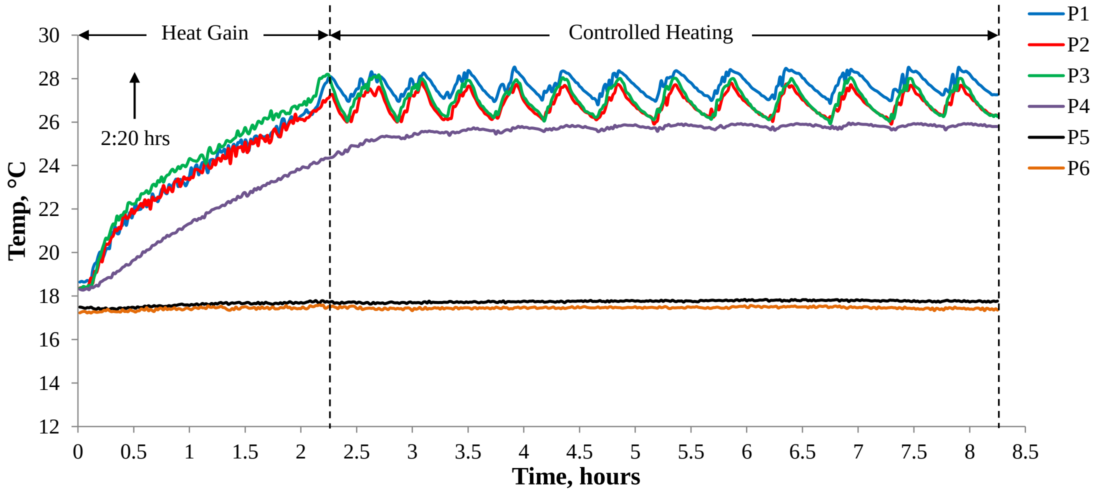
For non-continuous heating, the temperature gradient was positive until the interior air temperature reached 29°C. However, upon removal of the heat source, the interior air temperature (P1-P3) and wall temperature (P4) continuously dropped. In contrast, the exterior wall temperature (P5) and air temperature (P6) increased. Thus, the temperature gradient inside the model house was negative (P1-P3) and the outside temperature gradient remained positive (P5-P6). The temperature drop from 29°C to 22°C took around 5:35 hours, as shown in Figure 6.17. Table 6.5 shows the weather data for the new wall with polystyrene insulation on different testing days.

Table 6.5: Weather data for new wall with polystyrene insulation

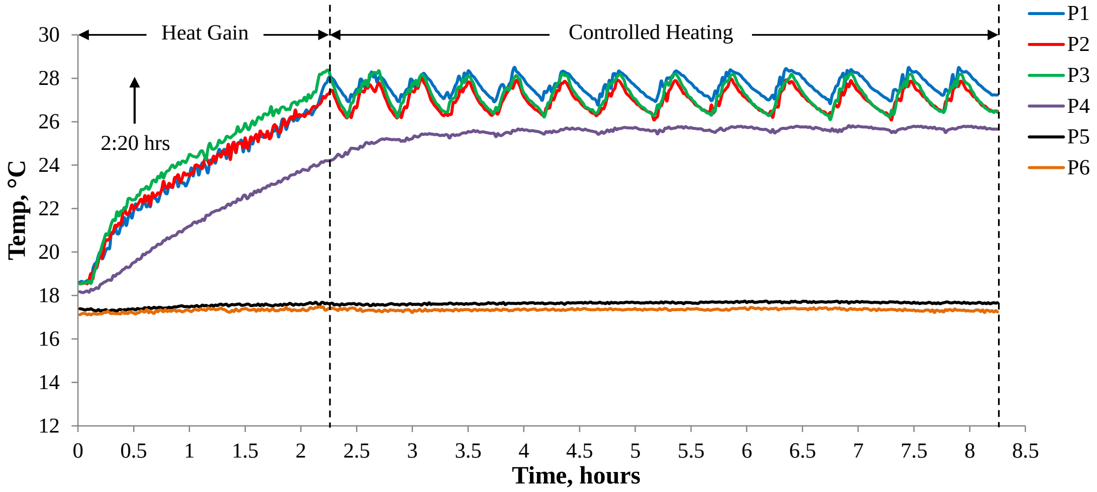
	Climate data	Continuous heating			Non-continuous heating		
		Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Indoor	Avg. temp, (°C)	17.7	17.6	17.5	16.5	16.9	14.8
	Relative humidity (RH, %)	45	40	41	43	44	47
Outdoor	High, low temp, (°C)	H= 23 L= 14	H= 22 L= 12	H= 21 L= 11	H= 19 L= 13	H= 17 L= 11	H=16 L=10
	Weather status	Hot	Hot	Hot	Sunny	Sunny	Sunny
	Wind speed, (mph)	14	15	16	14	13	15



a) Day 1

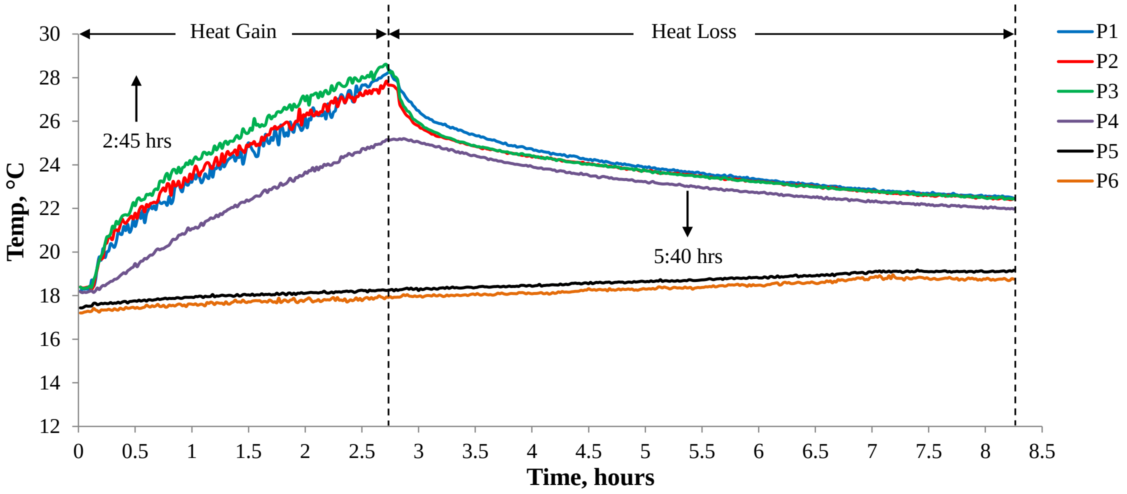


b) Day 2

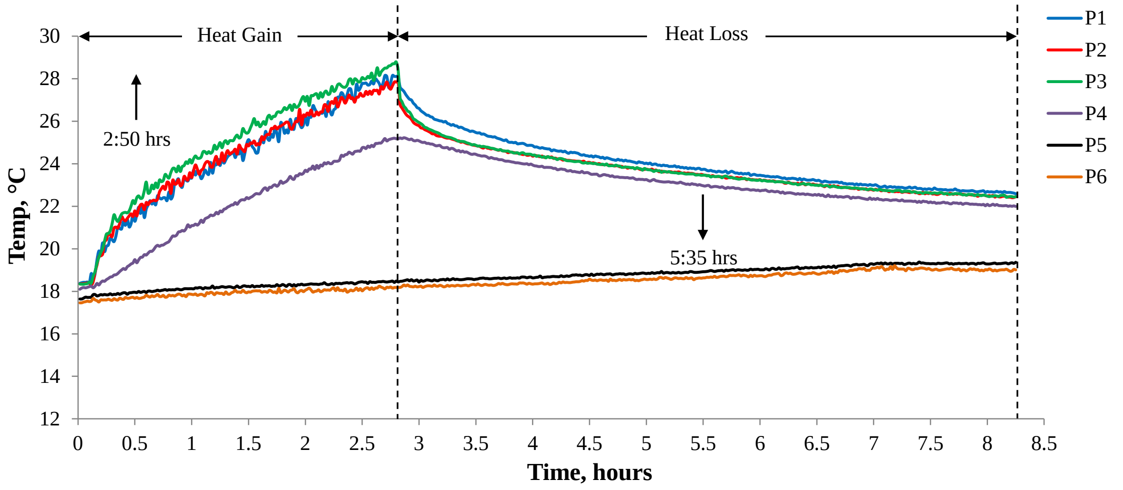


c) Day 3

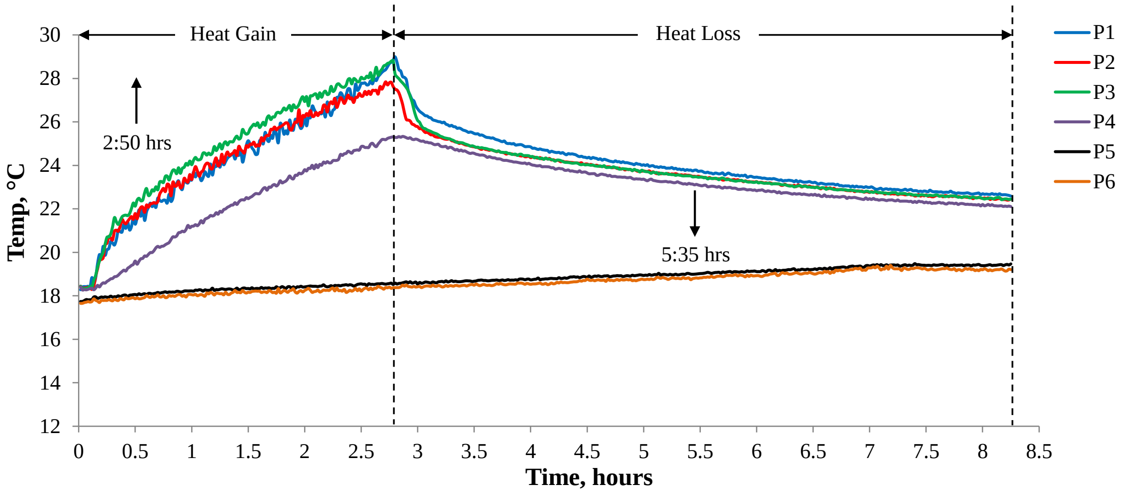
Figure 6.16:Temperature variation for new wall with polystyrene insulation, continuous heating



a) Day 1



b) Day 2



c) Day 3

Figure 6.17: New house wall system with polystyrene insulation, non-continuous heating

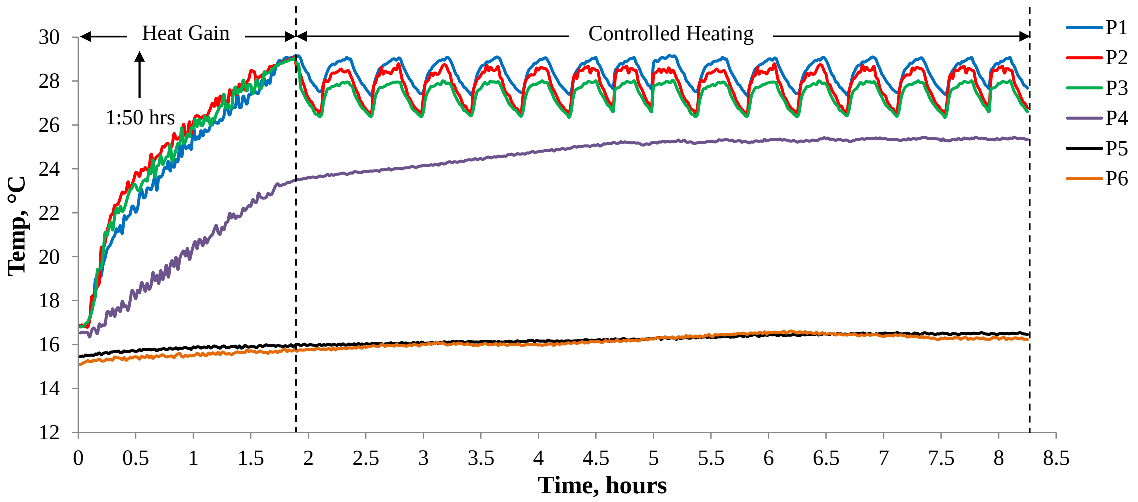
6.4.1.4 New Wall with Polyurethane Rigid Foam Insulation

For continuous heating, the highest temperature was set at 29°C and the lowest temperature at 26°C. The thermostat allowed generating heat when temperature dropped to 26°C. The thermostat switched off the heater when interior air temperature reached 29°C. Negligible variation in temperature was noted, as shown in shown in Figure 6.18. The measured temperatures for all six locations (P1-P6) are plotted in Figure 6.18. The Figure also indicates that the outside wall temperature (P5) and ambient air temperature (P6) have minimal variation. It may be noted that the experiment was undertaken in a controlled environment which allowed less ambient air temperature variation. The interior wall temperature showed relative fluctuation (P4) as expected compared to the temperature close to the heat source in the middle of the model. The Figure shows the temperature gradient drop from the highest to lowest (P1-P6).

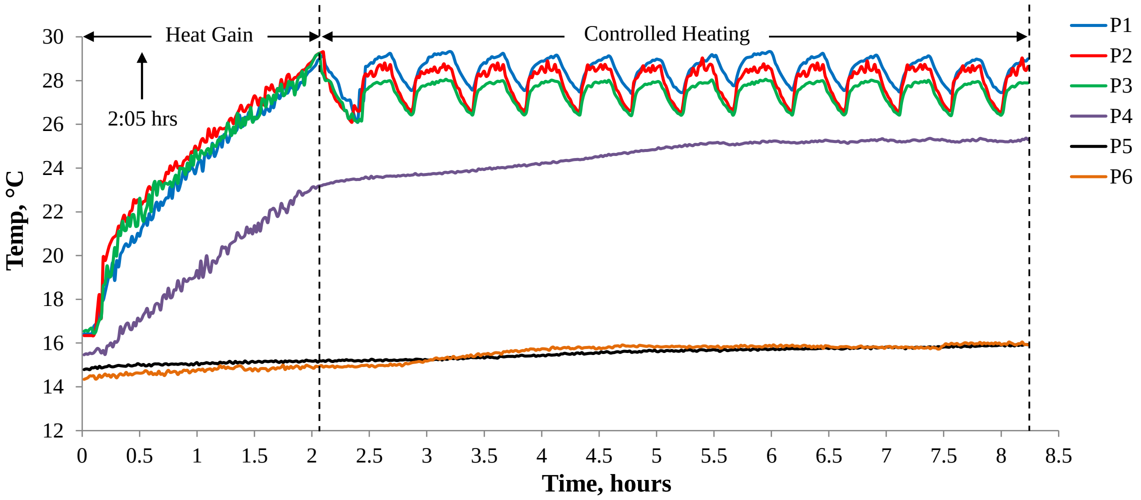
For non-continuous heating, the temperature gradient was positive until the interior air temperature reached 29°C. However, upon removal of the heat source, the interior air temperature (P1-P3) and wall temperature (P4) continuously dropped. In contrast, the exterior wall temperature (P5) and air temperature (P6) increased. Thus, the temperature gradient inside the model house was negative (P1-P3) and the outside temperature gradient remained positive (P5-P6). The temperature drop from 29°C to 21°C took around 6:20 hours, as shown in Figure 6.19. Table 6.6 shows the weather data for the new wall with polyurethane insulation on different testing days.

Table 6.6: Weather data for new wall with polyurethane board insulation

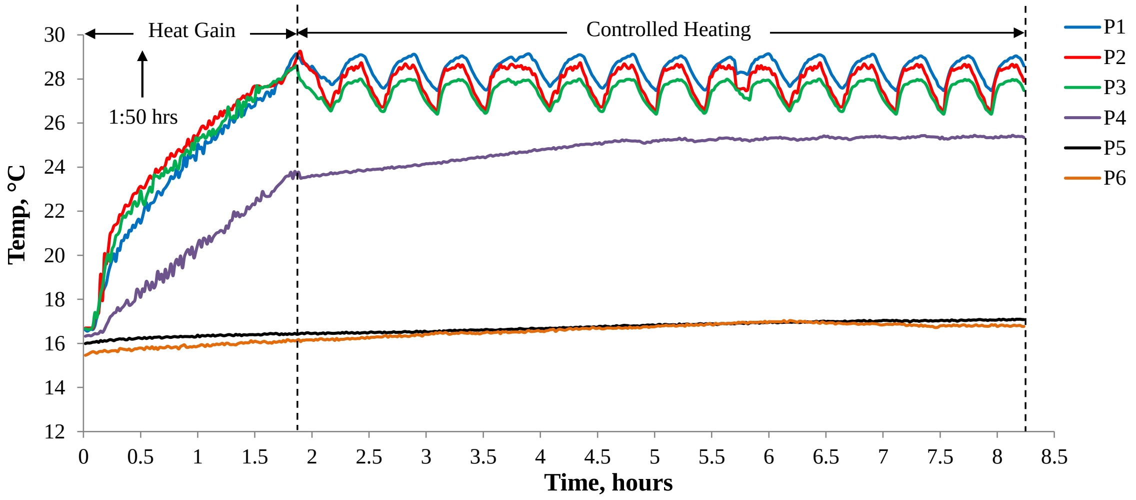
Climate data		Continuous heating			Non-continuous heating		
		Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
Indoor	Avg. temp, (°C)	12.5	11	10	12	12.5	13
	Relative humidity (RH, %)	56	52	49	54	55	57
Outdoor	High, low temp, (°C)	H= 13 L= 7	H= 13 L= 9	H=12 L= 8	H= 13 L= 8	H= 14 L= 7	H= 13 L= 7
	Weather status	Could	Could	Could	Rain	Could	Rain
	Wind speed, (mph)	11	12	14	14	13	12



a) Day 1

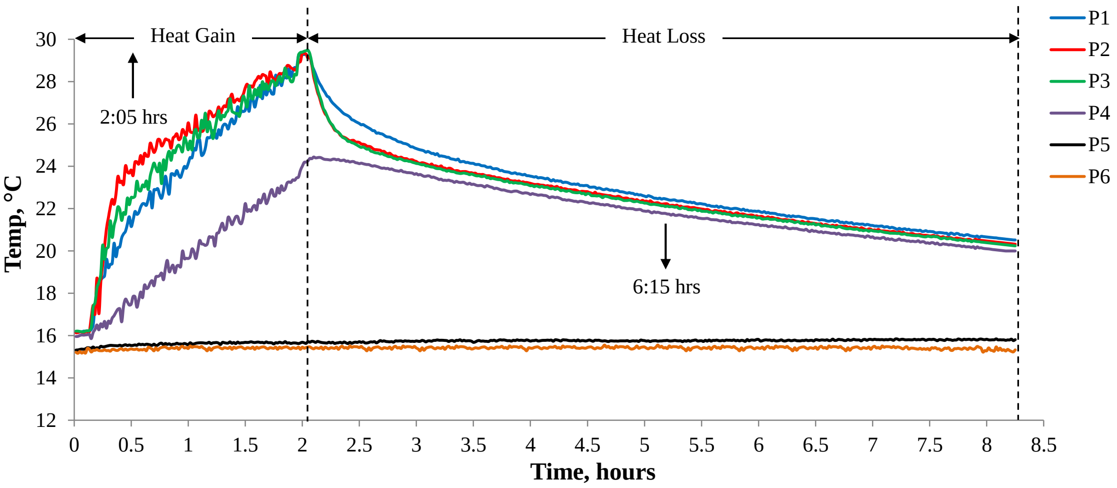


b) Day 2

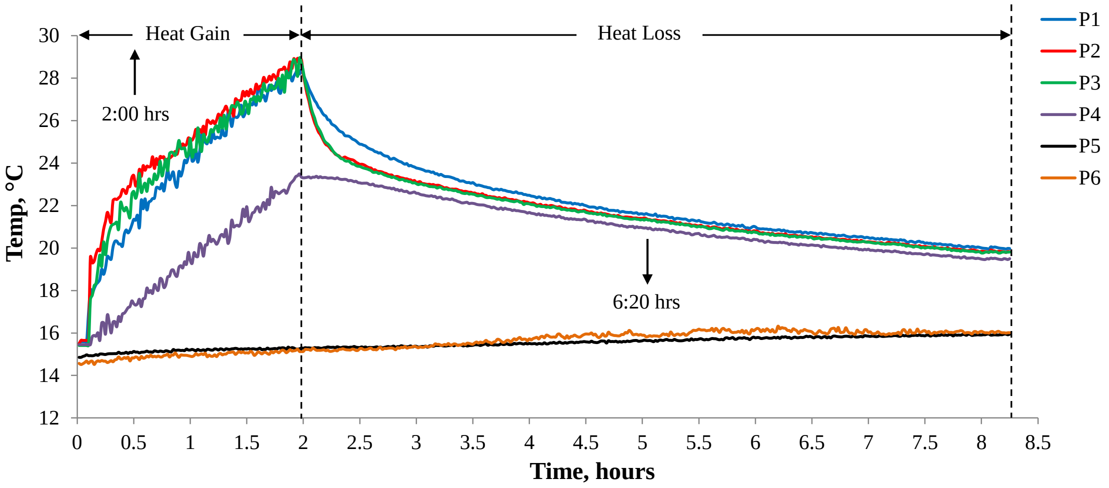


c) Day 3

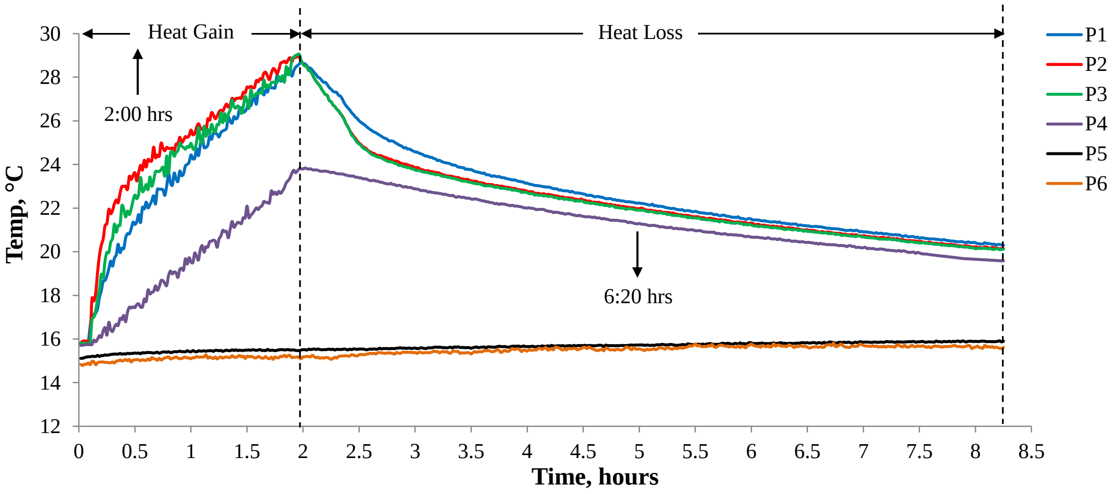
Figure 6.18: Temperature variation for new wall with polyurethane insulation, continuous heating



a) Day 1



b) Day 2



c) Day 3

Figure 6.19: Temperature variation for new wall with polyurethane insulation, non-continuous heating

6.4.2 Results for Cooling Experiment

In contrast to the heating experiment in the previous section, a cooling system was developed using an ice block to investigate heat transfer behaviour. The duration of this experiment was 22 hours, which is significantly longer than the heating experiment.

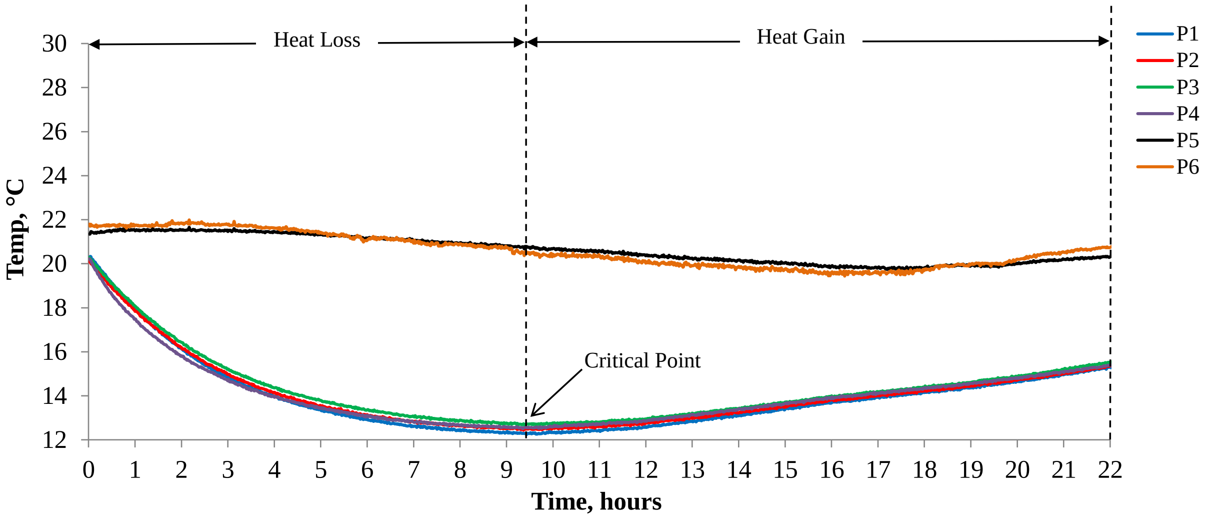
6.4.2.1 New Wall with Polystyrene Insulation

In order to evaluate the thermal performance of the experimental wall, it is imperative to study the effects of cooling. A new wall with polystyrene was used for the experiment wall. To understand the cooling effect, an ice block (350g) was used inside the scale model. The experiment was conducted for three days under different climate conditions, as shown in Table 6.7.

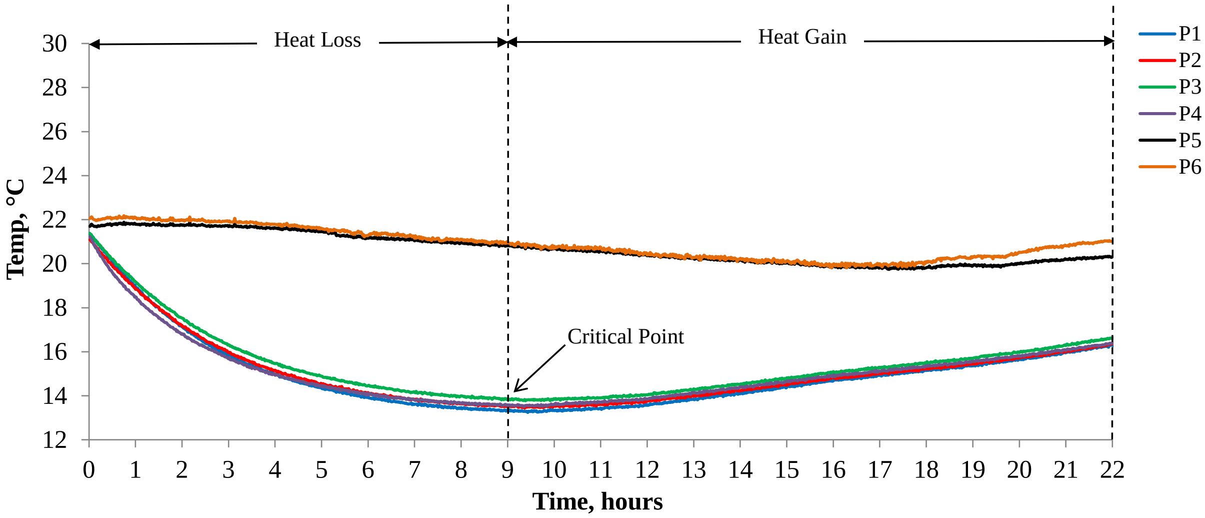
Table 6.7: Weather data for new wall system with polystyrene insulation, cooling experiment

	Climate data	Cooling experiment		
		Day 1	Day 2	Day 3
Indoor	Avg. temp, (°C)	21.4	21.4	21.8
	Relative humidity (RH, %)	42.2	43	39.5
Outdoor	High, low temp, (°C)	H= 19 L= 15	H= 18 L= 13	H= 17.5 L= 14.1
	Weather status	Hot	Hot	Hot
	Wind speed, (mph)	12	10	9

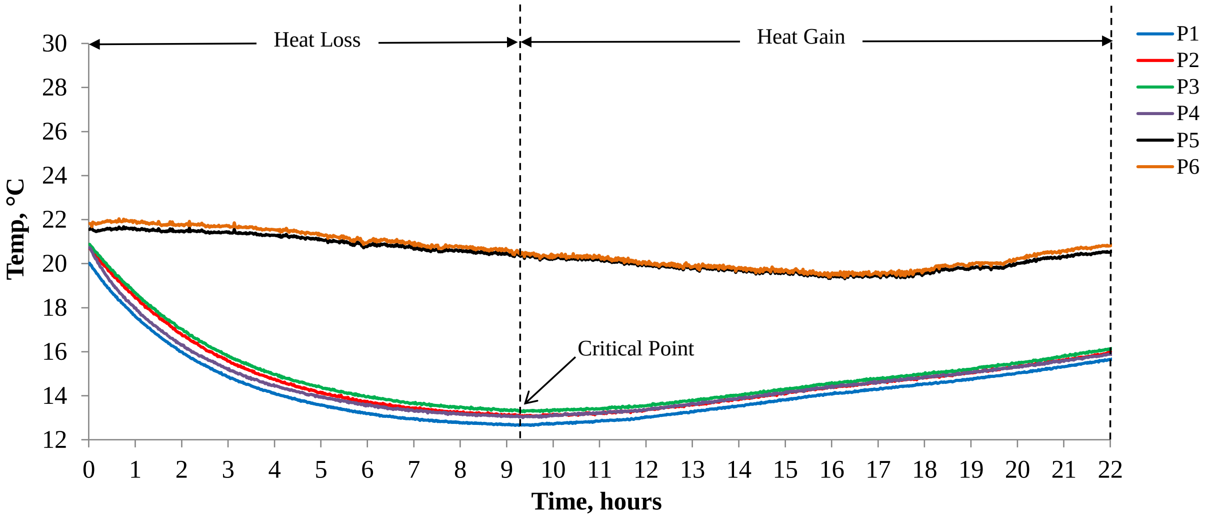
Figure 6.20 illustrates the variation of the temperature with respect to time. It is evident that the thermal behaviour of P1, P2, P3 and P4 is relatively the same for all points. The new house wall with polystyrene insulation maintains the same regime for heat movement during the test. However, a small variation in temperature is observed between the ambient temperature and outside surface temperature of the insulated concrete wall system. As a result of the cooling effect, a significant drop in heat inside the scale model was obtained. As the solid ice changed to a liquid phase inside the scale model, the model temperature equalised to the liquid temperature. The new house wall with polystyrene insulation maintained the model cooling (13°C) for nine hours until all ice was converted to water. Once all ice had completely melted, the water temperature and the interior air temperature started to rise.



a) Day 1



b) Day 1



c) Day 3

Figure 6.20: New wall with polystyrene insulation, cooling experiment

To estimate the total cooling energy inside the model and the heat flow rate, the following theoretical calculation and analysis were undertaken.

$$Q_{latent} = m_{ice} \times h_{lf} \tag{6.1}$$

$$Q_{latent} = 0.350 \times 333 = 116.55 \qquad [KJ]$$

$$Q_{sensible} = m_{water} \times cp \times (T_{finalwater} - 0°C) \qquad \text{Water} \tag{6.2}$$

$$Q_{sensible} = 1 \times 4.18 \times (11.5 - 0) = 48.07 \qquad [KJ]$$

$$m_{air} = \frac{PV}{RT_{p2,avg}} = \frac{101.32 \times 0.123}{0.287 \times (14.07 + 273)} = 0.151 \qquad [Kg]$$

(6.3)

$$Q_{sensible} = m_{air} \times Cp \times (T_{P2,critical} - T_{p2,initial}) \qquad \text{Air loss} \tag{6.4}$$

$$Q_{sensible} = 0.151 \times 1.005 \times (12.5 - 20.1) = -1.15 \qquad [KJ]$$

$$Q_{sensible} = m_{air} \times cp \times (T_{p2,end} - T_{p2,critical}) \qquad \text{Air gain} \tag{6.5}$$

$$Q_{sensible} = 0.151 \times 1.005 \times (15.6 - 12.5) = 0.47 \qquad [KJ]$$

Heat gain/loss for the scale model:

$$\dot{Q}_{\text{mod}el\,avg.} = \frac{\Delta T_{avg.}}{R_{total}} = \frac{T_{p6} - T_{p1}}{R_{total}} \; [KJ] (6.6)$$

$$R_{polystyrene} = \frac{x}{k.A \times 5sides} = \frac{0.2}{0.034 \times 0.25 \times 5} = 4.7 \qquad [^oC/W]$$

$$R_{plywood} = \frac{x}{k.A \times 5sides} = \frac{0.01}{0.16 \times 0.25 \times 5} = 0.05 \qquad [^oC/W]$$

$$R_{total} = 4.75 \qquad [^oC/W]$$

$$\dot{Q}_{\text{mod}el\,avg.} = \frac{\Delta T_{avg.}}{R_{total}} = \frac{21.0 - 14.5}{4.75} = 1.368 \qquad [W]$$

Heat gain/loss for the new house wall with polystyrene insulation:

$$\dot{Q}_{newwall.avg.} = \frac{\Delta T_{avg.}}{R_{total}} = \frac{T_{p5} - T_{p4}}{R_{total}} \tag{6.7}$$

$$R_{polystyrene} = \frac{x}{k.A} = \frac{0.06}{0.034 \times 0.25} = 7.05 \qquad [^{o}C/W]$$

$$R_{render} = \frac{x}{k.A} = \frac{0.01}{0.3 \times 0.25} = 0.13 \qquad [^{o}C/W]$$

$$R_{concert} = \frac{x}{k.A} = \frac{0.15}{0.38 \times 0.25} = 1.57 \qquad [^{o}C/W]$$

$$R_{plasterboard} = \frac{x}{k.A} = \frac{0.01}{0.21 \times 0.25} = 0.19 \qquad [^{o}C/W]$$

$$R_{total} = 8.94 \qquad [^{o}C/W]$$

$$\dot{Q}_{newwall,avg.} = \frac{\Delta T_{avg.}}{R_{total}} = \frac{T_{p5} - T_{p4}}{R_{total}}$$

$$= \frac{20.62 - 14.08}{8.94} = 0.734 \qquad [^{o}C/W]$$

Therefore, heat loss/gain balance for scale model and experimental house wall are as follows:

Total cooling = heat gain/loss scale model + new house wall with polystyrene insulation

$$Q_{latent,ice} + Q_{sensible,water} + Q_{sensible,airgain} + Q_{sensible,airloss} = Q_{\mathrm{mod}el,avg.+}Q_{newwall,avg} \tag{6.8}$$

$$116.55 + 48.07 + 0.47 + (-1.15) = 1.368 + 0.734$$

$$163.9[KJ] = 2.1[W]$$

$$\frac{163.9}{time, \sec}[KW] = 2.1[W]$$

$$\frac{163.9}{22 \times 60 \times 60}[KW] = 2.1[W]$$

$$0.00207[KW] = 2.1[W]$$

$$2.07[W] \approx 2.1[W]$$

The analytical analysis indicates that heat loss through the scale model is very small (~0.03 Watt). Thus, validation is done using the scale model to test any experimental house wall system.

6.4.3 Total Energy Required

Based on experimental data, the thermal performances for the conventional and new walls with different insulation materials were determined. The amount of energy required to heat the interior of the model was estimated by using a digital power meter during the experiment period. The energy consumption of the new wall system with different insulation materials was lower compared to the conventional wall. The conventional wall has the highest energy consumption by an average of 0.82MJ/m^2 and 0.65MJ/m^2 for continuous and non-continuous heating respectively, as shown in Figure 6.21 and Table 6.8.Of all insulation materials, polyurethane and polystyrene insulation proved better thermal insulation (see Figure 6.21). It may be worth mentioning that strawboard insulation showed better thermal performance than conventional wall insulation.

Table 6.8: Energy required for conventional and new wall with different insulation materials

Type of wall	Type of insulation material	Type of heat source	Day 1	Day 2	Day 3	Avg.
			MJ/m^2			
Conventional wall	Fibre glass	Continuous	0.81	0.82	0.82	0.82
		Non- continuous	0.66	0.65	0.65	0.65
New wall	Strawboard	Continuous	0.52	0.51	0.52	0.52
		Non-continuous	0.35	0.34	0.34	0.34
New wall	Polystyrene	Continuous	0.35	0.35	0.35	0.35
		Non-continuous	0.17	0.17	0.17	0.17
New wall	Polyurethane	Continuous	0.25	0.25	0.25	0.25
		Non-continuous	0.10	0.10	0.10	0.10

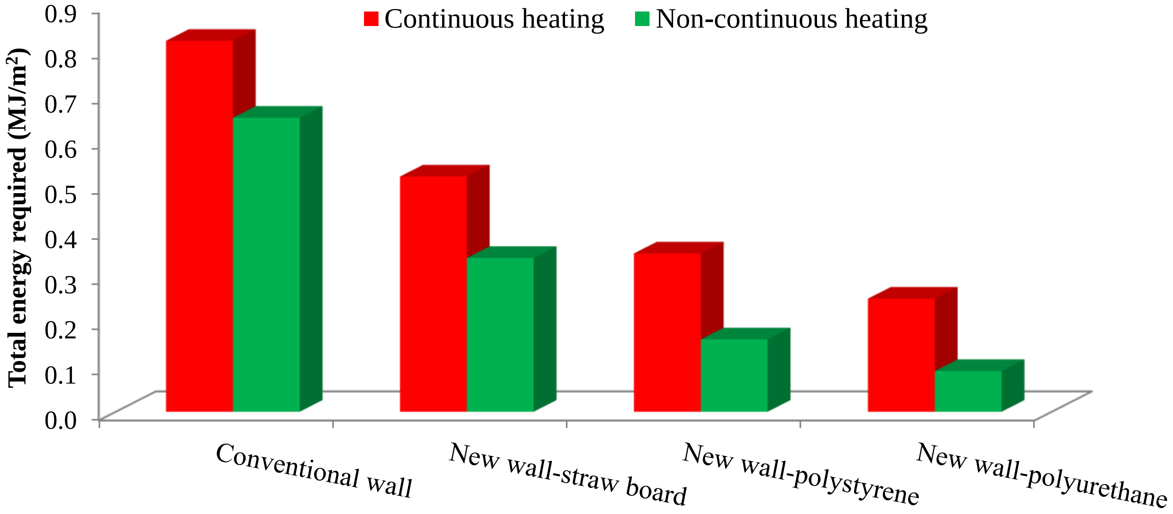


Figure 6.21: Energy required for conventional and new house wall with different insulation materials

6.4.4 Summary

Notably, all the new selected insulated house walls showed a longer time for releasing heat energy. Complete dissipation of heat in a conventional wall system is achieved in three hours. This time period is more than double that for the new house wall system with polyurethane insulation. A good insulating house wall results in reduced cooling and heating load and thus reduces energy consumption. Table 6.9 summarises the lag time for conventional and new house wall using different insulation materials.

Table 6.9: Lag time for conventional and new house wall with different insulation materials

House wall type	Insulation material	Average lag time/8 hrs. (hr:min)
Conventional wall	Fibreglass	3.00
New wall	Strawboard	4:40
New wall	Polystyrene	5:30
New wall	Polyurethane	6:20

CHAPTER 7 GENERAL DISCUSSION

In this work, computational modelling, theoretical analysis and experimental measurements have been used to understand the thermal performance of and develop new house wall systems that can provide better thermal efficiency compared to the presently used conventional house wall systems.

7.1 Computational and Experimental Findings

The thermal performance of 15 new house wall systems and a conventional house wall system were undertaken by computational modelling. The thermal performance behaviour of all 16 house wall systems were evaluated for 13 major cities/towns in Australia, encompassing cool, moderate, subtropical and tropical climate conditions for on-going heating and cooling. Based on thermal performance analysis, all house wall systems were ranked and benchmarked against the conventional house wall system. Both synthetic and natural insulation materials were used in the thermal modelling. The data clearly shows those synthetic insulation materials such as polyurethane and polystyrene outperformed fibreglass (synthetic) and the natural insulation material, strawboard. However, the toxicity of polyurethane is so high that it may pose a health hazard to house occupants during a fire. Therefore, the next better performing insulation materials, polystyrene (synthetic) and strawboard (natural), provide better options for application. In order to validate the modelling data, as mentioned earlier, a scale model house with fibreglass, polystyrene, polyurethane and strawboard insulation materials was experimentally investigated. The model house was exposed to Melbourne's moderate climate conditions and was monitored and measured for thermal performance. As Melbourne residential houses need over 85% of total energy for heating only, the model's thermal performance was investigated for heating only. The heating dominance for Melbourne climate conditions was determined using the degree-hour method based on hourly data for three years, as indicated in Chapter 5. The experimental data shown in Table 7.1 demonstrate a good agreement with the modelling data. The variation between experimental and computational modelling findings is lower than 10%.

An experimental investigation was undertaken for conventional and new house walls with different insulation materials used. In this part of the validation, the energy of heating required for conventional and new house wall with different insulation materials was used. The results obtained by the experiment shows that all new house walls with different insulation materials have a better energy saving. The thermal performance of a new house wall with polyurethane insulation has an optimum energy reduction.

The result found by computational modelling is in good agreement with the experimental measurement. The variations of the findings were lower than 10%.

Table 7.1: Heating energy required by AccuRate modeling and experimental measurements

		Experimental		Computational	Difference
Type of house wall	Type of insulation material	Energy consumed to heat scale model	Energy need if heater operates 302 days/year	Energy required for heating only	
		MJ/m^2	MJ/m^2.annum	MJ/m^2.annum	%
Conventional house wall	Fibre glass	0.347	$0.347 \times 302 = 104.8$	112.5	7.5
New house wall (Design 3)	Strawboard	0.276	$0.276 \times 302 = 83.4$	92.0	9.3
New house wall (Design 3)	Polystyrene	0.227	$0.227 \times 302 = 68.5$	75.4	9.0
New house wall (Design 3)	Polyurethane	0.188	$0.188 \times 302 = 56.7$	63.0	9.0

In order to understand the relative thermal performance of two accredited commercially available software packages, the Victorian Government's FirstRate5 was compared against the Australian federal government- approved and CSIRO-developed software, AccuRate. The input modelling data (building and climate) for modelling using both software packages were identical. The thermal performance was evaluated for the conventional house wall and the new house wall system (Design 3) for 13 major Australian cities/towns. Performance comparison of software packages is a general practice (e.g., Reddy, Maor & Panjapornpon, 2007; ASHRAE; Judkoff & Neymark, 1995; Delsante, Stokes & Walsh, 1983).

The thermal performance results based on modelling data are shown inTable 7.2 and Table 7.3 for the conventional and new house wall (Design 3) systems. The maximum variation in thermal performance and star rating between the two software packages is around 12%.

Table 7.2: Two simulation software results for conventional house wall

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy need MJ/m^2. annum		Star rating 0-10		Difference %
			AccR.	***FirsR.***	***AccR.***	***FirsR.***	***AccR.***	***FirsR.***	***AccR.***	***FirsR.***	
1	Melbourne	VIC	112.5	132.2	42.1	35.0	154.6	167.2	4.9	4.6	**-8.2**
2	Brisbane	QLD	7.9	13.9	67.4	70.07	75.3	82.0	3.7	3.5	**-8.9**
3	Darwin	NT	0.0	0.0	630.4	606.2	630.4	606.2	2.2	2.4	**3.8**
4	Hobart	TAS	186.9	207.7	12.8	8.7	199.7	216.4	5.1	4.7	**-8.4**
5	Adelaide	SA	53.6	64.5	96.0	106.2	149.6	160.7	4.3	4.1	**-7.4**
6	Sydney	NSW	13.1	21.1	63.4	68.3	76.5	83.4	3.7	3.6	**-9.0**
7	Canberra	ACT	176.1	190.6	42.3	49.3	218.4	239.9	4.9	4.6	**-9.8**
8	Rockhampton	QLD	0.7	2.4	168	179.8	168.7	182.2	2.9	2.7	**-8.0**
9	Perth	WA	26.2	44.2	95.7	90.5	121.9	134.7	3.9	3.6	**-10.5**
10	Alice Springs	NT	17.3	28.3	212.2	222.7	229.5	251.0	3.4	3.2	**-9.4**
11	Broome	WA	0.0	0.0	455.2	482.6	455.2	492.6	2.3	2.1	**-8.2**
12	Cairns	QLD	0.0	0.0	218.7	234.0	218.7	234.0	2.6	2.4	**-7.0**
13	Townsville	QLD	0.0	0.2	264.5	244.8	264.5	245.0	2.2	2.3	**7.4**

Table 7.3: Two simulation software results for new house wall (Design 3)

No.	City	State	Heating load MJ/m^2. annum		Cooling load MJ/m^2. annum		Total energy need MJ/m^2. annum		Star rating 0-10		Difference %
			AccR.	***FirsR.***	***AccR.***	***FirsR.***	***AccR.***	***FirsR.***	***AccR.***	***FirsR.***	
1	Melbourne	VIC	75.4	90.3	33.8	30.8	109.2	121.1	6.2	5.8	**-10.9**
2	Brisbane	QLD	1.6	8.6	57.0	55.6	58.6	64.2	4.8	4.6	**-9.6**
3	Darwin	NT	0.0	0.0	449.2	430.5	449.2	430.5	4.9	5.1	**4.2**
4	Hobart	TAS	143	137.1	3.0	22.9	146.0	160.0	6.0	5.7	**-9.6**
5	Adelaide	SA	28.7	45.3	58.6	50.5	87.3	95.8	6.3	6	**-9.7**
6	Sydney	NSW	3.1	11.9	51.1	47.5	54.2	59.4	4.8	4.6	**-9.6**
7	Canberra	ACT	151	124.3	15.2	61.9	166.2	186.2	6.2	5.9	**-12.0**
8	Rockhampton	QLD	0.0	1.1	125.5	137.0	125.5	138.1	4.6	4.8	**-10.0**
9	Perth	WA	8.8	22.5	67.4	61.9	76.2	84.4	6.2	5.9	**-10.8**
10	Alice Springs	NT	7.1	16	127.5	135.1	134.6	151.1	5.3	5.1	**-12.3**
11	Broome	WA	0.0	0.0	304.5	332.5	304.5	332.5	4.7	4.3	**-9.2**
12	Cairns	QLD	0.0	0.0	151.8	167.3	151.8	167.3	5.0	4.9	**-10.2**
13	Townsville	QLD	0.0	0.1	180.0	164.9	180.0	165.0	4.4	4.6	**8.3**

7.2 Economic Analysis

Energy savings are directly dependent on patterns of local climate/weather and materials used. The general features of the construction materials used in this study were in accordance with the Building Code of Australia (BCA). The average retail cost for building materials as of March 2013 is shown in Table 7.4. The assumptions taken into account are:

a) Construction and retail prices are averaged;
b) All prices are for the Melbourne metropolitan area;
c) Labour costs are included in accordance with Australian Labour Law;
d) Air conditioning costs are based on electricity use;
e) Heating costs are based on natural gas use.

Table 7.4: Retail cost for building materials

Material	Cost ($/m^2)	Material	Cost ($/m^2)
Brick	54.0	Polystyrene	7.0
Sisalation foil	4.0	Render	9.0
Timber frame and board	29.0	Polyurethane	10.0
Plaster board	15.0	Rock wool	8.0
Reinforced concrete	90.0	Sheep wool	9.0

In this study, the energy savings potential for ongoing heating and cooling for fifteen newly designed house wall systems, along with a conventional house wall system (brick veneer), were determined. In order to understand the overall economic impact, the net energy saving potential has been translated into a cost saving. As decisions to invest require a thorough economic analysis of expected costs and benefits, the economic analysis of new house wall systems and the conventional house wall system were undertaken using predominantly Simple Payback and Discounted (depreciated) Payback methods. The payback period indicates the number of years for the energy savings from the new house wall systems to offset the initial cost of the investment for the construction of such system. For simple payback estimation, Equation 7.1 was used.

$$Simple\ \ Payback\ (years) = \frac{Initial\ \ Cost\ \ (\$)}{Annual\ Saving\ (\$)} \tag{7.1}$$

Here, Initial Costis the construction cost difference for the new house wall system compared to the conventional house wall systems.

Annual Saving is the difference of energy consumption cost between the new house wall system and the conventional house wall system.

Simple payback is straightforward, user friendly and easy to understand. It assesses how quickly an investment might be paid back. Generally, the smaller the simple payback, the better it is for investment. It also shows if the investment is likely to be paid back within the expected lifetime. Despite its simplicity, simple payback does not include critical investment characteristics such as the time value of money (interest, inflation, opportunity cost, risk, etc.), energy price escalation, variable rate energy (gas/electricity) pricing, alternative investment options, and other financial uncertainties. Nevertheless, the simple payback formula is generally used to effectively screen out undesirable investments.

As the simple payback method does not include the time value of money, the alternative and most effective method is the Discounted (depreciated) Payback method. This method takes into account the effect of the time value of money. Discounted payback is estimated using Equation 7.2.

$$Discounted\ \ Payback\ (years) = A + \frac{B}{C} \tag{7.2}$$

Where,

A = Last period with a negative discounted cumulative cash flow;

B = Absolute value of discounted cumulative cash flow at the end of the period *A*;

C = Discounted cash flow during the period after *A*

If the discounted payback period is less than that of the target period, the investment is generally viable (Jan, 2013; Nikolaidis, Pilavachi, & Chletsis, 2009). Hence, the economic viability of all 15 new house wall systems and the conventional house wall system has been determined using both simple payback and discounted payback methods. The findings are shown in Table 7.5. A sample calculation procedure is shown for Design 1 in Table 7.6. Calculated economic data for other designs are furnished in Appendix E.

Table 7.5: Payback period

Parameter	**Unit**	**Conv.**	**D1**	**D2**	**D3**	**D4**	**D5**	**D6**	**D7**	**D8**	**D9**	**D10**	**D11**	**D12**	**D13**	**D14**	**D15**
Total Energy Required (TER)	MJ/year	16867.2	10953.6	10920.0	10920.0	9960.0	10203.2	10617.6	9889.6	12062.4	12062.4	11054.4	10763.2	10953.6	10897.6	10169.6	10080.0
Total Energy Saving (TES) =Conv.TER-New TER	MJ/year	-	5913.6	5947.2	5947.2	6907.2	6664.0	6249.6	6977.6	4804.8	4804.8	5812.8	6104.0	5913.6	5969.6	6697.6	6787.2
Energy Rate Cost (ERC)	$/MJ	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Energy Cost (EC) =TER×ERC	$/year	2530.1	1643.0	1638.0	1638.0	1494.0	1530.5	1592.6	1483.4	1809.4	1809.4	1658.2	1614.5	1643.0	1634.6	1525.4	1512.0
Energy Cost Saving (ECS) =EC of conv. wall - EC of new wall	$/year	-	887.0	892.1	892.1	1036.1	999.6	937.4	1046.6	720.7	720.7	871.9	915.6	887.0	895.4	1004.6	1018.1
Construction Cost (CC)	$\$/m^2$	11424.0	14336.0	13552.0	13552.0	13552.0	13552.0	13888.0	14672.0	13552.0	13552.0	13552.0	13552.0	14560.0	14896.0	13888.0	14896.0
Additional Construction Cost (ACC)	$\$/m^2$	-	2912.0	2128.0	2128.0	2128.0	2128.0	2464.0	3248.0	2128.0	2128.0	2128.0	2128.0	3136.0	3472.0	2464.0	3472.0
Payback Period	**Year**	**-**	**2.3**	**2.6**	**2.6**	**3.3**	**2.8**	**1.1**	**2.1**	**2.7**	**2.7**	**1.3**	**1.5**	**1.0**	**3.7**	**3.3**	**3.3**

Table 7.6: Discounted Payback method and calculation procedure for Design 1

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2912	1.0000	-2912.00	-2912.00
1	884.8	0.9524	842.67	-2069.33
2	884.8	0.9070	802.54	-1266.79
3	884.8	0.8638	764.32	-502.47
4	884.8	0.8227	727.93	225.46
Discounted (Depreciated) payback period (Years)				2.3

The construction and material costs for the new house wall systems are slightly higher than the conventional house wall system. However, the energy savings using new house wall systems are significantly higher for ongoing heating and cooling. A notable saving due to lower energy consumption can be achieved. The economic analysis clearly demonstrates that the discounted payback periods for all new house wall systems are between 1.1 and 3.3 years. The simple payback periods have also shown very similar results. Hence, investment in the new house wall systems is fully justified and economically viable. Economic viability will further be enhanced and payback periods will be shortened if the cost of carbon taxes is included.

7.3 Industrial Implications

The major practical implications of the research findings are manifold. Building communities (consumers, builders, regulatory authorities, policy makers, building materials manufacturing/production industry) can use scientifically proven findings in residential building and other relevant sectors. New insulation materials can be used in mainstream building construction as detailed data are now available through this research. The building construction method can be better optimised for enhancing further energy savings. This in turn will lead to low carbon emissions, economic benefits and sustainability. Moreover, building dwellers can have better thermal comfort inside their houses by minimising thermal fluctuation in day and night times.

At present, most construction and building companies and regulatory authorities are susceptible to embracing new house building technology and/or new building materials for mainstream public use because they do not possess scientifically proven data about the use of new construction methodology and materials. Most building regulatory authorities need solid scientific data for providing approval of new materials, especially a material’s toxicity and fire hazard in residential building construction. This research provides detailed scientific data about new synthetic and natural materials, their fire safety, toxicity and cost benefit. The housing industry and regulatory authorities can rely with confidence on the use and application of these materials in this important industry. Additionally, the developed thermal performance model can be used to estimate and understand the energy saving potential for any climate condition. Based on the prediction, the building material compositions can be altered according to the need for ongoing energy savings and the minimisation of construction cost.

The economic analysis clearly demonstrates that new house wall systems are cost effective and value for money. A notable cost saving can be achieved if the proposed wall systems are introduced in mainstream housing. This will also provide direct economic benefit to house dwellers.

7.4 Summary

Three ways, computational modelling, theoretical analysis and experimental measurements have been used to understand the thermal performance of house wall system. The developed new house wall system provides better thermal efficiency compared to the presently used conventional house wall systems.

CHAPTER 8 CONCLUSIONS &RECOMMENDATIONS FOR FURTHER WORK

8.1 Conclusions

The objective of this research, which was to develop a new house wall system that can provide better thermal performance for ongoing heating and cooling compared to currently used conventional (brick veneer) house walls, has been achieved. Additionally, the new house wall should have a higher fire resistance and lower level of toxicity. The house wall design can easily be adapted for variable climate conditions with minimal structural changes. A comprehensive study, which included analytical analysis, computational modelling and experimental investigation, has been undertaken, utilising 15 house wall designs, as well as a conventional house wall design. The following conclusions apply within the assumptions made in the analysis, modelling and experiments, the sensitivity of the measurements and the limits of scientific and engineering inference. In particular, it is emphasised that these conclusions apply to the range of house wall systems modelled and tested, and within the range of test conditions investigated. It is possible that some of the conclusions have much wider applications. The following major and minor conclusions are therefore drawn.

8.1.1 Major Conclusions

An optimally designed house wall system has been developed. The new design allows a saving of energy required for ongoing heating and cooling of up to 37% compared to currently use conventional house wall systems in Australia and elsewhere.

A theoretical model has been developed and validated. The model can be used for any location across the globe if local climate and building material data are available. The model is Excel-based and user friendly. It does not require specialised training or knowledge for its use.

The optimal position of insulation materials within house wall systems for different climate conditions has been determined. This allows reduction in further ongoing heating and cooling energy.

Double-glazed windows are better suited for conventional house wall systems than for new house wall systems. The effects of double glazed windows can be maximised for new house wall designs if the vacuum space is varied.

The cost savings due to lower energy requirements for ongoing heating and cooling are fully economically justified, despite the slightly higher investment required for the construction of new house wall systems. The minimum and maximum payback periods are found to be 1 year and 3.3 years, respectively.

8.1.2 Minor Conclusions

Several major insulation materials, synthetic and natural, have been identified for house wall systems that can provide cost benefit, fire resistance and lower toxicity. These materials are readily available anywhere in the world.

In cities or towns that require more heating than cooling, the inner position of the insulation is better. Similarly, the outer location of insulation provides better energy savings for houses located in tropical and subtropical climates.

The local micro climate, surrounding structures and protrusion affect the heating and cooling requirements. In cool climates, closely located houses need slightly less energy for heating and, similarly, in tropical climates, sparsely located houses require less energy for cooling due to better heat transfer to the open surroundings.

The data obtained by way of various computational software can vary notably. In this study, it was found to be up to 15%. Therefore, the star rating obtained by these software packages can also vary.

8.1.3 The Future Paths of Research

After undertaking the work presented here and reviewing the literature available in the public domain, the following areas have been identified for future work:

a) In order to understand the comprehensive thermal performance over a long period of time (2 years), the thermal behaviour of house wall systems should be monitored, measured and analysed with a full scale house made of conventional and new house wall systems.
b) In this research, the main focus was on the house wall system. Since energy loss/gain through the roof system is notable, it would be complementary and useful to study a new concept of roof system to develop an energy efficient system.
c) In this study, thermal comfort was considered as sensible interior temperature. No dynamic thermal comfort and humidity effects were considered. However, the dynamic effects of these parameters are worthwhile investigating.

d) The impact of dynamic behaviour of house occupants on thermal performance is beyond the capability of most accredited house energy rating software. It would be extremely useful to employ Computational Fluid Dynamics (CFD) modelling software in order to understand this phenomenon.

REFERENCES

Abdou, A. & Budaiwi, I. (2005). Comparison of thermal conductivity measurements of building insulation materials under various operating temperatures.*Build Phys*, 29 (2), pp.171-85.

Abd-Rabbo, S. & Adam, K. (1988). Trombe wall heat transfer analysis, *Solar Energy Research*, pp. 66.

Alam, F. & Theos, T. (2008). A New generation energy efficient residential house in Australia, *Proceedings of the 4th BSME-ASME International Thermal Engineering Conference (ICTE2008)*, ISBN: 984-300-002844-0, vol., pp.710-718.

Alam, F., Akbarzadeh, A., Dixon, C. & Theos, T. (2010).Thermal performance of residential house envelopes, *Proceedings of the International Conference on Mechanical, Industrial and Energy Engineering (ICMIEE2010)*, ISBN 978-984-33-2300-2 pp.152-158.

Alam, F., Rasul, M., Saman, W., Theos, T., Khan, M. & Akbarzadeh, A. (2009). Residential house energy rating in Australia, *Central Region Engineering Conference (CREC2009), Rockhampton, Australia*, ISBN: 1-921047-62-3, pp.1-6.

Aldawi, F., Alam, F., Date, A., Alghamdi, M. & Aldhawi, F. (2013). A new house wall system for residential buildings, *Energy and Buildings*, 67, pp.403-418.

Aldawi, F., Alam, F., Date, A., Kumar, A. & Rasul, M. (2012). Thermal performance modelling of residential house wall systems, *Procardia Engineering*,49, pp.161-168.

Aldawi, F., Date, A., Alam, F., Khan, I. & Alghamdi, M. (2013). Energy efficient residential house wall system, *Applied Thermal Engineering*, 58, pp.400-410.

Al-Homoud, D. & Mohammad, S. (2005). Performance characteristics and practical applications of common building thermal insulation materials, *Building and Environment*, 40(3), pp.353-366.

Alo, B. T. (2010). Brick Veneer Advantages. Website:http://www.ehow.com/list_6462617_brick-veneer-advantages.html, accessed on 20 October 2012.

Al-Sanea, S. A. & Zedan, M. F. (2011). Improving thermal performance of building walls by optimizing insulation layer distribution and thickness for same thermal mass, *Applied Energy*, 88(9), pp.3113-3124.

ANSI/ASHRAE Standard 55. (2010). Thermal Environmental Conditions for Human Occupancy.

Arslan, O. & Kose, R. (2006). Thermo economic optimization of insulation thickness considering condensed vapor in building, *Energy and Buildings*, 38(12), pp. 1400-8.

Asan, H. (1998). Effects of wall's insulation thickness and position on time lag and decrement factor, *Energy and Buildings*, 28(3), pp.299-305.

ASHRAE handbook. (2009). Fundamentals, SI Edition, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc. Atlanta.

Australian climatic zones, Australian Government, Bureau of Metrology. URL http://www.bom.gov.au/climate/environ/travel/map.shtml, accessed 11 September 2012.

Australian climatic zones, Australian Government, Bureau of Metrology, Website:http://www.bom.gov.au/climate/environ/travel/map.shtml, accessed 5 October 2011.

Australian Greenhouse Office (AGO, 2011). Australian residential building sector greenhouse gas emissions (1990-2010), *Department of the Environment and Heritage*.Canberra.

Baetens, R., Jelle, B.P. & Gustavsen, A. (2010). Phase change materials for building applications: a state-of-the-art review, *Energy and Buildings*, 42, pp.1361-1368.

Ballarini, I. & Corrado, V. (2012). Analysis of the building energy balance to investigate the effect of thermal insulation in summer conditions, *Energy and Buildings*, 52, pp.168-180.

Berkeley, L. (1996). The potential for reducing urban air temperatures and energy consumption through vegetative cooling, *National Laboratory, U.S. Department of Energy*, Energy efficient and renewable energy, USA.

Blengini, G.A. & Carlo, T. 2010. The changing role of life cycle phases, subsystems and materials in the LCA of low energy buildings, *Energy and Buildings*, 42, pp.869-880.

Boland, J. (1995). Synthetic climate data sets for locations with low measured data densities, paper presented to Solar 95, 29 November 1995.

Bolatturk, A. (2006). Determination of optimum insulation thickness for building walls with respect to various fuels and climate zones in Turkey. *Appl. Therm. Eng.*, 26, pp.1301.

Boonyartikarn, S. & Spiezle, S. (1990). Fiber Glass vs. Cellulose Installed Performance, University of Colorado.

Börjesson, P. & Gustavsson, L. (2000). Greenhouse gas balances in building construction: wood versus concrete from life-cycle and forest land-use perspectives, *Energy Policy*, 28(9), pp.575-588.

Bouden, C. & Gharab, N. (2005). An adaptive thermal comfort model for the Tunisian context: a field study results, *Energy and Buildings*, 37(9), pp.952-963.

Budaiwi, I. & Abdou, A. (2013). The impact of thermal conductivity change of moist fibrous insulation on energy performance of buildings under hot-humid conditions, *Energy and Buildings*, 60, pp.388-399.

Building Code of Australia (BCA). (2011). Handbook, *Australian Government States and Territories, Australian Building Codes Board*, Canberra.

Cabeza, L.F., Castell, A., Medrano, M., Martorell, I., Pérez, G. & Fernández, I. (2010). Experimental study on the performance of insulation materials in Mediterranean construction, *Energy and Buildings*,42, pp.630-636.

Cengel, Y. (1998). Introduction to Thermodynamics and Heat Transfer, McGraw-Hill, New York.

Chen, W., Ye, J., Bai, Y. & Zhao, X. L. (2012). Full-scale fire experiments on load-bearing cold-formed steel walls lined with different panels, *Journal of Constructional Steel Research*, 79, pp.242-254.

Chen, Y., Athienitis, A.K. & Galal, K. (2010). Modelling, design and thermal performance of a bipv/t system thermally coupled with a ventilated concrete slab in a low energy solar house: part 1, BIPV/T system and house energy concept, *Solar Energy*, 84, pp.1892-1907.

Chow, W. K. & Leung, C.W. (2001). Survey on partition walls commonly used in Hong Kong and estimation of the heat release rates during fire, *Architectural Science Review*, 44(4), pp.379-390.

Chowdhury, A., Rasul, M., Khan, M. & Alam, F. (2010). Performance analysis of a novel building material to achieve superior thermal comfort and energy efficiency in arid climate, *Proceedings of the International Engineering Conference on Hot Arid Regions (IECHAR2010)*, ISBN: 854-285-812-2-135-145.

Climate Action Network Australia (CANA). (2005). Inquiry into energy efficiency, submission to Productivity Commission, Melbourne.

Comfortable Low Energy Architecture, Thermal Comfort. URL http://new-learn.info/learn/packages/clear/thermal/index.html. accessed 28 October 2011.

Commonwealth Scientific and Industrial Research Organisation (CSIRO). (2004). AccuRate Software Manual.

Damineli, B.L, Kemeid, F.M., Aguiar, P.S. & John, V.M. (2010). Measuring the eco-efficiency of cement use, *Cement and Concrete Composites*, 32(8), pp.555-562.

Daouas, N., Hassen, Z. & Aissia, H.B. (2010). Analytical periodic solution for the study of thermal performance and optimum insulation thickness of building walls in Tunisia, *Applied Thermal Energy*, 30, pp.319-26.

David, R. & Steve, L. (2002). The Polyurethanes Book. New York, Wiley, ISBN 0-470-85041-8.

DCLG. (2006a). Code for Sustainable Homes: A step-change in sustainable home building practice, London, Department for Communities and Local Government.

Dear, R.J., Brager, G.S. & Cooper, D. (1997). Developing an Adaptive Model of Thermal Comfort and Preference (ASHRAE RP-884), Macquarie Research Ltd., Macquarie University/Centre for Environmental Design Research, Sydney.

Delsante, A. (1988). Theoretical calculations of the steady-state heat losses through a slab-on ground floor, *Building and Environment*, 23(1), pp.11-17.

Delsante, A., Stokes, A. & Walsh, P. (1983). Application of Fourier transforms to periodic heat flow into the ground under a building, CSIRO, pp.121-132.

Demirbas, M.F. (2006). Thermal energy storage and phase change materials: an overview Energy Sources, Part B: Economics, *Planning and Policy*, 1, pp.85-95.

Department of Health and Human Services (2011), *Report on Carcinogens*, 12th Edition, Australia.

Department of Health and Human Services of Australia, Australian Government, Website; http://www.humanservices.gov.au, accessed 5 July, 2013.

Dewsbury, M. (2011).The Empirical Validation of House Energy Rating (HER) Software for Lightweight Housing in Cool Temperate Climates.PhD thesis.University of Tasmania.

Dieckmann, J. (2008). Latent Heat Storage in Concrete, Technische Universität Kaiserslautern, Kaiserslautern.

Dioxide Information Analysis Center, CDIAC. (2010). Record high global carbon dioxide emissions from fossil-fuel combustion and cement, Carbon manufacture (2010). U.S. Department of Energy, World Data Center for Atmospheric Trace Gases. USA.

Dodoo, A., Gustavsson, L. & Sathre, R. (2012). Effect of thermal mass on life cycle primary energy balances of a concrete and a wood-frame building, *Applied Energy*, 92, pp.462-472.

Domínguez, F.M., Anderson, B., López, J.M.C. & Andrés, A.C. (2010). Uncertainty in the thermal conductivity of insulation materials, *Energy and Buildings*, 42, pp.2159-2168.

Drogemuller, R., Delsante, A., Moller, S., Sharpe, R., Blackmore, J. & Oakes, S. (1999). Scoping study of minimum energy performance requirements for incorporation into the building code of Australia, Australian Greenhouse Office-8.

Durmayaz, A., Kadioglu, M. & Sen, Z. (2008). An application of the degree-hours method to estimate the residential heating energy requirement and fuel consumption in Istanbul, *Energy*, 25, pp.1245-56.

Eckstein, D. (2006). BASIX – lessons from implementation in NSW, *paper presented to Building Council of Sustainable Energy National Conference,* Brisbane, Australia.

Ekici, B., Gulten, A. & Aksoy, U.T. (2012). A study on the optimum insulation thicknesses of various types of external walls with respect to different materials, fuels and climate zones in Turkey, *Applied Energy*, 92, pp.211-217.

Energy use in The Australian Residential Sector, 1986–2020. (2008). Department of the Environment, Water, Heritage and the Arts, Canberra, ISBN: 978-1-921298-14-1.

Farid, M.M., Khudhair, A.M., Razack, S.A.K. & Al–Hallaj, S. (2004). A review on phase change energy storage: materials and applications, *Energy Conversion and Management*, 45, pp.1597-1615.

Granja, Z.A.D. & Labaki, L.C. (2003). Influence of external surface color on the periodic heat flow through a flat solid roof with variable thermal resistance, *Int. J. Energy Res*,27, pp.771-9.

Gregory, K., Moghtaderi, K.B., Sugo, H., & Page, A. (2008). Effect of thermal mass on the thermal performance of various Australian residential constructions systems, *Energy and Buildings,* 40, pp.459-465.

Griffith, B.T., Arashteh, D. & Türler, D. (1995). Gas-filled panels: an update on applications in the building thermal envelope. In Proceedings of the BETEC Fall Symposium, *Super Insulations and the Building Envelope*, Washington, DC.

Gunter, O. (1985). Polyurethane Handbook. New York: Macmillan *Publishing Co*., Inc. ISBN 0-02-948920-2.

Gustavsson, L. & Sathre, R. (2006). Variability in energy and CO_2 balances of wood and concrete building materials, *Building and Environment*, 41, pp.940-951.

Haapio, A. & Viitaniemi, P. (2008). Environmental effect of structural solutions and building materials to a building, *Environmental Impact Assessment Review,* 28(8), pp.587-600.

Hart, G.H. (2008). Fire safety and thermal insulation: sorting out the details, Website:http://www.insulation.org/articles/article.cfm?id=io080901, accessed 12 September 2013).

Hasnain, S.M. (1998). Review on sustainable thermal energy storage technologies. Part I. Heat storage materials and techniques, *Energy Conversion and Management*, 39, pp.1127-1138.

Hearne Scientific Software Pty Ltd. (2011). Technical software for professional energy thermal performance for residential buildings *AccuRate Sustainability*.

Horne, R. & Hayles, C. (2008). Towards global benchmarking for sustainable homes: an international comparison of the energy performance of housing, *Journal of Housing and the Built Environment*, 23(2), pp.119-130.

Howard, B., Parshall, L., Thompson, J., Hammer, S., Dickinson, J. & Modi, V. (2012).Spatial distribution of urban building energy consumption by end use, *Energy and Buildings,* 45, pp.141-151.

Jan, I. .(2013). Discounted Payback Period, Website: http://accountingexplained.com/managerial/capital-budgeting/discounted-payback-period, acceded 19 of December, 2013.

Jelle, B.P. (2011). Traditional, state-of-the-art and future thermal building insulation materials and solutions – Properties, requirements and possibilities, *Energy and Buildings*, 43(10), pp.2549-63.

Jelle, B.P., Gustavsen, A. & Baetens, R. (2010). The path to the high performance thermal building insulation materials and solutions of tomorrow, *Journal of Building Physics*, 34, pp.99-123.

Jeong, Y, Lee, S. & Huh, J. (2010). Estimation of CO_2 emission of apartment buildings due to major construction materials in the Republic of Korea, *Energy and Buildings.*

Judkoff, R. & Neymark, J. (1995). International energy agency building energy simulation test (BESTEST) and diagnostic method, *National Renewable Energy Laboratory*.

Kalogirou , S., Florides, G. & Tassou, S. (2002). Energy analysis of buildings employing thermal mass in Cyprus, *Renewable Energy*, 27, pp.353-368.

Kaushika, N.D. & Sumathy, K. (2003). Solar transparent insulation materials: a review, *Renewable and Sustainable Energy Reviews*, 7, pp.317-351.

Kaynakli, O. (2008). A study on residential heating energy requirement and optimum insulation thickness, *Renewable Energy,* 33(6), pp.1164-72.

Kaynakli, O. (2011). A review of the economical and optimum thermal insulation thickness for building applications, *Renewable and Sustainable Energy Reviews*, 16, pp.415-425.

Khalifa, A.J.N. & Abbas, E.F. (2009). A comparative performance study of some thermal storage materials used for solar space heating, *Energy and Buildings*, 41, pp.407-415.

Khalifa, A.N. (1998). A study on a passively heated single-zone building using a thermal storage wall, *Solar Energy Research Center, Jadiriya*, PII: S0196-8904(98)00026-0.

Koivula, M.,¨la¨inen, H.,Virta, V., Hakkarainen, H., Hussein, T., Komulainen, J., Koponen, H., Hautala, M., PekkaKanerva, K., Pehkonen, A. & Sjo¨, A. (2005). Emissions from thermal insulations—part 2: evaluation of emissions from organic and inorganic insulations, *Building and Environment,* 40. pp.803-814.

Kolaitis, I., Malliotakis, E., Kontogeorgos, A., Mandilaras, I., Dimitrios, I. & Founti, M. (2013). Comparative assessment of internal and external thermal insulation systems for energy efficient retrofitting of residential buildings, *Energy and Buildings*, 64, pp.123-131.

Kordjamshidi, M. (2011). House Rating Schemes from Energy to Comfort Base, Berlin: Springer.

Korea Ministry of Environment. (2003). Report of international trends and our countermove in relation to climate change, Republic of Korea.

Kosny, J. & Kossecka, E. (2002). Multi-dimensional heat transfer through complex assemblies hourly energy simulation program, *Energy and Buildings*, 34, pp.445-454.

Kossecka, E. & Kosny, J. (2002). Influence of insulation configuration on heating and cooling loads in a continuously used building, *Energy and Buildings*, 34, pp.321-331.

Kumar, A., & Suman, B. M. (2013). Experimental evaluation of insulation materials for walls and roofs and their impact on indoor thermal comfort under composite climate, *Building and Environment*, 59, pp.635-643.

Lazko, J., Landercy, N., Laoutid, F., Dangreau, L., Huguet, M. H., & Talon, O. (2013). Flame retardant treatments of insulating agro-materials from flax short fibres, *Polymer Degradation and Stability*.

Leslie, K. (2009). What is a Brick Veneer Wall. Website:http://www.ehow.com/facts_5028545_brick-veneer-wall.html, accessed 15 July 2011.

Li, G., Guo, Y., & Ang, L. (2010). Study on thermal performance in winter of building envelope walls insulated with expanded polystyrene board, *International Conference on Digital Manufacturing & Automation*, Yantai, China.

Li, P. & Cheng, H. (2006). Thermal analysis and performance study for multilayer perforated insulation material used in space, *Applied Thermal Engineering*, 26, pp.2020-2026.

Liang, H.H. & Ho, M.C. (2006). Toxicity characteristics of commercially manufactured insulation materials for building applications in Taiwan, *Construction and Building Materials*, 21, pp.1254-1261.

Liendhard, J. (2011). A Heat Transfer Textbook, 3rd edition, ISBN 0971383529, Phlogiston Press, Cambridge.

Lorente, S., Petit, M. & Javelas, R. (1996). Simplified analytical model for thermal transfer in vertical hollow brick, *Energy and Buildings*, 24, pp.95-103.

Lstiburek, J. (2004). Insulations, sheathings and vapor retarders, 0412, *Building Science Corporation*.

Mahlia, T.M.I. & Iqbal, A. (2010). Cost benefits analysis and emission reductions of optimum thickness and air gaps for selected insulation materials for building walls in Maldives, Energy, 35, pp.2242-50.

Mick, W. (2007). Sustainable living: for home, neighbourhood and community, *west song Publishing*, ISBN 0-9659000-5-3.

Moffat, R. (1990). Describing the uncertainties in experimental results, *Experimental Thermal Fluid Science*; Statistical techniques for data analysis, Vol.1, pp.3-7.

Morrison, B. & Strachan, A. (1999). On the significance of modelling internal surface convection in dynamic whole-building simulation programs, *ASHRAE Transactions*, no. 105, pp.929-940.

Newman, D., Eschenbach, T. & Lavelle, J. (2004). Engineering economy analysis, Oxford University Press, Oxford.

Nicol, J. Raja, I.A, Allaudin, A. & Jamy, G.N. (1999). Climatic variations in comfortable temperatures: the Pakistan projects, *Energy and Buildings*, 30, pp.261-279.

Nicolajsen, A. (2005). Thermal transmittance of a cellulose loose-fill insulation material, *Building and Environment*, 40, pp.907-914.

Nikolaidis, Y., Pilavachi, P., & Chletsis, A. (2009). Economic evaluation of energy saving measures in a common type of Greek building, Applied Energy, 86(12), 2550-2559. vol.04.02.

Ochs, F., Heidemann., W. & Steinhagen, H.M. (2008). Effective thermal conductivity of moistened insulation materials as a function of temperature, *International Journal of Heat and Mass Transfer*, 51, pp.539-552.

Oleszkiewicz, I. (1994). The Concept and Practice of Performance-Based Building Regulations, Ottawa: National Research Council Canada & Institute for Research in Construction.

Olivier, J., Janssens, G. & Peters, J. (2012).Trends in global CO_2 emissions 2012 report, PBL Netherlands, Environmental Assessment Agency, Institute for Environment and Sustainability (IES) of the European Commission’s Joint Research Centre (JRC). PBL publication number: 500114022. ISBN: 978-92-79-25381-2.

Oral, G.K. & Yilmaz, Y. (2002). The limit U values for building envelope related to building for min temperate and cold climatic zones, *Building and Environment*, 37, pp.1173-1180.

Osmani, M. & O’Reilly, A. (2009). Feasibility of zero carbon homes in England by 2016: A house builder’s perspective, *Building and Environment*, 44(9), 1917-1924.

Ozel, M. (2011).Thermal performance and optimum insulation thickness of building walls with different structure materials, *Applied Thermal Engineering*, 31(17-18), pp.3854-3863.

Ozel, M. & Pihtili, K. (2008). Determination of optimum insulation thickness by using heating and cooling degree-day values in Turkish, *J. Eng. Nat. Sci.*, 26(3), pp.191-7.

Papadopoulos, A.M. (2005). State of the art in thermal insulation materials and aims for future developments, *Energy and Buildings*, 37, pp.77-86.

Pierquet, P., Bowyer, J. L. & Huelman, P. (1998). Thermal performance and embodied energy of cold climate wall systems, *Forest Products Journal*, 48(6), pp.53-60.

Rahman.S. (2010). Sustainable Housing and Outcomes of the Cairnlea Ecohome, Ph.D thesis, School of Civil, Environmental and Chemical Engineering College of Science, Engineering and Health, RMIT University, Melbourne.

Reddy, T., Maor, I., & Panjapornpon, C. (2007). Calibrating detailed building energy simulation programs with measured data - Part I: general methodology (RP-1051), *HVAC&R Research*, 13(2), pp.221-24.

Reneckis, D. & LaFave, J.M. (2012). Out-of-plane seismic performance and fragility analysis of anchored brick veneer, *Structural Safety*, 35, pp.1-17.

Report on energy use in the Australian residential sector 1986-2020.(2011). Department of the Environment, Water, Heritage and the Arts, Commonwealth of Australia, Canberra.

Saidur, R., Masjuki, H.H., Jamaluddin, M.Y. & Ahmed, S. (2007). Energy and associated greenhouse gas emissions from household appliances in Malaysia, *Energy Policy*, 35,pp.1648-1657.

Shenawy, A. & Zmeureanu, R. (2012). Exergy-based index for assessing the building sustainability, *Building and Environment.*

Stewart, D. (2004). Winter Comfort. Website: http://www.mbm.net.au/uss/winter_comfort.html, accessed 25 October 2011.

Stokes, B. (2007). Make ACDB Software for windows - user guide, Australian Greenhouse Office, Canberra.

Tommerup, H., Rose, J., & Svendsen, S. (2007). Energy-efficient houses built according to the energy performance requirements introduced in Denmark in 2006, *Energy and Buildings*,39(10), pp.1123-1130.

Tucker, S., Newton, P., Delsante, A., Ambrose, D., Johnston, S., Allen, B., Rasheed, B. &Remmers, T. (2002). AGO-CSIRO greenhouse efficient design, CSIRO.

Tummu, P., Chirarattananon, S., Hien, V.D., Chaiwiwatworakul, P., & Rakkwamsuk, P. (2013).Thermal performance of insulated walls enclosing residential spaces in Thailand, *Energy and Buildings*, 61, pp.323-332.

Turton, H. (2004). Greenhouse gas emissions in industrialised countries, where does Australia stand, Discussion paper number 66, ISSN 1322-5421. Australia.

Ucar, A. & Balo, F. (2009). Effect of fuel type on the optimum thickness of selected insulation materials for the four different climatic regions of Turkey, *Applied Energy*, 86, pp.730-736.

Wakefield, T., He, Y., & Dowling, V.P. (2009). An experimental study of solid timber external wall performance under simulated bushfire Attack, *Building and Environment*, 44, pp.2150-2157.

Walsh, P. & Delsante, A. (1983). Calculation of the thermal behaviour of multi-zone buildings,*Energy and Buildings*, 5(4), pp.231-242.

Wang, Y, Huang, Z. & Heng, L. (2007). Cost-effectiveness assessment of insulated exterior walls of residential buildings in cold climate, *Int. J. Project Manage*, 25, pp.143-9.

Warner, C.Y. & Arpaci, V.S. (1968). An experimental investigation of turbulent natural convection in air at low pressure for vertical heated flat plate, *Int. J.Heat Mass Transfer*, 11, pp.397-406.

Wilkes, K. (1991). Proceedings of the International Symposium on Roofing Technology.

Wong, N.M., Feriadi, H., Lim, P.Y., Tham, K.W., Sekhar, C. & Cheong, K.W. (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore, *Building and Environment*, 37, pp.1267-1277.

Wu, W. & Li, H. (2012). Advantage of external thermal insulation technique, 7th international conference of on system of systems engineering (SoSE). China.

Yesilata, B., Bulut, H. &Turgut, P. (2011). Experimental study on thermal behaviour of a building structure using rubberized exterior-walls, *Energy and Buildings*, 43(2-3), pp.393-9.

Zedan, U. M.F., & Mujahid, A.M. (1993). An efficient solution for heat transfers in composite walls with periodic ambient temperature and solar radiation, *Int. J. Ambient Energy*, 14(2), pp.83-98.

Zhao, H. & Magoulès, F. (2012). A review on the prediction of building energy consumption, *Renewable and Sustainable Energy Reviews*, 16(6), pp.3586-3592.

Zhu, L., Hurt, R., Correia, D. & Boehm, R. (2009). Detailed energy saving performance analyses on thermal mass walls demonstrated in a zero energy house, *Energy and Buildings*, 41, pp.303-310.

Zmeureanu, R. & Renaud, G. (2008). Estimation of potential impact of climate change on the heating energy use of existing houses, *Energy Policy*, 36, pp.303-310.

BIBLIOGRAPHY

A comparison of NatHERS, FirstRate and AccuRate predictions of the difference between slab-on-ground floors and suspended timber floors (2007). PN04.1008, Forest and Wood Products Research and Development Corporation.

ABCB. (2011b). History of the Building Code of Australia and the National Construction Code, Website:http://www.abcb.gov.au/index.cfm?objectid=F5A5E1E1-7608-11E0-9903001143D4D594, accessed 25 September 2013.

Adalberth, K. (2000). Energy use and environmental impact of new residential buildings. PhD Thesis, Department of Building Physics, Lund University, Sweden.

ALF 3.2 (Annual Loss Factor) - A Design Tool for Energy Efficient Houses. URL http://alf.branz.co.nz/help/internal-gains, accessed 3 June 2013.

Allen, E., Bloomfield, D., Bowman, N., Lomas, K., Allen, J., Whittle, J & Irving, A. (1985). Analytical and empirical validation of dynamic thermal building models, Paper presented to Building.

American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) (2001). Handbook of Fundamentals, Atlanta, GA, Chapter 23.

Arnaud, L. & Gourlay, E. (2001). Experimental study of parameters influencing mechanical properties of hemp concretes, *Construction and Building Materials*, pp.50-6.

Athienitis, A.K., Liu, C., Hawes, D., Banu, D. & Feldman, D. (1997). Investigation of the thermal performance of a passive solar test-room with wall latent heat storage, *Elsevier Building and Environment*, 32(5), pp.405-410.

Baehr, H. D. & Stephan, K. (2010).Wärme- und Stoffübertragung. 7. Auflage, Springer Verlag, Berlin.

Bellamy, L.A. & Mackenzie, D.W. (2001). Thermal Performance of Buildings with Heavy walls, Study Report No. 108, Branz: The Resource Centre for Building Excellence.

Bolatturk, A. (2008). Optimum insulation thicknesses for building walls with respect to cooling and heating degree-hours in the warmest zone of Turkey, *Build Environ*, 43(6), pp.1055-64.

Bribián, I.Z., Capilla, A.V. & Usón, A.A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential, *Building and Environment*, 46, pp.1133-1140.

Building technologies program energy efficiency and renewable energy (2010).Pacific Northwest National Laboratory.U.S. Department of Energy*, Buildings Energy Data Book.*

Buyukalaca, O., Bulut, H., & Yilmaz, T. (2001). Analysis of variable-base heating and cooling degree-days for Turkey, *Appl. Energy*, 69, pp.269, 283, 292.

CO_2 emissions from fuel combustion highlights. (2011). *IEA Publication.* Available from http://www.iea.org/publications/freepublications/publication, name, 4010, en.html, accessed 21 March 2012.

Comakli, K., &Yuksel, B. (2004).Environmental impact of thermal insulation thickness in buildings, *Applied Thermal Energy*, 24(2), pp.933-40.

Costello, Y.A., Melsheimer, S.S. & Edie, D.D. (1987). Heat transfer and calorimetric studies of a direct contact-latent heat energy storage system; thermal storage and heat transfer in solar energy system. *ASME Meeting*, San Francisco, CA.

Dombayci, O.A. (2007). The environmental impact of optimum insulation thickness for external walls of buildings, *Build Environ*, 42, pp.3855-9.

Durmayaz, A. & Kadioglu, M. (2003). Heating energy requirements and fuel consumptions in the biggest city centers of Turkey, *Convers Manage*, 44, pp.1177-1192.

Farid, M.M. & Khalaf A.N. (1994). Performance of direct contact latent heat storage units with two hydrated salts, *Solar Energy*, 52, pp.179-89.

Farid, M.M., Kim, Y. & Kanzawa, A. (1990).Thermal performance of heat storage module using PCMs with different melting temperatures-experimental.Trans ASME, *J. Solar Energy Eng*,112, pp.125-31.

Gan, G. & Awbi, H.B. (1994). Numerical simulation of the indoor environment, *Building and Environment*, 29, pp.449-459.

Glass, J., Dainty, A. & Gibb, A. (2008). New build: Materials, techniques, *Energy Policy*, 36, pp.4534-8.

Haberl, J. (2004). Literature review of uncertainty of analysis methods (DOE-2 Program), *Texas Commission on Environmental Quality*, Texas.

Hallet, J. & Keyser, G. (1979). Power characteristics of a continuous crystallization latent heat recovery system, *ASME Publ*, 21.

Han, J. W., Yang, W.J., Zhou, J., Zhang, G., Q., Zhang, Q. & Moschandreas, D.J. (2009). A comparative analysis of urban and rural residential thermal comfort under natural ventilation environment, *Energy and Buildings*,41(2), pp.139-145.

Hasselman, D. P. H. & Johnson, L. F. (1987). Effective thermal conductivity of composites with interfacial thermal barrier resistance.*Journal of Composite Materials*, 21(6), pp.508-515.

Humphreys, M., Setunge, S., Fenwick, J. & Alwi.S. (2006). Strategies for minimising the whole of life cycle cost of reinforced concrete, bridge exposed to aggressive environments, *Second International Conference on Quality Chain Management*, Stockholm.

Kedl, RJ. & Stovall, TK. (1989). Activities in support of the wax-impregnated wallboard concept: thermal energy storage researches activity review. U.S. Department of Energy, New Orleans, Louisiana.

Landman, K. & Delsante, A. (1987). Steady-state heat losses from a building floor slab with vertical edge insulation-II, *Building and Environment*, 22(1), pp.49-55.

Ma, J., Fricke, W. & Borst, L. (1984). Energie - EinLehrbuch der physikalischenGrundlagen. 2. Auflage, OldenbourgVerlag, München.

Maekawa, K., & Ishida, T. (1999). Service-life evaluation of reinforced concrete under coupled forces and environmental actions, University of Tokyo, 7-3-1 Hongo, Bunkyo ku, Japan.

Mahlia, T.M.I., Taufiq, B.N. Ismail, A.M. & Masjuki, H.H. (2007). Correlation between thermal conductivity and the thickness of selected insulation materials for building wall, *Energy and Buildings*, 39 pp.182–187.

Materials and Methods for Corrosion Control of Reinforced Prestressed Concrete Structure in New Construction Research (2000). Publication No. 00-081, US Department of Transport, Federal Highway Administration, McLean, VA 22101-2296.

May, P. (2003). Performance Based Regulation and Regulatory Regimes: The Saga of Leaky Buildings, *Law & Policy*, 25(4), pp.381-401.

Míguez, J., Porteiro, J., López-González, L., Vicuña, J., Murillo, S., Morán, J., & Granada, E. (2006). Review of the energy rating of dwellings in the European Union as a mechanism for sustainable energy, *Renewable and Sustainable Energy Reviews*, 10(1), pp.24-45.

Morillo´n, D., Sa´mano, D.A., vila, A,´ Ferna´ndez, J.L. (1997). The comfort zone and the oscillation of the driving temperature, *Applied Energy*, 57, pp.1-11.

Munoz, F.D., Anderson, B., López, J.M.C. & Andrés, A.C. (2010).Uncertainty in the thermal conductivity of insulation materials.*Energy and Buildings*, 42, pp.2159-2168.

Neeper, D.A. (2000). Thermal dynamics of wallboard with latent heat storage, *Solar Energy*, 68, pp.393-403.

Neymark, J., Judkoff, R., Alexander, D., Felsman, C., Strachan, P., & Wijsman, A. (2008). International Energy Agency building energy simulation test and diagnostic method (IEA BESTEST) - multi-zone non-airflow in-depth diagnostic cases: MZ320-MZ360, NREL/TP- 550-43827.

Ogbonna, A.C & Harris, D.J. (2008). Thermal comfort in sub-Saharan Africa: field study report in Jos-Nigeria, *Applied Energy*, 85(1), pp.1-11.

Oxizidis, S. & Papadopoulos, A. (2011). Energy, environmental and economic optimization of thermal insulation solutions by means of an integrated decision support system, *Energy and Buildings*, 43(2), pp.686-694.

Papakostas, K., Mavromatis, T. & Kyriakis, N. (2010). Impact of the ambient temperature rise on the energy consumption for heating and cooling in residential buildings of Greece, *Renew Energy*, 35, pp.1376-9.

Pehkuri, R., Rode, C. & Hansen, K.K. (2008). Non-isothermal moisture transport through insulation materials, *Building and Environment*, 43, pp.811-822.

Philips, A. (2010). The Disadvantages of Brick Veneer.Website:http://www.ehow.com/list_6670691_disadvantages-brick-veneer.html, accessed 5 July 2011.

Rudd, A., Chandra, S. & Tooley, J.1. (1993). Measured air-tightness and thermal insulation quality of 11 industrialized houses, Paper presented to EEBA Conference on Building Solutions, Boston, MA.

Salyer, I.O, & Sircar, A.K. (1990). Phase change materials for heating and cooling of residential buildings and other applications. In *Proceedings of 25th Intersociety Energy Conversion Engineering Conference*, pp. 236-43.

Sarak, H., & Satman, A. (2003). The degree-day method to estimate the residential heating natural gas consumption in Turkey: a case study, *Energy*, 28, pp.929-39.

Shaviv, E., Yezioro, A., & Capeluto, I. G. (2001). Thermal mass and night ventilation as passive cooling design strategy, *Renewable Energy*, 24(3), pp.445-452.

Sisman, N., Kahya, E., Aras, N. & Aras, H. (2007). Determination of optimum insulation thicknesses of the external walls and roof (ceiling) for Turkey's different degree-day regions, *Energy Policy*, 35, pp.5151-5.

Stec, A. A. & Hull, T. R. (2011). Assessment of the fire toxicity of building insulation materials, *Energy and Buildings*, 43(2), pp.498-506.

Stetiu, C. & Feustel, H.E. (1996). Phase change wallboard as an alternative to compressor cooling in Californian residences. In *Proceedings of 96 ACEE Summer Study for Energy Efficient Building*, California.

The full brick advantage, the gold standard in housing.URL http:// www.fullbrick.com.au, accessed 9 August 2012.

Ucar, A. & Balo, F. (2010). Determination of the energy savings and the optimum insulation thickness in the four different insulated exterior walls, *Renew Energy*, 35(1), pp.88-94.

UN Habitat: Global housing demand at critical levels. Website: http://www.unhabitat.org, accessed 8 October 2012.

Wärmeatlas, V.D.I. (2002). Berechnungsblätterfür den Wärmeübergang. VereinDeutscherIngenieure 9. Auflage, Springer Verlag, Berlin.

Ye, X.J., Zhou, Z.P., Lian, Z.W., Liu, H.M., Li, C.Z. & Liu,Y.M. (2006). Field study of a thermal environment and adaptive model in shanghai, *Indoor Air*, 16, pp.320-326

LIST OF PUBLICATIONS

The following is a list of publications arisen from this work:

Aldawi, F., Alam, F., Date, A., Alghamdi, M. & Aldhawi, F. (2013). A new house wall system for residential buildings, *Energy and Buildings*, (67), pp.403–418.

Aldawi, F., Date, A., Alam, F., Khan, I. & Alghamdi, M. (2013). Energy efficient residential house wall system, *Applied Thermal Engineering*, (58), pp. 400–410.

Aldawi, F., Alam, F. & Moria, H. (2013). Energy efficient house wall system for arid and moderate climatic regions, *Yanbu Journal of Engineering and Science (YJES),* ISSN: 1658–5321. Vol.6.

Aldawi, F., Alam, F., Date, A., Kumar, A., & Rasul, M. (2012). Thermal performance modelling of residential house wall systems, International Clean Energy Conference, *Procedia Engineering*, 49, pp.161–168.Sydney, Australia.

Aldawi, F., Alam, F., Khan, I. & Alghamdi, M. (2012). Effect of climates and building materials on house wall thermal performance, 5th BSME International Conference on Thermal Engineering (5thBSME2012), *Procedia Engineering*, Vol. 56, 2013, pp. 661–666.

Aldawi, F., Moria, H., Alam, F., & Akbarzadeh, A. (2011). Thermal performance study of conventional and new house wall systems, International Conference on Mechanical Engineering (ICME 2011), *Procedia Engineering*,(Paper no: 017), 18–20 December, Dhaka, Bangladesh.

Aldawi, F., Moria, H., Alam, F., Date, A. & Akbarzadeh, A. (2011). A smart house wall energy performance study for arid climatic region, *Proceedings of the Jordan International Energy Conference (JIEC2011),* 20–22 September, Amman, Jordan.

Aldawi, F., Moria, H., Alam, F., Dixon, C. & Akbarzadeh, A. (2011). Energy star rating of a traditional and innovative residential house, International Conference on Mechanical Engineering(ICMERE2011), *Procedia Engineering*,(Paper no:176),22–24 December, Chittagong, Bangladesh.

The following is a list of publications participated in other research area:

Alam, F., Chowdhury, H., Moria, H., Fuss, F. K., Khan, I., Aldawi, F. & Subic, A. (2011). Aerodynamics of Contemporary FIFA Soccer Balls, *The 5th Asia Pacific Congress on Sports Technology (APCST).* Melbourne, Australia, *pp.*28–31.

Alam, F., Steiner, T., Chowdhury, H., Moria, H., Khan, I., Aldawi, F. & Subic, A. (2011). A Study of Golf Ball Aerodynamic Drag, *The 5th Asia Pacific Congress on Sports Technology (APCST)*. Melbourne, Australia, pp. 28–31.

Khan, I., Chowdhury, H., Aldawi, F. & Alam, F. (2012).The effect of climate change on power generation in Australia, *Proceedings of the International Conference on Thermal Engineering (5th BSME2012),* 21–23 December, Dhaka, Bangladesh.

Moria, H., Alam, F., Chowdhury, H., Aldawi, F., & Subic, A. (2011). Aerodynamic analysis of Speedo Fastskin-I swimsuit. In M. T. Islam (Ed.), *Proceedings of the International Conference on Mechanical Engineering and Renewable Energy 2011 (ICMERE2011) (Paper no:178)*. Chittagong University of Engineering & Technology, Chittagong, Bangladesh.

Moria, H., Chowdhury, H., Aldawi, F. & Alam, F. (2013). A cylindrical methodology for the study of fabric aerodynamics, *Procedia Engineering*, (56), pp. 297-302.

APPENDIX A: Simulated House Description

A.1 Simulated House Plan View

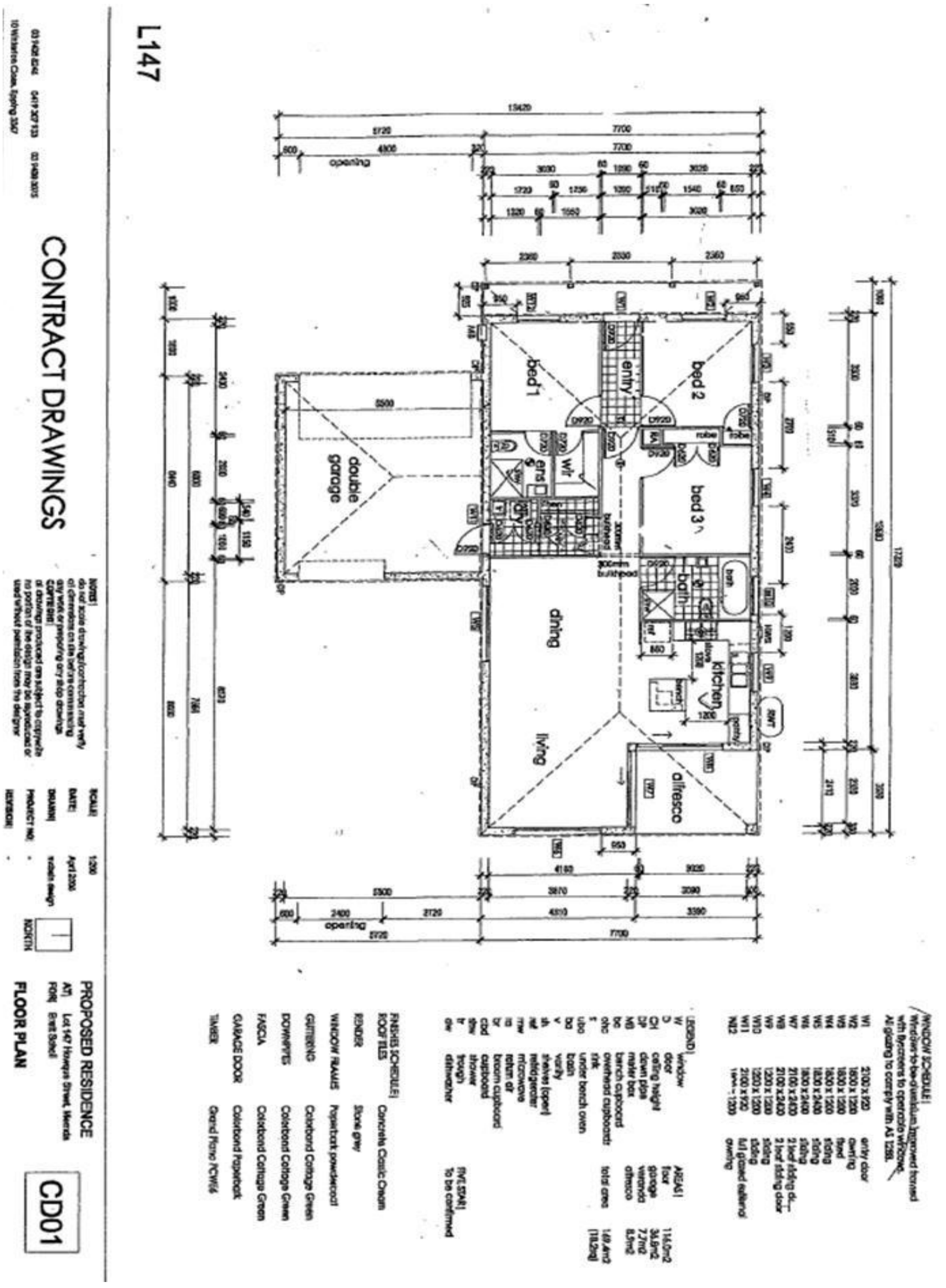


Figure A.1: House description used in computational modeling

Table A.1: External wall details for conventional house

Zone	External Wall	Construction	Azimuth	Length	High	Area	Fixed shade
Bed 1	1	Brick veneer(single side)	270	3.25	2.40	7.80	None
Bed 1	2	Brick veneer(single-side)	180	3.40	2.40	8.16	None
Bed 2	1	Brick veneer(single-side)	0	3.08	2.40	7.39	None
Bed 2	2	Brick veneer(single-side)	0	4.90	2.40	11.76	None
Bed 3	1	Brick veneer(single-side)	0	3.49	2.40	8.38	None
Bath	1	Brick veneer(single-side)	90	2.06	2.40	4.94	None
kitchen	1	Brick veneer(single-side)	0	3.24	2.40	7.78	None
Living	1	Brick veneer(single-side)	0	2.63	2.40	6.31	None
Living	2	Brick veneer(single-side)	90	4.09	2.40	9.82	None
Living	3	Brick veneer(single-side)	180	8.08	2.40	19.39	None
Living	4	Brick veneer(single-side)	0	4.05	2.40	9.72	None
Living	5	Brick veneer(single-side)	90	3.31	2.40	7.94	None
Landry	1	Brick veneer(single-side)	180	1.75	2.40	4.20	None
Toilet	1	Brick veneer(single-side)	180	1.09	2.40	2.62	None

Table A.2: Internal walls details for conventional and new house

Zone	Internal Wall	Construction	Length	High	Area	Fixed shade
Bed 1	1	Plaster board on studs	3.25	2.40	7.80	None
Bed 1	2	Plaster board on studs	3.40	2.40	8.16	None
Bed 2	1	Plaster board on studs	3.08	2.40	7.39	None
Bed 2	2	Plaster board on studs	4.90	2.40	11.76	None
Bed 3	1	Plaster board on studs	3.49	2.40	8.38	None
Bath	1	Plaster board on studs	2.06	2.40	4.94	None
kitchen	1	Plaster board on studs	3.24	2.40	7.78	None
Living	1	Plaster board on studs	2.63	2.40	6.31	None
Living	2	Plaster board on studs	4.09	2.40	9.82	None
Living	3	Plaster board on studs	8.08	2.40	19.39	None
Living	4	Plaster board on studs	4.05	2.40	9.72	None
Living	5	Plaster board on studs	3.31	2.40	7.94	None
Landry	1	Plaster board on studs	1.75	2.40	4.20	None
Toilet	1	Plaster board on studs	1.09	2.40	2.62	None

Table A.3: House specifications, single dwelling case study

	Group	Components
Structure	Footing/slab on ground	Concrete slab on ground
	Upper floors	Timber floor – Particle boards on timber joists
	External wall, conventional house	Brick veneer, timber frames with internal insulation batts and internal plaster board
	External walls, new insulated house	Reinforced concrete, insulation materials and internal plaster board
	Internal walls	Timber framed with plasterboard finish
	Roof	Concrete tiles on timber trusses
	Window	Aluminium windows and timber doors
Finishes	Carpet	Living room, family area and bedrooms
	Ceramic	Ceramic floor tiling (kitchen, bathrooms, toilet and laundry)
	Ceiling	Plaster board ceiling
	Paint	White paint on wall and ceiling

APPENDIX B: Further Results for Computational Method

B.1 Inner Insulation Results

Table B.1: Total Energy required for inner insulation system (polystyrene R1.5)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	75.4	33.8	109.2	6.2
2	Brisbane	QLD	1.6	54.0	55.6	4.9
3	Darwin	NT	0.0	407.2	407.2	5.1
4	Hobart	TAS	143.0	19.0	162.0	5.8
5	Adelaide	SA	28.7	58.6	87.3	6.3
6	Sydney	NSW	3.1	47.8	50.9	4.9
7	Canberra	ACT	151.0	34.2	185.2	5.6
8	Rockhampton	QLD	0.0	120.5	120.5	4.6
9	Perth	WA	8.8	63.4	72.2	5.9
10	Alice Springs	NT	7.1	127.5	134.6	5.4
11	Broome	WA	0.0	304.6	304.6	4.8
12	Cairns	QLD	0.0	151.8	151.8	5.0
13	Townsville	QLD	0.0	162.4	162.4	4.6

Table B.2: Energy required for inner insulation system (cellulose fibre-R1.5)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	75.4	33.7	109.1	6.2
2	Brisbane	QLD	1.5	54.1	55.6	4.9
3	Darwin	NT	0.0	408.5	408.5	5.1
4	Hobart	TAS	143.0	18.9	161.9	5.8
5	Adelaide	SA	28.7	58.6	87.3	6.3
6	Sydney	NSW	3.0	48.0	51.0	4.9
7	Canberra	ACT	150.9	34.3	185.2	5.6
8	Rockhampton	QLD	0.0	120.6	120.6	4.6
9	Perth	WA	8.7	63.4	72.1	5.9
10	Alice Springs	NT	7.0	127.4	134.4	5.4
11	Broome	WA	0.0	305.0	305.0	4.8
12	Cairns	QLD	0.0	151.4	151.4	5.1
13	Townsville	QLD	0.0	166.3	166.3	4.6

Table B.3: Energy required for inner insulation system (rock wool batts)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	75.3	33.8	109.1	6.2
2	Brisbane	QLD	1.6	54.0	55.6	4.9
3	Darwin	NT	0.0	407.8	407.8	5.1
4	Hobart	TAS	142.8	19.0	161.8	5.8
5	Adelaide	SA	28.7	58.6	87.3	6.3
6	Sydney	NSW	3.0	48.0	51.0	4.9
7	Canberra	ACT	150.8	34.3	185.1	5.6
8	Rockhampton	QLD	0.0	120.5	120.5	4.6
9	Perth	WA	8.7	63.5	72.2	5.9
10	Alice Springs	NT	7.0	127.4	134.4	5.4
11	Broome	WA	0.0	304.6	304.6	4.8
12	Cairns	QLD	0.0	152.0	152.0	5.0
13	Townsville	QLD	0.0	166.5	166.5	4.5

Table B.4: Energy required for inner insulation system (sheep wool)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	75.4	33.8	109.2	6.2
2	Brisbane	QLD	1.6	54.0	55.6	4.9
3	Darwin	NT	0.0	407.7	407.7	5.1
4	Hobart	TAS	142.9	19.0	161.9	5.8
5	Adelaide	SA	28.7	58.6	87.3	6.3
6	Sydney	NSW	3.0	48.0	51.0	4.9
7	Canberra	ACT	150.9	34.3	185.2	5.6
8	Rockhampton	QLD	0.0	120.6	120.6	4.6
9	Perth	WA	8.7	63.5	72.2	5.9
10	Alice Springs	NT	7.1	127.3	134.4	5.4
11	Broome	WA	0.0	304.6	304.6	4.8
12	Cairns	QLD	0.0	152.0	152.0	5.0
13	Townsville	QLD	0.0	166.5	166.5	4.6

Table B.5: Energy required for inner insulation system (straw board)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	92.0	34.3	126.3	5.6
2	Brisbane	QLD	2.2	55.4	57.6	4.8
3	Darwin	NT	0.0	432	432.0	4.7
4	Hobart	TAS	169.7	18.6	188.3	5.3
5	Adelaide	SA	36.9	61.6	98.5	5.9
6	Sydney	NSW	4.4	49.6	54.0	4.8
7	Canberra	ACT	180.0	33.1	213.1	5.1
8	Rockhampton	QLD	0.0	127.4	127.4	4.3
9	Perth	WA	11.5	64.8	76.3	5.7
10	Alice Springs	NT	9.5	134.3	143.8	5.1
11	Broome	WA	0.0	324.8	324.8	4.5
12	Cairns	QLD	0.0	158.2	158.2	4.8
13	Townsville	QLD	0.0	174.3	174.3	4.3

Table B.6: Energy required for inner insulation system (wood chip or particle board)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	96.3	33.5	129.8	5.5
2	Brisbane	QLD	2.0	55.6	57.6	4.8
3	Darwin	NT	0.0	443.0	443.0	4.5
4	Hobart	TAS	176.3	18.1	194.4	5.2
5	Adelaide	SA	38.4	61.0	99.4	5.9
6	Sydney	NSW	4.5	49.6	54.1	4.7
7	Canberra	ACT	186.0	31.6	217.6	4.9
8	Rockhampton	QLD	0.0	128.2	128.2	4.3
9	Perth	WA	11.5	64.3	75.8	5.7
10	Alice Springs	NT	9.0	134.7	143.7	5.1
11	Broome	WA	0.0	332.6	332.6	4.3
12	Cairns	QLD	0.0	160.6	160.6	4.7
13	Townsville	QLD	0.0	177.7	177.7	4.2

Table B.7: Energy required for inner insulation system (glass fibre-R1.5)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	75.5	33.8	109.3	6.1
2	Brisbane	QLD	1.6	54.0	55.6	4.9
3	Darwin	NT	0.0	407.3	407.3	5.1
4	Hobart	TAS	143.1	19.0	162.1	5.8
5	Adelaide	SA	28.8	58.6	87.4	6.3
6	Sydney	NSW	3.1	47.9	51.0	4.9
7	Canberra	ACT	151.1	34.3	185.4	5.6
8	Rockhampton	QLD	0.0	120.7	120.7	4.6
9	Perth	WA	8.8	63.4	72.2	5.9
10	Alice Springs	NT	7.1	127.6	134.7	5.4
11	Broome	WA	0.0	304.7	304.7	4.8
12	Cairns	QLD	0.0	152.0	152.0	5.0
13	Townsville	QLD	0.0	165.9	165.9	4.6

Table B.8: Energy required for inner insulation system (straw bale rendered)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	93.2	34.6	127.8	5.6
2	Brisbane	QLD	2.3	55.5	57.8	4.8
3	Darwin	NT	0.0	431.7	431.7	4.7
4	Hobart	TAS	171.8	18.7	190.5	5.2
5	Adelaide	SA	37.8	62.0	99.8	5.9
6	Sydney	NSW	4.6	49.3	53.9	4.8
7	Canberra	ACT	182.0	34.2	216.2	4.9
8	Rockhampton	QLD	0.0	127.4	127.4	4.3
9	Perth	WA	12.1	65.7	77.8	5.6
10	Alice Springs	NT	10.1	135.9	146.0	5.1
11	Broome	WA	0.0	325	325.0	4.5
12	Cairns	QLD	0.0	158.1	158.1	4.8
13	Townsville	QLD	0.0	173.9	173.9	4.3

Table B.9: Energy required for inner insulation system (polyurethane)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	70.7	33.7	104.4	6.3
2	Brisbane	QLD	1.4	53.7	55.1	4.9
3	Darwin	NT	0.0	401	401.0	5.2
4	Hobart	TAS	135.4	19.1	154.5	6.0
5	Adelaide	SA	26.5	57.7	84.2	6.4
6	Sydney	NSW	2.7	47.5	50.2	4.9
7	Canberra	ACT	142.8	34.3	177.1	5.7
8	Rockhampton	QLD	0.0	119.4	119.4	4.6
9	Perth	WA	7.9	62.8	70.7	5.9
10	Alice Springs	NT	6.3	124.5	130.8	5.4
11	Broome	WA	0.0	299.5	299.5	5.0
12	Cairns	QLD	0.0	150.0	150.0	5.1
13	Townsville	QLD	0.0	164.6	164.6	4.6

B.2 Outer Insulation

Table B.10: Total Energy required for outer insulation system (polystyrene R1.5)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	69.0	28.7	97.7	6.5
2	Brisbane	QLD	0.3	52.0	52.3	5.2
3	Darwin	NT	0.0	428.3	428.3	4.8
4	Hobart	TAS	131.3	17.4	148.7	6.2
5	Adelaide	SA	21.7	50.5	72.2	6.9
6	Sydney	NSW	1.1	45.8	46.9	5.3
7	Canberra	ACT	135.8	28.5	164.3	6.0
8	Rockhampton	QLD	0.0	117.4	117.4	4.7
9	Perth	WA	3.0	52.7	55.7	6.8
10	Alice Springs	NT	1.4	111.2	112.6	6.0
11	Broome	WA	0.0	313.1	313.1	4.7
12	Cairns	QLD	0.0	154.9	154.9	4.9
13	Townsville	QLD	0.0	166.3	166.3	4.7

Table B.11: Energy required for outer insulation system (cellulose fibre-R1.5)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	69.1	28.7	97.8	6.5
2	Brisbane	QLD	0.3	51.9	52.2	5.2
3	Darwin	NT	0.0	428.7	428.7	4.8
4	Hobart	TAS	131.4	17.5	148.9	6.1
5	Adelaide	SA	21.8	50.4	72.2	6.9
6	Sydney	NSW	1.1	45.8	46.9	5.3
7	Canberra	ACT	136.0	28.5	164.5	6.0
8	Rockhampton	QLD	0.0	117.4	117.4	4.7
9	Perth	WA	3.0	52.7	55.7	6.8
10	Alice Springs	NT	1.4	111.1	112.5	6.0
11	Broome	WA	0.0	313.2	313.2	4.7
12	Cairns	QLD	0.0	155.2	155.2	4.9
13	Townsville	QLD	0.0	172.5	172.5	4.3

Table B.12: Energy required for outer insulation system (rock wool batts)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	69.0	28.6	97.6	6.5
2	Brisbane	QLD	0.3	52.0	52.3	5.2
3	Darwin	NT	0.0	428.4	428.4	4.8
4	Hobart	TAS	131.2	17.4	148.6	6.2
5	Adelaide	SA	21.7	50.4	72.1	6.9
6	Sydney	NSW	1.1	45.8	46.9	5.3
7	Canberra	ACT	135.7	28.5	164.2	6.0
8	Rockhampton	QLD	0.0	117.4	117.4	4.7
9	Perth	WA	2.9	52.8	55.7	6.8
10	Alice Springs	NT	1.4	111.2	112.6	6.0
11	Broome	WA	0.0	313.0	313.0	4.7
12	Cairns	QLD	0.0	155.1	155.1	4.9
13	Townsville	QLD	0.0	172.6	172.6	4.3

Table B.13: Energy required for outer insulation system (sheep wool)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	69.0	28.7	97.7	6.5
2	Brisbane	QLD	0.3	52.0	52.3	5.2
3	Darwin	NT	0.0	428.3	428.3	4.8
4	Hobart	TAS	131.3	17.4	148.7	6.1
5	Adelaide	SA	21.7	50.5	72.2	6.9
6	Sydney	NSW	1.1	45.8	46.9	5.3
7	Canberra	ACT	135.8	28.5	164.3	6.0
8	Rockhampton	QLD	0.0	117.4	117.4	4.7
9	Perth	WA	2.9	52.9	55.8	6.8
10	Alice Springs	NT	1.4	111.2	112.6	6.0
11	Broome	WA	0.0	313.0	313.0	4.7
12	Cairns	QLD	0.0	155.0	155.0	4.9
13	Townsville	QLD	0.0	172.6	172.6	4.3

Table B.14: Energy required for outer insulation system (straw board)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	87.0	29.1	116.1	5.9
2	Brisbane	QLD	0.6	52.9	53.5	5.1
3	Darwin	NT	0.0	447.5	447.5	4.4
4	Hobart	TAS	160.3	16.9	177.2	5.4
5	Adelaide	SA	31.3	53.6	84.9	6.4
6	Sydney	NSW	2.3	47.3	49.6	5.0
7	Canberra	ACT	168.2	27.8	196.0	5.4
8	Rockhampton	QLD	0.0	122.5	122.5	4.4
9	Perth	WA	6.1	55.6	61.7	6.4
10	Alice Springs	NT	3.6	120.0	123.6	5.7
11	Broome	WA	0.0	330.1	330.1	4.4
12	Cairns	QLD	0.0	159.9	159.9	4.8
13	Townsville	QLD	0.0	179.6	179.6	4.1

Table B.15: Energy required for outer insulation system (wood chip board)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	92.6	28.6	121.2	5.8
2	Brisbane	QLD	0.7	53.1	53.8	5.1
3	Darwin	NT	0.0	453	453.0	4.4
4	Hobart	TAS	169.0	17.1	186.1	5.3
5	Adelaide	SA	34.2	54.2	88.4	6.3
6	Sydney	NSW	2.7	47.6	50.3	4.9
7	Canberra	ACT	178.3	27.3	205.6	5.2
8	Rockhampton	QLD	0.0	124	124.0	4.4
9	Perth	WA	7.1	56.1	63.2	6.4
10	Alice Springs	NT	4.4	121.7	126.1	5.6
11	Broome	WA	0.0	335.8	335.8	4.3
12	Cairns	QLD	0.0	162.0	162.0	4.7
13	Townsville	QLD	0.0	181.7	181.7	4.0

Table B.16: Energy required for outer insulation system (glass fibre-R1.5)

No.	City	State	Heading energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	69.2	28.6	97.8	6.5
2	Brisbane	QLD	0.3	52	52.3	5.2
3	Darwin	NT	0.0	428.6	428.6	4.8
4	Hobart	TAS	131.5	17.4	148.9	6.1
5	Adelaide	SA	21.8	50.5	72.3	6.9
6	Sydney	NSW	1.1	45.8	46.9	5.3
7	Canberra	ACT	136.1	28.4	164.5	6.0
8	Rockhampton	QLD	0.0	117.4	117.4	4.7
9	Perth	WA	3.0	52.8	55.8	6.8
10	Alice Springs	NT	1.4	111.2	112.6	6.0
11	Broome	WA	0.0	313.3	313.3	4.7
12	Cairns	QLD	0.0	155.0	155.0	4.9
13	Townsville	QLD	0.0	172.7	172.7	4.3

Table B.17: Energy required for outer insulation system (straw bale rendered)

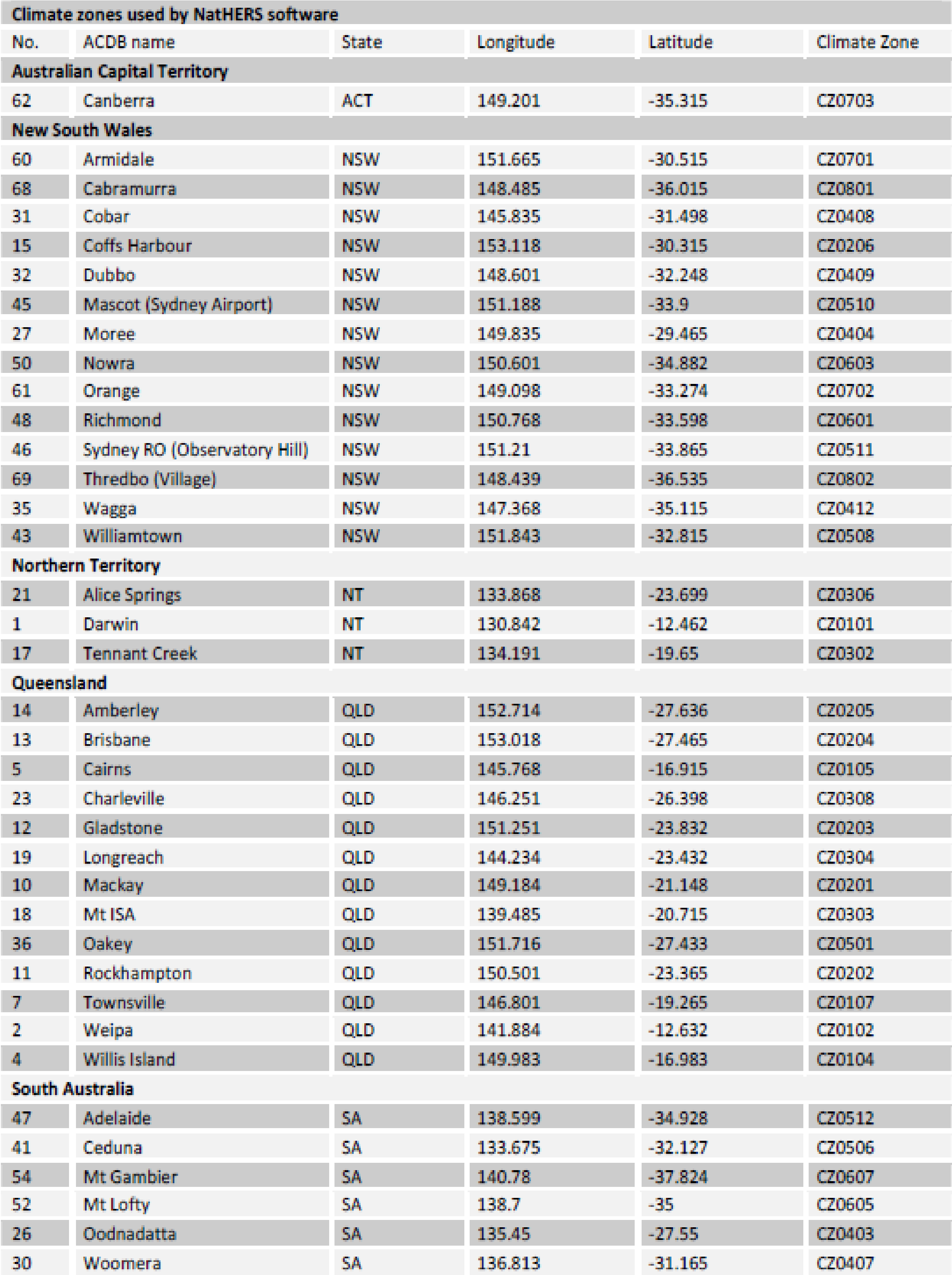
No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	87.5	29.2	116.7	5.9
2	Brisbane	QLD	0.7	52.9	53.6	5.1
3	Darwin	NT	0.0	448.1	448.1	4.4
4	Hobart	TAS	161.2	16.9	178.1	5.4
5	Adelaide	SA	31.6	53.9	85.5	6.4
6	Sydney	NSW	2.4	47.4	49.8	5.0
7	Canberra	ACT	169.3	28.0	197.3	5.3
8	Rockhampton	QLD	0.0	122.9	122.9	4.4
9	Perth	WA	6.2	56.0	62.2	6.4
10	Alice Springs	NT	3.8	120.5	124.3	5.7
11	Broome	WA	0.0	330.8	330.8	4.4
12	Cairns	QLD	0.0	160.1	160.1	4.7
13	Townsville	QLD	0.0	180.0	180.0	4.1

Table B.18: Energy required for outer insulation system (polyurethane)

No.	City	State	Heating energy required (MJ/m^2.annum)	Cooling energy required (MJ/m^2.annum)	Total energy required (MJ/m^2.annum)	Star rate (0-10)
1	Melbourne	VIC	64.3	28.6	92.9	6.7
2	Brisbane	QLD	0.2	51.9	52.1	5.2
3	Darwin	NT	0.0	423.1	423.1	4.8
4	Hobart	TAS	123.4	17.6	141.0	6.3
5	Adelaide	SA	19.2	49.4	68.6	7.1
6	Sydney	NSW	0.9	45.6	46.5	5.3
7	Canberra	ACT	127.0	28.6	155.6	6.2
8	Rockhampton	QLD	0.0	116.3	116.3	4.7
9	Perth	WA	2.3	52.3	54.6	6.9
10	Alice Springs	NT	1.0	108.7	109.7	6.1
11	Broome	WA	0.0	308.2	308.2	4.7
12	Cairns	QLD	0.0	153.7	153.7	4.9
13	Townsville	QLD	0.0	170.8	170.8	4.4

B.3 Climate Zones Used by NatHERS Software

Table B.19: Australian climate zones used by NatHERS software



Climate zones used by NatHERS software					
No.	ACDB name	State	Longitude	Latitude	Climate Zone
Australian Capital Territory					
62	Canberra	ACT	149.201	-35.315	CZ0703
New South Wales					
60	Armidale	NSW	151.665	-30.515	CZ0701
68	Cabramurra	NSW	148.485	-36.015	CZ0801
31	Cobar	NSW	145.835	-31.498	CZ0408
15	Coffs Harbour	NSW	153.118	-30.315	CZ0206
32	Dubbo	NSW	148.601	-32.248	CZ0409
45	Mascot (Sydney Airport)	NSW	151.188	-33.9	CZ0510
27	Moree	NSW	149.835	-29.465	CZ0404
50	Nowra	NSW	150.601	-34.882	CZ0603
61	Orange	NSW	149.098	-33.274	CZ0702
48	Richmond	NSW	150.768	-33.598	CZ0601
46	Sydney RO (Observatory Hill)	NSW	151.21	-33.865	CZ0511
69	Thredbo (Village)	NSW	148.439	-36.535	CZ0802
35	Wagga	NSW	147.368	-35.115	CZ0412
43	Williamtown	NSW	151.843	-32.815	CZ0508
Northern Territory					
21	Alice Springs	NT	133.868	-23.699	CZ0306
1	Darwin	NT	130.842	-12.462	CZ0101
17	Tennant Creek	NT	134.191	-19.65	CZ0302
Queensland					
14	Amberley	QLD	152.714	-27.636	CZ0205
13	Brisbane	QLD	153.018	-27.465	CZ0204
5	Cairns	QLD	145.768	-16.915	CZ0105
23	Charleville	QLD	146.251	-26.398	CZ0308
12	Gladstone	QLD	151.251	-23.832	CZ0203
19	Longreach	QLD	144.234	-23.432	CZ0304
10	Mackay	QLD	149.184	-21.148	CZ0201
18	Mt ISA	QLD	139.485	-20.715	CZ0303
36	Oakey	QLD	151.716	-27.433	CZ0501
11	Rockhampton	QLD	150.501	-23.365	CZ0202
7	Townsville	QLD	146.801	-19.265	CZ0107
2	Weipa	QLD	141.884	-12.632	CZ0102
4	Willis Island	QLD	149.983	-16.983	CZ0104
South Australia					
47	Adelaide	SA	138.599	-34.928	CZ0512
41	Ceduna	SA	133.675	-32.127	CZ0506
54	Mt Gambier	SA	140.78	-37.824	CZ0607
52	Mt Lofty	SA	138.7	-35	CZ0605
26	Oodnadatta	SA	135.45	-27.55	CZ0403
30	Woomera	SA	136.813	-31.165	CZ0407

Tasmania					
67	Hobart	TAS	147.323	-42.882	CZ0708
65	Launceston (Ti Tree Bend)	TAS	147.14	-41.44	CZ0706
66	Launceston Airport	TAS	147.2	-41.5	CZ0707
64	Low Head	TAS	146.8	-41.067	CZ0705
Victoria					
63	Ballarat	VIC	143.854	-37.56	CZ0704
59	Cape Otway	VIC	143.5	-38.9	CZ0612
57	East Sale	VIC	147.117	-38.1	CZ0610
55	Melbourne RO	VIC	144.976	-37.818	CZ0608
34	Mildura	VIC	142.157	-34.193	CZ0411
56	Moorabbin	VIC	145.095	-37.975	CZ0609
53	Tullamarine (Melbourne Airport)	VIC	144.842	-37.675	CZ0606
58	Warrnambool	VIC	142.484	-38.384	CZ0611
Western Australia					
51	Albany	WA	117.884	-35.017	CZ0604
40	Bickley	WA	116.091	-32.008	CZ0505
6	Broome	WA	122.236	-17.962	CZ0106
22	Carnarvon	WA	113.66	-24.89	CZ0307
44	Esperance	WA	121.892	-33.861	CZ0509
29	Forrest	WA	128.1	-30.85	CZ0406
37	Geraldton	WA	114.615	-28.779	CZ0502
24	Giles	WA	128.3	-25.031	CZ0401
16	Halls Creek	WA	127.668	-18.227	CZ0301
28	Kalgoorlie	WA	121.47	-30.75	CZ0405
33	Katanning	WA	117.555	-33.691	CZ0410
9	Learmonth	WA	114.081	-22.241	CZ0109
42	Mandurah	WA	115.723	-32.529	CZ0507
49	Manjimup	WA	116.148	-34.249	CZ0602
25	Meekatharra	WA	118.497	-26.591	CZ0402
20	Newman	WA	119.73	-23.358	CZ0305
38	Perth	WA	115.974	-31.928	CZ0503
8	Pt Hedland	WA	118.601	-20.31	CZ0108
39	Swanbourne	WA	115.76	-31.957	CZ0504
3	Wyndham	WA	128.122	-15.488	CZ0103

APPENDIX C: Analytical Method

C.1: Values of air Properties at Certain Temperatures

Table C.1: Properties of air at atmospheric pressure

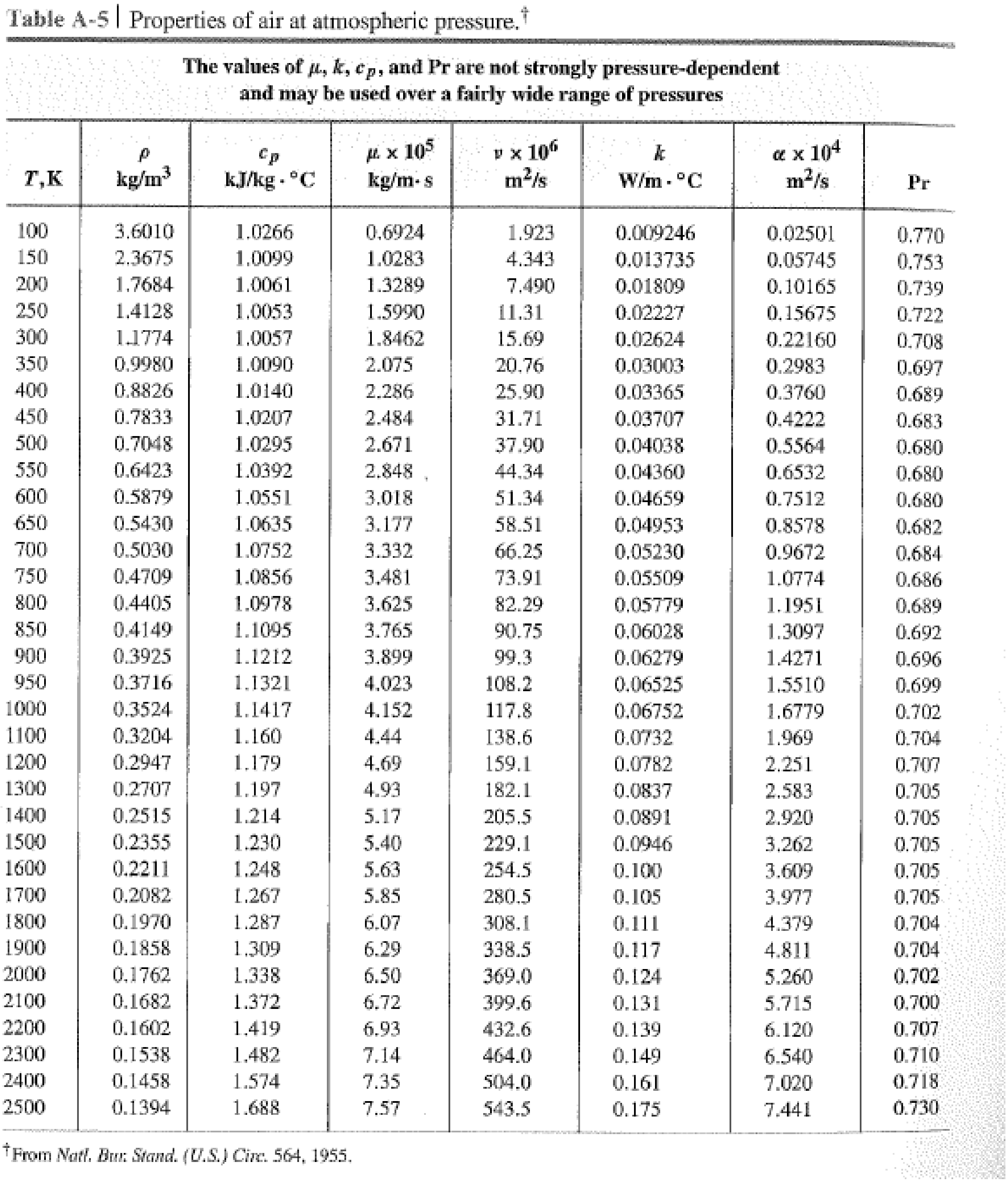


Table A-5 | Properties of air at atmospheric pressure.[†]

The values of μ, k, c_p, and Pr are not strongly pressure-dependent and may be used over a fairly wide range of pressures

T, K	ρ kg/m^3	c_p kJ/kg · °C	$\mu \times 10^5$ kg/m · s	$\nu \times 10^6$ m^2/s	k W/m · °C	$\alpha \times 10^4$ m^2/s	Pr
100	3.6010	1.0266	0.6924	1.923	0.009246	0.02501	0.770
150	2.3675	1.0099	1.0283	4.343	0.013735	0.05745	0.753
200	1.7684	1.0061	1.3289	7.490	0.01809	0.10165	0.739
250	1.4128	1.0053	1.5990	11.31	0.02227	0.15675	0.722
300	1.1774	1.0057	1.8462	15.69	0.02624	0.22160	0.708
350	0.9980	1.0090	2.075	20.76	0.03003	0.2983	0.697
400	0.8826	1.0140	2.286	25.90	0.03365	0.3760	0.689
450	0.7833	1.0207	2.484	31.71	0.03707	0.4222	0.683
500	0.7048	1.0295	2.671	37.90	0.04038	0.5564	0.680
550	0.6423	1.0392	2.848	44.34	0.04360	0.6532	0.680
600	0.5879	1.0551	3.018	51.34	0.04659	0.7512	0.680
650	0.5430	1.0635	3.177	58.51	0.04953	0.8578	0.682
700	0.5030	1.0752	3.332	66.25	0.05230	0.9672	0.684
750	0.4709	1.0856	3.481	73.91	0.05509	1.0774	0.686
800	0.4405	1.0978	3.625	82.29	0.05779	1.1951	0.689
850	0.4149	1.1095	3.765	90.75	0.06028	1.3097	0.692
900	0.3925	1.1212	3.899	99.3	0.06279	1.4271	0.696
950	0.3716	1.1321	4.023	108.2	0.06525	1.5510	0.699
1000	0.3524	1.1417	4.152	117.8	0.06752	1.6779	0.702
1100	0.3204	1.160	4.44	138.6	0.0732	1.969	0.704
1200	0.2947	1.179	4.69	159.1	0.0782	2.251	0.707
1300	0.2707	1.197	4.93	182.1	0.0837	2.583	0.705
1400	0.2515	1.214	5.17	205.5	0.0891	2.920	0.705
1500	0.2355	1.230	5.40	229.1	0.0946	3.262	0.705
1600	0.2211	1.248	5.63	254.5	0.100	3.609	0.705
1700	0.2082	1.267	5.85	280.5	0.105	3.977	0.705
1800	0.1970	1.287	6.07	308.1	0.111	4.379	0.704
1900	0.1858	1.309	6.29	338.5	0.117	4.811	0.704
2000	0.1762	1.338	6.50	369.0	0.124	5.260	0.702
2100	0.1682	1.372	6.72	399.6	0.131	5.715	0.700
2200	0.1602	1.419	6.93	432.6	0.139	6.120	0.707
2300	0.1538	1.482	7.14	464.0	0.149	6.540	0.710
2400	0.1458	1.574	7.35	504.0	0.161	7.020	0.718
2500	0.1394	1.688	7.57	543.5	0.175	7.441	0.730

[†] From *Natl. Bur. Stand. (U.S.) Circ.* 564, 1955.

C.2: Sample of Analytical Calculation

The developed theoretical model “Microsoft Excel” is utilized for the analytical analysis of conventional and new house wall (Design 1). The analysis here is only conducted for first day and first hour of January. Conventional house wall in Melbourne city was used in this example.

$$T_{film} = \frac{T_{air.in} + T_{air.out}}{2} = \frac{22.0 - 24.4}{2} = 23.2^{O}C = 296.2K \approx 300K \qquad (5.8)$$

At this temperature (300 Kelvin) the following can be read: *Pr*=0.71, *k=0.02624,*

v=1.57×10^{-5} and $\beta = \frac{1}{T_f} = \frac{1}{296.2} = 0.00337$

$$Ra_{in} = \frac{g\beta\left(T_{air.in} - T_{film}\right)\delta^3}{\nu^2}\Pr = \frac{9.81 \times 0.00337(22.0 - 23.2) \times 1^3}{(1.57 \times 10^{-5})^2} \times 0.71 = 1.04 \times 10^8 \qquad (5.9)$$

$$Ra_{in} = \frac{g\beta\left(T_{film} - T_{out}\right)\delta^3}{\nu^2}\Pr = \frac{9.81 \times 0.00337(23.2 - 24.4) \times 1^3}{(1.57 \times 10^{-5})^2} \times 0.71 = 1.14 \times 10^8 \qquad (5.10)$$

$$Nu_{in} = \left[0.825 + \frac{0.387 Ra_{in}^{1/6}}{\left[1 + \left(0.492/\Pr^{9/16}\right)\right]^{8/27}}\right]^2 = \left[0.825 + \frac{0.387(1.04 \times 10^8)^{1/6}}{\left[1 + \left(0.492/0.71^{9/16}\right)\right]^{8/27}}\right]^2 = 66.15 \qquad (5.11)$$

$$Nu_{in} = \left[0.825 + \frac{0.387 Ra_{out}^{1/6}}{\left[1 + \left(0.492/\Pr^{9/16}\right)\right]^{8/27}}\right]^2 = \left[0.825 + \frac{0.387(1.14 \times 10^8)^{1/6}}{\left[1 + \left(0.492/0.71^{9/16}\right)\right]^{8/27}}\right]^2 = 68.02 \qquad (5.12)$$

$$h_{in} = \frac{k_{air}}{\delta} Nu_{in} = \frac{0.02}{1} \times 66.15 = 1.32 W/m^2.^{o}C \qquad (5.13)$$

$$h_{out} = \frac{k_{air}}{\delta} Nu_{out} = \frac{0.02}{1} \times 68.02 = 1.36 W/m^2.^{o}C \qquad (5.14)$$

In order to calculate the total heat gain or loss through house wall system, the following equations and relations has been used.

For heat gain/loss by inner convection:

$$Q_{gain/loss} = h_{in} \times A \times (T_{air.in} - T_{wall.in}) \qquad (5.15)$$

For heat gain/loss by conduction:

$$Q_{gain/loss} = \frac{k_{wall} \times A \times (T_{wall.in} - T_{wall.out})}{l} \tag{5.16}$$

For heat gain/loss by outer convection:

$$Q_{gain/loss} = h_{out} \times A \times (T_{wall.out} - T_{air.out}) \tag{5.17}$$

From equation (5.15): $T_{wall.in} = T_{air.in} - \frac{Q_{gain/loss}}{h_{in} \times A}$ (5.18)

From equation (5.16):

$$T_{wall.out} = T_{wall.in} - \frac{Q_{gain/loss} \times l}{k_{wall} \times A} \tag{5.19}$$

Substitute equation (5.18) in (5.19):

$$T_{wall.out} = T_{airl.in} - \frac{Q_{gain/loss}}{h_{in} \times A} - \frac{Q_{gain/loss} \times l}{k_{wall} \times A} \tag{5.20}$$

Substitute equation (5.20) in (5.17):

$$Q_{gain/loss} = h_{out} \times A \times (T_{air.in} - \frac{Q_{gain/loss}}{h_{in} \times A} - \frac{Q_{gain/loss} \times l}{k_{wall} \times A} - T_{air.out})$$

Then, final equation for heat gain /loss by conduction and convection (inner and outer) through a plane house wall can be rearranged as:

$$Q_{gain/loss} = \frac{h_{out} \times A \times (T_{air.in} - T_{air.out})}{\left(1 + \frac{h_{out} \times A}{h_{in} \times A} + \frac{h_{out} \times A \times l}{k_{wall} \times A}\right)}$$

(5.21)

$$Q_{gain/loss} = \frac{1.70 \times 1 \times (22.0 - 24.4)}{\left(1 + \frac{1.36 \times 1}{1.32 \times 1} + \frac{1.36 \times 1 \times 1}{1.75 \times 1}\right)} = -1.45W$$

The radiation heat gain/loss between inside wall surface emissivity and its area to the surrounding surface at inner temperature can be expressed as:

$$Q_{loss/gain} = \varepsilon_{plasterboard} \times \sigma \times A \times ({T_{air.in}}^4 - {T_{wall.in}}^4) \tag{5.22}$$

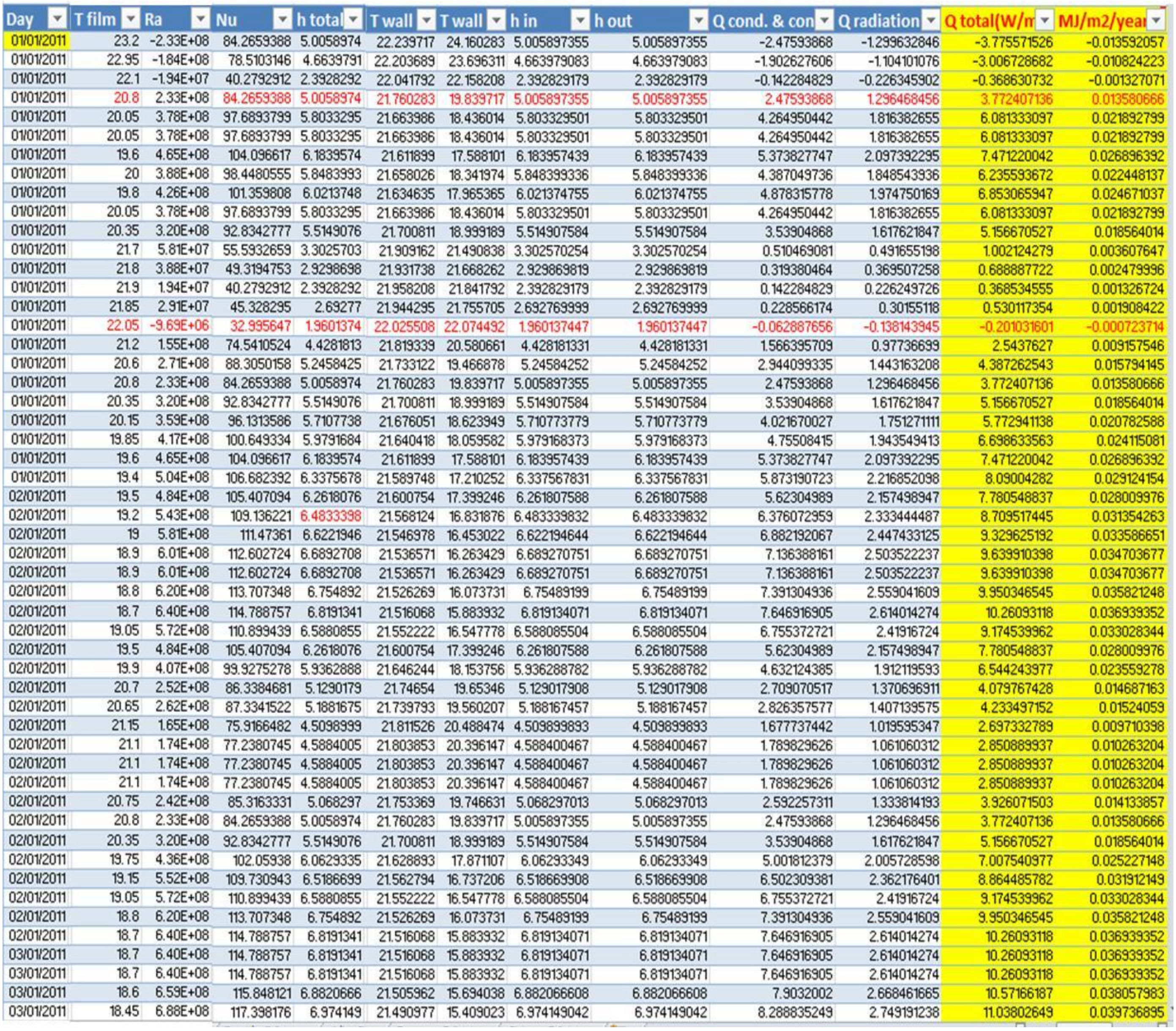
$$Q_{loss/gain} = 0.93 \times 5.67 \times 10^{-8} \times 1 \times (295.0^4 - 295.15^4) = -0.812W$$

Now, the total heat gain or loss by conduction, convection and radiation through 1 m^2 of conventional house wall are:

$$Q_{loss/\,gain} = -1.45 + (-0.812) = -2.26W$$

$$Q_{loss/\,gain} = -2.26W\,/\,Area = -2.26W\,/\,1m^2 = -2.26W\,/\,m^2 = -0.0081MJ\,/\,m^2\,/\,year$$

Figure C.1 shows a screenshot for theoretical model used in theoretical analysis. The negative sign mean heat loss and positive sign mean heat gain or opposite.



Day	T film	Ra	Nu	h total	T wall	T wall	h in	h out	Q cond. & con	Q radiation	Q total(W/m	MJ/m2/year
01/01/2011	23.2	-2.33E+08	84.2659388	5.0058974	22.239717	24.160283	5.005897355	5.005897355	-2.47593868	-1.299632846	-3.775571526	-0.013592057
01/01/2011	22.95	-1.84E+08	78.5103146	4.6639791	22.203689	23.696311	4.663979083	4.663979083	-1.902627606	-1.104101076	-3.006728682	-0.010824223
01/01/2011	22.1	-1.94E+07	40.2792912	2.3928292	22.041792	22.158208	2.392829179	2.392829179	-0.142284829	-0.226345902	-0.368630732	-0.001327071
01/01/2011	20.8	2.33E+08	84.2659388	5.0058974	21.760283	19.839717	5.005897355	5.005897355	2.47593868	1.296468456	3.772407136	0.013580666
01/01/2011	20.05	3.78E+08	97.6893799	5.8033295	21.663986	18.436014	5.803329501	5.803329501	4.264950442	1.816382655	6.081333097	0.021892799
01/01/2011	20.05	3.78E+08	97.6893799	5.8033295	21.663986	18.436014	5.803329501	5.803329501	4.264950442	1.816382655	6.081333097	0.021892799
01/01/2011	19.6	4.65E+08	104.096617	6.1839574	21.611899	17.588101	6.183957439	6.183957439	5.373827747	2.097392295	7.471220042	0.026896392
01/01/2011	20	3.88E+08	98.4480555	5.8483993	21.658026	18.341974	5.848399336	5.848399336	4.387049736	1.848543936	6.235593672	0.022448137
01/01/2011	19.8	4.26E+08	101.359808	6.0213748	21.634635	17.965365	6.021374755	6.021374755	4.878315778	1.974750169	6.853065947	0.024671037
01/01/2011	20.05	3.78E+08	97.6893799	5.8033295	21.663986	18.436014	5.803329501	5.803329501	4.264950442	1.816382655	6.081333097	0.021892799
01/01/2011	20.35	3.20E+08	92.8342777	5.5149076	21.700811	18.999189	5.514907584	5.514907584	3.53904868	1.617621847	5.156670527	0.018564014
01/01/2011	21.7	5.81E+07	55.5932659	3.3025703	21.909162	21.490838	3.302570254	3.302570254	0.510469081	0.491655198	1.002124279	0.003607647
01/01/2011	21.8	3.88E+07	49.3194753	2.9298698	21.931738	21.668262	2.929869819	2.929869819	0.319380464	0.369507258	0.688887722	0.002479996
01/01/2011	21.9	1.94E+07	40.2792912	2.3928292	21.958208	21.841792	2.392829179	2.392829179	0.142284829	0.226249726	0.368534555	0.001326724
01/01/2011	21.85	2.91E+07	45.328295	2.69277	21.944295	21.755705	2.692769999	2.692769999	0.228566174	0.30155118	0.530117354	0.001908422
01/01/2011	22.05	-9.69E+06	32.995647	1.9601374	22.025508	22.074492	1.960137447	1.960137447	-0.062887656	-0.138143945	-0.201031601	-0.000723714
01/01/2011	21.2	1.55E+08	74.5410524	4.4281813	21.819339	20.580661	4.428181331	4.428181331	1.566395709	0.97736699	2.5437627	0.009157546
01/01/2011	20.6	2.71E+08	88.3050158	5.2458425	21.733122	19.466878	5.24584252	5.24584252	2.944099335	1.443163208	4.387262543	0.015794145
01/01/2011	20.8	2.33E+08	84.2659388	5.0058974	21.760283	19.839717	5.005897355	5.005897355	2.47593868	1.296468456	3.772407136	0.013580666
01/01/2011	20.35	3.20E+08	92.8342777	5.5149076	21.700811	18.999189	5.514907584	5.514907584	3.53904868	1.617621847	5.156670527	0.018564014
01/01/2011	20.15	3.59E+08	96.1313586	5.7107738	21.676051	18.623949	5.710773779	5.710773779	4.021670027	1.751271111	5.772941138	0.020782588
01/01/2011	19.85	4.17E+08	100.649334	5.9791684	21.640418	18.059582	5.979168373	5.979168373	4.75508415	1.943549413	6.698633563	0.024115081
01/01/2011	19.6	4.65E+08	104.096617	6.1839574	21.611899	17.588101	6.183957439	6.183957439	5.373827747	2.097392295	7.471220042	0.026896392
01/01/2011	19.4	5.04E+08	106.682392	6.3375678	21.589748	17.210252	6.337567831	6.337567831	5.873190723	2.216852098	8.09004282	0.029124154
02/01/2011	19.5	4.84E+08	105.407094	6.2618076	21.600754	17.399246	6.261807588	6.261807588	5.62304989	2.157498947	7.780548837	0.028009976
02/01/2011	19.2	5.43E+08	109.136221	6.4833398	21.568124	16.831876	6.483339832	6.483339832	6.376072959	2.333444487	8.709517445	0.031354263
02/01/2011	19	5.81E+08	111.47361	6.6221946	21.546978	16.453022	6.622194644	6.622194644	6.882192067	2.447433125	9.329625192	0.033586651
02/01/2011	18.9	6.01E+08	112.602724	6.6892708	21.536571	16.263429	6.689270751	6.689270751	7.136388161	2.503522237	9.639910398	0.034703677
02/01/2011	18.9	6.01E+08	112.602724	6.6892708	21.536571	16.263429	6.689270751	6.689270751	7.136388161	2.503522237	9.639910398	0.034703677
02/01/2011	18.8	6.20E+08	113.707348	6.754892	21.526269	16.073731	6.75489199	6.75489199	7.391304936	2.559041609	9.950346545	0.035821248
02/01/2011	18.7	6.40E+08	114.788757	6.8191341	21.516068	15.883932	6.819134071	6.819134071	7.646916905	2.614014274	10.26093118	0.036939352
02/01/2011	19.05	5.72E+08	110.899439	6.5880855	21.552222	16.547778	6.588085504	6.588085504	6.755372721	2.41916724	9.174539962	0.033028344
02/01/2011	19.5	4.84E+08	105.407094	6.2618076	21.600754	17.399246	6.261807588	6.261807588	5.62304989	2.157498947	7.780548837	0.028009976
02/01/2011	19.9	4.07E+08	99.9275278	5.9362888	21.646244	18.153756	5.936288782	5.936288782	4.632124385	1.912119593	6.544243977	0.023559278
02/01/2011	20.7	2.52E+08	86.3384681	5.1290179	21.74654	19.65346	5.129017908	5.129017908	2.709070517	1.370696911	4.079767428	0.014687163
02/01/2011	20.65	2.62E+08	87.3341522	5.1881675	21.739793	19.560207	5.188167457	5.188167457	2.826357577	1.407139575	4.233497152	0.01524059
02/01/2011	21.15	1.65E+08	75.9166482	4.5098999	21.811526	20.488474	4.509899893	4.509899893	1.677737442	1.019595347	2.697332789	0.009710398
02/01/2011	21.1	1.74E+08	77.2380745	4.5884005	21.803853	20.396147	4.588400467	4.588400467	1.789829626	1.061060312	2.850889937	0.010263204
02/01/2011	21.1	1.74E+08	77.2380745	4.5884005	21.803853	20.396147	4.588400467	4.588400467	1.789829626	1.061060312	2.850889937	0.010263204
02/01/2011	21.1	1.74E+08	77.2380745	4.5884005	21.803853	20.396147	4.588400467	4.588400467	1.789829626	1.061060312	2.850889937	0.010263204
02/01/2011	20.75	2.42E+08	85.3163331	5.068297	21.753369	19.746631	5.068297013	5.068297013	2.592257311	1.333814193	3.926071503	0.014133857
02/01/2011	20.8	2.33E+08	84.2659388	5.0058974	21.760283	19.839717	5.005897355	5.005897355	2.47593868	1.296468456	3.772407136	0.013580666
02/01/2011	20.35	3.20E+08	92.8342777	5.5149076	21.700811	18.999189	5.514907584	5.514907584	3.53904868	1.617621847	5.156670527	0.018564014
02/01/2011	19.75	4.36E+08	102.05938	6.0629335	21.628893	17.871107	6.06293349	6.06293349	5.001812379	2.005728598	7.007540977	0.025227148
02/01/2011	19.15	5.52E+08	109.730943	6.5186699	21.562794	16.737206	6.518669908	6.518669908	6.502309381	2.362176401	8.864485782	0.031912149
02/01/2011	19.05	5.72E+08	110.899439	6.5880855	21.552222	16.547778	6.588085504	6.588085504	6.755372721	2.41916724	9.174539962	0.033028344
02/01/2011	18.8	6.20E+08	113.707348	6.754892	21.526269	16.073731	6.75489199	6.75489199	7.391304936	2.559041609	9.950346545	0.035821248
02/01/2011	18.7	6.40E+08	114.788757	6.8191341	21.516068	15.883932	6.819134071	6.819134071	7.646916905	2.614014274	10.26093118	0.036939352
03/01/2011	18.7	6.40E+08	114.788757	6.8191341	21.516068	15.883932	6.819134071	6.819134071	7.646916905	2.614014274	10.26093118	0.036939352
03/01/2011	18.7	6.40E+08	114.788757	6.8191341	21.516068	15.883932	6.819134071	6.819134071	7.646916905	2.614014274	10.26093118	0.036939352
03/01/2011	18.6	6.59E+08	115.848121	6.8820666	21.505962	15.694038	6.882066608	6.882066608	7.9032002	2.668461665	10.57166187	0.038057983
03/01/2011	18.45	6.88E+08	117.398176	6.974149	21.490977	15.409023	6.974149042	6.974149042	8.288835249	2.749191238	11.03802649	0.039736895

Figure C.1: Screenshot for theoretical model used in calculation

C.3: Degree Hours

The following example illustrates the degree hour method used in the study. The measured temperatures used in the estimation were only for the first week of January for Melbourne.

Table C.2: Degree hours for Melbourne in January-2011

Date	Time	Outside temp.	Inside temp.	Need cooling (+ve)	Need heating (-ve)
01/01/2011	00:00	24.4	22.0	2.4	2.4
01/01/2011	01:00	23.9	22.0	1.9	1.9
01/01/2011	02:00	22.2	22.0	0.2	0.2
01/01/2011	03:00	19.6	22.0	-2.4	-2.4
01/01/2011	04:00	18.1	22.0	-3.9	-3.9
01/01/2011	05:00	18.1	22.0	-3.9	-3.9
01/01/2011	06:00	17.2	22.0	-4.8	-4.8
01/01/2011	07:00	18	22.0	-4.0	-4
01/01/2011	08:00	17.6	22.0	-4.4	-4.4
01/01/2011	09:00	18.1	22.0	-3.9	-3.9
01/01/2011	10:00	18.7	22.0	-3.3	-3.3
01/01/2011	11:00	21.4	22.0	-0.6	-0.6
01/01/2011	12:00	21.6	22.0	-0.4	-0.4
01/01/2011	13:00	21.8	22.0	-0.2	-0.2
01/01/2011	14:00	21.7	22.0	-0.3	-0.3
01/01/2011	15:00	22.1	22.0	0.1	0.1
01/01/2011	16:00	20.4	22.0	-1.6	-1.6
01/01/2011	17:00	19.2	22.0	-2.8	-2.8
01/01/2011	18:00	19.6	22.0	-2.4	-2.4
01/01/2011	19:00	18.7	22.0	-3.3	-3.3
01/01/2011	20:00	18.3	22.0	-3.7	-3.7
01/01/2011	21:00	17.7	22.0	-4.3	-4.3
01/01/2011	22:00	17.2	22.0	-4.8	-4.8
01/01/2011	23:00	16.8	22.0	-5.2	-5.2
02/01/2011	00:00	17	22.0	-5.0	-5
02/01/2011	01:00	16.4	22.0	-5.6	-5.6
02/01/2011	02:00	16	22.0	-6.0	-6
02/01/2011	03:00	15.8	22.0	-6.2	-6.2
02/01/2011	04:00	15.8	22.0	-6.2	-6.2
02/01/2011	05:00	15.6	22.0	-6.4	-6.4
02/01/2011	06:00	15.4	22.0	-6.6	-6.6
02/01/2011	07:00	16.1	22.0	-5.9	-5.9
02/01/2011	08:00	17	22.0	-5.0	-5
02/01/2011	09:00	17.8	22.0	-4.2	-4.2
02/01/2011	10:00	19.4	22.0	-2.6	-2.6
02/01/2011	11:00	19.3	22.0	-2.7	-2.7
02/01/2011	12:00	20.3	22.0	-1.7	-1.7
02/01/2011	13:00	20.2	22.0	-1.8	-1.8

02/01/2011	14:00	20.2	22.0	-1.8	-1.8
02/01/2011	15:00	20.2	22.0	-1.8	-1.8
02/01/2011	16:00	19.5	22.0	-2.5	-2.5
02/01/2011	17:00	19.6	22.0	-2.4	-2.4
02/01/2011	18:00	18.7	22.0	-3.3	-3.3
02/01/2011	19:00	17.5	22.0	-4.5	-4.5
02/01/2011	20:00	16.3	22.0	-5.7	-5.7
02/01/2011	21:00	16.1	22.0	-5.9	-5.9
02/01/2011	22:00	15.6	22.0	-6.4	-6.4
02/01/2011	23:00	15.4	22.0	-6.6	-6.6
03/01/2011	00:00	15.4	22.0	-6.6	-6.6
03/01/2011	01:00	15.4	22.0	-6.6	-6.6
03/01/2011	02:00	15.2	22.0	-6.8	-6.8
03/01/2011	03:00	14.9	22.0	-7.1	-7.1
03/01/2011	04:00	15.1	22.0	-6.9	-6.9
03/01/2011	05:00	15	22.0	-7.0	-7
03/01/2011	06:00	14.7	22.0	-7.3	-7.3
03/01/2011	07:00	14.7	22.0	-7.3	-7.3
03/01/2011	08:00	15.4	22.0	-6.6	-6.6
03/01/2011	09:00	15.5	22.0	-6.5	-6.5
03/01/2011	10:00	16.8	22.0	-5.2	-5.2
03/01/2011	11:00	18.4	22.0	-3.6	-3.6
03/01/2011	12:00	18.6	22.0	-3.4	-3.4
03/01/2011	13:00	19.5	22.0	-2.5	-2.5
03/01/2011	14:00	19.1	22.0	-2.9	-2.9
03/01/2011	15:00	19.5	22.0	-2.5	-2.5
03/01/2011	16:00	19.5	22.0	-2.5	-2.5
03/01/2011	17:00	18.8	22.0	-3.2	-3.2
03/01/2011	18:00	17.7	22.0	-4.3	-4.3
03/01/2011	19:00	16.9	22.0	-5.1	-5.1
03/01/2011	20:00	15.7	22.0	-6.3	-6.3
03/01/2011	21:00	15	22.0	-7.0	-7
03/01/2011	22:00	14.4	22.0	-7.6	-7.6
03/01/2011	23:00	14	22.0	-8.0	-8
04/01/2011	00:00	13.7	22.0	-8.3	-8.3
04/01/2011	01:00	13.3	22.0	-8.7	-8.7
04/01/2011	02:00	13.4	22.0	-8.6	-8.6
04/01/2011	03:00	13.1	22.0	-8.9	-8.9
04/01/2011	04:00	13.3	22.0	-8.7	-8.7
04/01/2011	05:00	13	22.0	-9.0	-9
04/01/2011	06:00	12.8	22.0	-9.2	-9.2
04/01/2011	07:00	14.4	22.0	-7.6	-7.6
04/01/2011	08:00	15.2	22.0	-6.8	-6.8
04/01/2011	09:00	16.8	22.0	-5.2	-5.2
04/01/2011	10:00	18.6	22.0	-3.4	-3.4
04/01/2011	11:00	19.7	22.0	-2.3	-2.3

04/01/2011	12:00	19.8	22.0	-2.2	-2.2
04/01/2011	13:00	20.3	22.0	-1.7	-1.7
04/01/2011	14:00	21.7	22.0	-0.3	-0.3
04/01/2011	15:00	19.5	22.0	-2.5	-2.5
04/01/2011	16:00	20.5	22.0	-1.5	-1.5
04/01/2011	17:00	19.9	22.0	-2.1	-2.1
04/01/2011	18:00	19.8	22.0	-2.2	-2.2
04/01/2011	19:00	18.8	22.0	-3.2	-3.2
04/01/2011	20:00	18	22.0	-4.0	-4
04/01/2011	21:00	17.4	22.0	-4.6	-4.6
04/01/2011	22:00	17.5	22.0	-4.5	-4.5
04/01/2011	23:00	17.1	22.0	-4.9	-4.9
05/01/2011	00:00	16.6	22.0	-5.4	-5.4
05/01/2011	01:00	16.9	22.0	-5.1	-5.1
05/01/2011	02:00	16.3	22.0	-5.7	-5.7
05/01/2011	03:00	15	22.0	-7.0	-7
05/01/2011	04:00	14.8	22.0	-7.2	-7.2
05/01/2011	05:00	14.9	22.0	-7.1	-7.1
05/01/2011	06:00	15.6	22.0	-6.4	-6.4
05/01/2011	07:00	16.2	22.0	-5.8	-5.8
05/01/2011	08:00	17.8	22.0	-4.2	-4.2
05/01/2011	09:00	18.5	22.0	-3.5	-3.5
05/01/2011	10:00	19.5	22.0	-2.5	-2.5
05/01/2011	11:00	20.7	22.0	-1.3	-1.3
05/01/2011	12:00	20.5	22.0	-1.5	-1.5
05/01/2011	13:00	20.7	22.0	-1.3	-1.3
05/01/2011	14:00	20.3	22.0	-1.7	-1.7
05/01/2011	15:00	20.7	22.0	-1.3	-1.3
05/01/2011	16:00	19.4	22.0	-2.6	-2.6
05/01/2011	17:00	20.7	22.0	-1.3	-1.3
05/01/2011	18:00	19.4	22.0	-2.6	-2.6
05/01/2011	19:00	18.3	22.0	-3.7	-3.7
05/01/2011	20:00	17.9	22.0	-4.1	-4.1
05/01/2011	21:00	17.6	22.0	-4.4	-4.4
05/01/2011	22:00	17.4	22.0	-4.6	-4.6
05/01/2011	23:00	17.2	22.0	-4.8	-4.8
06/01/2011	00:00	17.1	22.0	-4.9	-4.9
06/01/2011	01:00	17.1	22.0	-4.9	-4.9
06/01/2011	02:00	16.6	22.0	-5.4	-5.4
06/01/2011	03:00	16.8	22.0	-5.2	-5.2
06/01/2011	04:00	16.2	22.0	-5.8	-5.8
06/01/2011	05:00	16.5	22.0	-5.5	-5.5
06/01/2011	06:00	17.2	22.0	-4.8	-4.8
06/01/2011	07:00	17.5	22.0	-4.5	-4.5
06/01/2011	08:00	17.9	22.0	-4.1	-4.1
06/01/2011	09:00	19.7	22.0	-2.3	-2.3

06/01/2011	10:00	22.2	22.0	0.2	0.2
06/01/2011	11:00	23.5	22.0	1.5	1.5
06/01/2011	12:00	24	22.0	2.0	2
06/01/2011	13:00	25.2	22.0	3.2	3.2
06/01/2011	14:00	25.6	22.0	3.6	3.6
06/01/2011	15:00	26.4	22.0	4.4	4.4
06/01/2011	16:00	26.9	22.0	4.9	4.9
06/01/2011	17:00	30.3	22.0	8.3	8.3
06/01/2011	18:00	29.8	22.0	7.8	7.8
06/01/2011	19:00	30.4	22.0	8.4	8.4
06/01/2011	20:00	28.5	22.0	6.5	6.5
06/01/2011	21:00	26.2	22.0	4.2	4.2
06/01/2011	22:00	24.9	22.0	2.9	2.9
06/01/2011	23:00	22.9	22.0	0.9	0.9
07/01/2011	00:00	21.7	22.0	-0.3	-0.3
07/01/2011	01:00	22.7	22.0	0.7	0.7
07/01/2011	02:00	21.9	22.0	-0.1	-0.1
07/01/2011	03:00	21.9	22.0	-0.1	-0.1
07/01/2011	04:00	21.5	22.0	-0.5	-0.5
07/01/2011	05:00	23.6	22.0	1.6	1.6
07/01/2011	06:00	23.3	22.0	1.3	1.3
07/01/2011	07:00	24.3	22.0	2.3	2.3
07/01/2011	08:00	25.6	22.0	3.6	3.6
07/01/2011	09:00	26.3	22.0	4.3	4.3
07/01/2011	10:00	27	22.0	5.0	5
07/01/2011	11:00	28.4	22.0	6.4	6.4
07/01/2011	12:00	28.6	22.0	6.6	6.6
07/01/2011	13:00	30.2	22.0	8.2	8.2
07/01/2011	15:00	32.1	22.0	10.1	10.1
07/01/2011	16:00	32.6	22.0	10.6	10.6
07/01/2011	17:00	32.8	22.0	10.8	10.8
07/01/2011	18:00	32.2	22.0	10.2	10.2
07/01/2011	19:00	31.7	22.0	9.7	9.7
07/01/2011	20:00	30.8	22.0	8.8	8.8
07/01/2011	21:00	29.6	22.0	7.6	7.6
07/01/2011	22:00	28.6	22.0	6.6	6.6
07/01/2011	23:00	26.9	22.0	4.9	4.9
08/01/2011	00:00	26.2	22.0	4.2	4.2

Total of degree days (°C)	**196.1**	**- 563.7**
Total degree hour for both cooling & heating (° C)	**759.8**	
Need of cooling (%)	**25.8**	
Need of heating (%)	**74.2**	

APPENDIX D: Experimental Instruments and Measurements

D.1 Data Taker

The Data Taker DT800 was used to record temperature at different measuring points connected by electrical thermo couple wires “T” type. The technical specifications are as follows:

Analogy Inputs

- Universal channels that support most sensors
- Uncomplicated, flexible, powerful programming
- 12 to 42 analogy channels (depending on sensors)
- Solid state multiplexer, protected to ±40V
- Common mode range: either ±13V, or –2V to 22V, selectable
- Lightning protection: secondary, via ±30V

Channels:

- Two wire (differential): 24 (measures signal between the 2 wires)
- Inputs sharing a common terminal: 42 (six groups, each has seven single ended inputs with one shared common, 6×7 =42)
- 3-wire or 4-wire: 12
- 3-wire with one shared terminal: 18
- 3-wire with two shared terminals: 36
- Half bridges: 30
- 4-wire with two shared terminals: 18
- 6-wire bridges: 6
- 6-wire bridges with two shared terminals: 18
- Sensor configurations may be mixed in any way.

Measure

- DC Voltage ±10mV (res 1µV) up to ±10V (res 1mV),
- Current, including 4-20mA,
- Accuracy: DC Voltage: 0.015% at 25°, or 0.1% over the range -45 to 70°C
- AC voltage & current,
- Frequency measurement and period
- Resistance to 25k ohms, acc 0.04% at 25°C, or 0.2% -45 to 70°C.
- Thermocouples type B, C, D, E, G, J, K, N, R, S, T; accuracy (case at 25°) per NIST Mono. 125
- Reference junction compensation accuracy: ±0.2°C with case at 25°, or ±0.5°C, -20 to +60°C with thermocouple integrity testing.
- RTDs: Pt (385 or 392), Cu, Ni, 10 to 10,000ohms bridges acc 0.05%, 4-wire, 0.15% 3-wire
- Strain gauges, bridges, 4-wire, 6-wire
- Temperature Sensors, Monolithic: LM34,35,45,50,60 AD590,592, Si diode
- Fundamental Input Range Resolution and Accuracy (voltage, resistance, frequency)
- Time stamping of readings can be set to up to 3 decimal places (sub-second).
- Sensor Excitation: Programmable with 12 bit resolution, available on any analog channel as a balanced output:
- DC Voltage mode, balanced: 0 to ±10V @ up to 15mA (+ve is on * terminal, and -ve is on # terminal, useful for bridges),
- DC Current mode: 0 to 20mA, DC Power mode: 0 to 200mW
- The 'SP' Sensor power terminal can be set to any voltage up to 10VDC, and can supply 100mA.
- Analog outputs: 1 dedicated channel ±10V in 10mV steps, 20mA max.
- Shared and mutually exclusive with the burst mode analog trigger function.

Internal Channels:

Temperature (thermocouple ref. junction): 2 ref voltage channels, 2 internal battery voltages and external supply voltage.

Digital Inputs & Outputs

- 8 bi-directional Digital Channels / Counters, including 2 Sensitive Inputs for induction coils (magnetic pick-up, 10mV sensitivity, 1kHz max, shared with bi-directional channels) counters are 32-bit (>4,000,000,000), 50Hz, active when logger is asleep.
- 8 Digital Input only channels
- 8 Digital Outputs, open drain FETs, +30V, 100mA
- Serial sensor channel RS232, RS422, RS485 (300 to 56Kbps), with RTS, CTS handshake, programmable prompt string, and parse.
- A programmable data parsing string allows multiple assignments of data to internal channel variables.
- Power for sensors: switched 12V, 500mA
- SDI-12 support: (Serial Data Interface at 1200 bps).
- SDI-12 is a standard to interface battery powered data recorders with micro-processor based sensors
- Designed for environmental data acquisition (EDA). 3-wire, 5V, -ve logic. See http://www.sdi-12.org or SDI-12 Info (Wiki)
- Calculation Channels: Any expression involving variables & functions.
- Functions: sin, cos, tan, asin, acos, atan, abs, sqrt,
- Average, maximum, minimum, time of max, time of min, variance, integral, histogram, rainflow (fatigue analysis)
- Resolution: programmable 14 bit to 18 bit (1µV) resolution
- Accuracy to 0.1% over -20°C to + 60°C
- Scheduling of Data Acquisition: No of schedules: 11, Schedules rates: 50msec to days; Max number of channels: 500
- Normal sampling speeds up to 100 Hz, to achieve noise and 50Hz mains rejection, many samples are taken at a much faster rate, then averaged.

Sampling Modes

- Normal Mode
- Sampling for accuracy and noise rejection by interleaved sampling over one or more line cycle periods.
- Effective resolution: 16 bits
- Common mode rejection 20mV range: 130dB
- Fast Mode

- Fast continuous sampling with reduced noise rejection
- Effective resolution: 15 bits
- Burst Mode
- Provides sampling of fast events with triggering capability
- Sampling speed: 1kHz to 100kHz
- Effective resolution: 13bits
- Trigger: pre, mid and post triggering
- Trigger source: analog level or digital input
- Buffer size: 100 to 65,000 raw samples
- Minimum time between bursts: 100ms - 30s
- Virtually Simultaneous 40Hz sampling in 5 channels can be achieved by the interleaved sampling.
- Burst mode sampling - speeds from 1 kHz to 100 kHz, 13-bit (raw data is processsed into engineering units at the end of the burst, can take some seconds).
- Up to 65,000 samples in a burst.
- Pretrigger data can be captured... trigger point can be anywhere in the burst mode data buffer.
- The burst mode runs continuously, the triggering initiates the process which freezes the data in the burst memory for later processing into formatted data.

Data Storage:

- DT800's internal memory, 2MB, can store 120,000 readings.
- An inserted PC Card (PCMCIA) memory card can store 60,000 readings per megabyte. (PC Card = PCMCIA card)
- File format: Windows. If the PC Card is pulled out of the logger and put into a PC, the data can be transferred as Windows files.
- PC Card Flash Memory (PCMCIA): 48MB ATA, 3V or 5V. or ATA hard disks.
  With adaptor: Compact Flash, Smart Media, Sony Memory Stick. Card voltage: 3 or 5V.
- Capacity: 60,000 data points per megabyte (5 channels per schedule)

Communications:

- RS232 (115kbps) and PC Card Modem communications, card modems (phone, cell & radio).
- Ethernet 10Base-T, TCP/IP, UDP, PPP, logger must remain awake. File tranfer protocol: FTP
- Field upgradeable FLASH based firmware via Internet
- Internal battery, 4 hours to 3 months of battery operation depending on sampling rate
- Compact powder-coated steel case, 270mm x 110mm x 95mm, 3.2Kg

Features to be added in January 2004:

- 2.5 times faster logging in fast mode (i.e. 200Hz), via the RS232 port.
- SMS messaging is easier with new types of Alarms,
- Modem handling is easier - DT800 can configure a modem using a "straight thru" cable.
- Built-in self-correcting features... can restart itself and also attached equipment.
- It can test integrity of sensors & flag data that is suspect.
- New event management facilities provide speed performance analysis of machinery or other applications being monitored.

Power Supply:

- External 11 to 28VDC, 4W, Battery charging: 15W, Sleeping: 2mW (250µA)
- Typical low power operation: 20mW
- Internal Lead-Acid battery 12V 2.2AH gives 6hours of normal operation; low power: 2 months.
- Memory and real time clock battery: Lithium, ½AA 3.6V 400mAH
- Temperature range: -45° to +70°C, humidity: 85% non-condensing.
- supplied with DeLogger (DeLogger is not fully Win 7 compliant), DeTransfer, DePlot, DeMerge software,
- AC power pack (15VDC 750mA), RS232 cable, and 2 manuals, (see details of hardware accessories below)
- 2 cage clamp tools to assist wiring to the terminals
- shipping carton: 36x22x23cm, 5.1kg

Integrated Solution

The DT800 can also be programmed to perform very powerful tasks using the DataTaker command instruction set. Commands are sent to the unit via a terminal program such as DeTransfer or Windows Hyper terminal. The command instructions allow the DT800 to be configured for more complex data logging applications where the DT800 is to be integrated into a system. Note: DeTransfer is free to download via the DataTaker website, www.datataker.com.

Multi-Channel Inputs

Boasting multi input software selectable channels that support a range of sensors including thermocouples, PT100, Thermistors, AC and DC voltage, 4-20mA current (via shunts), resistance, bridges, strain gauges, frequency and more.

Digital I/O

With sixteen digital I/O channels the DT800 can be used to record when a switch contact is turned on/off or to control a small relay by turning it on or off plus much more. See the technical brochure for more details on the digital I/O channels.

Sampling Speed

- Typical data logging sampling speeds range from once per second to once per hour. The DT800 can sample down to 100ms but this will vary up and down due to the number and type of channels needed to be measured.

- Burst Mode. In burst mode the DT800 can record up 50kHz or 200µs on a single channel, this sampling speed drops as the number of channels is increased. Add to this the ability to pre and post trigger and the DT800 becomes very handy for taking snapshots of data.

Remote data transfer

- Remote data transfer via TCP/IP across a Local Area Network(LAN) or Wide Area Network (WAN) is a great way to access data remotely. The DT800 can be connected to just about any ADSL, Cable or 3G (NextG) modem with a TCP/IP network connection allowing the DT800's data to be retrieved anywhere around the world over the internet. If security is an issue, then a Virtual Private Network (VPN) can also be set up for data security.
- The built in RS232 port on the DT800 can support PSTN or GSM modems for remote dial-in and dial-out or SMS Text messages and can be sent via the SMSX GSM modem.

Manual data transfer

- Manual data transfer on the DT800 is performed in two ways, either via a PCMCIA card or direct to the PC.
- Data Logger or Data Acquisition
- The DT800 is a true Data Logger that can operate as a standalone unit and does not require a computer to record data.

Complete kit

The DataTaker DT800 includes all the standard accessories to get you going right away. One great advantage with the DataTaker range is that the software is supplied FREE on CD and it can also be downloaded from the DataTaker website along with any firmware and software updates.

- Mains adaptor - 240volt AC to 15 volt DC, 800mA.
- RS232 cable.
- Resource CD includes:
- User Manual
- Software
- Video Tutorials
- Technical notes
- other resource
- Terminal Screwdriver

The DT800 is a complex but easy to use data logger that can be used for an almost endless list of applications and with so many features bundled in, the DT800 is a high-end unit with a cost effective price tag.

Figure D.1: Data Taker (DT800)

D.2 Digital DC Power Meter

An ideal addition to any low voltage DC system this digital power meter features real time display of the voltage, current draw, and power consumption. Once running it also stores minimum and maximum voltage, current, and power, together with cumulative amp hours and watt hours consumed by the connected equipment. Suitable for DC systems from 5 to 60 volts and available in versions suitable for inline connection or (MS6172 -For remote connection with a separate current shunt: Digital DC Power Meter to suit 50mV External Shunt. Mount the meter using the included snap-in bracket or magnetically on any ferrous surface.

Dimensions: 45(W) x 41(L) x 23(D) mm, Operating current: 12mA peak

Measurement Specifications:

- Voltage Range: 5-60VDC (0-60VDC with external DC power source), Wattage Range: 0-3600W

Logging Specifications:

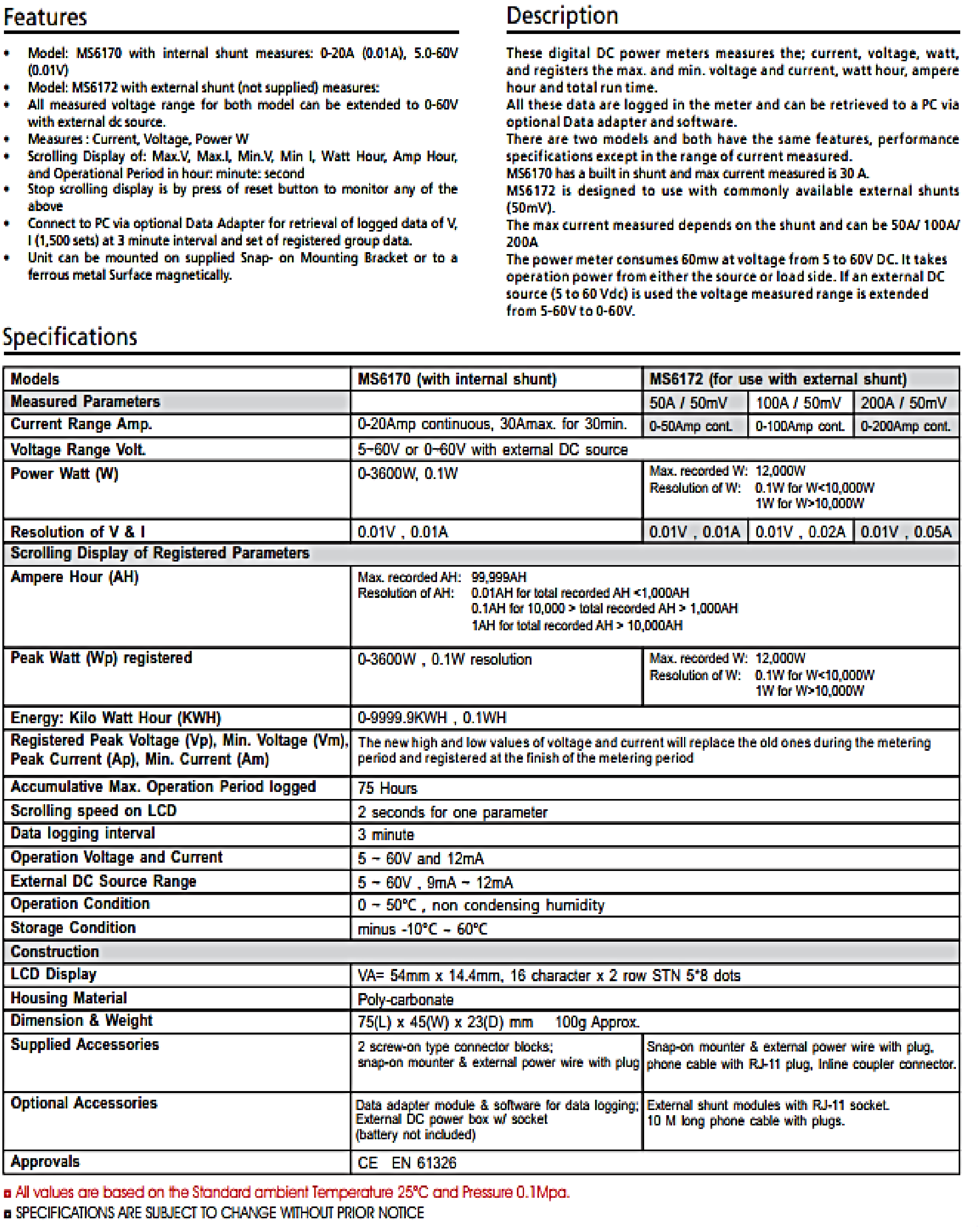
- Cycle Time: 15 minutes
- Maximum Amp Hours: 99,999Ah
- Maximum Kilowatt Hours: 9,999.9kWh
- Maximum Cumulative Log Time: 225 hours

Digital DC Power Meter with Internal Shunt

- Continuous Current Range: 0-20A
- Peak Current: 30A for 30 minutes

Enhance the data collection of the MS-6170 or MS-6172 DC power meter by connecting to your PC with this USB data adaptor. The included software allows you to access live data and download stored data from the power meter memory. Data is graphed to show power usage over time and can then be exported for further analysis and logging over long periods. Pack includes data interface module, data cable, USB cable, and PC software.

Figure D.2: Digital DC Power Meter



Features

- Model: MS6170 with internal shunt measures: 0-20A (0.01A), 5.0-60V (0.01V)
- Model: MS6172 with external shunt (not supplied) measures:
- All measured voltage range for both model can be extended to 0-60V with external dc source.
- Measures : Current, Voltage, Power W
- Scrolling Display of: Max.V, Max.I, Min.V, Min I, Watt Hour, Amp Hour, and Operational Period in hour: minute: second
- Stop scrolling display is by press of reset button to monitor any of the above
- Connect to PC via optional Data Adapter for retrieval of logged data of V, I (1,500 sets) at 3 minute interval and set of registered group data.
- Unit can be mounted on supplied Snap- on Mounting Bracket or to a ferrous metal Surface magnetically.

Description

These digital DC power meters measures the; current, voltage, watt, and registers the max. and min. voltage and current, watt hour, ampere hour and total run time.
All these data are logged in the meter and can be retrieved to a PC via optional Data adapter and software.
There are two models and both have the same features, performance specifications except in the range of current measured.
MS6170 has a built in shunt and max current measured is 30 A.
MS6172 is designed to use with commonly available external shunts (50mV).
The max current measured depends on the shunt and can be 50A/ 100A/ 200A
The power meter consumes 60mw at voltage from 5 to 60V DC. It takes operation power from either the source or load side. If an external DC source (5 to 60 Vdc) is used the voltage measured range is extended from 5-60V to 0-60V.

Specifications

Models	**MS6170 (with internal shunt)**	**MS6172 (for use with external shunt)**		
Measured Parameters		50A / 50mV	100A / 50mV	200A / 50mV
Current Range Amp.	0-20Amp continuous, 30Amax. for 30min.	0-50Amp cont.	0-100Amp cont.	0-200Amp cont.
Voltage Range Volt.	5~60V or 0~60V with external DC source			
Power Watt (W)	0-3600W, 0.1W	Max. recorded W: 12,000W Resolution of W: 0.1W for W<10,000W 1W for W>10,000W		
Resolution of V & I	0.01V , 0.01A	0.01V , 0.01A	0.01V , 0.02A	0.01V , 0.05A
Scrolling Display of Registered Parameters				
Ampere Hour (AH)	Max. recorded AH: 99,999AH Resolution of AH: 0.01AH for total recorded AH <1,000AH 0.1AH for 10,000 > total recorded AH > 1,000AH 1AH for total recorded AH > 10,000AH			
Peak Watt (Wp) registered	0-3600W , 0.1W resolution	Max. recorded W: 12,000W Resolution of W: 0.1W for W<10,000W 1W for W>10,000W		
Energy: Kilo Watt Hour (KWH)	0-9999.9KWH , 0.1WH			
Registered Peak Voltage (Vp), Min. Voltage (Vm), Peak Current (Ap), Min. Current (Am)	The new high and low values of voltage and current will replace the old ones during the metering period and registered at the finish of the metering period			
Accumulative Max. Operation Period logged	75 Hours			
Scrolling speed on LCD	2 seconds for one parameter			
Data logging interval	3 minute			
Operation Voltage and Current	5 ~ 60V and 12mA			
External DC Source Range	5 ~ 60V , 9mA ~ 12mA			
Operation Condition	0 ~ 50°C , non condensing humidity			
Storage Condition	minus -10°C ~ 60°C			
Construction				
LCD Display	VA= 54mm x 14.4mm, 16 character x 2 row STN 5*8 dots			
Housing Material	Poly-carbonate			
Dimension & Weight	75(L) x 45(W) x 23(D) mm 100g Approx.			
Supplied Accessories	2 screw-on type connector blocks; snap-on mounter & external power wire with plug	Snap-on mounter & external power wire with plug, phone cable with RJ-11 plug, Inline coupler connector.		
Optional Accessories	Data adapter module & software for data logging; External DC power box w/ socket (battery not included)	External shunt modules with RJ-11 socket. 10 M long phone cable with plugs.		
Approvals	CE EN 61326			

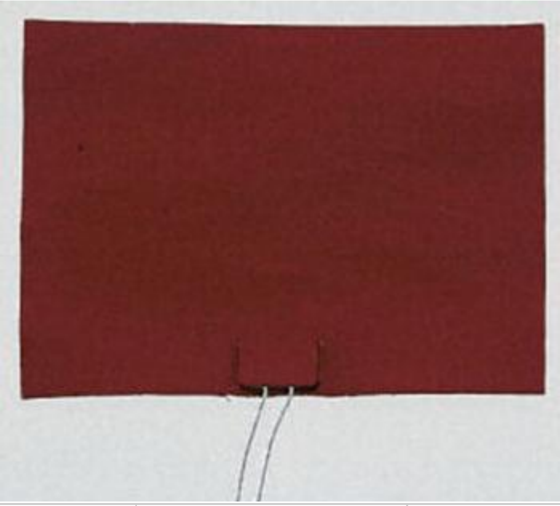
▪ All values are based on the Standard ambient Temperature 25°C and Pressure 0.1Mpa.

▪ SPECIFICATIONS ARE SUBJECT TO CHANGE WITHOUT PRIOR NOTICE

Figure D.3: Features and description of digital DC power meter

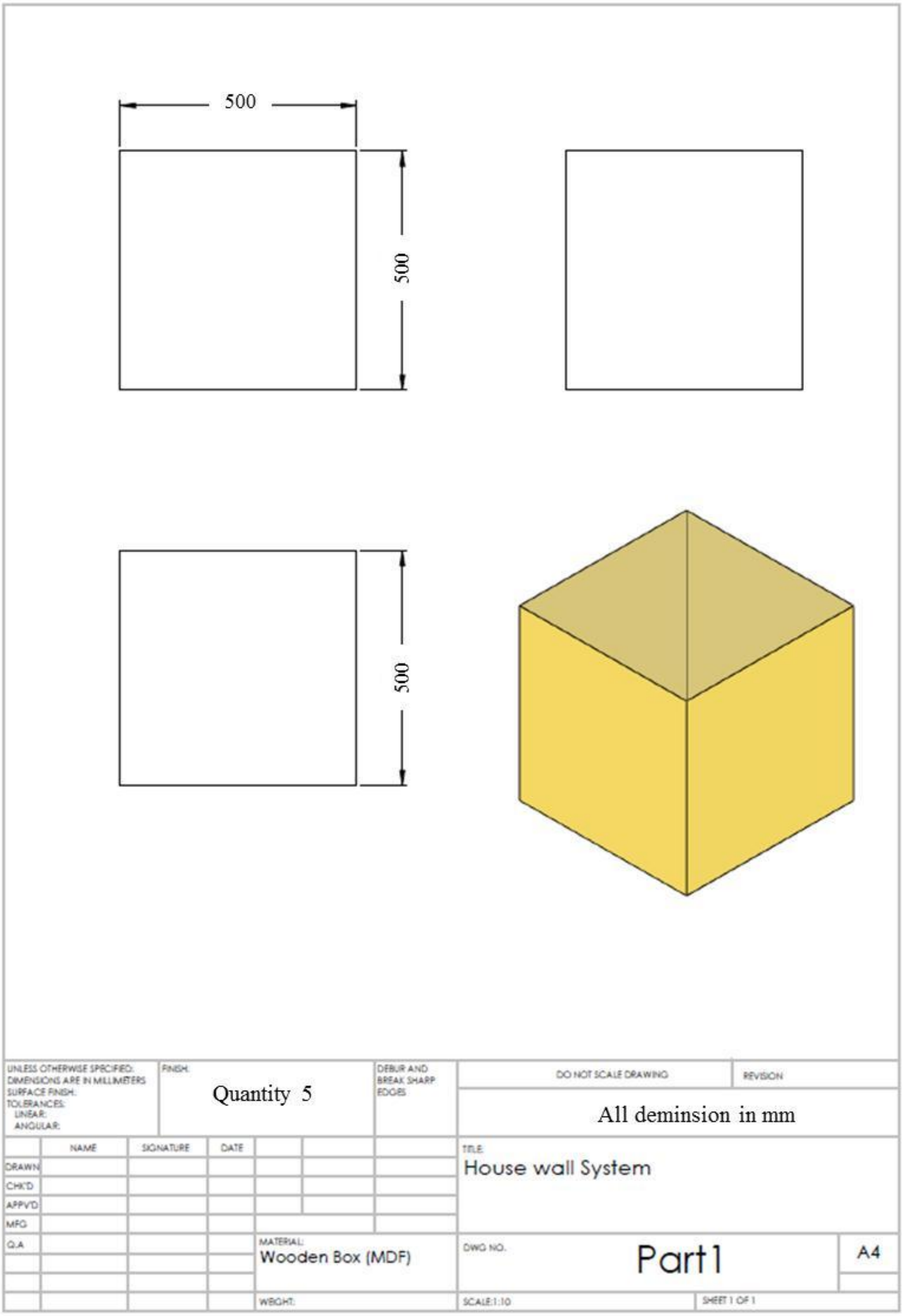
D.3 DC Mat Heater

Figure D.4: Mat heater

Product	Model NO.		Material	Hardness
Silicone Heater	XD-H-1460		Orange High Temperature Silicone	60±3
Shape			Data	
Size: mm			Rated Voltage	Customize
			Rated Wattage	00.07-1/cm2
			Static Resistance	Customize
			Max Temperature can bear	200 C
			Max Used Temperature	180-200 C
			Compressive Strength	≥3KV
			Insulation Resistance	≥100MΩ
			Tensile Strength	≥8.0Mpa/M2
			Elongation at Break	≥4%
Length: Customize	Cable	300mm(standard)	Peel Strength	≥2500N/M2
Width: Customize	Specification of the cable	AWG22	Compressive Stress	>15kg/cm2
Thickness: 1.5mm	Colour of Cable	Orange or white	Heating Wire	Nickel-chromium wire
Parts	Adhesive	Thermostat	Thermistors	

D.4 Scale Model Drawing

The construction materials used in the experimental set up have been constructed at RMIT workshop based on the following drawing:



FINISH: Quantity 5

All deminsion in mm

TITLE: House wall System

MATERIAL: Wooden Box (MDF)

DWG NO. Part1

A4

SCALE:1:10

SHEET 1 OF 1

Figure D.5: Plywood box, part 1

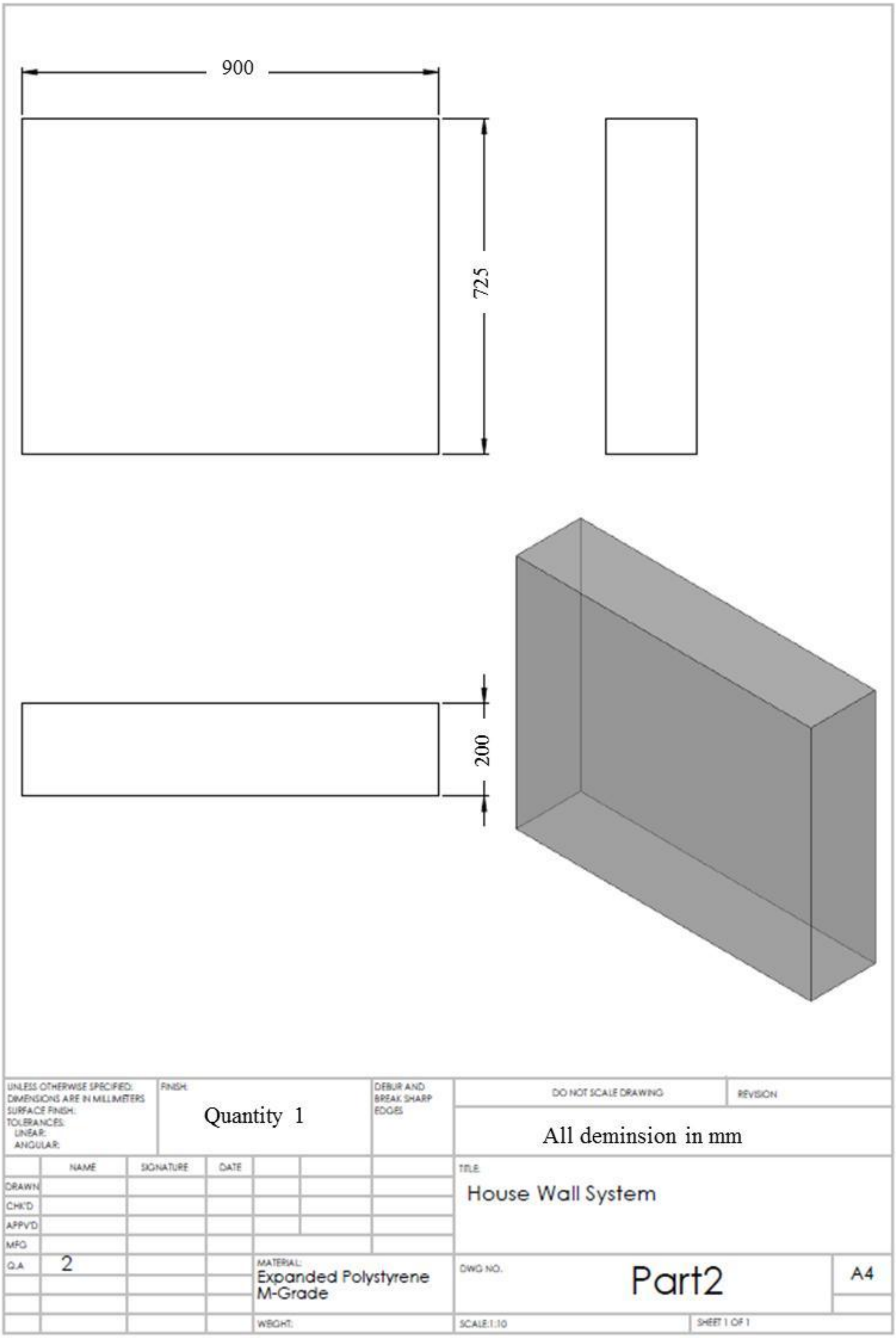


Figure D.6: Polystyrene insulation, part 2

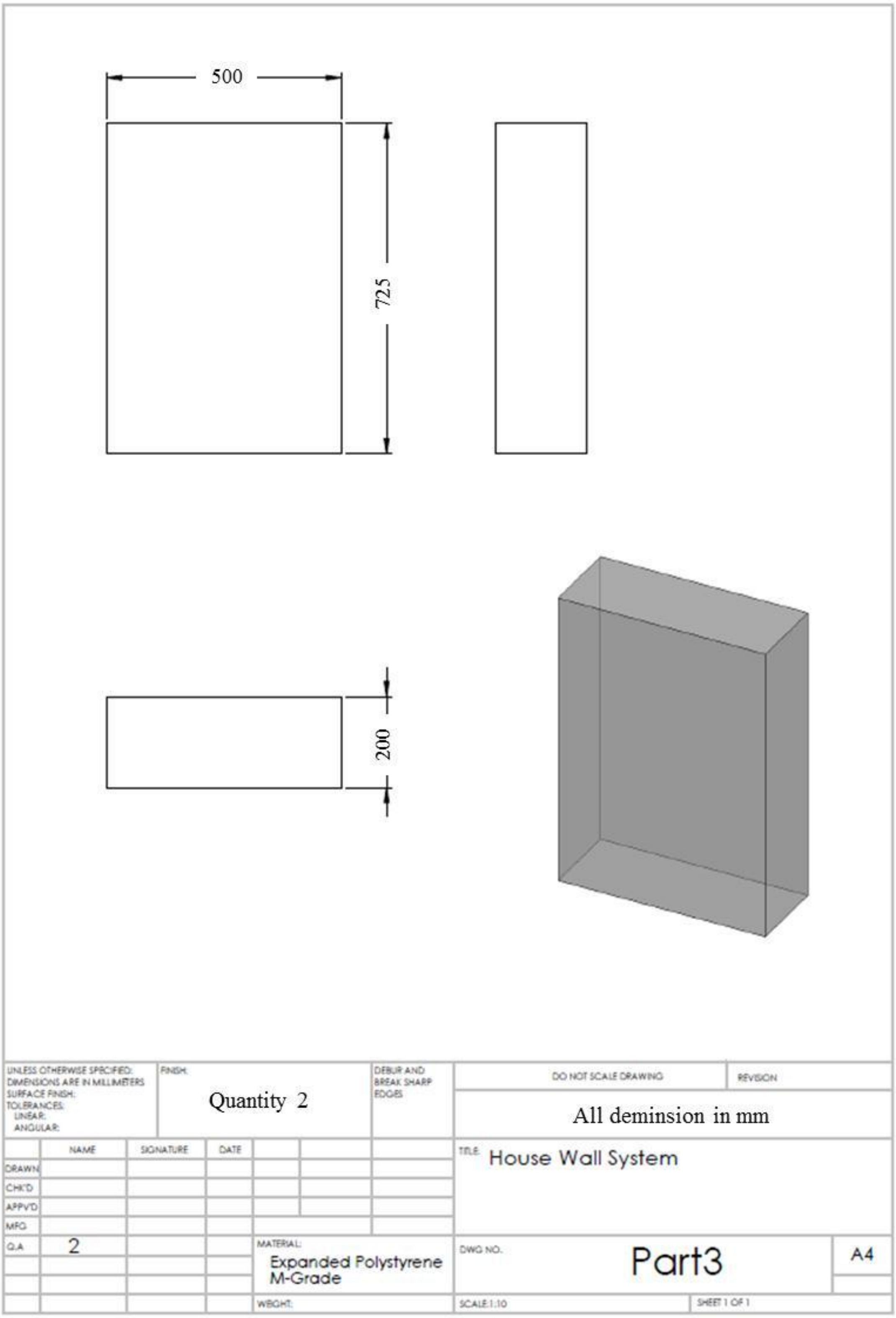
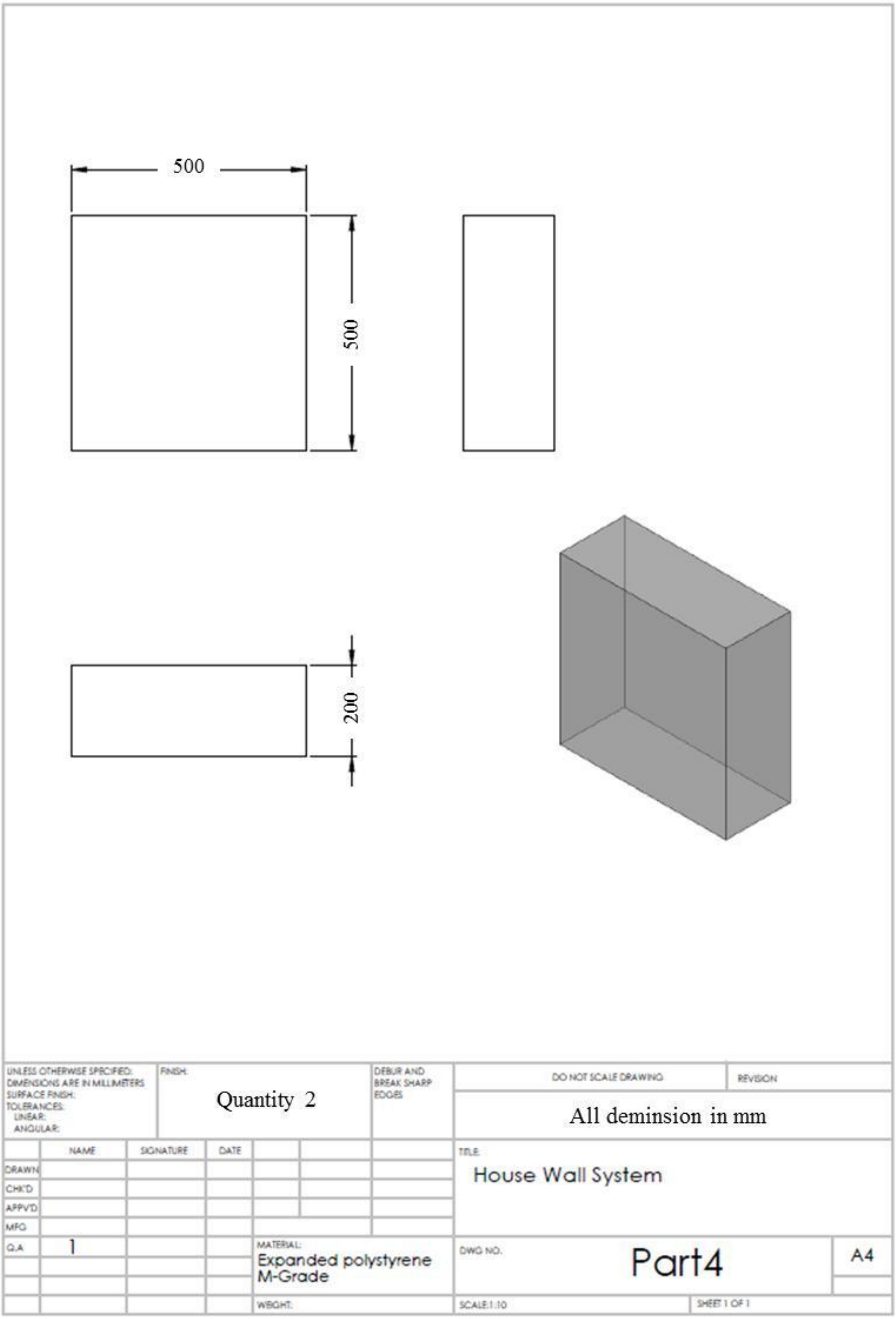


Figure D.7: Polystyrene insulation, part 3



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:

FINISH: Quantity 2

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

All deminsion in mm

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A	1		

TITLE: House Wall System

MATERIAL: Expanded polystyrene M-Grade

DWG NO. Part4

A4

WEIGHT:

SCALE:1:10

SHEET 1 OF 1

Figure D.8: Polystyrene insulation, part 4

APPENDIX E:Further Results for Economic Analysis

E.1: Economic Analysis

Table E. 16: Discounted Payback method and calculation procedure for Design 1

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2912	1.0000	-2912.00	-2912.00
1	884.8	0.9524	842.67	-2069.33
2	884.8	0.9070	802.54	-1266.79
3	884.8	0.8638	764.32	-502.47
4	884.8	0.8227	727.93	225.46
Discounted (Depreciated) payback period (Years)				2.3

Table E. 17: Discounted Payback method and calculation procedure for Design 2

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2912	1.0000	-2912.00	-2912.00
1	884.8	0.9524	842.67	-2069.33
2	884.8	0.9070	802.54	-1266.79
3	884.8	0.8638	764.32	-502.47
4	884.8	0.8227	727.93	225.46
Discounted (Depreciated) payback period (Years)				2.3

Table E. 18: Discounted Payback method and calculation procedure for Design 3

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2128	1.0000	-2128.00	-2128.00
1	694	0.9524	660.95	-1467.05
2	694	0.9070	629.48	-837.57
3	694	0.8638	599.50	-238.07
4	694	0.8227	570.96	332.89
Discounted (Depreciated) payback period (Years)				2.6

Table E. 19: Discounted Payback method and calculation procedure for Design 4

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2128	1.0000	-2128.00	-2128.00
1	862	0.9524	820.95	-1307.05
2	862	0.9070	781.86	-525.19
3	862	0.8638	744.63	219.44
Discounted (Depreciated) payback period (Years)				3.3

Table E. 20: Discounted Payback method and calculation procedure for Design 5

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2912	1.0000	-2912.00	-2912.00
1	996	0.9524	948.57	-1963.43
2	996	0.9070	903.40	-1060.03
3	996	0.8638	860.38	-199.64
4	996	0.8227	819.41	619.77
Discounted (Depreciated) payback period (Years)				2.8

Table E. 21: Discounted Payback method and calculation procedure for Design 6

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2464	1.0000	-2464.00	-2464.00
1	940	0.9524	895.24	-1568.76
2	940	0.9070	852.61	-716.15
3	940	0.8638	812.01	95.85
Discounted (Depreciated) payback period (Years)				1.1

Table E. 22: Discounted Payback method and calculation procedure for Design 7

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-3584	1.0000	-3584.00	-3584.00
1	1041.6	0.9524	992.00	-2592.00
2	1041.6	0.9070	944.76	-1647.24
3	1041.6	0.8638	899.77	-747.46
4	1041.6	0.8227	856.93	109.46
Discounted (Depreciated) payback period (Years)				2.1

Table E. 23: Discounted Payback method and calculation procedure for Design 8

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2128	1.0000	-2128.00	-2128.00
1	716.8	0.9524	682.67	-1445.33
2	716.8	0.9070	650.16	-795.17
3	716.8	0.8638	619.20	-175.98
4	716.8	0.8227	589.71	413.74
Discounted (Depreciated) payback period (Years)				2.7

Table E. 24: Discounted Payback method and calculation procedure for Design 9

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2128	1.0000	-2128.00	-2128.00
1	716.8	0.9524	682.67	-1445.33
2	716.8	0.9070	650.16	-795.17
3	716.8	0.8638	619.20	-175.98
4	716.8	0.8227	589.71	413.74
Discounted (Depreciated) payback period (Years)				2.7

Table E. 25: Discounted Payback method and calculation procedure for Design 10

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2128	1.0000	-2128.00	-2128.00
1	873.6	0.9524	832.00	-1296.00
2	873.6	0.9070	792.38	-503.62
3	873.6	0.8638	754.65	251.03
Discounted (Depreciated) payback period (Years)				1.3

Table E. 26: Discounted Payback method and calculation procedure for Design 11

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2128	1.0000	-2128.00	-2128.00
1	918	0.9524	874.29	-1253.71
2	918	0.9070	832.65	-421.06
3	918	0.8638	793.00	371.94
Discounted (Depreciated) payback period (Years)				1.5

Table E. 27: Discounted Payback method and calculation procedure for Design 12

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-3136	1.0000	-3136.00	-3136.00
1	884.8	0.9524	842.67	-2293.33
2	884.8	0.9070	802.54	-1490.79
3	884.8	0.8638	764.32	-726.47
4	884.8	0.8227	727.93	1.46
Discounted (Depreciated) payback period (Years)				1.0

Table E. 28: Discounted Payback method and calculation procedure for Design 13

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-3472	1.0000	-3472.00	-3472.00
1	896	0.9524	853.33	-2618.67
2	896	0.9070	812.70	-1805.97
3	896	0.8638	774.00	-1031.97
4	896	0.8227	737.14	-294.83
5	896	1.0000	896.00	601.17
Discounted (Depreciated) payback period (Years)				3.7

Table E. 29: Discounted Payback method and calculation procedure for Design 14

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-2464	1.0000	-2464.00	-2464.00
1	1008	0.9524	960.00	-1504.00
2	1008	0.9070	914.29	-589.71
3	1008	0.8638	870.75	281.03
Discounted (Depreciated) payback period (Years)				3.3

Table E. 30: Discounted Payback method and calculation procedure for Design 15

Year	Cash Flow	Present Value	Discounted Cash Flow	Cumulative Discounted Cash Flow
n	CF	PV1$=1/(1+i)^n	CFxPV1$	CF-CFxPV1$
0	-3584	1.0000	-3584.00	-3584.00
1	1019.2	0.9524	970.67	-2613.33
2	1019.2	0.9070	924.44	-1688.89
3	1019.2	0.8638	880.42	-808.47
Discounted (Depreciated) payback period (Years)				3.2