Université de Montréal

NATURAL AIR CONDITIONING – TRADITIONS AND TRENDS:

HIGH PERFORMANCE OF SUSTAINABLE INDOOR VENTILATION IN A HOT AND DRY CLIMATE

par

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Présenté par:

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a été évalué par un jury composé des personnes suivantes :

Résumé

De nos jours, l'utilisation accrue de combustibles à base de fossiles et l'électricité met en péril l'environnement naturel à cause des niveaux élevés de pollution. Il est donc plausible de prévoir des économies d'énergie significatives grâce à la climatisation dite «naturelle»». En accord avec les objectifs acceptés à l'échelle internationale d'une architecture «verte» et durable, l'utilisation de cours intérieures associées aux capteurs de vent, aux murs-Trombe et à d'autres systèmes de climatisation naturelle (aussi bien traditionnels que nouveaux), paraît prometteuse. Ce mémoire propose une analyse de nouvelles approches à la climatisation naturelle et à la production d'air frais avec une consommation minimale d'énergie, eu égard aux traditions et aux tendances, en particulier dans les zones climatiques chaudes et sèches comme l'Iran. Dans ce contexte, regarder l'architecture de l'Islam et la discipline du Qur'an paraissent offrir un guide pour comprendre l'approche musulmane aux processus de décision en design. Nous regardons donc les traditions et les tendances en ce qui concerne la climatisation naturelle à travers l'élément le plus important du contexte islamique, à savoir le Qur'an.[1]

C'est pourquoi, à l'intérieur du thème de la *tradition*, nous avons pris en compte quelques considérations concernant l'influence de l'Islam, et en particulier le respect de la nature associé à un équilibre entre l'harmonie et l'individualité. Ce sont autant de facteurs qui influencent la prise de décisions visant à résoudre des problèmes scientifiques majeurs selon la philosophie et les méthodes islamiques ; ils nous permettent de faire quelques recommandations.

La description des principes sous-jacents aux capteurs à vent et des antécédents trouvés dans la nature tels que les colonies de termites, est présentée également.

[1] Dans ce texte l'orthographe «Qur'an» est utilisée à la place de la forme: «Coran»

Sous la rubrique *tendances*, nous avons introduit l'utilisation de matériaux et de principes de design nouveaux. Regarder simultanément ces matériaux nouveaux et l'analogie des colonies de termites suggère de bonnes approches à la conception d'abris pour les victimes de tremblements de terre dans les régions sisimques. Bam, une ville iranienne, peut être considérée comme un exemple spécifique illustrant où les principes exposés dans ce mémoire peuvent s'appliquer le plus adéquatement.

Mots-clés: architecture islamique, contexte du Qu'an, capteurs à vent, murs-Trombe.

Abstract

Nowadays due to the increased use of fossil fuels and electricity, the natural environment is in danger because of high levels of pollution. Hence by creating natural air conditioning, we may save a significant amount of energy. In line with the global objective of sustainable and green architecture, the use of patios to save energy and natural ventilation coupled with wind-catchers, Trombe walls and other natural air conditioning systems (both traditional and emerging architectural elements) seems pertinent. This thesis analyzes designs to produce natural air conditioning and cooler air with the minimum amount of energy, with regard to the tradition and the trends, especially in hot and dry climate regions like Iran. In this context, looking to Islamic Architecture and the Qur'anic discipline of thought are considered as a guide to the way Muslims approach the design-decision making process. We therefore look to the traditions and the trends of natural air conditioning through the most important element of the Islamic context (the Qur'an[2]).

So, within the theme of "tradition", we have introduced some thinking about the influence of Islam and particularly the respect of nature while providing for a balance between harmony and individuality, such as proposing one special kind of decision-making process to solve the main scientific problems according to the Islamic philosophy and the accompanying methods, suggesting some recommendations.

Descriptions of (a) the principles of wind-catchers and (b) antecedents in nature such as the termite hills are pursued as well.

Under "trends", we have introduced the use of novel materials and novel design principles. Looking at the new materials and simultaneously at the analogy of the termite mounds suggests one good sample of design of a shelter for people in earthquake-prone regions. Bam, an Iranian city, can be considered to be a specific context in which the general considerations expressed in this thesis can be most usefully applied.

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[2] In this text, the spelling "Qur'an" is used for the alternative "Coran".

Keywords: Islamic architecture, Qur'anic context, wind-catcher, Trombe walls

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I dedicated this thesis to the owner of Qur'an.

Appreciation

The work of each is never the work of one. This work is the result of an effort combination of several individuals, and I am pleased to thank them.

Firstly, I would like to thank my research director, Professor Colin Henry Davidson, who allowed me to conduct this research.

It gives me great pleasure in acknowledging the support and help of Madam Simone Zriel, and Professor Tiiu Poldma. I would like to express my deepest gratitude to Madam Lucienne Fiant, who helped me a lot. I cannot find words to express my gratitude to the professors, who participated in the jury.

Second, I extend our thanks to all the teachers that I met during those years at University of Montreal, especially faculty of Aménagement. Finally, I also thank my wife Zahra Esmaeili and my son Ali, for their supports and patience.

Prolegomenon

Natural air conditioning – Looking to the tradition

The purpose of prolegomenon is to introduce some thinking about the influence of Islam especially in the Qur'anic context and particularly the respect of nature and looking to some of the aspects to provide a balanced between harmony and individuality. This is important because it provides some culturally relevant insights into the priorities that have guided the established of design principles, particularly regarding the disciplined use of resources found in nature.

Some of the important points about the interpretation of wind/s and future of the wind-catcher via the Qur'anic context:

The Qur'an is the most important and original Islamic document. It is universally recognized the first source document of the Islamic context. So, it is an important source of guidance about Islamic architecture and urbanism and the interpretation of its salient features.

Some important points about wind/s in the Qur'an:

Like every other Islamic discipline, architecture and its development was very much influenced and directed by the Holy Qur'an and its philosophy of life.

The spirit of Islamic faith was the unifying factor, which kept together different designs of building and molded them into a style representing the spirit of Unity in multiplicity - a unique characteristic of the Islamic architecture. It also reflects the remarkable sense of harmony and equilibrium between the different, and even the opposite elements. This is because the keynote of the Islamic practices, including architecture, is the interdependence and interrelation of all things in the Universe. There is complete equilibrium in Islamic architectural designing, as well as in city planning, between the natural environment and the natural forces and elements, like water, air, light and wind, which are essential to human life. In planning their buildings for residence, worship or business and the streets within the town area and for other basic necessities of the city life, Muslim architects made the maximum use of the natural factors available in the area. In hot areas, narrow streets were built to preserve the cool air of the night during the hot hours of the day. When the temperatures were very high, wind towers were built to ventilate residential buildings and low basements were used during summer for spending the hot hours of noon and also for cisterns to keep the water cool.

As a matter of fact wind and wind-catchers are some parts of the natural air conditioning system, which arise from the Islamic architecture. Significantly some important points about wind/s can be found in the Qur’anic context:

15:22

to top

وَأَرْسَلْنَا ٱلرِّيَٰحَ لَوَٰقِحَ فَأَنزَلْنَا مِنَ ٱلسَّمَآءِ مَآءً فَأَسْقَيْنَٰكُمُوهُ وَمَآ
أَنتُمْ لَهُۥ بِخَٰزِنِينَ ٢٢

Sahih International

And We have sent the fertilizing winds and sent down water from the sky and given you drink from it. And you are not its retainers.

(Al-Hijr, Qur’an 15:22)

30:48
to top

ٱللَّهُ ٱلَّذِى يُرْسِلُ ٱلرِّيَٰحَ فَتُثِيرُ سَحَابًا فَيَبْسُطُهُۥ فِى ٱلسَّمَآءِ كَيْفَ يَشَآءُ
وَيَجْعَلُهُۥ كِسَفًا فَتَرَى ٱلْوَدْقَ يَخْرُجُ مِنْ خِلَٰلِهِۦ ۖ فَإِذَآ أَصَابَ بِهِۦ مَن
يَشَآءُ مِنْ عِبَادِهِۦٓ إِذَا هُمْ يَسْتَبْشِرُونَ ﴿٤٨﴾

Sahih International
It is Allah who sends the winds, and they stir the clouds and spread them in the sky however He wills, and He makes them fragments so you see the rain emerge from within them. And when He causes it to fall upon whom He wills of His servants, immediately they rejoice

(Ar-Rum, Qur’an 30:48)

38:36
to top
in surah

فَسَخَّرْنَا لَهُ ٱلرِّيحَ تَجْرِى بِأَمْرِهِۦ رُخَآءً حَيْثُ أَصَابَ ﴿٣٦﴾

Sahih International
So We subjected to him the **wind** blowing by his command, gently, wherever he directed,

(Sad, Qur’an 38:36)

Why the Qu'ran helps understand the tradition in a way that indicates some directions for the future:

Firstly, according to the Qur’anic context, it is possible to predict the role of something, which came from tradition, like a wind-catcher and the role it can play in the future. Muslim people believed that Allah knows all of the sciences and He indicated His knowledge, which is belonging to the past and future, in the Qur’an. Thus the use of his knowledge, which already indicated in the Qur’an, regarding to the Qur’anic context is recommended. Therefore, a new form of wind-catcher could be based, in the future, on scientific simulations according to the Qur'anic principles.

Secondly, according to the Quranic context, wind/s plays role of messenger, which carries important and good tidings, so we could imagine the following diagram:

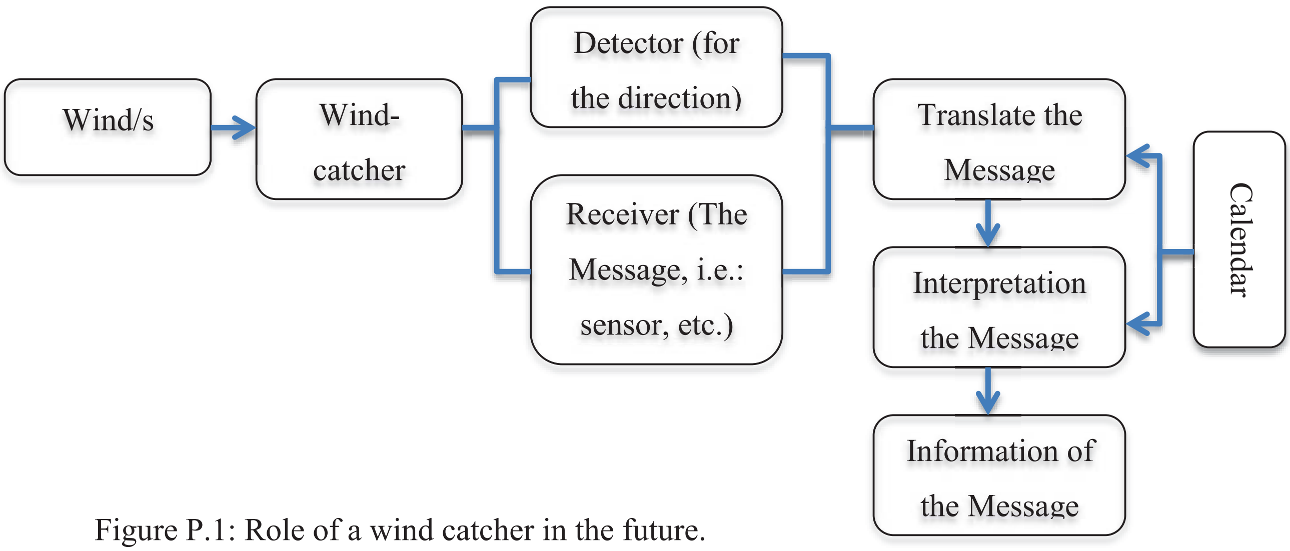

Figure P.1: Role of a wind catcher in the future.

This kind of information is so important according to the different geographical area. We are able to predict some of the hurricane, aerology, and use in agriculture and so on.

Definition of the Revelation (Qur'an):

> "The Qur'an, the last revealed word of God, is the primary source of every Muslim's faith and practice. It deals with all the subjects which concern human beings: wisdom, doctrine, worship, transactions, law, etc., but its basic theme is the relationship between God and His creatures. At the same time, it provides guidelines and detailed teachings for a just society, proper human conduct, and an equitable economic system.
>
> Note that the Qur'an was revealed to Muhammad ﷺ in Arabic only. So, any Qur'anic translation, either in English or any other language, is neither a Qur'an,

nor a version of the Qur'an, but rather it is only a translation of the meaning of the Qur'an. The Qur'an exists only in the Arabic in which it was revealed."[3]

The Qur'anic discipline of thought can guide the way Muslims approach the design-decision making process:

• To identify the method/s via the Qur'anic context and the Islamic resources to explore Islamic Architecture or the Islamic Urbanism.

• To identify a kind of process to manage the research/s via the Islamic references, especially the Qur'an to solve the scientific problem/s especially in the Islamic Architecture.

• To identify the role of the wind/s and the wind-catcher as a part of Islamic Architecture via the Qur'anic context.

• Proving the success of religious methods for approaches in the Islamic architecture that respond critically and thoughtfully to contemporary conditions, and beliefs in the Islamic sciences.

Conclusion:

What conclusion can be drawn from this glance at the Qur'an and its lessons? How can one look at the explanation of some rules and principles of the Islamic architecture and the Islamic Urbanism via the Qur'anic context?

Those descriptions of ideal buildings amidst a natural environment stimulated architectural styles in the early Islamic Era and produced architectural wonders such as the famous wind-catchers in the Islamic countries. Other Muslim countries bear evidence of the grandeur and

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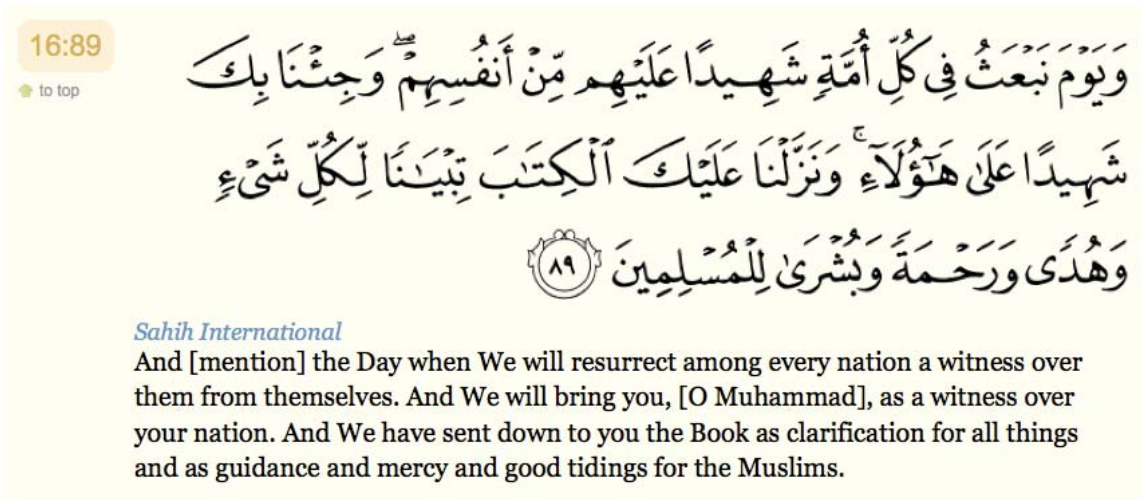
[3] http://www.islam-guide.com/ch3-7.htm, 21/3/2011

majesty of the architectural styles and modes, which sprang from the Qur'anic studies. The massive structural beauty and simplicity of those buildings, especially of mosques remind one of the Majesty and Greatness of The Creator.

Finally, according to the following verse the clarification for all things is in the Qur’an. This book is guidance, so we could use is to answer all of our problems.


16:89

to top

وَيَوْمَ نَبْعَثُ فِي كُلِّ أُمَّةٍ شَهِيدًا عَلَيْهِم مِّنْ أَنفُسِهِمْ ۖ وَجِئْنَا بِكَ
شَهِيدًا عَلَىٰ هَٰؤُلَاءِ ۚ وَنَزَّلْنَا عَلَيْكَ الْكِتَابَ تِبْيَانًا لِّكُلِّ شَيْءٍ
وَهُدًى وَرَحْمَةً وَبُشْرَىٰ لِلْمُسْلِمِينَ ٨٩

Sahih International

And [mention] the Day when We will resurrect among every nation a witness over them from themselves. And We will bring you, [O Muhammad], as a witness over your nation. And We have sent down to you the Book as clarification for all things and as guidance and mercy and good tidings for the Muslims.

(An-Nahl, Qur’an 16:89)

So depending on the Qur’anic discipline of thought, which can guide the way Muslims approach the design-decision making process and problem solving, the human Wisdom is needed to understand and realize the revelation and it is playing the role of the basic principal, but the revelation (Qur’an) is necessary to complete the human’s wisdom. Also, it help to identify the method/s via the Qur’anic context and the Islamic resources to explore Islamic architecture or the Islamic urbanism.

Chapter I. Introduction

Nowadays due to the increased use of fossil fuels and electricity, the natural environment is in danger of high levels of pollution. The specific approach and design of natural air conditioning systems will vary based on local climate and building type. Almost all historic buildings were ventilated naturally, although many of these have been compromised by mechanical systems and the addition of partition walls. Hence by creating natural ventilation with Wind-Catchers and other systems; we may save a significant amount of energy. However, the amount of ventilation depends critically on the careful design of indoor ventilation systems, and the size, form, function and placement of openings in the ventilation systems.

Interior comfort depends primarily on the control of temperature. Active cooling using refrigerant-based devices can be replaced by passive cooling methods using surrounding natural resources. Savings are not only obtained by avoiding refrigerant gases, but also by reducing energy demand. It is clear that these gases, which are used in the refrigerant, are many times more harmful to the climate than CO_2.

Natural air conditioning systems, unlike fan-forced ventilation, uses the natural forces of wind and buoyancy or solar energy to deliver fresh air into buildings. Fresh air is required in the buildings to alleviate odours, to provide oxygen for respiration, and to increase thermal comfort. Natural ventilation is ineffective at reducing the humidity of incoming air especially with the use of traditional materials.[4]

The movement to design and construct green buildings, also referred to as permanent ventilation systems, seeks to reduce the impact buildings have on the environment, and hence make buildings more sustainable. With an increased awareness of the cost and environmental impacts of energy use, design of comfortable and natural air conditioning has become an increasingly attractive method for reducing energy consumption. Thus, avoiding the use of energy and the cost for providing acceptable indoor environmental quality and maintaining a comfortable, healthy, and productive indoor climate rather than the more prevailing approach of using mechanical ventilation represent a value and an asset. Especially in hot and dry climates and many buildings types, natural air ventilation can be used as an alternative to air-conditioning plants, thus saving on energy consumption. The different natural cooling systems presented in this study, are all existing and have been used for years although often overshadowed by the arrival of air conditioners.

Pressure differences can be caused by wind or the buoyancy effect that is created by temperature differences. Natural ventilation systems rely on pressure differences from inside and outside buildings, to provide comfortable condition for people who live there and to move fresh air through the buildings. More specifically, the amount of ventilation will depend critically on the form, function, size and placement of openings in the wind-catcher if there is one, particularly if combined with Trombe walls and other natural air conditioning systems. In all cases, a natural ventilation system is as a circuit of fresh air, with equal consideration given to supply and exhaust. The relations between openings of Trombe walls and Wind-catchers are part of the techniques to complete the airflow circuit through a building. Trombe walls are used as the heater in the historic buildings, but Wind-catchers are used as a cooler.

[4] http://www.wbdg.org/resources/naturalventilation.php?r=envelope, 15/02/2010

The wind-catcher has been used in Iran since early times, it is one of the special masterpieces of Iran's architecture and it is also the signs of prior' intelligence in agreement with the climate, it can be considered as the most specific examples of clean energy. The biggest numbers of wind-catchers is in Iran; these wind-catchers are made in two areas: the hot and humid area in south (such as “Bushehr Port”) and the hot and dry area of the central plateau (such as Yazd and Bam). (Azami, A., 2005)

Environmental and natural phenomena play a very significant role in laying out the region's interrelated Cultural, economic and social infrastructures.

The buildings in the Iranian desert regions are constructed according to the specific climatic conditions and differ with those built in other climates. Due to the lack of access to heating and cooling equipment, in ancient times architects were obliged to rely on natural energies to render the inside condition of the buildings pleasant.

This thesis explains natural air conditioning systems through looking to the tradition and the trends. Obviously, the Islamic way to approach major issues such as the use of natural resources, and which arise out of the Qur’anic context are considered.

Problem Definition

How can the traditional natural air conditioning systems, especially those found in Islamic architecture, develop in the future as a sustainable system of ventilation with regard to the Islamic discipline? The question of research is: Is these scope for using a high performance materials approach and proposing new materials (an important aspect of the efficiency of housing in hot-dray climate when looking at Wind-catcher, Trombe wall and other natural air conditioning systems, especially in Islamic countries)? Can the new materials, forms and methods provide comfortable condition for people, energy saving and consumption, especially in hot and dry climates?

Definition of the Subject of Research:

The central subject of this research is Natural air conditioning – tradition and trends, in the context of providing comfortable condition for people. The hot and dry climate in Islamic countries such as Iran together with the tradition of Islamic architecture are considered for this research.

This research illustrates the fact that many of the traditional principles, elements, and methods of architectural morphology correspond to the objective conditions of climate, culture, religion, and way of life in specific area like Iran. There are four major factors of architecture shaping dwellings that have remain unchanged for centuries and have retained their importance nowadays, notably according to the Islamic rules and principles, and their influence. The new level of development of buildings should be qualitatively based on climate-ecological modeling of spaces, the development of national traditions in architecture, on natural-climatic zoning, and the ecology of human beings, coupled with the conservation and restoration of the environment. Adaptations are required mainly related to working out the problems of rapid construction, expansion of the typology of buildings and structures, increased construction volumes, requirements regarding comfort and the quality of life.

Goals and Objectives

This report has some broad goals: Evaluating traditional natural air conditioning in hot and dry climates and checking whether there is any place for modern methods, materials and forms. Four aspect are very important in this context: A) Use of new materials to provide adequate adaptability of the buildings and ventilation systems, specifically considering intelligent materials. B) Use of computers to manage the performance of indoor ventilation and to provide a development system using novel computational techniques for building/shelter's thermal airflow, and air quality analysis. C) Use of bio-thermal energy, i.e. the concept of utilizing composting material to generate heat and biogas to develop an alternative energy source and operation of ventilation systems, including lessons learnt from bio mimicry approach; such as two gardens inside termite mounds. D) Introduction of some thinking about the influence of Islamic thought and particularly the respect of nature.

Organization of the Report

This thesis is divided into eight stages, which focus on:

(a) Natural air conditioning, looking to tradition, including the influence of Islam and particularly the respect of nature while providing for a balanced between harmony and individuality, (b) "Tradition", in which there are two categories, which describe the principles of wind-catchers and other natural ventilation systems and antecedents in nature such as the termite hills considering bio mimicry.

(c) Natural air conditioning with regard to the "trends", and the use of novel materials and novel design principles.

Therefore, the thesis consider eight stages:

Stage One- Reviewing the Literature; Looking at the features of traditional and historical ventilation systems of buildings in hot and dry climates (e.g. wind-catcher). History and analyses of the natural air-conditioning systems (See page 32 for more details).

Stage Two- Determining the requirements of low-energy cooling techniques and comparing them together. Comparing the wind-catchers with other ventilation systems (See page 33 for more details).

Stage Three- Indicating the gap between the ventilation systems of the traditional buildings and providing permanent ventilation system and comfortable conditions. (See page 33 for more details).

Stage Four- Looking at the system of ventilation in termite mounds as a good example of natural ventilation. There are some lessons, which can be learnt from the Termite Mound as well. Within the practice of applying bio mimicry to real world engineering problems to arrive at sustainable design solutions (See page 33 for more details).

Stage Five- Looking at the problems and the difficulties of wind-catcher design and the second for logical solutions to solve these problems (See pages in chapter III for more details).

Stage six- Looking at new materials to see if any are economically and technically appropriate for improving natural air conditioning systems (See pages in chapter V for more details).

Stage seven- Looking into the tradition of the natural air conditioning system in Islamic architecture and in the Islamic context, including the use of patio energy and natural ventilation recognizing wind-catchers as a traditional Persian architectural element (See pages in chapter III for more details).

Stage eight- Exploring the management systems of the sustainable ventilation (MSSV), is indicated to control ventilation of buildings together with the bio-thermal energy (See pages in chapter VI for more details).

Research Methods: This master thesis brings together material selected carefully from the literature, including books and scientific reports based on field studies and in-situ research. The originality of the research lies in the selection of domains considered to be pertinent and the juxtaposition of material usually not considered together. The published material, includes (a) documents that were created at the time of an event or on a subject the writer has chosen to study in the context of an event or topic, and (b) documents for which the sources used are published documents.

The key methodological problem is developing a method to select the source documents. This method is iterative, in the sense that there was a cyclic process of establishing a preliminary design of the subject area and its limits followed by a preliminary survey of the literature followed by a revision of the subject area and its limits, leading to an enlarge survey of the literature. After several repeats of this process, the subject domain was fixed and the iterative survey brought into focus and winnowed down.

This master thesis is not based on experimental research; it is, however, influenced by the author's personal experience with building in a hot and dry climate.

As already mentioned, the novelty of this research lies in its use of existing knowledge brought together in what is claimed to be a novel way. More specifically, the research is exploratory in nature; it falls into the category of applied research, since it looks at real-life situation (essentially wind catcher) and seeks to understand with an examination of wind catchers, what they are and what principles they seem to embody. The iterative search sought to identify the raison d'être of wind catchers and how they worked. The next step was directed towards the broader subjects of improving thermal comfort (in hot dry climates) by natural, low energy means. The information garnered was add to that wind catchers, and was analyzed jointly.

An interesting secondary line of literature-based research was opened, regarding climate control in nature (i.e. the case of termite mounds), opening the door to some reflection about biomimétisme (biomimicry) in building.

This process was repeated, until, it was felt that sufficient information had been collected and sorted for the requirements of this thesis.

Note that the originality of this research, as has already been mentioned, lies in the blending of several point of view, centered on the significant of wind catchers for thermal comfort. Its finding can be judiciously generalized within the relevant climatic and cultural regions of Middle East and northern Africa.

Chapter II. Natural air conditioning – looking to the tradition particularly in Iran:

The purpose of this chapter is to establish the principals of the Natural air conditioning, especially the use of wind-catchers:

- Characteristics of hot-dry climates
- Some of design solutions for hot-dry climates
- Features of Hot and Dry Regions
- Effects of Wind on buildings and ventilation
- Architectural Problems in Hot and Dry Regions
- Main trends in the design of the buildings especially in hot and dry climate region of Iran.

Geographic:

Four regions in Iran:

- Iran are divided into the four clematis (Figure 2.1)
- 1- Mild and humid climate (southern coast of Caspian Sea)
- 2- Cold climate (western mountains)
- 3- Hot and dry climate (central deserts)
- 4- Hot and humid climate (southern coast of Iran)

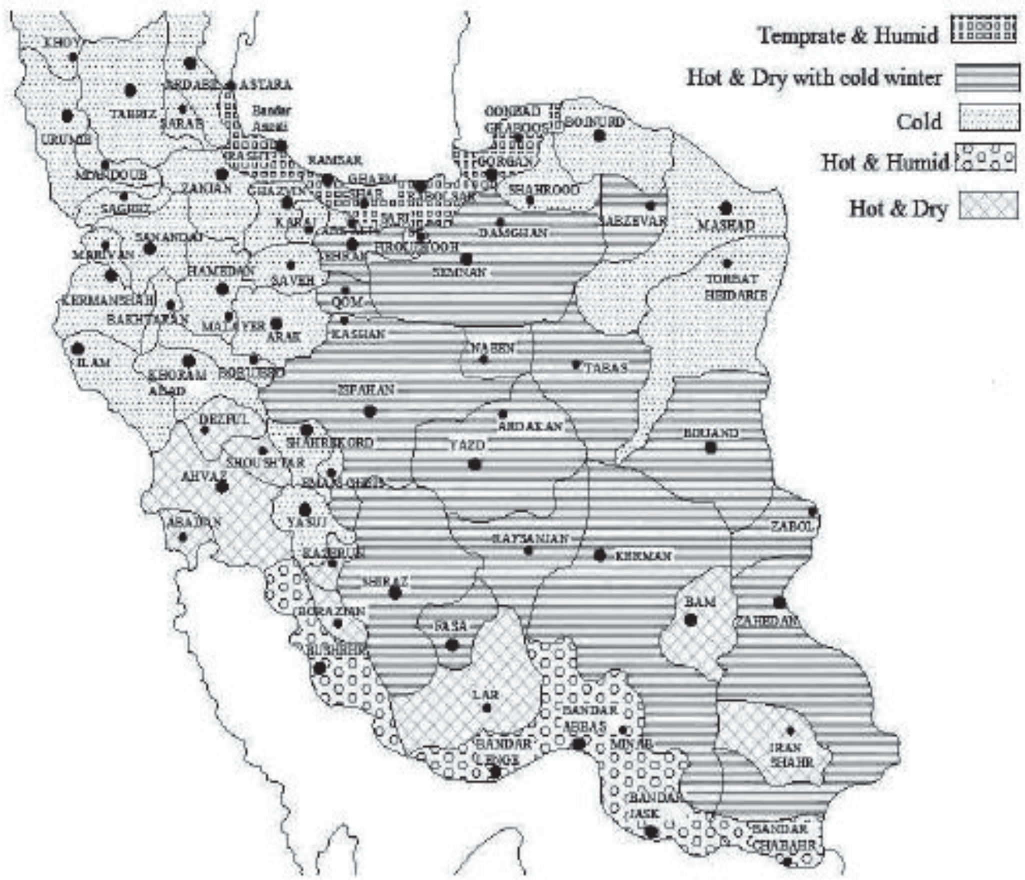


Figure 2.1. Four climatic divisions in Iran (Source: M. Kasmaee, 2010)

Climate of Iran:

There are different geographical locations in Iran and this provides various climates.
Every climate has its special characteristics. Iranian researchers like Tavasoli, M. and Kasmaee, M., indicated in their book (1980) on the climatic of Iran. They worked on the climatic divisions of Iran. They divided Iran based on Koppen‘s method. Koppen divided the world based on grow of plants. (Köppen, Wladimir, Climate Classification Systems, 1884).

Iran is basically divided into four climatic regions: Mild – Humid Climate, Cold Climate. Hot – Mild Climate, Hot – Arid Climate.
In a vast country such as Iran, with different climatic zones, traditional builders in the past have presented a series of logical solutions for human comfort. In these documents, a natural cooling system like: Badgir (wind-catcher) in hot and dry climate are examined, together with at the features of this kind of climate.

Hot-Dry Climate:

This Climate covers most parts of the central Iranian plateau. It receives almost no rain for at least six month of the year; hence it is very hot and dry. In this area, in most of the months of year the sky is without cloud and the humidity very low. In this kind of climate the winter is very cold and the summer is very hot – arid. Therefore temperature is very variable; in the past, this has led to a series of logical solutions in building for human comfort. It is interesting to draw a connection between the architecture and the climate, as it is demonstrate in the form of physical and architectural characteristics in a particular region (Soflaee, F., Shokouhian, M., 2005).

Characteristics of hot-dry climates:

•High daytime temperatures
•Large temperature variations
•High winds
•Very high solar intensity –reflected by ground
•Water is scarce
•Low humidity

Some of design solutions for hot-dry climates:

- •Provide maximum shade,
- •Balance extremes of summer and winter by using movable parts,
- •Provide ventilation with regulation,
- •Avoid large exposed surfaces,
- •Use reflective outer surfaces,
- •Use thermal mass to balance extremes of temperature,
- •Use evaporative cooling (Fathy, Hassan, 1986)

Building Orientation and Shading Devices:

Mahyari indicated in his research that most of the world's hot climate areas are situated in the subtropical latitudes, where the highest intensities of the impinging solar radiation in summer occurs on the western and eastern walls. In winter, of course the northern hemisphere has the highest intensity of impinging radiation on the southern facade.

The northern wall of a courtyard is the southern elevation in a courtyard house. When there is a courtyard with a number of rooms around the southern wall of the courtyard, it is the most shaded area all through the seasons, a feature especially in the old and the traditional Iranian houses. The rooms behind this wall is the most preferred area to live in summer. But, the rooms behind this wall are very cold in winters. Roofs are provided with parapets as high as 1-2 m, which further provide shade on roof surfaces. Shade in smaller courtyards is more significant than in larger ones. (Mahyari, Ali, 1996).

To minimise the impact of the sun in summer is the main objectives in selecting suitable building orientation. The aim is to maximise the solar impact in winter, and to reduce the internal daytime temperatures in summer. A north-south orientation is therefore preferable to one east-west (Givoni, 1976). However, Bonine (1980) states that the orientation of settlement in traditional Iranian housing is not due principally to climatic factors, and that the exact direction of the courtyards is based on an orthogonal network of lanes and water channels that have been laid out in the direction of greatest slope to irrigate cultivated fields and gardens, which were common in traditional houses in the past (Bonine, 1980).

Construction design zoning of the Iranian territories and climatic modeling of buildings space in different areas:

Methods, Shapes and functions of climate control of the Iranian buildings**:**

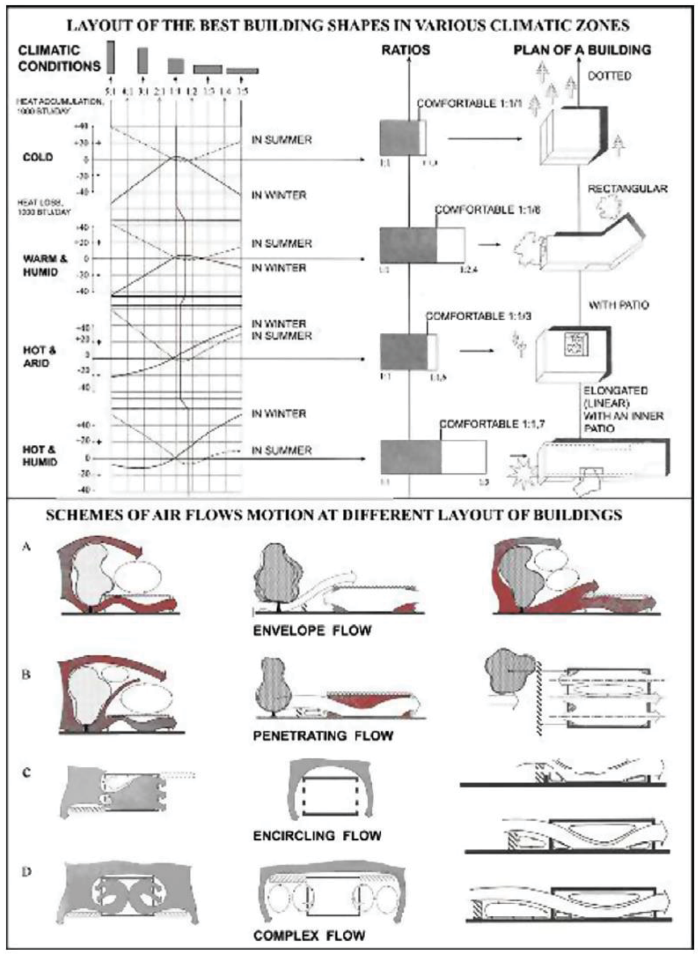


Figure 2.2.The typical methods of controlling the influence of climate on the buildings in Iran (Kasmaee, M., 2010)

Features of the traditional architecture of Iran in the different climate zones and relevant design zones.

Table 2. 1. The main common characteristics of Iranian traditional architecture, in accordance with the construction design zoning (Source: Ghazbanpor, 2001)

NO.	Characteristic	Construction design zone			
		Northern Construction Design Zoning	North-western Construction Design Zoning	South-eastern Construction Design Zoning	Southern Construction Design Zoning
1	Climate	Warm humid	Cold	Hot arid	Hot humid
2	Mode of operation	Close, half-open	Close, half-open	Open, half-open, close	Half-open, open, isolated
3	Form of the plan	Extended, linear	Compressed, compact and dotty	Compact, dotty with a patio	Extended, linear with summer dwellings
4	Type of a covering	Slope	Flat, saddle, 2/4-hipped roof	Flat, domical	Flat, domical
5	Orientation to the cardinal	East, South, West, In the sea	South-East, South, South-West	South-East, South	South-East, South, In the sea
6	Foundation of buildings	On plinth	On plinth, On the ground	On the ground	On the ground
7	Square of window openings	Large	Small	Small	Middle
8	Utilization of natural ventilation airing	Middle	Small	Large	Large
9	Composition of buildings	Isolated	Blocked (for heat accumulation)	Blocked (for heat Isolation)	Isolated
10	Predominant colors of outer decoration	Arbitrary	Dull colors, dark colors	Bright, light colors	Bright colors
11	Thermal insulation of exterior protective structures	Temperate thermal Insulation	High thermal insulation	High thermal insulation, horizontal sun protection	Temperate thermal Insulation, horizontal and vertical sun protection
12	Prevention of natural influence	Cold and wind protection	Cold and wind protection	Hot and wind protection	Hot and cold wind protection
13	Correlation of premises	Within heated volume	Within heated volume	Open spaces with transforming protective structures for day and night residence	Open spaces with transforming protective structures for day and night residence

The largest climatic area in Iran is the hot and dry region. Dry desert has covered much of the vast area of Iran. Most of these areas are located in the central and eastern regions. Lack of cloud and little humidity causes a high variation of temperature between day and night. This range sometimes reaches to 30˚C in desert regions. The characters of this region are cold winters and hot and dry summers.

The variable characteristics of different climates in Iran have affected the creation of the cities and also their architectural formation, which is reflected in the native architectural forms and structures in different areas of Iran. Therefore, there are two items that have very important roles in suitable designing, in terms of the exact distinction of climate districts in the country, and also the climate characteristics in each of the different areas. (Kasmaie Morteza, 2005)

Firstly, attention is paid to the study of native architecture characteristics in one of the most important climate area in Iran (Hot and Dry climate). Secondly, the relationship between climate and architecture of this area is indicated. Finally, a determination of architecture typology in hot arid climate is considered.

Features of Hot and Dry Regions:

Wind:

Mahyari reported that the prevailing wind speed is generally low in the morning. He also demonstrated it will increase towards noon to reach a maximum in the afternoon. Winds are frequently accompanied by windstorm of dust and sand. Storms are generated by an advancing cold front. There is considerable erosion and the formation of sand dunes, which may reach as high as 300 meters; they are mostly created by dust during the winter months. Since night winds are required for structural cooling and ventilation of buildings, this is most disadvantageous when occurring at night. Furthermore windless periods are frequent in some areas of the hot and dry zone. (Mahyari, Ali, 1996)

Wind data:

Wind data are best presented graphically. Wind roses are one of the most important graphs to analyse the data. (For more information see wind data in the Appendix 1)

Sky Condition and Solar Heat Radiation

Where convection heat transfer phenomena are dominant in many regions, radiation is the most powerful in arid zones. The solar radiation strikes the arid land directly. Up to 95% of the solar radiation may reach the ground, especially in open desert lands. Because clouds form so rarely and the moisture content of the air is often very low, direct solar radiation is intense on horizontal surfaces (up to 800 or 900 w $/m^2$), and is further increased by reflection from light colored terrain. (Givoni, 1976)

Hot dry regions receive a great amount of solar radiation during the day, but they tend to rapid cooling after sunset. Whereas in temperate climates only about half of the heat stored in the ground is emitted at night and the other half is radiated back to the ground by clouds and vegetation, in hot dry regions approximately 95% of the heat stored in the terrain is lost by radiation because of the absence of clouds and the low level of atmospheric moisture. It is emitted by radiation into the higher layer of the atmosphere. The sky of some areas of Kavir (which in Persian has the same meaning as the word "Sahara") and the deserts are without cloud, but dust haze and storms are frequent, during the greater part of the year. These are caused by intensive heating of the air near the ground occurring mainly in the afternoon. (Givoni, 1976) After a dust storm, a mass of extremely lightweight particles form a dry fog and remain in the atmosphere for a long period of time, but larger particles will settle down. Consequently there is limiting visibility in the affected area. (Golany, 1982)

Air Temperature:

The latitude has a greater effect on winter temperatures than on summer temperatures. Thus with increasing latitude the winters become relatively much colder than do the summers, and the annual range therefore, greater. During the summer, maximum day temperatures range between 40° C to 50° C and night temperatures range between 15° - 25° C. In the cool seasons, nighttime mean temperatures are between 5° C to 15° C. (Givoni, 1976). These wide ranges of temperatures are attributed to the low humidity and absence of cloud. The geographical latitude influences the annual range.

Humidity:

Relative humidity is usually low in a hot and dry climate. However, in certain districts in areas which are often regarded as arid on the basis of temperature and rainfall data, the maximum relative humidity may be as high as 70%. In Khoramshahr and Khozestan (two Iranian cities where are situated in the south west of Iran), for instance, this high humidity is called "Shargi". The vapour pressure is fairly steady, varying with the location and season from about 5 to 15 mm Hg. So, the relative humidity fluctuates with the air temperature, ranging from below 20% in the afternoon to over 40% at night (Givoni, 1976). The clear sky and dry air permit a more rapid escape of energy, which is always in such conditions.
Hence, the greater the amount of absorption of solar energy, the larger the amount of water vapours in the air and terrestrial radiation in the atmosphere.

Precipitation:

The hot dry zone, especially in Iran, receives less than 250 mm of precipitation annually. Large areas have only 50-150 mm per year, and some areas have no rainfall at a1l. There is an extreme deficit of moisture, with an average evaporation rate of 2500-3000 mm per year, and the ground water as the main source of water (George, 1977).

Occasional violent flash storms do occur, breaking suddenly and lasting only short periods of time, mainly in the winter (Givoni, 1976).

A "ghost rain" is an extraordinary phenomenon of many hot dry regions. The few clouds that have managed to float over a dry region suddenly condense and rain begins to fall. Then, shortly before it reaches the ground the rain encounters a layer of heated air that has formed just above the ground. It instantly evaporates and most of the already rare rainfall is lost. The cooling produced by the evaporation sometimes causes the layer of hot air to dissipate, so that, if there is a second fall, it has a chance to reach the ground. (George, 1977)

Architectural Problems in Hot Dry Regions:

In cold seasons natural gas and other products of oil are simply burnt to provide indoor comfortable condition, but in hot seasons, the only energy available to cool the buildings is electricity. Both the products of oil and electricity for a number of reasons are highly subsidised in Iran and other oil-producing countries, therefore the people do not appreciate the real value of these kinds of energies. As a result, buildings, built in the new quarters of these cities, are fully dependent upon artificial heating and cooling means including the hot and dry regions of Iran.

The architecture of the past century was typically based upon the concepts of the internationally accepted principle of the Modern Architecture and the Modern Movement; moved away from the Iranian traditions and it does not respect the climate of the region and relies upon energy consuming mechanical equipment. So, design for climate change and adaptation is now virtually unknown. As a fashion, large windows with one layer of the glass have appeared in the external envelope of the buildings, and the thickness of the walls is reduced. This carelessness causes a huge loss of energy via the windows and the walls. (Mahyari, Ali, 1996)

Oil is mainly needed for transportation systems and for industry, which is the most important source of energy consumption but a substantial portion of this energy in the past decades has been used to provide heating and cooling for buildings. Pollution and many environmental problems have been caused by over use of this valuable resource. But this process cannot be continued for much longer time because the main problem is that the reserves of oil are naturally limited. In the hot dry regions like central Iran the dominant problem is a great demand for air conditioning and refrigeration; the energy used for heating is not basically significant. Eventually, design for passive devices and climate adaptation will be a natural and affordable solution for the next generations. (Mahyari, Ali, 1996)

> "The energy expended on the heating, cooling, and control of humidity in buildings is considerable. If this energy, now produced from fossil fuels, could be saved and climate control could be achieved by some other means for example, the United States alone would save over 25 percent of its energy needs." (Fried, 1980)

Also, cool passive system is one of the necessary solution for houses, because in emergency conditions, if the electricity supply is cut off for whatever reason for example after a disaster like an earthquake, there will be much difficulty in providing oil or electricity for people and ventilation for their houses.

Main trends in the design of the buildings especially in hot-dry climate region of Iran:

The basic types of residential developments are the houses formed around half-open or closed patios (two, three patios). Various arguments of housing, from locked chain double row, are recommended.

To improve the microclimate in built-up areas the following important criteria are recommended:

– Formation of constructed areas from compact rarefied to carpet high density to reduce overheating.

– Arrangement of ventilated attic spaces, walls with ventilated cavities, roofs and ventilating shafts (Badgir or Wind-Catcher).

– Protection of public playgrounds, footpaths, patios, and dwellings from hot scorching Northwest (with sand and dust) and Northeast winter winds.

– Planting, water, gardens, landscaping, and forming open spaces (See Figures 2.3, Figure 2.4 and Figure 2.5). In the samples below there are some landscaping with regarding to water, gardens and walls with ventilated cavities in the famous Iranian cities (Pyrnia, M. ,1981).

Figure 2.3. The Boroujerdis ' house, Kashan, Iran. [5]

[5] Source: www.Flickr.com, 2008

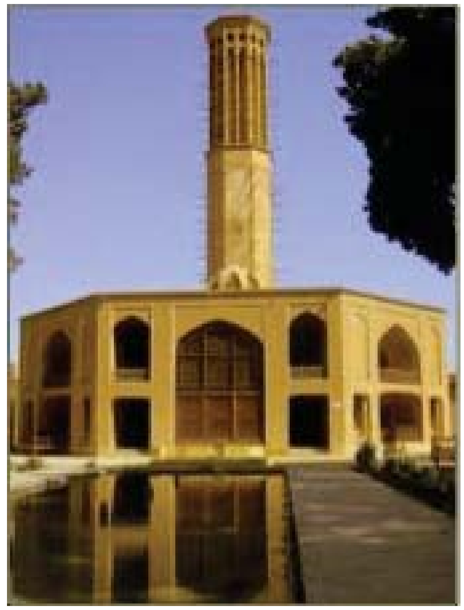


Figure 2.4. Dowlat Abad garden wind catcher.[6]

Figure 2.5. Naji Grden, Yazad, the central open space beside the landscape includes a system of storm water ponds (for natural ventilation) and wind-catcher. (Source: Photo by

[6] Source: www.Flickr.com, 2008

Reza Dehghanizadeh.)

Traditionally, the tendency favors the erection of public buildings of domical shape and Ayvan (Small traditional courtyard in the traditional home) types with patios and one or two-tier arcades. In addition, there should be thorough cross ventilation of premises, protection of premises from overheating in summer time (by increasing the external thermal protection structures, multi-layered fencing, vertical and horizontal shading, and cultivation of vineyards and heat-resistant vines (lianas)), organization of open summer premises i.e. Hyatts, Galleries, Terraces (Tavassoli. M., 1974).

So, considering the nature and climatic conditions of Iran, the followings are among the most important requirements according to the municipal rules for building design.

1. Protecting buildings from hot air.

2. Protecting buildings from rain.

3. To provide comfort conditions appropriate for human use, increasing the humidity of the air inside a building.

4. Creating the fresh air conditions in the inner spaces.

5. Making use of favourable factors of outdoor air and the temperature differences throughout the day.

6. Providing solar protection of the building (vertical and horizontal shading).

7. Using solar and wind energy as energy-saving factors (heating, lighting) for the building.

8. Reducing the penetration in of dust in the buildings.

9. Reducing thermal conductivity of structures and improving energy efficiency of space-planning of the building (Tavassoli. M., 1974).

These thermal / cooling requirements can be represented geographically (Figure 2.6)

The definitions of the letters on the diagrams (Figure 2.6) are (Moradchelleh, Abdolbaghi, 2010):

N: the zone of comfortable climate.

N0: the zone of temperate climate.

M: the zone with selection of building materials with regard to the climate that renders significant influence on the temperature inside buildings.

M0: the zone of temperate climate with selection of building materials.

V: the zone of aeration.

V0: the zone of ventilation and natural ventilation.

EC: the zone of use of water conditioners.

EC0: the zone of use of the water conditioners in buildings with sunshields, with coloring the buildings in white.

AC: the zone requiring enhanced ventilation.

D: The zone, premises of which require humidifying the air.

W: The zone, premises of which require extracts/fans, using devices to reduce humidity.

H: The zone of significant influence of building materials on the thermal insulation of buildings.

H0: the zone of thermal insulation materials for buildings, depending on the climate."

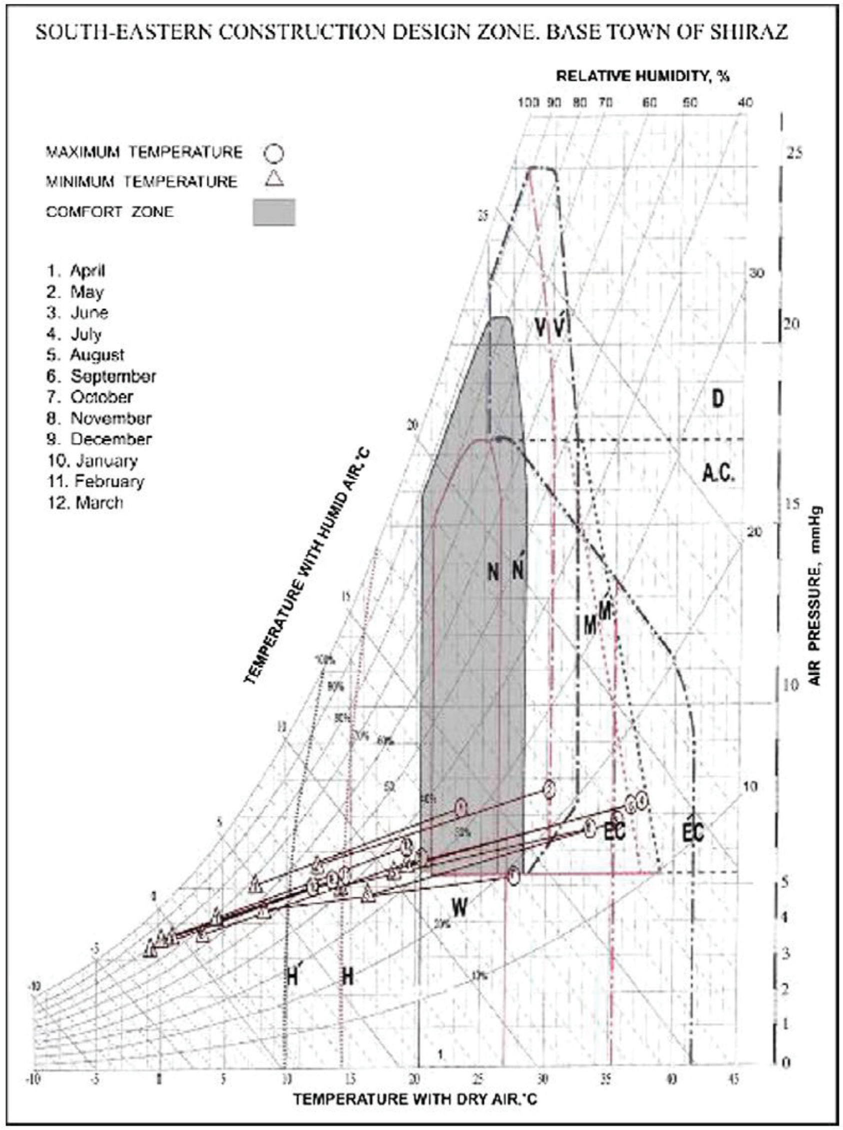


Figure 2.6. Climate-ecological modelling of space (for hot arid climate South-eastern Construction Design Zoning) (Source: Kasmai M., Ahmadinezhad, 2003; Tahbaz , Jalilian, 2008).

Circulation of natural air ventilation in hot and dry climate:

In Hot and dry areas, natural ventilation rate in the day should be minimum, because the inside air temperature is increased when there is entry of the warm air outside.

When humidity in these areas is low, even low-speed airflow can cool the body through sweat evaporation; therefore high speed is not necessary for air-cooling through evaporation.

Due to low outside air temperature, at night natural ventilation can quickly create cooling of internal air temperature levels.

To fully understand the potential contribution of natural ventilation system it is necessary to proceed through four stages.

Stage One- Reviewing the Literature:

To understand the influences of the parameters related to climate and weather conditions, the following aspects have been considered.

a) The climate of hot arid regions in general has to be understood.

b) The features of architectural buildings in hot arid regions have to be understood in terms of their importance, including the interaction of the arid climate and the buildings layout, orientation, material, colour of building, and the spatial arrangement of the structure.

c) Traditional wind-catchers within their architectural context have been analysed in terms of their impact on thermal comfort. Reviewing the history of wind-catcher in the Middle East and in the contemporary architecture can provide a wide perspective of the concept.

d) Natural air conditioning and thermal comfort below the wind-catchers, solar chimney walls can be studied. The performance of a wind-catcher in traditional buildings is compared with the contemporary performance requirements.

Stage Two- Determining the Experimental Requirements for Low-energy Cooling Techniques:

A typical traditional building in hot and dry climate and a number of typical ventilation systems have to be selected; models of them demonstrate similar characteristics to the real structure within their original context, leading to understanding the performance of wind-catchers. To achieve this understanding, the following aspects have been examined.

a) Experimental methodology of wind studies and circulation in the wind-catcher and another ventilation system (e.g. solar chimney wall) will be reviewed; leading to an understanding of the interaction between wind and a building
b) The procedures of ventilation and comfort conditions in the space will be identified and associated with wind-catchers and other systems like Trombe walls.

Stage Three- Performing The Simulation Studies:

A number of traditional wind-catchers will be selected, modelled and analysed and compared with another system of ventilation in hot and dry climate to understand the performance of different concepts of wind-catcher.

Stage Four- Discussion and indicating some of the Results:

Every aspect of research has its results, so in the final stage, the results obtained from previous stages have to be related together and discussed, to identify a good method and materials for final project in hot and dry climate and with regard to the new Islamic method/s, which will be mentioned in the trendy part of the natural air conditioning.

The potential contribution of natural ventilation system has to be assessed in form of the characteristics of hot-dry climates:

Hot arid climates usually have the potential for evaporation from the soil surface and from vegetation which exceeds the average annual precipitation. The capacity of the climate to acquire water evaporated from the soil surface and transpired from plants is often greater than the water added to the soil through precipitation (Trewartha, 1954).

Since water deficiency in any area depends not only upon the quantity of rain that falls but also upon the rate at which it is lost through evaporation and transpiration, called evapotranspiration; the process, in which water, is transferred from the land to the atmosphere by evaporation from the soil and other surfaces and by transpiration from plants.

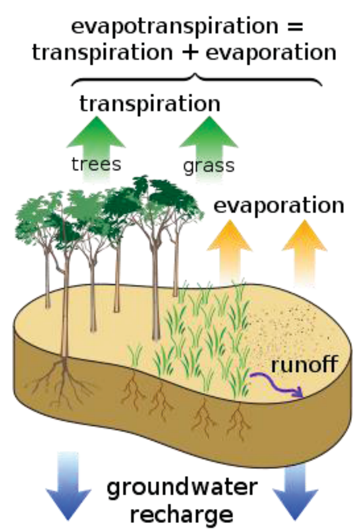


Figure 2. 7. Evaportranspiration [7]

[7] Source: https://commons.wikimedia.org/wiki/File:Surface_water_cycle.svg, 3/4/2011

> “It is clear that no specific amount of rainfall can be used to define the boundary of dry climates in any precise way. Instead it must be determined whether the precipitation is greater or less than the water needed for evapotranspiration.
> The boundary separating humid from dry climate is determined by a combination of rainfall and temperature conditions and not by rainfall alone. In such combination where water deficiency exceeds the water need, the climate is considered dry and, vice versa, where precipitation is in excess of the water needed, the climate is viewed as humid.” (Mahyari, Ali, 1996)

Air conditioning intrinsic problems:

Air conditioning systems have high-energy demands for cooling. In addition, the rates of airflow are often substantially higher than with simple mechanical ventilation systems, thus requiring heavy-duty energy guzzling fans. The additional proportion of energy consumption is not matched by a proportional increase in comfort. While a suitable building design combined with an appropriate environmental control strategy would obviate the need for such air conditioning, the system is often operated for large fractions of the day. There are obviously some circumstances in which air conditioning is necessary. However, its use should be justified by the particular circumstances.

In general it can be asserted that climate-sensitive design can eliminate the need for air conditioning in most instances. (Peter F. Smith, 2005).

Aspects of methods for optimizing ventilation inside the building:

Alternate Cooling Techniques include:

Comfort ventilation: which causes an increase in comfort by increasing airflow rates with the building.

Night purge ventilation: naturally or mechanically at night when the outside air temperature is presumably cooler than inside.

Thermal mass:

- Traditional examples include:
  - Dense building types with very thick walls
- Some of recent examples are:
  - "Trombe Walls"
  - Interior Water Walls or Containers
  - Phase Change Materials
- Seasonal Effects divided into the following:
- Cooling Season
  - Dampen the effect of outside temperature variations
  - Shift time of highest cooling loads to the night hours
  - Absorb excessive internal gains during daytime hours (usually combined with night ventilation strategies)
- Heating Season
  - Store solar energy absorbed for use during the night time hours when temperatures are low and the sun is not visible
  - Potential overheating problems due to excessive direct solar gains should be avoided. (Mahyari, Ali, 1996)

Passive buildings requirements:

Passive buildings require occupant involvement to ensure their success, unlike most contemporarily designed buildings that rely on "Thermostat" control to regulate the temperature and relative humidity (comfort) in buildings.

Occupants need to be educated as to when to open and close windows, raise and lower shades, and otherwise control some of the non-automated means of controlling the effects of the sun and wind on the interior environments of the building.

Because of limitations in achieving an interior climate that falls in the middle of the "comfort zone", sometimes Passive Buildings will require occupants to accept a wider range of acceptable temperature and relative humidity values.

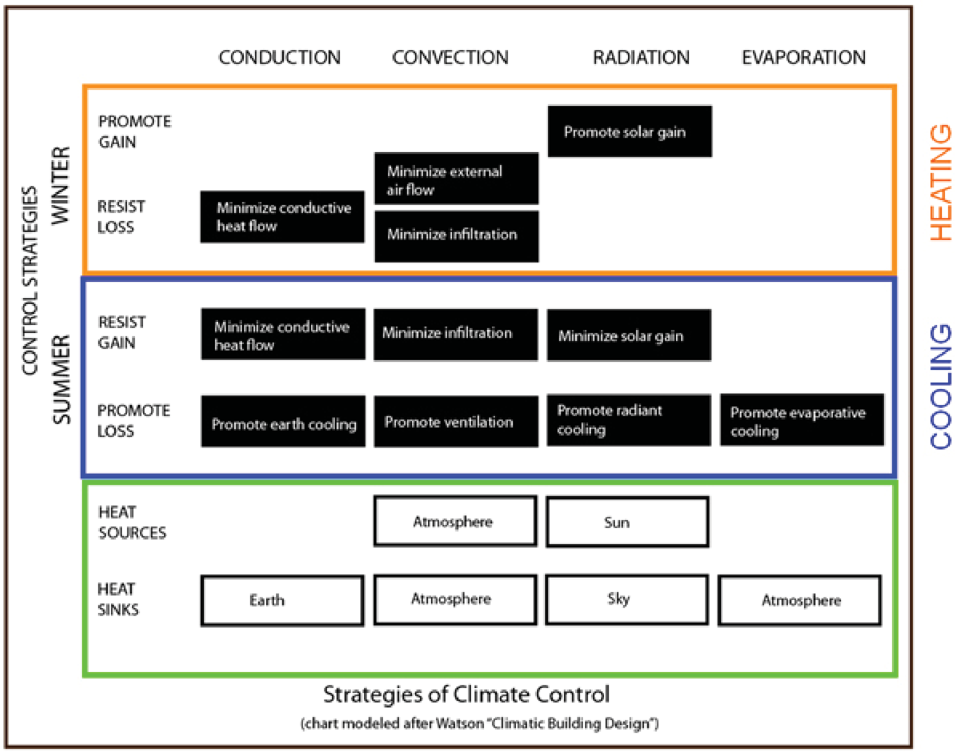


Figure 2.8. Strategies of climate control [8]

[8] Source :http://www.architecture.uwaterloo.ca/faculty_projects/terri/carbon-aia/strategies1d.html, 06/09/2011

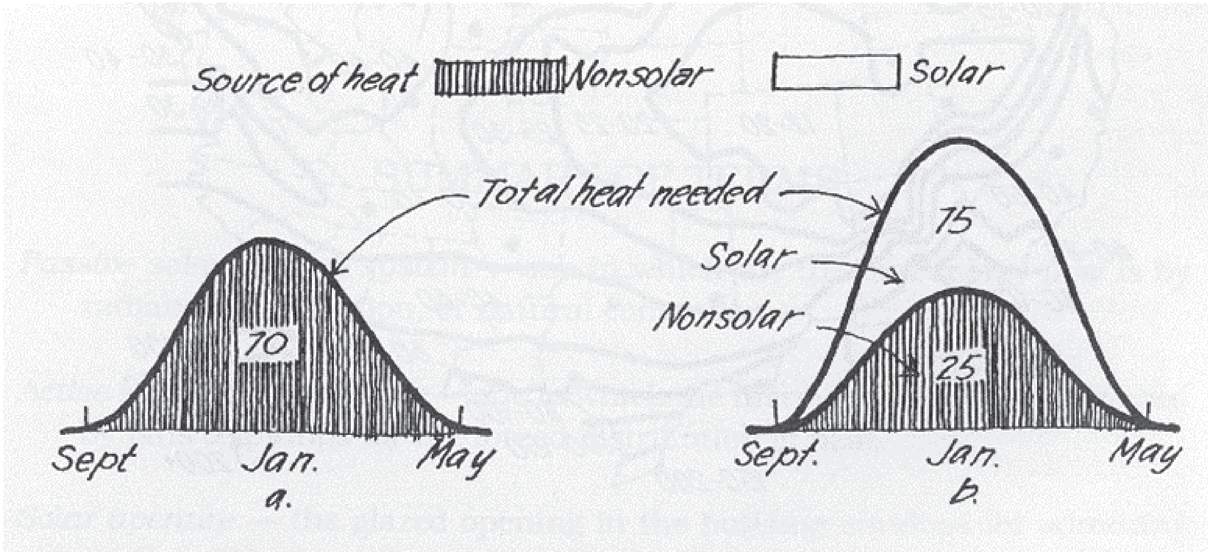


Figure 2.9. Performance comparison of: (a) Reference non-solar building and (b) Passive solar building. (Source: Redrawn from Stein et al., 1986)

Compare some systems taken together and analyze them:

Passive Cooling Techniques:

- Passive cooling systems are the least expensive means of cooling a home, which maximizes the efficiency of the building envelope without any use of mechanical devices.
- Relying on natural heat sinks to remove heat from the building. They derive cooling directly from evaporation, convection, and radiation without using any intermediate electrical devices.
- Using passive cooling strategies rely on daily changes in temperature and relative humidity.
- Applying each system depends on the climatic conditions in the different area.

- Selecting design strategies reduce heat gains to internal spaces. This is very important key to encourage the designer to use of advanced materials as well.

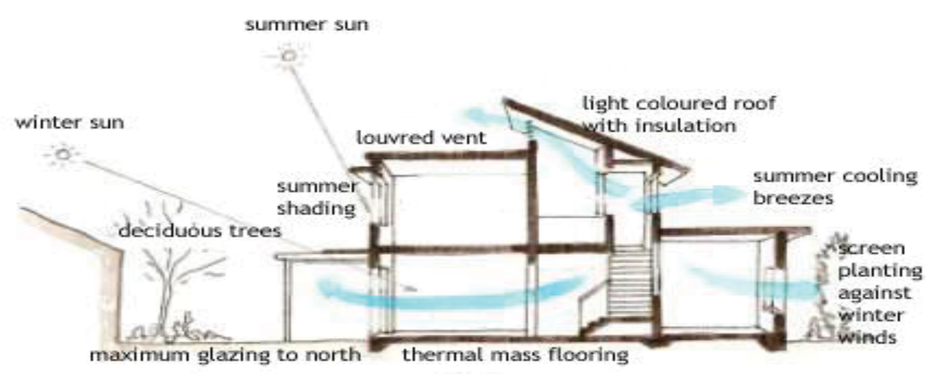


Figure 2.10. Differences between summer and winter

Some of passive cooling systems include:

A- Natural Ventilation
B- Shading
C- Courtyard Effect
D- Passive Down Draught Cooling
E- Earth Air Tunnels
F- Mechanism of the Evaporative Cooling
G- Roof Spray System
H- Trombe Wall
I- Wind Catchers

A. Natural Ventilation:

In order to have good natural ventilation, openings must be placed at opposite pressure zones. Outdoors breezes create air movement through the house interior by the 'push-pull' effect of positive air pressure on the windward side and negative pressure, which is created by suction on the leeward side.

Designers often choose to enhance natural ventilation using tall spaces called stacks in buildings, as well.
The windows play a dominant role in inducing indoor ventilation due to wind forces.
With openings near the top of stacks, warm air can escape whereas cooler air enters the building from openings near the ground.

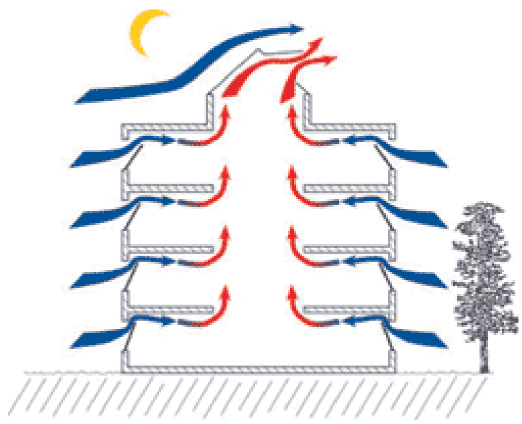


Figure 2.11. Direction of Wind (cool air) during the night. [9]

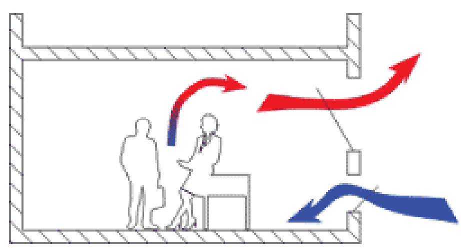


Figure 2.12. Direction of Wind during the night to remove hot air inside of small part of a building. [10]

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[9] Source: http://www.yourhome.gov.au/technical/pubs/fs46.pdf, 12/3/2010

[10] Source: http://www.yourhome.gov.au/technical/pubs/fs46.pdf, 12/3/2010

In most buildings, exhausting the warm air quickly can be a problem, thus creating inappropriate internal conditions.

With the design of high ceilings throughout the breeze zone combined with clerestory, which is a high window above eye level. Whit windows at the ceiling height on three walls, the rising hot air is allowed to escape. Also, the main purpose of making the clerestory is to bring outside light, fresh air, or both into the inner space.

Initially the rising air creates a low-pressure zone on the cool mass floor, pulling air along the floor from other areas of the house as well as any open doors.

Then the rising and escaping air creates an interior low pressure that should pull in large volumes or exterior air from the patio doors.

Depending on the primary wind direction and which doors are opened relative to time of day and shade, we can create a breeze of cooler incoming air.

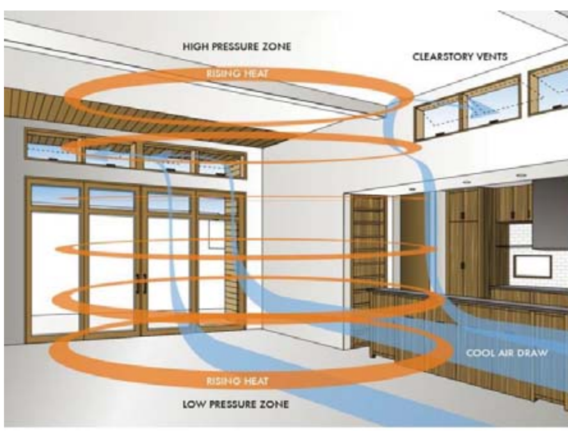

Figure 2.13. Differences between High Pressure zone and Low Pressure zone. [11]

[11] Source: http://imberaksehouse.ca/?cat=3, 12/3/2010

B. Shading:

- Heavily and multi insulated roofs and walls need less shading.
- Solar control is an effective method that is a critical requirement for both cooling-load dominated and passively solar-heated buildings.
- The most effective and old method of cooling a building is to shade windows, walls and roof of building from direct solar radiation.
- Overhangs on outside facade of the building are suitable and have effect on the buildings.
- Use slatted or louvered shades to allow more daylight to enter, while shading windows from direct sunlight.
- Extend the overhang beyond the sides of the window to prevent solar gain from the side.
- Reduce solar heat gain by recessing windows into the wall.

Figure 2.14. A simple sketch of reduce solar heat by add louver shades. [12]

C. Courtyard Effect:

- Due to incident solar radiation in a courtyard, the air gets warmer and rises. If the roof surfaces are sloped towards the internal courtyard, cooled replacement air sinks into

[12] Source: http://www.sustainable-buildings.org, 12/3/2010

the court and enters the living space through low-level openings. Then it gets warmed up, and leaves the room through higher-level openings.

- Cool air from the ground level flows through the louvered openings of rooms surrounding a courtyard, thus producing airflow.
- At night, convection and radiation cool the warm roof surfaces.
- If this heat exchange reduces roof surface temperature to wet bulb temperature of air, condensation of atmospheric moisture occurs on the roof and the gain due to condensation limits further cooling.

Figure 2.15. The role of Court Yard to ventilate indoor buildings. [13]

[13] Source: http://www.sustainable-buildings.org/index.php?option=com_cstudy&task=details&sid=84, 12/3/2010

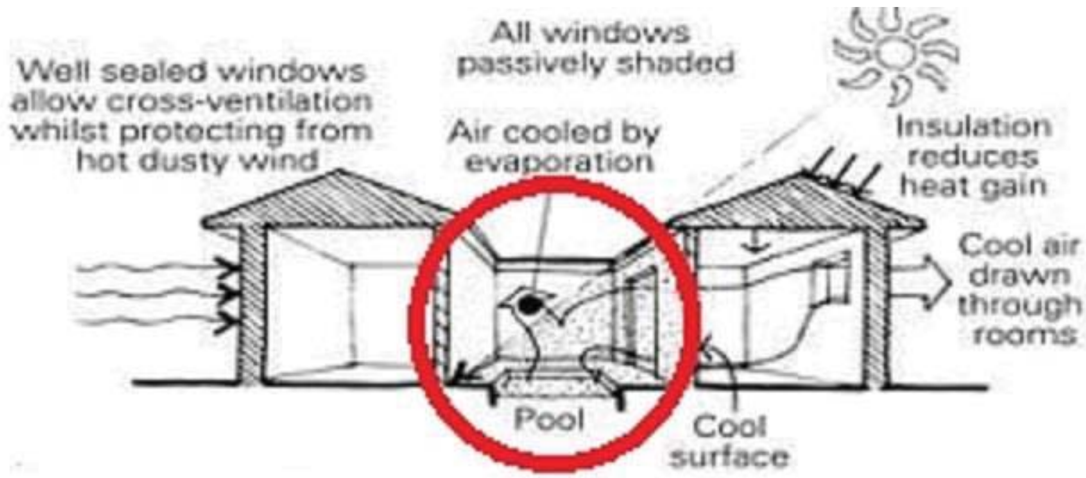

Figure 2.16. The role of the pool in the court to ventilate cool air. [14]

- However, the courtyard does not receive intense solar radiation. It would lead to conduction and radiation heat gains into the building.

D. Passive down Draught Cooling:

- Evaporative cooling has been used for many centuries in parts of the middle-east countries, notably in Iran and Middle East countries.

[14] Source: http://www.sustainable-buildings.org, 12/3/2010)

- In this system, wind-catchers escort outside air over water-filled pots, inducing evaporation and causing a significant drop in temperature before the air enters the interior.

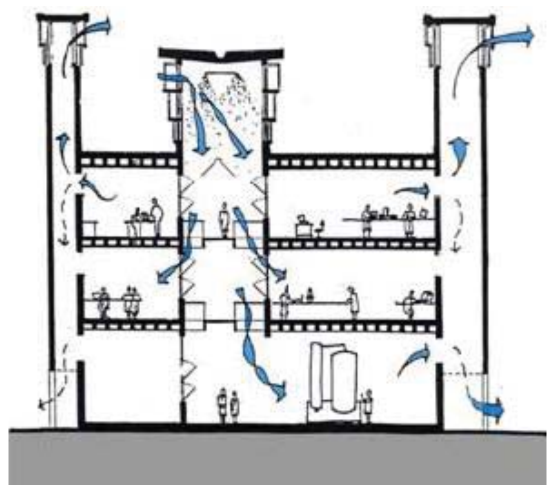

Figure 2.17. Function of Passive down Draught. [15]

- Such wind-catchers become primary elements of the architectural form.

- Passive down draught evaporative cooling is particularly effective in hot and dry climates. It has been used to effectively cool the Torrent Research Centre in Ahmedabad. (Source: Torrent Research Centre in Ahmedabad: http://besharp.archidev.org/spip.php?article139, 2010).

[15] Source: www.sustainable-buildings.org, 12/3/2010

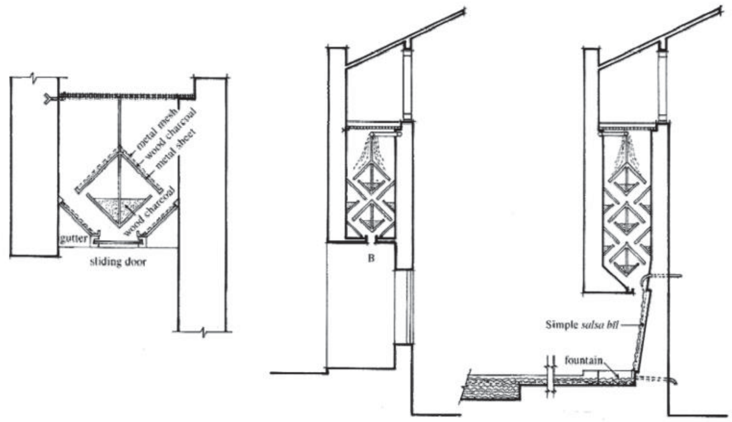

Figure 2.18. Other details of passive down draught wind-catchers. Sprinkle the water on the wall. [16]

Figure 2.19. Passive down draught cooling in Ahmedabad. [17]

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[16] Source: www.sustainable-buildings.org, 12/3/2010

[17] Source: www.sustainable-buildings.org, 12/3/2010

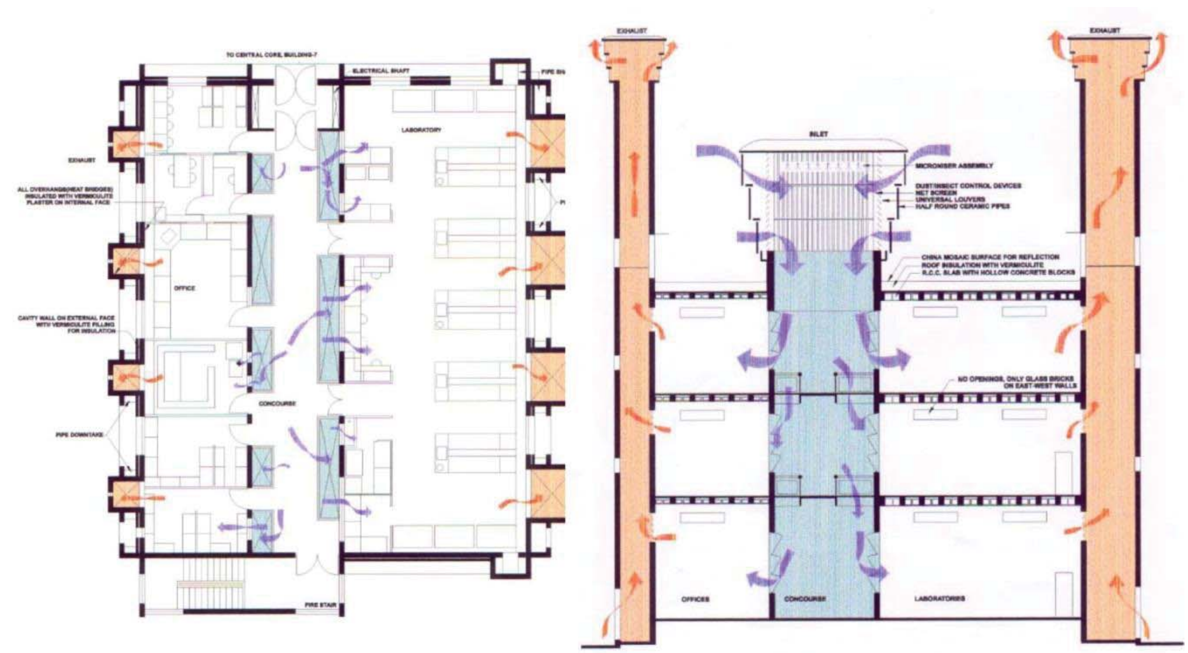

Figure 2.20. (Left) First Floor Plan (Right) Section. [18]

Earth Air Tunnels:

Some features of earth air tunnel include:

- In this kind of system, daily and annual temperature fluctuations decrease with the increase in depth below the ground surface.
- A tunnel in the form of a pipe or otherwise embedded at a depth of about 4 m below the ground will acquire the same temperature as the surrounding earth at its surface.
- The temperature inside the earth remains nearly constant round the year and is nearly equal to the annual average temperature of the place, at a depth of about 4 m below ground.

[18] Source: www.sustainable-buildings.org, 12/3/2010

- In conclusion, the ambient air ventilated through this tunnel will get cooled in summer and warmer in winter. This air can be used for cooling in summer and heating in winter.

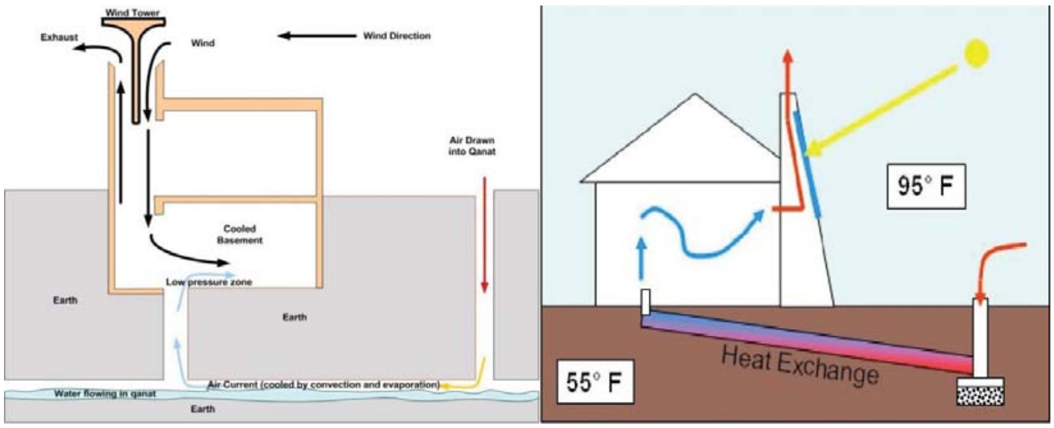

Figure 2.21. The role of Earth air Tunnel in ventilation with: (Left) Wind-catcher (Right) Solar Chimney. [19]

- Two blowers installed in the tunnels speed up the process.
- It creates an air current for the cooler air from the underground tunnels to replace the warm air. Because of the cooler air underground, this needs to be circulated in the living space. Each room has a solar chimney; warm air rises and escapes through the chimney.
- During winter, the same mechanism supplies warm air from the tunnel.

[19] Source: http://www.sustainable-buildings.org, 12/3/2010

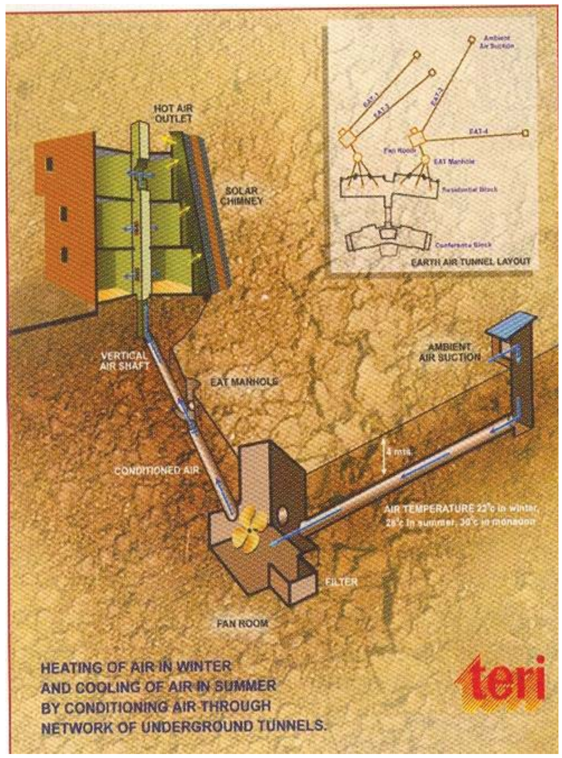

Figure 2.22. Passive Space Conditioning Using Earth Air Tunnel System. [20]

E. Mechanism of the Evaporative Cooling:

- This system is effective in hot dry climates where the atmospheric humidity is low.
- Evaporating water is the reason why evaporative cooling lowers indoor air temperature.

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[20] Source: http://www.sustainable-buildings.org/index.php?option=com_cstudy&task=details&sid=24, 12/3/2010

- In evaporative cooling, the sensible heat of air is used to evaporate water, thereby cooling the air, which, in turn, cools the living space of the building.
- Increases the rate of evaporation by increasing in contact between water and air.
- The presence of a body of water such as a pond, lake, and sea near the building or a fountain in a courtyard can provide a cooling effect.
- The most commonly used system is a desert cooler, which comprises water, evaporative pads, a fan, and pump.

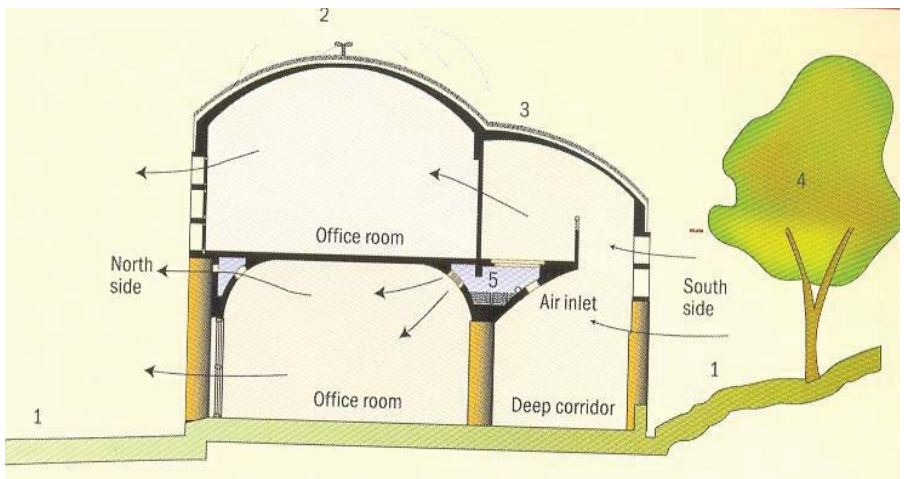

Figure 2.23. 1. Ground cover; 2.Water sprinkler; 3.Insulated roof; 4.Shading trees; 5.Water trough [21]

F. Roof Spray System:

As a matter of fact, in this kind of system solar energy impacting on the roof surface can be negated before any of the other building's defense mechanisms come in to play. And since no humidity is added to the space, this strategy is suitable even in a humid climate, such as exists in north of Iran.

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[21] Source: www.sustainable-buildings.org, 12/3/2010

The space inside is cooled indirectly and excess humidity is kept outside, by cooling the exterior skin of a structure. In addition, by attacking heat at the roof surface, evaporative cooling is utilized where temperatures are highest (due to greater exposure to radiation) and relative humidity is lowest because air will hold more water vapour at higher temperatures. This system is available when the water are available.

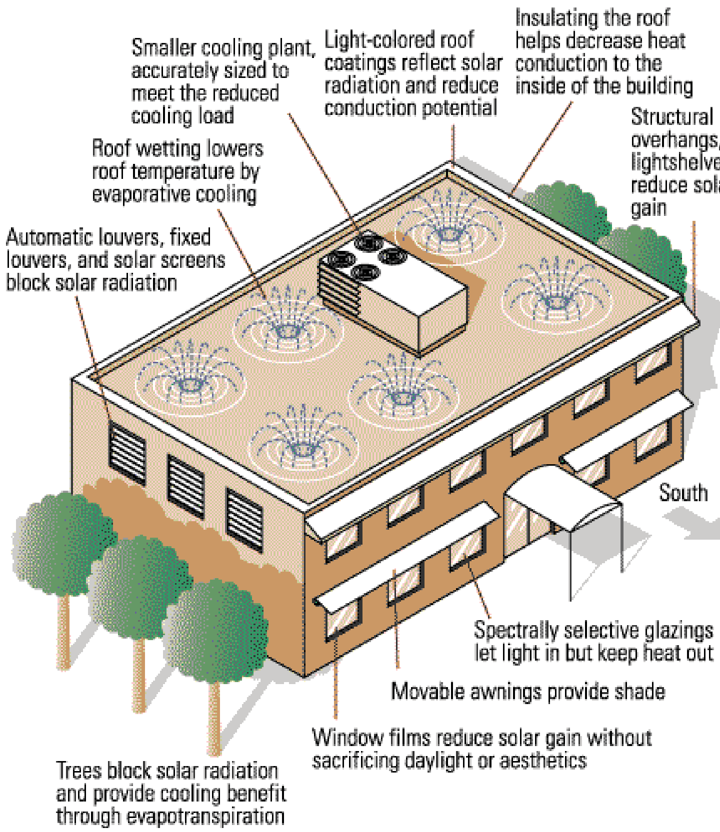

Figure 2.24. Some details of Roof Sprays. [22]

[22] Source: www.sustainable-buildings.org, 12/3/2010

G. Trombe wall:

Definition and performance of the Trombe wall:

Trombe wall is a form of active solar thermal systems that is indirect gain, which means:

> "In this form of design a heat absorbing element is inserted between the incident solar radiation and the space to be heated; thus the heat is transferred in an indirect way. This often consists of a wall placed behind glazing facing towards the sun, and this thermal storage wall controls the flow of heat into the building. The main elements High thermal mass element positioned between sun and internal spaces, the heat absorbed slowly conducts across the wall and is liberated to the interior some time later."
> (Source: Peter F., Smith, 2005, Architecture in a Climate of Change, Architectural Press, Oxford, pp. 49-50)

Theory of Trombe Walls:

- Primarily a passive heating element used to delay the impact of solar radiation.
- Intended to cooperate with direct gain through windows to provide heating via solar radiation during all parts of the day and night.
- Most useful on south, southeast, and southwest facades in the buildings to absorb better the sun radiation.

System components of Trombe Walls:

- Thermally massive wall that is constructed with brick, concrete, stone and water, painted a dark color to absorb solar radiation.
- Air gap is added to in this kind of system and helps the performance of the Trombe wall.
- Wall cover must be transparent glass to allow sunlight to get through to the thermal mass and to block some of the heat loss to the outside environment.

Open Trombe Walls versus Closed Trombe Walls:

- Some features of the open Trombe-wall system are include:
    - Similar to a mini-sunspace where the air in the gap between the cover and the wall mass is allowed to circulate to an interior space.
    - More important if no visual link to the outside.
    - These have fallen out of favour in the United States of America, due to difficulty in controlling the amount of exchange between the air gap and the attached space and owing to the loss of the delay factor that is easier to combine in wall with windows; also it raises maintenance issues.
- The features of the closed system are:
    - Air gap between the wall mass and the cover is sealed.
    - Heat is trapped and absorbed better into the thermal mass.

Performance of the Trombe Walls:

- This system is the best for heating when wall mass has both a high storage capacity and a high thermal conductivity. High thermal conductivity increases heat gain/loss of the overall wall assembly.
- Wall cover should be as transparent as possible but also thermally resistive.
- Solar gain must be kept out of the Trombe wall in summer through use of:
    - Shading devices
    - Specialized transparent insulation materials
    - Electrochromic or thermochromic glazing
- Trombe walls are usually but not necessarily restricted to simple flat south-facing walls.

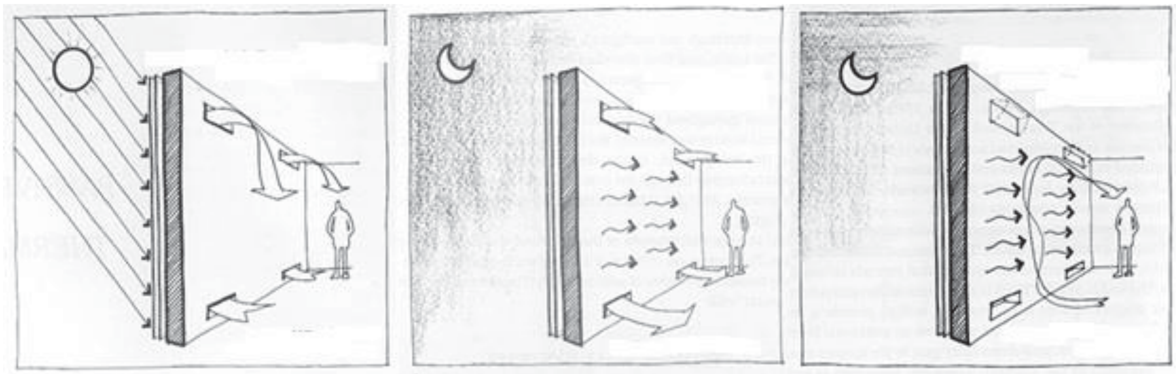

Figure 2.25. Different direction of air ventilation during the Day and the Night. [23]

Whether or not a wall has flaps, and flaps that automatically close off when the air direction reverses, becomes a critical issue in making sure that preheating of the room occurs in the morning hours.

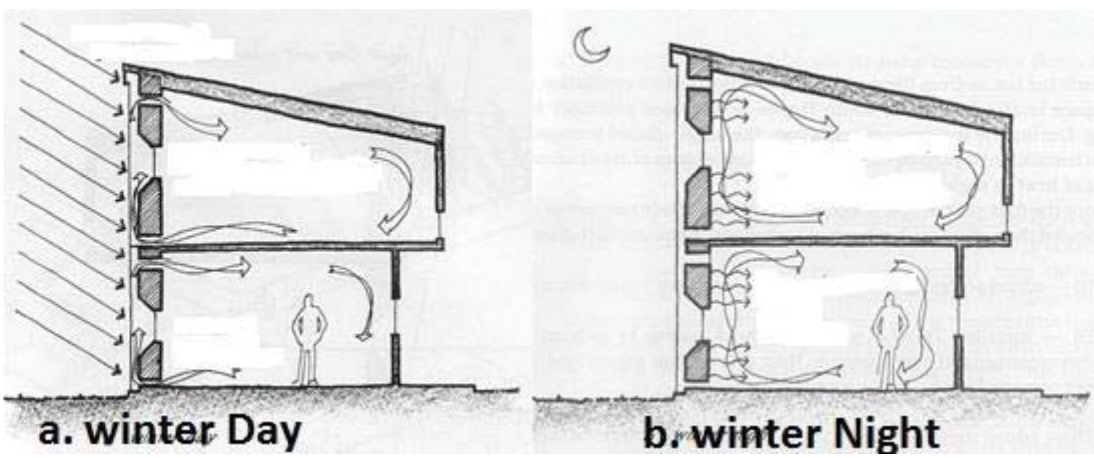

Figure 2.26. The features of the Trombe wall in (a) winter day (b) winter night. [24]

[23] Source: images.google.com, 12/02/2012
[24] Source: images.google.com, 12/02/2012

Different ventilation details of the Trombe Wall:

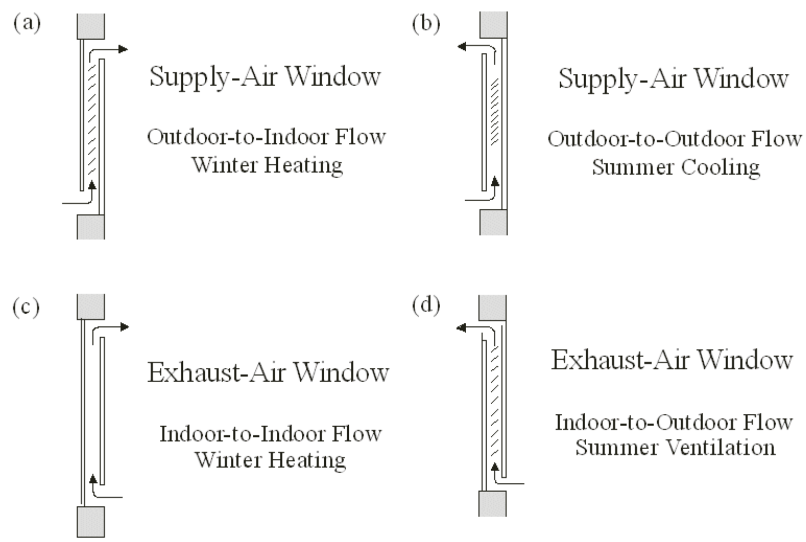

Figure 2.27. Airflow windows to preheat incoming ventilation air and the application (Source: Gosselin , Chen ,2008, http://www.sciencedirect.com/science/journal/03787788)

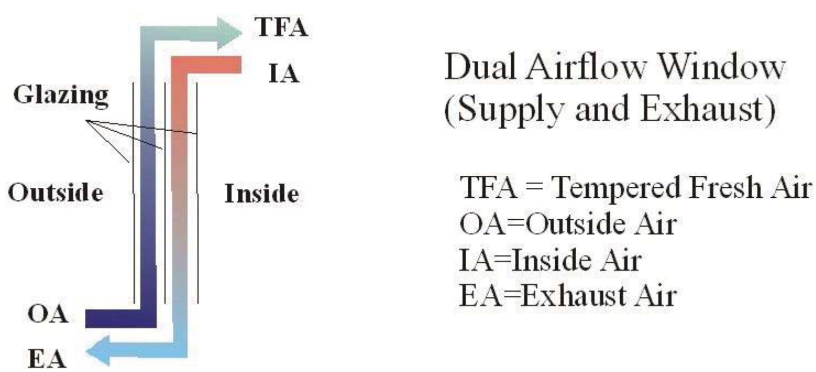

Figure 2.28. Triple-glazed air flow window serving as a counter flow heat exchanger. (Source: Gosselin , Chen ,2008, http://www.sciencedirect.com/science/journal/03787788)

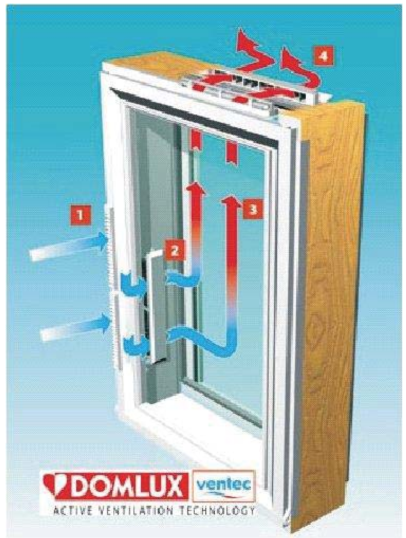

Figure 2.29 An airflow window showing (1) external air inlet, (2) sound-attenuating filter, (3) gap between glazings, where the air warms, and (4) adjustable discharge vent. (Source: www.domus.fi, Original source: Energy and the new reality 1: energy efficiency and the demand for energy services, Leslie Daryl Harvey, 2010, PP. 138-140)

Conclusion:

A study of this kind of requirement confirmed that most of the traditional principles, elements, and methods of architectural and structural morphology correspond to the objective conditions of climate, culture, religion, and way of life in Iran. These four major factors of architecture have ensured that the shape of the dwellings remained unchanged for centuries and have retained their importance even nowadays. The new levels of development of buildings throughout the country should be qualitatively based on the development of national traditions in architecture, bearing in mind the ecology of human beings, natural-climatic zoning, climate-ecological modeling of spaces, and conservation and restoration of the environment. Adaptations are required mainly related to working out the problems of new construction, increased construction volumes, high levels of comfort and improved quality of life. They are also related to the contemporary expansion of the typology of buildings and structures.

Chapter III. Natural air conditioning – wind catchers

Wind-catchers or wind towers are design features common in hot dry climate, typically in central Iran. They rely on a complex system of technical and material design features which, together, influence their overall performance.

In the preceding chapter, various strategies for using natural process and forces to contain heat gain in hot and dry climates are explained. In this chapter, the principle behind wind catchers are derived from an examination of examples in order to be able to propose modification or innovation in their designs.

Interestingly by the mass of this structure the incoming air would be cooled and effect the microclimate indoors in regions in hot and humid climates in southern of Iran, where the air temperature rises to 50 centigrade in summer and the heat combined with humidity provide very adverse conditions.

Performance of the Wind-Catcher:

- In a wind-catcher, the hot air enters the tower through the openings in the tower, gets cooled, and thus becomes heavier and sinks down.
- The inlet and outlet of rooms induce cool air movement.
- In the presence of wind, air is cooled effectively and flows faster down the tower and into the living area.
- After a whole day of air exchanges, the exterior membrane of the tower becomes warm in the evenings.
- The walls absorb heat during daytime and release it at night, which cause warming the cool night air in the tower.
- During the night, cooler ambient air comes in contact with the bottom of the tower through the rooms.

- Warm air moves up, because warm air is lighter than the cool air, which creates an upward draft, and draws cool night air through the doors and windows into the building.
- The system works effectively in hot and dry climates where fluctuations are high.
- A wind catcher works well for individual units not for multi-storied apartments, so this kind of ventilation system is appropriate for individual spaces.
- Design in dense urban areas, the wind catcher has to be high enough to be able to catch enough air.

Note: According to this specific characteristic, urban designers are able to create new spaces in neighbourhoods for better ventilation in the Islamic cities.

- The protection from driving rain is difficult in this system.

Figure 3.1. Wind - catcher in Yazad, Iran. [25]

[25] Source: Wind tower section, http://www.brightdirections.co.uk/best.php?q=wind-tower-section, 15/04/2013

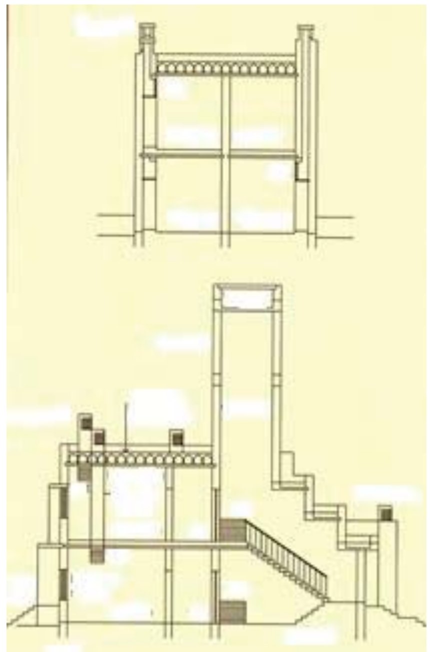

Figure 3.2. Wind-tower in Jodhpur Hostel to catch favourable cool wind from south-west for passive cooling. [26]

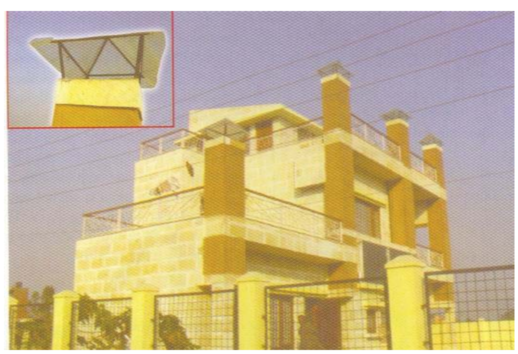

Figure 3.3. Building-integrated chimney in Sudha and Atam Kumar's residence in New Delhi from effective ventilation especially during humid season. [27]

[26] Source: www.sustainable-buildings.org, 12/02/2011

[27] Source: www.sustainable-buildings.org, 12/02/2011

The history and the definition of wind-catchers:

Wind-towers or Wind-catchers as the name implies, are ventilated architectural elements for natural air conditioning by wind. They have been used for centuries in several countries with hot and dry climates, particularly in the Middle East. Bad-gir and Malqaf are respectively the indigenous Persian and Arabian names for wind-towers and literally mean wind-catcher.
As a matter of fact in the traditional architectures, a typical wind-catcher consists of a tower and a head projecting above the roof of the building. The tower head may have vents on only one side facing the predominant wind direction.

There is literary evidence in the historical Persian context that a new form of wind-catcher, called "badahanj" from the Persian meaning "drawer of wind", was introduced from Iran to Egypt (Rosenthal, 1978, p. 2).
Several different forms of the "badahanj" were built in the houses of Cairo and later, in the fourteenth century, they became known as "malqat " (Lezine, cited in Roaf 1988). Some historical evidence of the more elaborate examples has been recorded. Experts suggest that wind-catchers were associated with the two recesses at the back of the great throne hall in Babylon (c.600 BC) and again with the sophisticated air circulation system at the Sassanian fire temple at Firozabad (c.250 AD). There were also six fourteenth century examples of the first proven cases of wind-catchers on the Plateau (Dasht-e-Iran), one in Khorasan (North East Iranian province) and five in Yazd, which are two historical and important Iranian cities (Roaf, cited in Beazley, et al., 1982)
The simplest example of wind-catchers is reputedly found in the Mochica Indians of Peru (200 BC - 700 AD). (Figure 3.4) They used wind-catchers to ventilate their buildings. This is interpreted from a pot, representing a three-story house with several wind catchers toward the sea on its roof (Rudofsky 1964, Von Hagen cited in Roaf, 1988). This example is widely

used as historical evidence of early wind catchers but the lack of its continuation in building in Peru over the history calls this evidence into question.

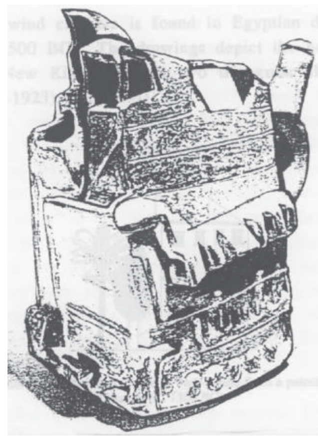

Figure 3.4. A pot representing wind-catchers, OD tile roof. Made by tile Modlica Indians of Peru. (Source: Roaf. 1988, “The Wind catcher of Yazad”, PhD Thesis, Department of Architecture, Oxford Poytechnic, pp. 35)

The wind catcher concept is also used in an extremely primitive fashion by the Bedouin of Cyrenaica to ventilate and cool their tents. It is a simple vent consisting of a woven extension of the tent cloth supported on sticks (Peters, cited in Roaf, 1988). Also the historical name of this kind of wind-catcher in Iran is Kapar/Kafar, which has been used for a long time. (Figure 3.5).

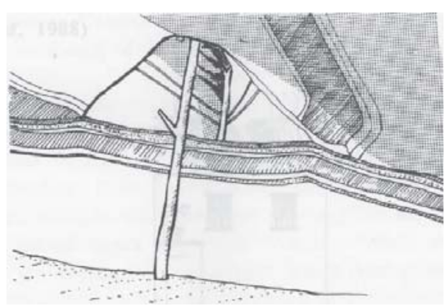

Figure 3.5. Interior of Cyrenaican Bedouin tent sbowing tile stick supports of tile tent cloth wind catcher. (Source: Peters. ciled in Roaf. 1988, “The Wind catcher of Yazad”, PhD Thesis, Department of Architecture, Oxford Poytechnic, pp. 36)

However, two, three or four sides of the tower may also be open to accommodate wind in all directions. The tower would be subdivided, respectively, into two or more groups of shafts. This subdivision allows air to move separately up and down the tower at the same time and provides more surface area in contact with the air. Consequently, the roof-top breeze is drawn and is diverted to the summer living spaces, or vice versa, the indoor air is exhausted.Around 1500 BC, Archaeologists found one example of wind-catchers in Egyptian drawings on papyrus. The drawings depict the house of the wealthy of the New Kingdom with two triangular shaped wind catchers (Davies, 1923), (Figure 3.6).

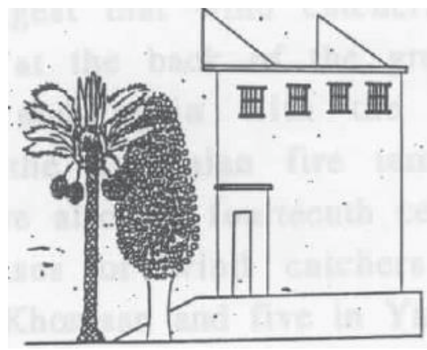

Figure 3.6. Wind catcher of the Pbaraonic house of Neb-Amon from a painting 011 his tomh, nineteen Dynasty (C. 1300 BC). (Source: Mahmudi, Mahnaz & Mofidi Shemirani, Seyd Majid, Identity of Iranian Wind-catcher and the history, 15/04/2013, pp. 27)

Around 1300 BC, another example of the wind-catcher is found in a painting on the walls of the Neb-Amon tomb from the middle Kingdom. It is suggested there are two wind-catchers facing in opposite directions (Badawy 1958, Rudofsky 1977, Beazley et al., 1982, Fathy, 1985, 1986). (Figure 3.7) Roaf argues that it is possible those elements may be the stair-wells to roofs. But she indicates that certainly examples where the apex of the angular roof coincides with an outer wall are more likely to be wind-catchers (Roaf, 1988)

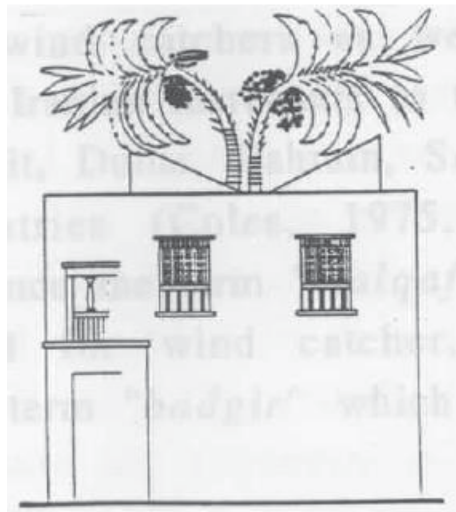

Figure 3.7. Picto-graph 011 Papuri found in the tombs of the New Kingdom in Egypt (l580-3m BC) (Source: Badawy 1948.and FathY 1986).

. European travellers had recorded wind-catchers with interest, including Marco Polo in the thirteenth century. They were very popular from the seventeenth century, in most of the cities of Iran, notably in Yazd, located on the "silk road", an important centre of trade and intellectual activities in that era.

They can be seen on buildings today from Pakistan to Egypt in many different shapes and sizes where the climate is hot and dry or as mentioned previously in some relatively humid regions. However, they are not found in the temperate Mediterranean coast regions of Syria, Lebanon, Palestine, Caspian coast and mountainous area of Iran, and the heartlands of Arabia.

> “The technology of the wind-catchers as well as the term "badgir" were carried by Iranian merchants to the other side of the Persian Gulf in Kuwait, Emirates, Bahrain, Saudi Arabia, and other countries. (Coles, 1975, Golany 1980, Beazley, et al., 1982). Since the term "malqaf" is the Arabian (Egyptian Arabian) word for wind-catcher. Other Arabian countries use the Persian term "badgir" which strengthens this

suggestion. Despite the advent of mechanical equipment, wind-catchers are still considered cheap and efficient enough to be constructed in many villages and cities such as Yazd and Kerman in Iran. There are thousands of wind-catchers exist today, from one to six hundred years. (Roaf, 1988)" (Mahyari, Ali, "The Wind catcher", PhD Thesis, Sydney University Australia, 1996)

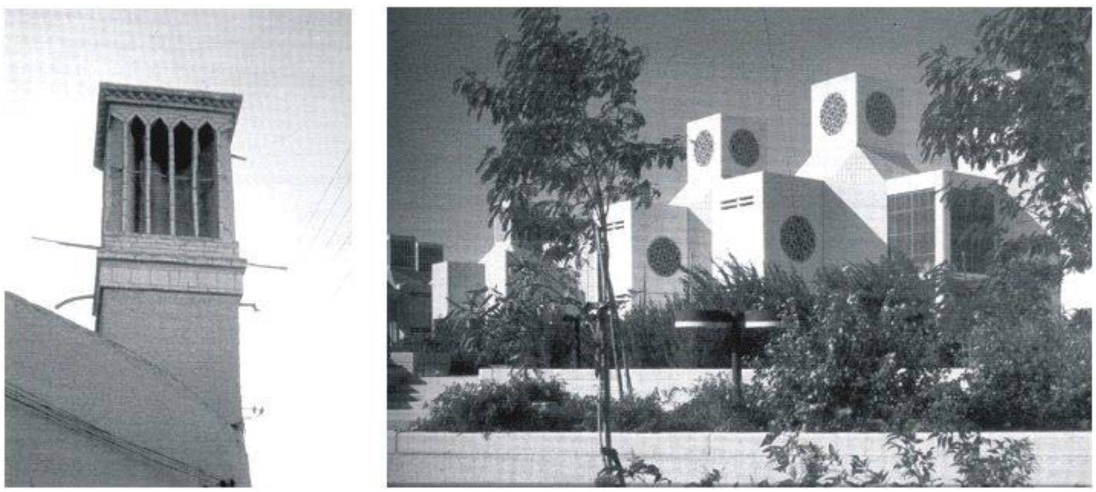

Figure 3.8. Winds catchers in Iran (Left) and Doha (Right). (Source: Koch-Nielsen, 2002)

Figure 3.9. Wind catcher at Sir Sanfred Fleming College, Peterborough, Canada. (Source: Loghman Azar, Line Architects, Toronto)

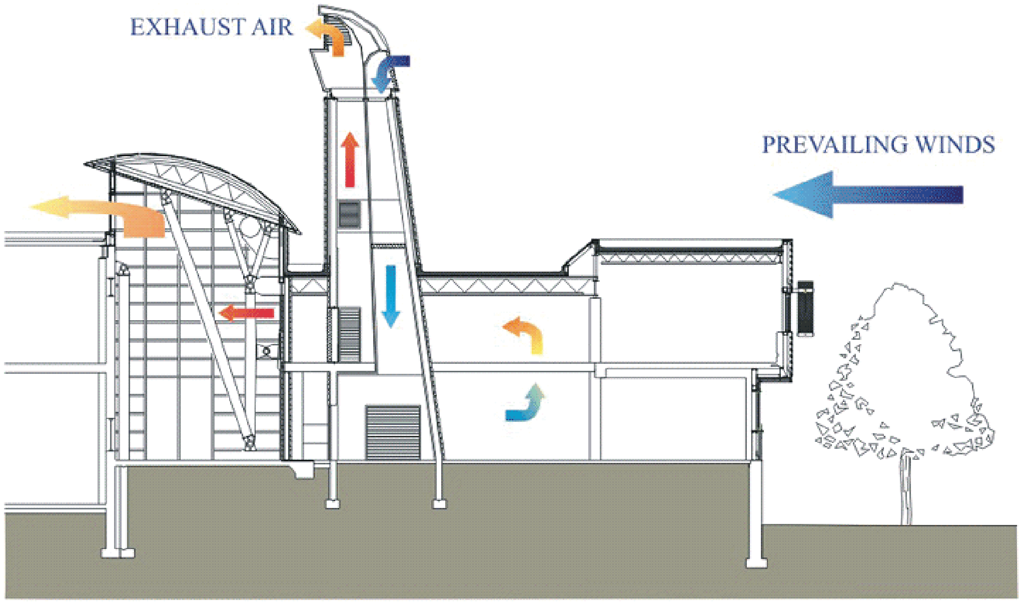

Figure 3.10. Airflow at Sir Sanfred Fleming College, Peterborough, Canada. (Source: Loghman Azar, Line Architects, Toronto)

Review of the function of a Wind-catcher:

To maximize cooling ventilation through the air movement in hot and arid zones ingenious devices for catching the wind were designed. These devices are strikingly different in appearance, dependent on wind direction and site. When there is strong prevailing wind direction, different types of wind scoops all aimed in the same direction were designed (Lechner, 1991). These devices are characterised by the opening surfaces that facing cool breeze and are located at a high point in the house. The roof of that opening is inclined at an angle designed to divert the wind downward toward the airshaft and directly to the rooms and corridors. The different design of wind scoops in Yazd in Iran and Dubai in Arabic Emirates were devised to catching prevailing winds, as seen in the following figures.

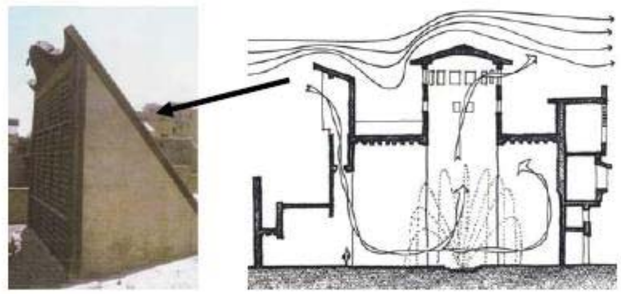

Figure 3.11. Malqaf, a Cairane house, Egypt. (Source: Fathy, 1986)

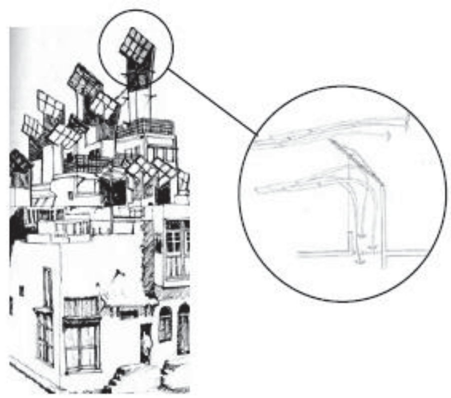

Figure 3.12. The wind scoops in Hyderabad, Pakistan. (Source: Fathy, 1986)

When there was no prevailing wind direction, wind-catchers with many openings were used as in Iran and other Arabic countries, close to the Persian Gulf. (Battle McCarthy Consulting Engineers, 1999).

These towers rise above the roof and are divided by internal blades. They create separate air ducts. (Figure 3.13)

Figure 3.13. An example of wind-catcher and internal blades wind-catchers in Iran. (A'zami, 2005)

At the leeward side, warmed interior air will be sucked out. At the windward side, air is led through the channels to the interior space of building. (Figure 3.14 a). In the absence of wind, the towers continue to ventilate rooms through stack effect (A'zami, 2005) (Figure 3.14 b).

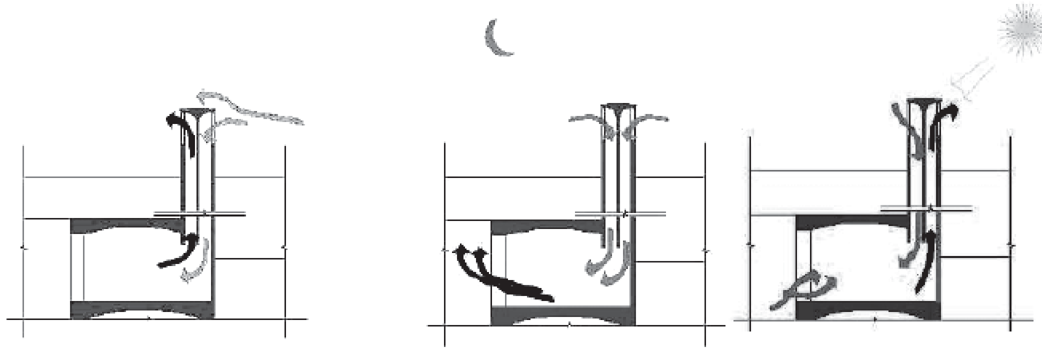

Figure 3.14. (a) Traction and suction in wind-catcher (b) Air movement during the day and night by stack effect. (A'zami, 2005)

The smart combination of domed roof, wind-catcher and fountain which, in some cases in Iran which date back to about 900AD (Bahadori, 1978), were instrumental in creating better thermal comfort for occupants of the building (Figure 3.16). In some cases architects used their talent and experience to create a unique shape (Figure 3.17).

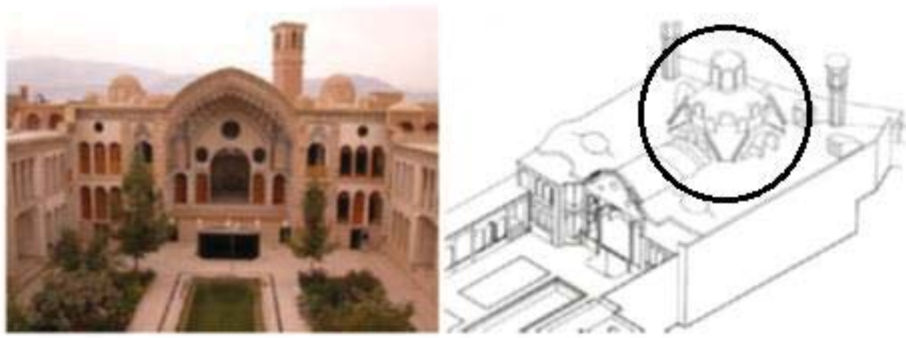

Figure 3.15. Emrani House (left), Borujerdi House (right). [28]

Figure 3. 16. Outside and inside the wind catcher of Borujerdi House[29]

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[28] Source: Borujerdis_House , http://en.wikipedia.org/wiki/Borujerdis_House, 2/12/2011
[29] Source: Borujerdis_House , http://en.wikipedia.org/wiki/Borujerdis_House, 2/12/2011

Figure 3.17. Some unique design of wind-catcher in Iran. [30]

Analysis of wind-catchers:

Performance and related aspects of the design of wind-catcher:

A wind-catcher is a device with real form and constant structure in Iran architecture, it leads the suitable wind through the inner part of the building and it makes a significant contribution to comfort. There are actually two kinds of main functions for wind-catchers:

- The function depends to the principle of traction of opening facing the wind and the suction of openings back against the wind.
- It is also working according to temperature difference.

A typical wind catcher look like a chimney, with one end rising from the roof and the other end in the basement of the building. The upper part of the tower is divided into several vertical air passages that terminate in openings in the sides of the tower. Tower designs differ in the height of the tower, the cross section of the air passages, the placement and number of the

[30] Source: http://www.a2plus.it/%D8%B7%D8%B1%D8%A7%D8%AD%DB%8C/?lang=fa, 4/4/2013

openings and the placement of the tower with respect to the structure it cools. The hot and dry regions of some of the Islamic countries and Iran have fairly fixed seasonal and daily patterns of wind. The "wind-catcher, harnesses the prevailing summer winds to cool the air circulation through a building. (Bahadori, Mehdi, 1978)

The wind-tower operates by changes in the temperature and thus the density of the air in and around the tower. The difference in density creates a draft, pulling air either up or down through the tower. Doors in the lower part of the tower open into the basement, especially in the summer, and the central hall of the main floor of the building. Opening or closing the doors from the tower and the doors of the rooms off the central hall can control the flow of air through different parts of the building.

Wind condition and the time of day affect the operation of the tower. Moreover, the tower can operate like a chimney, when there is no wind at night, the tower circulates air by pulling it upward and out through the tower openings.

Wind catcher is separated into numerous vertical air passages by internal partitions or shafts. The shafts on top end in to opening on the sides of the tower head. The flow inside the wind tower is in two directions, up and down. Precisely, when the wind blows from one direction the windward opening will be the inlets and the leeward opening will be the outlet and vice versa.

. The mechanisms as follows. The chimney walls that is including the internal walls that separate the air channels. It has absorbed heat during the day. Since heat flows in the direction of reducing temperature, the walls transfer heat to the cool night air in and around the chimney. The configuration of the upper part of the chimney, specifically the thickness of the walls and the cross section of the air passages, is designed to provide adequate heat-storage capacity and heat-transfer space for the task. Since the warmer air is less dense, the air pressure at the top of the tower is reduced, due to creating an upward draft.

The air in the building is drawn up through the chimney, and cool ambient air is pulled into the building through the doors and windows. The process continues during the night, so that cool air is kept circulating through the construction.

When there is a wind at night, the air is forced to circulate in the opposite way; the accommodations are cooled by night air coming down the chimney rather than through the doors and windows. Nevertheless, the chimney walls warm the night air before it enters the building, the cooling can still be sufficiently effective to bring the temperature in the construction close to that of the ambient air. The exterior walls and the roof of the building radiate kept solar heat to the night sky, which further cools the building. Since the desert sky, especially in Iran, tends to be very clear at night, the radiative heat transfer to it is particularly effective.

When there is no wind during the day, the operation of the tower is the reverse of a chimney. The walls of the upper part of the chimney have been cooled during the prior night. Hot ambient air comes in contact with them and is cooled. Being denser than the hot air, the cooled air sinks down through the chimney, creating a downdraft. The cooled air is pushed through the construction and ultimately out through the doors and windows, entraining area air with it (Bahadori, Mehdi, 1978).

So there are two conditions: A) if there is no wind during the day, when the temperature of the tower reaches that of the ambient air, the circulation of air down through the tower and into the building ceases and the tower begins to operate like a chimney. B) When there is a wind during the day, the rate of circulation is increased. The cool air can be circulated through any room in the building by the appropriate arrangement of doors in the tower and the rooms. The operation of the chimney is not constant throughout the day and night. Because the cooling effect and the period of each phase of chimney operation change according to fluctuations in the air temperature, the intensity of solar radiation, the wind velocity and so on. It requires a trap to control the air-flow.

Sensible cooling happens when there is a change in the temperature of air without a change in its humidity, or water vapour content. Evaporative cooling occurs when there is a change in the temperature and the humidity, and it can play an important role in the operation of wind towers. For example, when the basement wall of a chimney is damp, as is often the case, the air coming down the chimney is cooled both sensibly and evaporatively. In other words, water on the wall absorbs enough heat to be vaporized. Since vaporization requires relatively large amounts of heat, wind towers that incorporate evaporative processes can cool the air quite effectively.

In addition, before refrigerators came into wide use in Iran, the damp basements of wind chimneys served as cold-storage spaces. So it was working as a traditional refrigerator in the Islamic countries like Iran.

Furthermore, the humidifying of the air that accompanies evaporative procedures is an important contribution to comfort at minor temperatures. Another way of exploiting evaporative cooling is to place a small pool with a fountain at the bottom or above of the wind catcher. Wind can be sensibly and evaporatively cooled coming down the chimney and then evaporatively cooled by the pool and the fountain before it enters the places of the construction.

The cooling is effective even on windless nights. When the tower operates like a chimney: the outside air flows over the underground stream. Where it is evaporatively and sensibly cooled, and then up through the shaft into the structure. It mixes with the basement air and is finally vented from the top of the chimney. (Bahadori, Mehdi, 1978)

Catching the wind functional form of a curve roof:

A curved roof is most effective when it incorporates an air vent. The operation of an air vent depends on the fact that when air flows over a cylindrical or spherical object, the velocity at the apex of the object increases: consequently the pressure at the apex decreases. If there is a hole at the apex of a domed or cylindrical roof, the difference in pressure induces the hot air under the roof to flow out through the vent.

A small cap in which there are openings that direct the wind across the vent usually protects an air vent. Since the functioning of the vent depends on air flowing over a curved surface, roofs with vents are oriented to present the maximum curve to the wind.

In areas where the wind is a prevailing one, cylindrical roofs are built with the axis of the cylinder perpendicular to the wind direction; in areas where the winds blow in all directions domed roofs are employed. Air vents are usually placed over the living rooms of buildings.

Wind-catchers can be employed in conjunction with curved roofs, which are another source of comfort in Iran's hot summer climate. Curved (domed or cylindrical) roofs offer many advantages over flat ones. They are inherently stronger: therefore they can be made lighter and do not require the support of wood beams, which are scarce in the desert areas.

Furthermore, the hot air that gathers under a curved roof is well above the living area of the room the roof covers. In this way the room is kept more comfortable, and heat transfer from the roof to the room is limited because a high temperature is maintained next to the roof.

Any roof absorbs solar heat directly by radiation, and flat and curved roofs of the same base area absorb about the same amount of solar radiation. A roof loses most of its heat, however, not by radiation but by convection: that is, the principal heat loss depends on the movement of air across the roof. A curved roof has a larger convection heat-transfer area and transfers heat more efficiently than a flat roof. Therefore a curved roof is more easily cooled.

Some of the problems of traditional design of the wind-catcher:

One problem with wind catchers is that they admit dust, insects and birds into a building.

Modern wind-towers are equipped with screens to keep out at least the insects and birds. Increasing the cross- sectional area of the airflow reduces the wind velocity at the bottom of the tower, which allows the dust to settle on shelves called dust pockets. The placement of the openings at the top of the tower can also control the infiltration of dust; in areas where dusty winds blow in one direction and dust-free winds blow in the other, the openings are placed accordingly. Taller towers bring in less dust, but they are expensive to build and maintain. Another way of keeping the dust out of a building is to construct a tower with a base that is wider than the rest of the tower.

Wind catchers are still in service in some of the Arabic countries and Iran. Also, they are even included in some new buildings. They are of course intended only for summer use and must be properly closed in winter. For example, in Bam, thin walls seal off the towers. If the towers are not closed in winter, they greatly increase infiltration heat losses.

Wind-catcher Function in Qanat or Reservoir of water:

In some areas on the arid plains of Iran water is brought from the highlands by the system of underground aqueducts called Qanats. A passive cooling system of the cistern type actually incorporates several other passive systems. The cistern is a reservoir sink 10 to 20 meters, into the ground, covered by a domed roof and surrounded by several wind-catchers. The design of the cistern takes advantage of the seasonal temperature changes in the desert and the insulating properties of the ground. The purpose of the cisterns is to hold the water at a reasonably low temperature during the hot summer months. Also, this kind of system is reputed to have some surprising benefits in some of the ancient cities like Esfahan. According to the people's beliefs, Qanats reduced earthquake forces.

The problem of the people is their need for cold water while saving energy by an economical way. In the arid zones of Iran the winter nights are very cold. In winter cold water is admitted to the cisterns, partly filling them. In summer the domed roof of the cistern is warmed by the sun, and so is the air and the top layer of water in the cistern. Before the deeper layers of the water are warmed, however, the water in the top layer evaporates and the water vapour is carried away by a draft across the surface, maintained by the wind-towers. In this way the water is kept cold.

In fact, a cistern cooling system operates in one of two ways. If it has a domed roof with an air vent in it, the air flows down the wind-catcher, across the water and up through the vent. This airflow entrains the mixture of air and water vapour under the roof. If the cistern has an air vent, however, dust, insects and other matter can fall into it and foul the water. Therefore some cisterns are constructed without vents. In these cisterns the flow of air from the tower is short-circuited: the air flows down through the passages on one side of the tower and back up through the passages on the other side, entraining the mixture of air and water vapour in the cistern and inducing it to flow out through the openings on the leeward side of the tower. Cisterns of either type are not much used at present because, although the water they supply is cold, it is also stagnant and therefore not safe for direct human consumption.

A cistern system effectively operates by storing energy from one season to another.

Many passive cooling and heating systems operate on this principle especially in the Islamic culture and architecture in the different Islamic countries.

Figure 3.18. Qanats used in conjunction with a wind-tower can provide cooling as well as a water supply. Wind-towers of Ab-Anbar (An Ab-Anbar is a traditional Qanat fed reservoir for drinking water in Persian antiquity.) [31]

Ab-anbar is a traditional reservoir or cistern of drinking water in Persian antiquity. The Persian phrase literally translates as “water reservoir” (Figure 3.20).

[31] Source: http://www.pushpullbar.com/forums/showthread.php?6921-windcatcher, 2011-02-27

Figure 3. 19. Ab anbar or “water reservoir”. [32]

Wind-catcher function in Yakhchal or traditional ice-making systems:

Another example of wind catcher is the traditional ice-making system of Iran. The function is like the cistern; and for similar reasons, the icemaker has been abandoned for health reasons. In Iran's arid regions the night time temperature of the air in winter is usually only a few degrees above freezing. With an icemaker, ice can be produced in winter and stored for the summer. The system depends on radiation losses to the sky on clear, cold winter nights. So it is like architectural refrigeration in the Islamic architecture with regard to saving electrical energy and so on.

The icemaker consists of a large storage pit 10 to 15 meters deep and one or more shallow rectangular ponds, 10 to 20 meters wide on a north-south axis and several hundred meters long on an east-west axis. An adobe wall is built on the south side of each pond, high enough to shade the entire width of the pond during the ice-making season.

Lower walls at the east and west ends of the pond shield it from early-morning and late afternoon solar radiation.

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[32] Source: www.google.ca/image

On cloudless winter nights each pond is filled with water. Water in such a pond loses heat to the sky by radiation and receives heat from the air by convection and from the ground by conduction. The walls along the pond, however, shield the pond from the wind and thus reduce the heat gain by convection. (When there are several ponds, their parallel walls contribute to the overall shielding effect.) Under these circumstances the heat loss by radiation to the night sky is sufficient to freeze the water in the pond. The weather conditions dictate to what depth the water can be made to freeze.

The traditional materials that are used to construct this kind of building have insulating properties and are economic as well.

Sometimes the pond is filled a few centimeters at a time during the night, which increases the rate of ice formation. On the following day the ice is cut up and placed in the storage pit. While that is being done the walls of the pond help to keep the ice from melting in the heat of the daytime sun. On the other hand, conduction from the ground tends to melt the bottom of the ice, so that it can be more easily removed.

Three kinds of Passive Systems cool the traditional Iranian buildings (One Snapshot of wind-catcher in Yazd or City of the wind-catchers):

A wind-catcher, a domed roof and an air vent are three elements of the passive systems to cool the Iranian buildings, which are made according to the Islamic rules and the Islamic architecture. The wind-catcher acts to cool the ambient air and circulate it through the building. Projecting from the tower are the ends of wood beams that reinforce it; the ends are left in place to provide support for scaffolds for maintenance of the tower. The domed roof next to the tower acts to keep the room, under the roof cool. The small structure on top of the domed roof covers the air vent, which also acts to cool the room below and maintain a circulation of air through it. The three systems keep the building comfortable during the summer months.

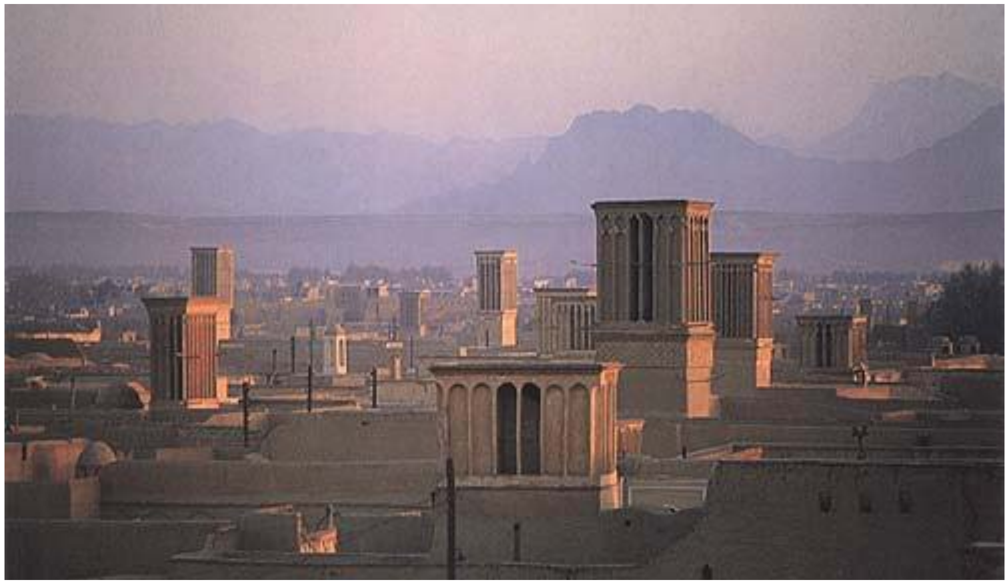


Figure 3.20. Yazad is famous of City of wind catcher [33]

Wind-Catcher Operation in the day and night, the phenomenon of the "time lag":

A wind catcher operates in various ways according to the time of day and the presence or absence of wind. The walls and airflow passages of the tower absorb heat during the day and release it to the cool air at night. The next day the walls are cool. When there is no wind, hot ambient air enters the tower through the openings in the sides and is cooled when it comes in contact with the tower. As already explained, since the cooler air is denser than the warmer air, it sinks down through the tower, creating a downdraft.

When there is a wind, the air is cooled more effectively and flows faster. Doors in the lower part of the tower open into the central hall and basement of the building. When these doors are open, the cooled air from the tower is pushed through the building and out of the windows and other doors, entraining heated room air with it. The cooled air's path of circulation depends on the arrangement of doors in the tower and the building. Some of the air flowing

[33] Source: images.google.com, 12/02/2012

down the windward passages of the tower is forced back up through the opposite air passages and out through the leeward openings. When there is no wind at night, the tower operates like a chimney. Heat that has been stored in walls, which constructed by the traditional materials, during the day warms the cool night air in the tower. Since the warmer air is less dense than the cooler air, the pressure at the top of the tower is reduced, creating an updraft. Air in building is entrained up through the tower and cool night air is pulled into building through the doors and windows. When there is wind at night, air flows down tower and through building, since tower walls warm night air before it enters building, rate of cooling can be lower.

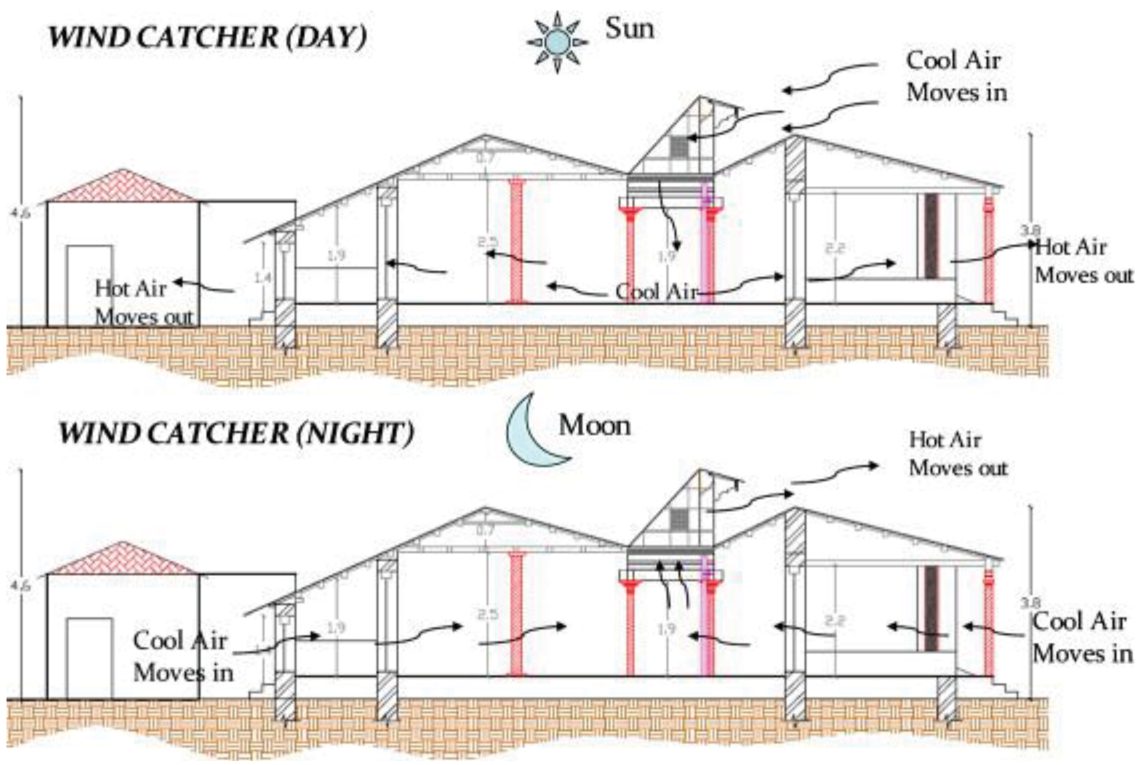


Figure 3.21. Wind-Catcher Operation in the day and night [34]

[34] Source: images.google.com, 12/02/2012

Diversity of Wind-Catchers

Wind-Catchers are divided into three categories according to their external form (see figure 3.23). The One-Directional is the simplest of them. These wind-catchers are built in the direction of the most agreeable wind and are closed off in all the other directions. This type is safe from storms and heavy winds.

The Two-Directional type has two opposite sides with high slim windows and no barriers.

The Four-Directional wind-catchers is the third kind, which are built in a more complex way than the other kinds. These types are usually divided by brick, wood or plaster partitions. In some cases large pools were placed under the channels, so the pool's water would absorb the heat and dust of the incoming wind to produce cool clean air in the summer.

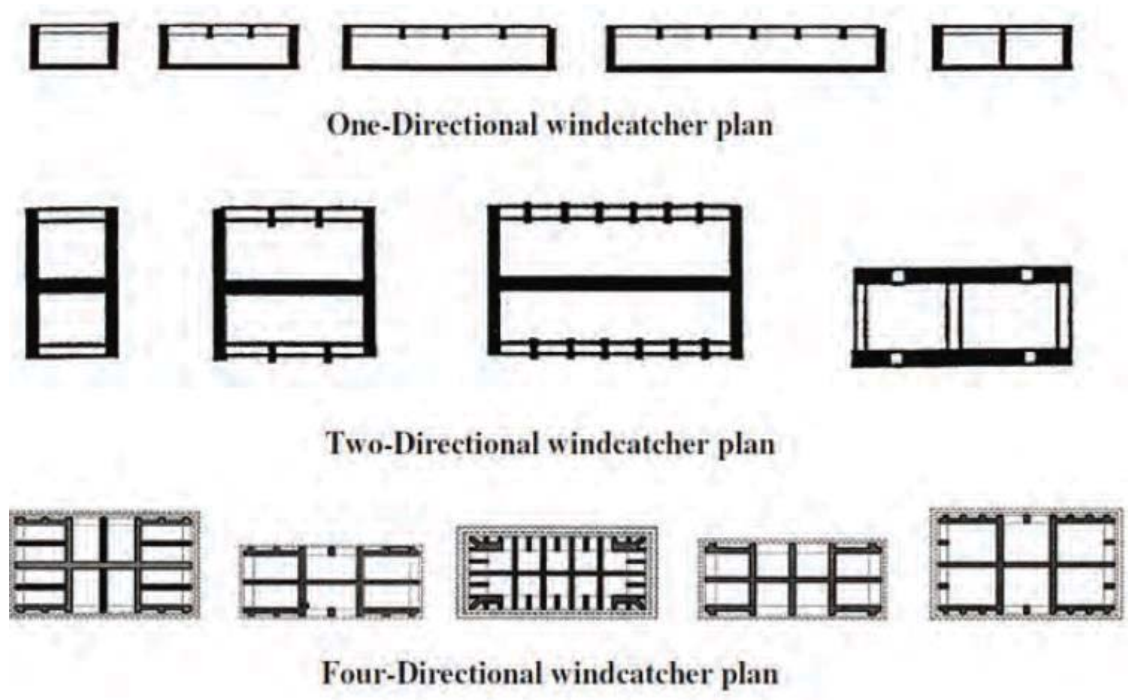


Figure 3.22. Wind-Catcher’s Diversity plans. (Source: Mahyari, Ali, 1996)

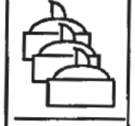
In Yazd, another ancient Iranian city like Bam and in some other central regions of Iran, Multi-Directional (Polygonal and sometimes even circular) Wind-Catchers are common. This fourth type, can draw agreeable and pleasant winds from almost any direction and channel it into the building.

The Fifth kind of Wind-Catchers is the Pipe like tube. In this type instead of the usual rectangular external form we see a few elbow-like pipes. The two-story the channels and vents in this type, function like the multi-directional kind. To build this kind of Wind-Catchers first you have to build a large tower with apertures and ordinary partitions on four sides. Then independently from each side, bring some partitions the middle of it to a higher level. The result is a slim wind-catcher placed in the middle of a large one in which the thinner one is 1-2 meters higher. If any of the central Wind-Catchers partitions fall apart then the large four sided one would still be secure and vice versa. (Figure 3.23)

Figure 3.23. Wind-catcher Diversity in Iran. (Source: Mahyari, Ali, 1996)

A summary of the discussion, as well as the characteristics of each type of wind catcher together with the description of the climatic aspects are presented in Table 3.01

Table 3.1. A comparison between various types of the wind catchers with respect to climate in the Middle East. (Source of Table: Mahyari, Ali, 1996, The Wind Catcher- A passive Cooling Device-For Hot Arid Climate, p. 25)

	Afghanistan	Egypt	Iraq	Iran	Persian Gulf	Pakistan
						
Climate Region	Semi Hot-Arid	Hot-Arid	Hot-Arid	Hot-Arid	Hot-Humid	Hot-Humid
Wind direction	North	North-West	North-West	North-West North-East North	See Breeze	South-West
Cross Sectional Shape	Square	Rectangle	Rectangle	Rectangle Square Hexagonal	Square	Square
Dimensions (m) (Average)	1 x 1		0.5 x 0.15 1.20 x 0.60	0.5 x 0.8 0.7 x 1.1	1 x 1	1 x 1
Height (m)	1.5 Above the Roof	One story Above the Roof	1.80 - 2.10	1-5	1: -5	up to 5
Orientation with Respect to Wind	Normal	Normal	Normal	Diagonal	Diagonal	Diagonal
Top-End Shape	Inclined with 30°	Inclined with 30°	Inclined with 45°	Flat	Flat	Inclined with 45°
Space Vented by the Tower	All Rooms	Reception & Room	Basement Only	Reception & Basement	Reception & other Rooms	All Rooms
Concept of Flow	Uni-Direction	Uni-Direction	Multi-Direction	Multi-Direction	Multi-Direction	Uni-Direction
Use of evaporative Cooling	No	Sometimes	Sometimes	Sometimes	No	No

It is necessary to say that wind catchers are different structures from each other according to their functional particularities. Regional differences of hot and dry climates and some social, technical and economic factors, and various functions of buildings are affective in this regard. (Azami A., 2005)

Orientation:

The orientation of wind-catchers in some of the Iranian cities is different from Bam and this difference is related to some affective factors specially direction and characteristics of the wind. Consequently locating wind-catcher opening in regard to the four geographical cardinal points is determined by the climatic function of the wind-catcher and by using the force of the prevailing wind. (Azami, A., 2005)

Dimension and Materials of Traditional Wind-Catcher (Components):

The main structure of a typical wind catcher consists of a tower, several vents, and partitions. The form of the tower is most commonly square or rectangular and its size varies from 50 x 80 to 70 x 110 cm, while the largest tower is recorded as large as 500 x 500 cm. A typical wind catcher of Bam for example is built either of mud brick or more commonly of baked brick covered with mud plaster. The main partitions continue to the centre of the tower, forming a separate shaft behind the vents while secondary partitions remain as wide as the external wall, about 20-25 cm.

The tower is either built of exposed brick or finished by mud plaster. Mud plaster (kah- gel) is a mixture of wet earth with fine or chopped coarse straw. White limestone plaster or Gatch (Gach) is also used in external decorative features of wind catchers. Timber beams are used to support partitions at various heights, and to tie the structure together, as they increase the shear resistance of the tower. The ends of the beams are left outside of the structure to provide a ladder and scaffolding to build up the tower and for use during subsequence maintenance. The external walls of the tower on top terminate in a set of vertical partitions, built of mud brick, baked bricks, or "farshi" tiles (baked square pavers). These partitions form a plane grid of vents, ending in a heavy masonry roof on top of the tower.

A survey shows that over 60% of all wind catchers protrude less than 3 meters above the roof parapet level and only 15% rise above 5 meters high. The higher towers carry the potential for structural failure, particularly in the head of the towers, which are weakened by a number of vents. (Figure 3.24). (Source: Mahyari, Ali, 1996,)

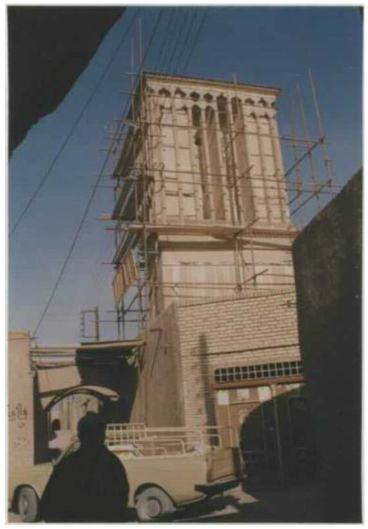


Figure 3.24. A typical wind catcher under repair in Yazd, 1993. In which open and blank vents are evident. (Source: Mahyari, Ali, 1996)

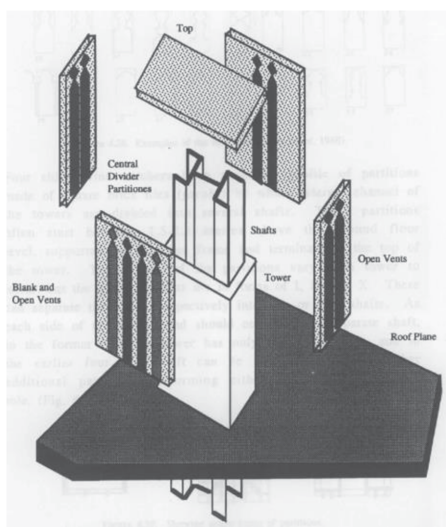


Figure 3.25. A typical wind catcher and main elements. (Source: Mahyari, Ali, 1996)

Some Functional Shortcomings of Traditional Wind-Catcher:

Wind-catcher defined as a traditional structure for natural ventilation and sustainable air-conditioning. Wind-catchers are part of the representative architecture in hot and dry areas in Iran, which are used to create pleasant temperatures. The proper function of a wind-catcher as a structure and as a process for natural air conditioning can be assessed in terms of effectiveness in reaching a pleasant and suitable condition within the building question.

This condition also depends on the temperature and relative humidity. Traditional Wind-Catchers have been designed and built with the technology and materials of their own time. Therefore there are the following limits, which can be improved with modern technology:

On this basis the use of two kinds of wind catchers, one with wettable (soakable) columns and the other with wettable surfaces (shafts) resolves most of traditional wind-catchers problems.

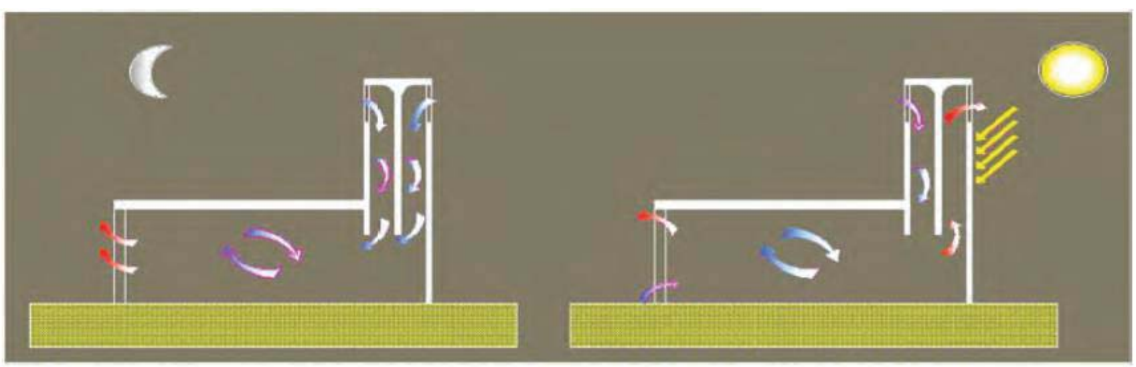


Figure 3.26. The function according to temperature difference.[35]

1. Wind-Catchers have no use in areas with weak and slow winds.

[35] Source: images.google.com, 12/02/2012

2. Even in buildings with basements and after exposing the wind to wet surfaces, wind catchers fail to meet the full potential of evaporative cooling. Note that in warm and dry areas evaporative cooling is an extremely useful process for creating agreeable temperatures.
3. Due to the mass and heat capacity of the materials used in Wind-catchers, the amount of cooling energy stored in the wind catchers' mass is relatively small. This amount of energy is unable to satisfy the diurnal needs of a hot day, or the surfaces exposed to the air might not be enough to offset high amounts of heat transfer.
4. A fraction of the entering wind exits from the opposite and other apertures before going down the wind column. This problem is not seen in one directional wind-catchers.
5. Dust, Insects and occasionally small birds enter the building. (Farhadi Shabestari Ali, Ahmadkhani Maleki Bahram)

Comparing some advantages and disadvantages of wind-catchers in hot and dry climate region:

Advantages of the traditional wind catchers:

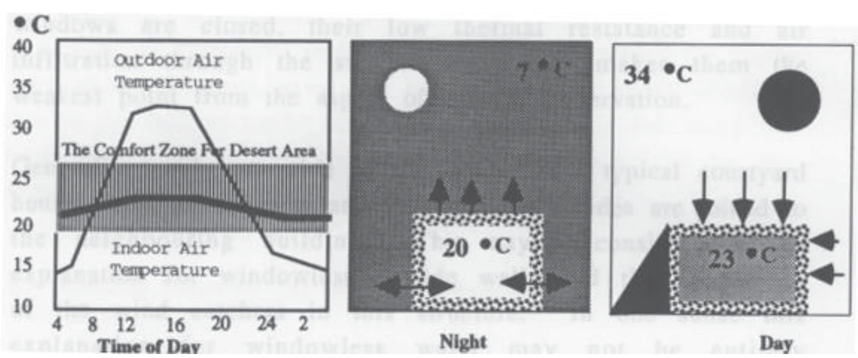


Figure 3.27. A general concept of air temperature indoor and outdoor of a thick masonry building during the day and night. (Source: Mahyari, Ali, 1996)

"… The traditional Iranian houses, in their design and construction, rely heavily on natural sources of energy. By maximising sunshine in winter and shade in summer, and also using natural ventilation, the courtyard house effectively utilises cheap natural energy. The common concept is clearly based upon climatic factors, and therefore, this should be stressed when studying or planning for any development in these regions.” (Source: Mahyari, Ali, 1996)

"The thick adobe walls, usage of the insulating properties of the ground, and the passive cooling systems of domes, wind towers, and air vents contrast sharply with the modem Iranian house whose electrical air conditioner cannot compensate for the thin walls, large windows, and a design based upon Western architectural manuals." (Bonine, 1980)

Disadvantages of operation of Wind-catchers:

The prevailing wind speeds are generally low in the morning increasing towards noon to reach a maximum in the afternoon. They are frequently accompanied by windstorms of sand and dust, probably because storms are generated by an advancing cold front.

Most such dust during the winter months is also the cause for the formation of sand dunes, which may reach as high as 300 meters. In contrast, windless periods are frequent in some regions of the hot dry zone. This is most disadvantageous when occurring at night since night winds are required for structural cooling and ventilation of buildings. (Source: Mahyari, Ali, 1996)

Table 3.2. Comparing some advantages and disadvantages of wind-catchers.

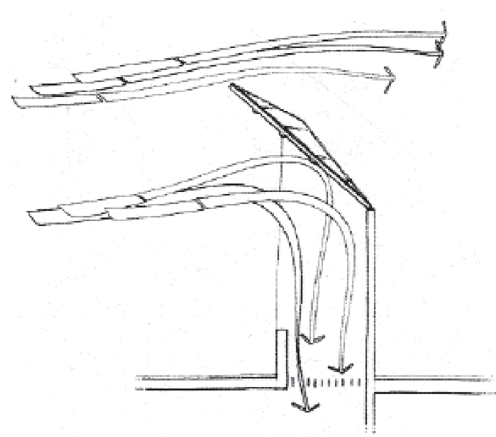
	Advantages and disadvantages of Wind Catcher of Traditional Building in Hot and Dry Climate	Normal Conditions	Post Disaster Conditions
1	**Economy**	Wind-catcher has an impressive economy. (Wind-catcher system provides the benefit of night-time cooling or "free cooling", which is considered to be one of the most important aspects of the Wind-catcher natural ventilation strategy.)	Wind-catcher has an impressive economy after disaster, because it cause to help the people to save the energy in undesirable conditions and provide comfort condition for them with minimum expenses.
2	**Vernacular Materials**	Used of "Lightweight straw loam", in order to increase thermal insulation. It is Economic.	1-Poor quality of construction, e.g. materials, workmanship, absence of cross stones or bonding Units (are the factors affecting the level of damage in masonry and traditional buildings). 2- Lack of interconnection between masonry structure and roof or floors, especially at upper levels. 3-inadequate resistance capacity of materials and structure. 4-Poor connectivity of diaphragm to vertical elements of the lateral resisting systems, particularly when structural walls are present. 5-Incomplete and inadequate lateral force - resisting system. 6- Lack or weakness of foundation.
3	**Safety**	In normal condition this element is safety for people, who live inside the building.	Foundation soil problems, which include liquefaction, settlement, weathering effects(are the factors affecting the level of damage in masonry and traditional buildings)
4	**Time of Construction**	Time of construction is long but enough in normal condition.	After disaster, we do not have enough time to construct a wind catcher after we constructed a shelter, so we should combine them together.
5 6	**Function in the Summer**	During summer months, the volume control by people to open fully at night time to provide the cool night air. Also it is useful during the day when the wind is blowing.	During summer months, the volume control dampers are programmed to open fully at night time to encapsulate the cool night air. Also it is useful during the day when the wind is blowing.
7 8	**Function in the Winter Days**	In normal condition during winter there aren't any benefits to provide comfort condition.	In post disaster condition during winter there aren't any benefits to provide comfort condition.
9	**Health**	In traditional form of wind catcher dust and sand that accompanied by wind is incontrollable, which is not good for the health.	The wind has lots of dust and sand after earthquake in post disaster conditions, which is not good for the breathing apparatus of the people.

Modern wind-catchers:

Bahadori (1994) and Azami (2005) describe modern designs of wind-catchers, which use control dampers to control volumetric flow rate and solar collectors to enhance the stack effect for exhausts at purpose designed exits (Figure 3.28. Left). A study by Bahadori, (1994) investigated a wind-catcher coupled with evaporative cooling columns that can increase the cooling potential (Figure 3.28. Right). He also provide detailed methodology for designing and siting it.

Figure 3.28. (Left) Wind-catcher with solar collector Fig. (Right) Wind-catcher with cooling columns. (Source: A`zami A., 2005)

The new design of wind scoops can rotate about an axis so as to always have the opening facing the incident wind. These types were found to be significantly better at producing positive pressure rather than suction cowls which back the wind and develop negative pressures for air extraction (Adekoya, 1994).A good example of a rotating wind scoops used for natural air conditioning is at the ICI chemicals visitor centre in Runcorn, UK (Khan et al., 2008) (Figure 3.29).



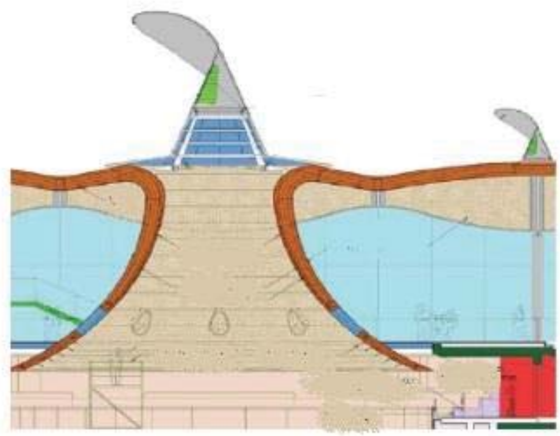
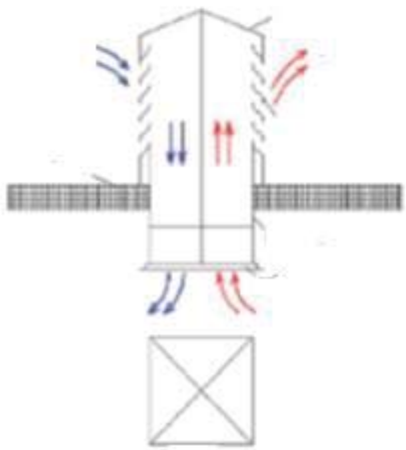


Figure 3.29. Public sector building in Wales. (Source: Khan et al., 2008)

A recent improvement in wind-catcher design is the Monodraught Solar Boost seen in (Figure 3.29. (Right). When the solar panel reaches 14 V an intelligent power control device will boost the power to the fan to 25V resulting in a 250 % increase in the speed of the fan and hence of the flow rate.

This kind of wind-catcher was launched in 1990. It was called Monodraught (Figure 3.29. Left). It shows the basic operational principles of its system. The system is normally divided into four quarters, which run the full length of the device and become air intakes or extractors depending on wind direction, consequently making it less vulnerable to periodic wind changes and negating the need for any possible rotation to face the wind. It has also weatherproof louvers protect the interior of the building and volume control dampers to moderate flow (Khan et al., 2008).



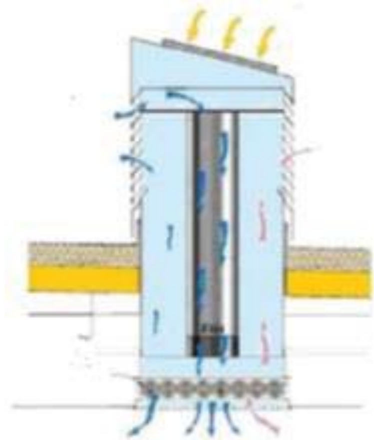


Figure 3.30. (Left) Operating principle of Monodraught (Right) Recent design of Monodraught, Solar Boost. (Source: Khan et al., 2008).

Wind-catcher or Badgir in traditional Iranian architecture:

In the past, without modern facilities, it was only the intelligent architecture of the buildings that enabled people to tolerate the hot summer.

The ventilation structures called “Badgirs” were the most important means by which the interior was cooled. The wind-catcher operates according to the condition of the wind and sun radiation in the region. In ancient times and in traditional buildings in arid and dry regions the air trap functioned like the present modern air conditioning system.

The Badgir's material again plays another role. Due to high fluctuation of temperature differences between day and night in this climate and particularly night time coldness, Badgir which is made with mud-brick, gets cool by radiation and convection.

The system works, even when there is no wind, but when the wind is blowing this system does not have problems. Because during the day, if there is wind, then cool air flows faster and at night, with wind, it may absorb the heat of the walls, because the night wind is cool enough. (Azami, A., 2005)

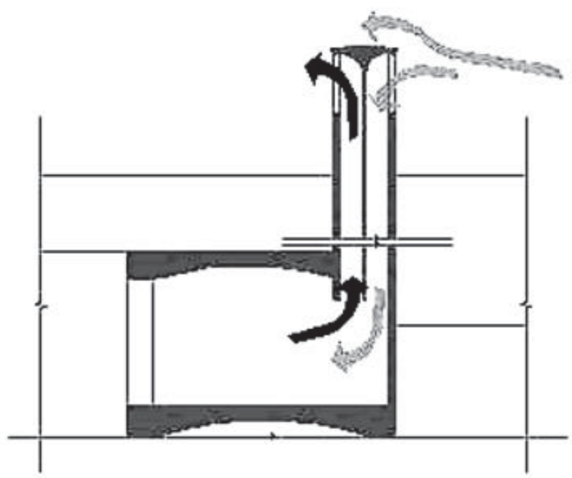


Figure 3.31. Traction and suction in wind-catcher. (Source: Azami, A., 2005)

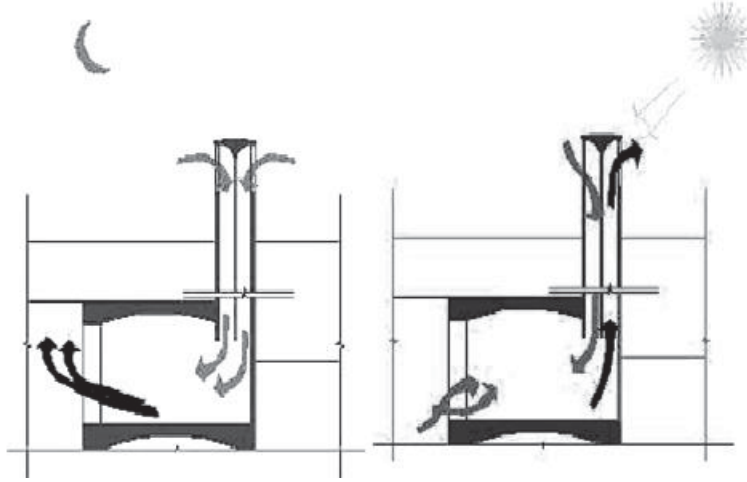


Figure 3.32. Wind-catcher functions during the day and night. (Source: Azami, A., 2005)

Summary:

A wind-catcher system that cools air evaporatively as well as sensibly is particularly effective. There are two kinds of cooling that operate in the traditional passive system, especially in Iran. Air in the upper part of a wind-catcher is sensibly cooled. When water is introduced into a system, evaporative cooling occurs. In sensible cooling, heat loss from the air results in a decreased air temperature but no change in the water vapour content of the air. Such cooling involves a change in both the water-vapour content and the temperature of the air. When unsaturated air comes in contact with water, some of the water is evaporated. This process is driven by heat from the air, so that the temperature of the air is decreased as its water vapour content is increased. In most wind-catchers water in the ground seeps through to the inside of the basement wall of the tower, so that air passing over the wall is evaporatively cooled. (Bahadori, Mehdi, February 1976, Passive Cooling Systems in Iranian Architecture, pp. 2-9)

Briefly, there are two functions for Wind-Catcher:

> "**Night operation:** When there is no wind blowing at night, the wind tower acts as a chimney. The tower walls, which have been heated during the day, transfer heat to the cool night ambient air. The heated air is then exhausted through the tower openings. The chimney action of the tower maintains a circulation of ambient air through the building and cools the structure of the building including the tower itself." (C. Gallo, M. Sala, A.A.M. Sayigh, 1988)

When there is wind blowing at night, the air circulation will be opposite to that described above and the walls and rooms will also be cooled.

> “**Day operation:** When there is no wind blowing during the day, the tower operates as the reverse of a chimney. The hot outside air in contact with the cold walls of the tower (cooled from previous night) is cooled and pulled down through the towers passages. When there is wind blowing, both the air circulation and the rate of cooling are increased, and thus, cooler air is delivered to further position inside the building, the performance of the wind tower is affected, beside its geometrical forms (height, cross sectional plan, tower orientation and location of its outlets), by the climatic conditions. It is most effective in dry arid regions. In such regions the diurnal variation is large and night air temperature is low.” (C. Gallo, M. Sala, A.A.M. Sayigh, 1988)

In houses the wind-catcher is usually located in the summer-sitting part of the house.

Wind-catchers are often related to halls, pools and basements. They thus cause the air circulation to circulate in the building. They also are related to the moisturizing elements such as: 1- Houz (means: pool), 2-Bagh (means: garden), 3- Trees, 4- basement walls and underground structure.

Wind-catchers materials are always of Adobe, Brick, Mud, Plaster (گچ gach, A kind of white earth from which lime is made) and wood Shvrnh or "Shoruneh". It is one of the type’s wood of, which resist against natural factors and termite attacks.

The temperature difference between the inside and outside the building and its different parts causes the pressure difference and moves the air.

A passive cooling system exploits the very features of the climate it seeks to overcome.

For this reason the passive cooling and ventilating systems of Iran cannot be applied at random in other areas of the world. These systems could work well, however, in climates similar to the climate of Iran. For example, although the cistern and ice-making systems have been abandoned for public-health reasons in Iran, they could be employed in Iran and elsewhere to supply cold water and ice for purposes other than direct human consumption.

In climates where the passive cooling systems of Iran cannot be applied they should still be of interest. They demonstrate the possibilities of working with rather than against the external environment. In the future, architects and engineers will need to take more account of climate and might well examine the possibilities it affords for passive heating, cooling and ventilating systems. With this information they should be able to design buildings that have modern amenities and yet consume minimal amounts of energy.

Chapter IV. Natural air conditioning antecedents in nature:

Introduction:

In chapter II, systems using natural sources of energy to improve thermal comfort in buildings in hot dry climates were presented, showing, for example, how air movement and air cooling could be obtained. In chapter III the particular case of the use of wind catcher was explained in detail. In this chapter (chapter IV), within the perspective of mimicry in architecture, natural "air conditioning" in the complex systems of termite mounds is explored. In fact, termite mound and their structure have been used as examples of biomimetic design for climate control in building.

Structure and Function in the Termite Mound's ventilation in hot and dry climate:

Termite mounds provide a good example of adapting the geometry found in the mound structures produced by colonies of the termite to help solve problems of thermal control and ventilation. These termites have evolved a construction technique, which extends the thermo-regulatory, digestive, respiratory, and pulmonary systems found within all animals into the structures they inhabit. These structures respond and adapt to constantly changing internal conditions and external weather influences, to provide a comfort condition in which the colony can flourish.

Two types of ventilation could be distinguished. They are the result of convection currents and diffusion of CO_2, both processes that depend on temperature patterns.

The externally driven ventilation in termite mound seems to be more effective than the internally driven ventilation, as CO_2 concentrations are lower in cathedral-shaped mounds than in dome-shaped mounds; within the cathedral-shaped mounds it was lower during the day than during the night. The externally driven ventilation appears to be the prevailing ventilation mechanism for cathedral-shaped of termite mounds. However, under cooler environmental conditions, internally driven ventilation might occur, resulting in less efficient gas exchange.

This is to be expected when considering (1) the higher temperatures resulting in increased diffusion rates, and (2) the available surface for gas exchange, (3) the circulation of air currents.

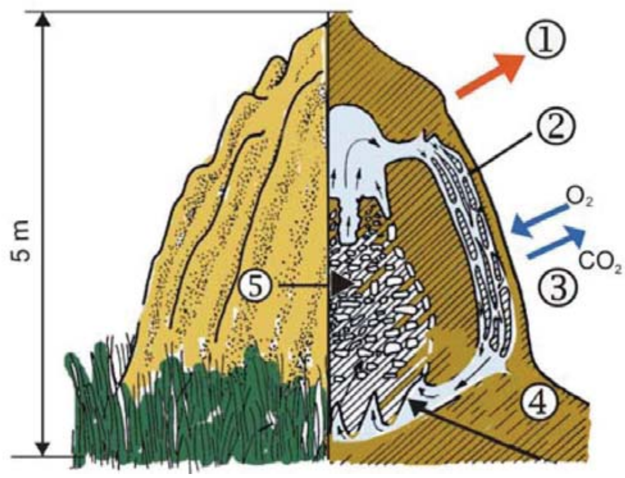


Figure 4.1. An anthill of termites: analogy with a 'HVAC' system in the techniques (1.heat extraction, finned radiator, 2. air shaft, 3.ventilation and moisture transfer, 4.cellar: refrigerator, 5.chamber of termites). [36]

Externally driven ventilation versus internally driven ventilation in the termite mounds:

Through externally driven ventilation, air circulates continuously from the nest through peripheral air channels, and respiratory gases can be exchanged effectively through the whole

[36] Source: http://inhabitat.com/building-modelled-on-termites-eastgate-centre-in-zimbabwe/, 15/4/2011

surface of the ridges. When internally driven ventilation prevails, air seems not to circulate within the mound, and, additionally, in the case of the dome-shaped mounds the exchange area is almost exclusively limited to the surface at the top of the mound. This limitation in gas exchange areas might explain the occurrence of a large chimney (i.e., one tall central turret), with the central shaft running up inside, the dome-shaped mounds. These mounds were closed, and thus the chimneys could not serve to increase the gradient in wind velocity between the base and the top of the mound that favors ventilation in open mounds (Darlington, 1984, 1997). However, in contrast to the rest of the mound, the chimney had thin walls. Therefore, it might be the main gas exchange structure and increases the available gas exchange area as air can be exchanged when rising inside the central shaft to the top of the mound.

The role of the shape and the structure of the termite mound:

The structure of the mounds is an adaptation to the environmental temperature constrained by the need for gas exchange (Korb and Linsenmair, 1998, 1999a). In the relatively cold gallery forests, the termites have to insulate their nests as much as possible to reduce loss of heat (produced by the metabolism of the termites and their fungi) to the environment and to maintain appropriate nest temperatures. Therefore, they construct dome-shaped mounds with thick walls and reduced surface areas (Korb and Linsenmair, 1998). However, this reduction in surface area is constrained by the necessity for exchange of respiratory gases (Korb and Linsenmair, 1999a). In contrast, in the cathedral-shaped mounds which occur when the ambient temperatures are more appropriate, the termites can construct these cathedral-shaped mounds with large surfaces that facilitate gas exchange (Korb and Linsenmair, 1999a).

Thus, ambient temperature influences the type of ventilation directly by determine the temperature patterns in and around the mound and indirectly by determining the mound structure.

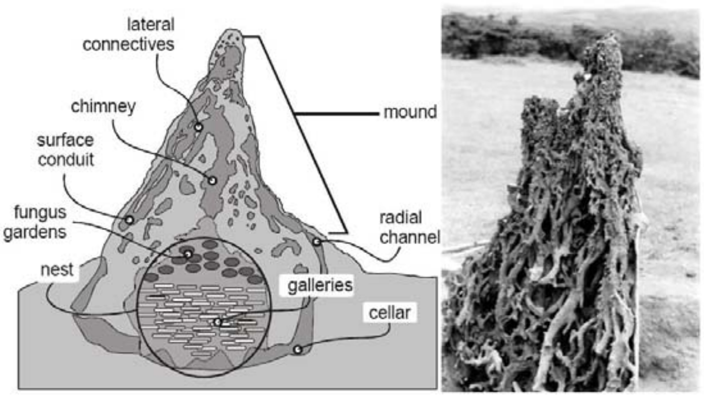


Figure 4.2. (Left) Schematic cross-section through a mound of Macrotermes michaelseni, showing layout of tunnel. (Right) The shape of external envelope of a termite mounds. [37]

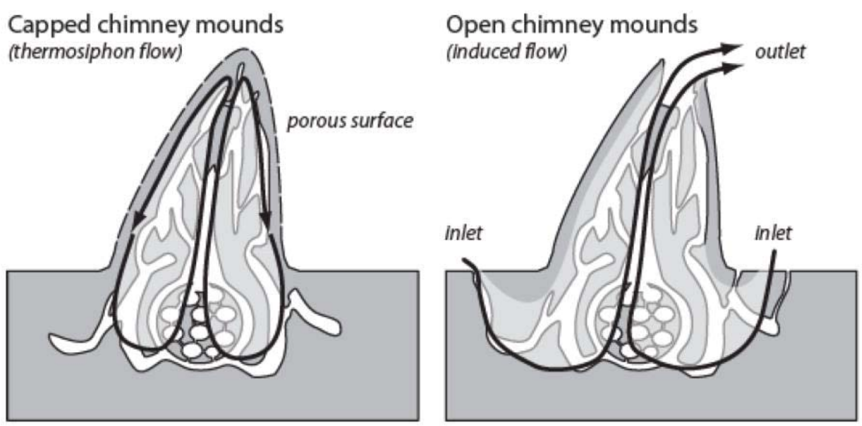


Figure 4.3. Two early models for mound ventilation. Left, Thermosiphon flow thought to occur in capped chimney mounds. Right, Induced flow thought to occur in open chimney Mounds. [38]

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[37]Source: http://www.mountmorelandconservancy.co.za/Bio-Diversity-Mount-Moreland -Conservancy/Termites-Ant-hill.html, 21/4/2011

[38] Source: http://inhabitat.com/building-modelled-on-termites-eastgate-centre-in-zimbabwe/, 15/4/2011

Boundary layer effects and wind-induced pressures for ventilation:

The termite mounds capture kinetic energy in wind by converting it to potential energy, i.e. pressure. These dynamic pressures, as they are called, are readily predicted by the Bernoulli principle.

When the wind is intercepted by the mounds and is made to slow down, as they are at the mounds' windward surface (left in figure 4.4), the lost kinetic energy is transformed to a positive pressure. Where the mounds intercepting winds are made to speed up, as they will when they pass around the mound, the added kinetic energy is compensated by a reduction of pressure, i.e. a suction pressure. Suction pressures are particularly strong at the mound's lateral surfaces with respect to wind (middle). The mound's leeward surface (right) will also experience suction pressures, although these will be weaker than at the mound's lateral surface.

Figure 4.4. The simulation pictures of wind direction and air suction on the membrane of termite mound. [39]

[39] Source: http://www.esf.edu/efb/turner/old%20site/termite/gas%20exchange%20wind.html, 21/5/2010

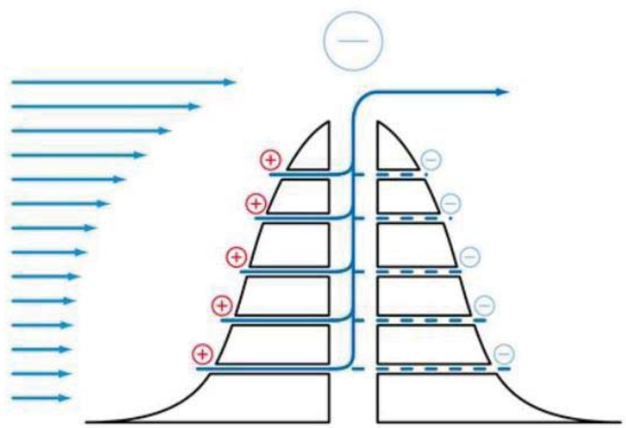

Figure 4.5. The positive and negative direction of wind and air circulation in termite's mound. [40]

Thus, the mound's interception of the wind imposes a complex pressure field on the mound's surface. Because the mound surface is porous, these pressures can drive air through the mound surface, forcing it inward on the upwind surfaces, and drawing it out at the lateral and downwind surfaces.

This wind-induced pressure field at the mound surface affects pressures within the mound. The vertical gradient in wind-induced pressure translates, for example, into a vertical pressure gradient within the surface conduits that can be found within the mound that is correlated with wind speed.

[40] Source: http://www.esf.edu/efb/turner/old%20site/termite/gas%20exchange%20wind.html, 21/5/2010

These vertical pressure differences can drive bulk flows of air within the mound, particularly in the surface conduits (Source: http://www.esf.edu/efb/turner/termite/gas%20exchange%20wind.html, 17/08/2011).

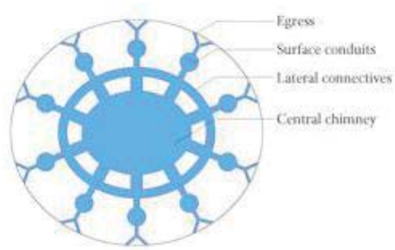

Figure 4.6. A horizontal section diagram of a termite's mound, focusing on the network of the conduits. [41]

The distribution of pressures from the chimney to all surface conduits may be due to two factors:

- The steady upward pressure in the chimney from metabolism-induced buoyancy in the nest
- The damping of wind-induced pressures and flows in the surface conduits by the reticulum of lateral connectives in the mound

Two general ventilation types can be distinguished according to mound structure (Noirot, 1990): (1) open ventilation systems in which the walls of the mounds have holes through which air can stream in and out due to differences in wind velocity at different mound heights (Darlington, 1984, 1997; Geiger, 1965) or due to the shape of the holes (Darlington, 1984; Weir, 1973) or (2) closed ventilation systems in which the mounds have no holes and the surface (wall) of the mounds is the exchange area between interior and exterior of the mounds

[41] Source: http://architecturalecologies.com/projects/A-Study-on-Architecture-in-Moving-Air/, 15/5/2011

(Darlington, 1985, 1989). (http://beheco.oxfordjournals.org/content/11/5/486.full, 17/08/2011).

Knowledge obtained from study of termite mounds can open the door to suggestion for the design of ventilation system:

The most likely natural disaster a Monolithic Dome may encounter is an earthquake. It would take an external force many times as large as the earthquake to reach the design strength of the new material itself. The Monolithic Dome has a number of unique benefits: energy savings, healthy environment, disaster protection, longevity, and construction affordability. (http://www.monolithic.com/topics/benefits, 2011-02-27)

Figure 4.7. The Successive exterior layers. [42]

[42] Source: http://architecturalecologies.com/projects/A-Study-on-Architecture-in-Moving-Air/, 15/5/2011

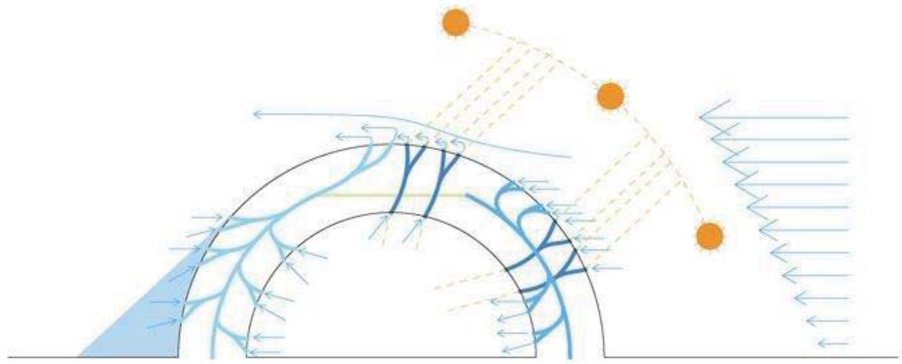

Figure 4.8. Function of air circulation through the exterior layers during the day. [43]

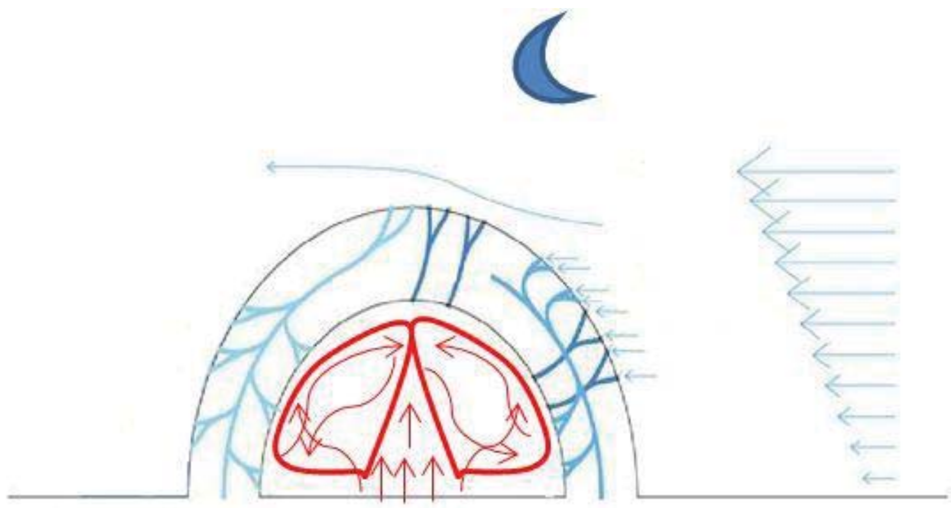

Figure 4.9. Function of air circulation inside the shelter during the winter night. (Distribution of warm air in the winter night; it already stored in thermal mass during the day). [44]

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[43] Source: http://architecturalecologies.com/projects/A-Study-on-Architecture-in-Moving-Air/, 15/5/2011

[44] Source: http://architecturalecologies.com/projects/A-Study-on-Architecture-in-Moving-Air/, 15/5/2011

Functions of Chimney Tree and Wind-catcher Tree Conduits:

The location of the cooler air within the system is at the higher levels and around ~~inside~~ the interior skin.

Therefore, it causes ventilation air to rise within the wall through sucking the exterior air at the shaded side, thus ventilating the interior air through the Venturi effect around the topside of the dome. The functions of a chimney tree as a cooler air system are different during nights and days. (See Figures 4.8. & 4.9.) (http://www.monolithic.com/topics/benefits, 2011-02-27).

Shrub Conduits:

According to the previous discussion about Trombe wall and thermal mass system, the function of shrub conduits is similar. The system of shrub conduits allows the dome to let the natural air penetrate through them during days, when there is daylight. Also, the function during nights is like the function of a Trombe wall.

The role of materials that are used as a net of air purifiers is very important, because of preventing of dust and sand inside the dome. (http://www.monolithic.com/topics/benefits, 2011-02-27).

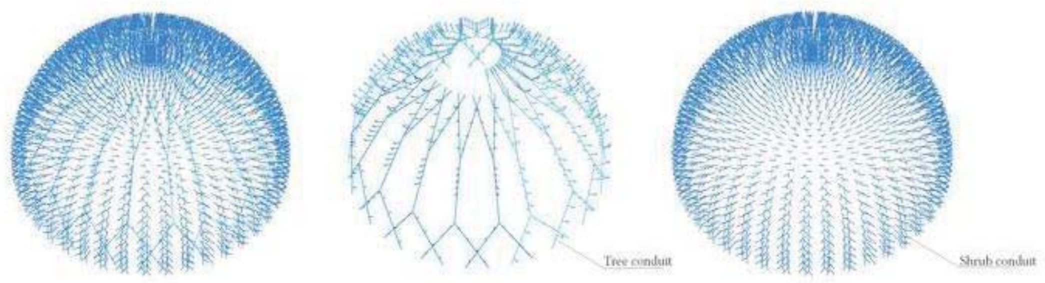

Figure 4.10. Application of Branching Organisation of Termites Mounds to skin structure of Architecture. [45]

Figure 4.11. Ventilation system predicted using the computer simulation process; Organisation of the Branching Skin with Branching Conduits. [46]

[45] Source: http://architecturalecologies.com/projects/A-Study-on-Architecture-in-Moving-Air/, 15/5/2011
[46] Source: http://architecturalecologies.com/projects/A-Study-on-Architecture-in-Moving-Air/, 15/5/2011

Biomimicry - Some Lessons learnt from Termite Mounds:

Natural systems function without waste, and within an integrated web of relationships and interdependence, which sustain the system over the long term. There is a lot that can be learned from nature. Using natural systems as inspiration supports the creation of buildings that minimise the need for energy for heating and cooling, and in many cases improves the amenity as well as indoor environmental quality. For example, a termite nest inspired Eastgate Centre in Harare, which has passive ventilation and cooling:

The Eastgate Building in Harare, Zimbabwe, is just one example of sustainable architecture that uses dramatically less energy by copying the successful strategies of indigenous natural systems. The building - the country's largest commercial and shopping complex - uses the same heating and cooling principles as a local termite mound.

Figure 4.12. Eastgate Building in Harare, Zimbabwe. [47]

[47] Source: http://inhabitat.com/building-modelled-on-termites-eastgate-centre-in-zimbabwe/, 12/4/2010

Figure 4.13. (Left) Exterior of the Eastgate Centre, Harare, Zimbabwe, showing its distinctive chimneys. (Right) Interior of Eastgate Centre. [48]

Features of the building, which are like lungs:

This enhanced conception of how termite mounds work is based on a model of termite mounds and opens the door to the potential of termite-inspired building designs. No longer need such designs be constrained by the long-prevailing models of induced-flow and thermosiphon flow. In contrast, a clear vision of how termite mounds actually work literally opens a whole new spectrum of wind energy to explore and exploit.

Consider, for example, the traditional conception of the wall. In most building designs, walls are erected as barriers to isolate spaces: internal spaces from the outside world, internal spaces from one another and so forth. Resolving this paradox is what forces building designs to include operable windows and infrastructure such as, fans, ducts, air conditioning, heating etc. All essentially to undo what the erection of the walls did in the first place. In short, the paradox forces building design toward what we call the “building-as-machine” paradigm.

Living systems, which also are avid space-creators, resolve the paradox in a different way: by erecting walls that are not barriers but adaptive interfaces, where fluxes of matter and energy across the wall are not blocked but are managed by the wall itself.

[48] Source: http://inhabitat.com/building-modelled-on-termites-eastgate-centre-in-zimbabwe/, 12/4/2010

This is illustrated dramatically in the complex architecture of the interface that termites build into their mounds to manage the environment in their collectively constructed space (the nest).

New rapid manufacturing and free-form fabrication techniques make it feasible to build walls that incorporate some of these design principles. Imagine, for example, porous walls that are permeated with a complex reticulum that, like in the termite mound, acts as a low-pass filter for turbulent winds. In this instance, an interior space of a building could be wind-ventilated without having to resort to tall chimneys, and without subjecting the inhabitants to the inconvenient gustiness that attends to the usual means of local wind capture, namely opening a window. Designer have imagined a cladding system that mimics the termite mound's complex interface at the surface with its conduits and egress tunnels (Figure 4.14). One could employ such claddings as whole-building wind-capture devices, which greatly expand a building's capacity for wind capture. Indeed, imagine a wall that is tuned for differential mass exchange where the high-frequency components of turbulent winds can evaporatively cool a porous wall's surface layers and provide natural cooling for air forced through the walls by the wind's lower-frequency components.

Figure 4.14. Some imagined biomimetic designs. Top left. The surface conduit-egress tunnel complex. A rendering of a building enveloped by porous "surface conduits." The block elements for an artificial surface conduit. (Source: Turner, J Scott and Soar, Rupert C, 2008).

Chapter V. Wind Catcher: Materials and their performance – from tradition to modernity

Introduction:

In this chapter, examples of natural ventilation and air conditioning drawn from centuries long traditions, are revisited to explore the potential to improve them with contemporary material and modern control methods.

The gap between performance criteria and traditional building

It is important to recognize at the start what aspects of the physical construction can be varied in order to achieve the desired performance of buildings. Identifying what can be varied also identifies what has to be chosen and specified if an unambiguous solution is to be defined. Choices have to be made for the materials to be formed into components that have a defined shape and size. Each component has then to be given the spatial relationship with other components together with the joints between them and the necessity for them to act within and as part of a whole building. This simple identification of the variables is represented in the following diagram:

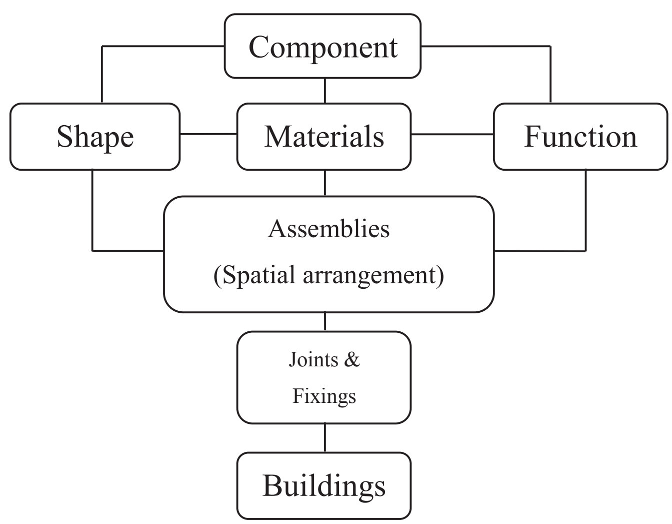

Figure 5.1. Components of Buildings

This specification will have to include:

- The material of which components are to be made and the quality of that material.
- The shape and size into which the material has to be formed.
- The function of each component, giving the actions and activities assigned to or required or expected of a buildings system.
- The relationship of each part either to an absolute position defined in a reference framework or relative to another part of the construction or the surrounding environment.

This specification determines the space that the components and their joints will occupy. It may be in competition for this space with other parts of the construction and/or the usable space of the building itself. The choice of construction cannot be confirmed until this has been checked and it has been established that there is a unique space for each part of the building.

Joints and fixings also need to be identified by their components parts, their material, shape and size and spatial relationships, as they themselves are part of the assembly. Any components associated with junctions also have to be specified.

The process of choice is therefore about defining the components, their materials, shape and size and their spatial relationships, including the joints and fixing necessary to complete the building. The focus of technological knowledge is to help in taking decisions about these variables to create a building/shelter that is safe and has utility. This is technical choice that has to be made following the creation of a design concept and coming before the management of the construction process.

Additional performance criteria:

Features of Material Components, and Shapes of buildings constructed in earthquake prone regions

With the devastation caused by this natural occurring disturbance, there has been increased clamour and agitation for construction of buildings and structures that are earthquake proof. Although protection to buildings can never be perfect, will be reassuring to know that most buildings are quake-resistant in order to reduce the amount of human and capital loss usually associated with earthquakes.

Materials selection criteria:

The materials must meet certain classes of criteria of materials properties (Ashby and Jones 1980). These classes of criteria include:

1- Economic factors

2- Mechanical properties

3- Non mechanical properties

4- Production/construction considerations

5- Aesthetic properties

Recent advances in the technology of construction materials have resulted in the development of better quality, more economical and safer materials. These materials are commonly referred to as high-performance materials. New materials such as polymers, adhesives, composites, geotextiles, coatings, cold-formed metals are developed and used now because one knows more about the molecular structure of such materials. Also, because of the continuous research efforts, Nano-materials, and various synthetic products are competing with traditional architectural materials. In addition improvements have been made to existing materials by changing their molecular structures or including additives to improve quality, economy, and performance, which are needed for use for construction under extreme construction. However, due to the long quantity and bulk of materials used in architectural projects, the architect frequently works with locally available materials that are not as highly refined as the materials used in other engineering fields. As a result, architectural materials frequently have highly variable properties and characteristics.

Economic Factors related to Materials:

There are some Economic factors of the materials, which should be considered in the selection of the materials; they include:

1- Availability and cost of raw materials.

2- Manufacturing cost

3- Transportation

4- Placing

5- Maintenance

All materials deteriorate over time and with use. This deterioration affects both the maintenance cost and the useful life the structure. The rate of deterioration varies among materials. Thus, in analyzing the economic selection of a material, the life cycle cost should be evaluated in addition to the initial costs of the construction. (S. Mamlouk, Michael - P. Zaniewski, John, 2006)

Materials for Hot Dry Environment in traditional Buildings:

Vernacular buildings always rely on the most readily available materials, especially in hot and dry climates, thus mud is used almost universally for walls.

(Vernacular building is referred that building built by the people. Architecture without drawings might be another way of describing much of it) (Source: Roaf, quoted in Beazley, et al., 1982).

Other traditional materials of high mass are used for thick walls, such as stone, bricks, adobe, etc. The thermo physical properties of these materials are of primary importance in desert regions. These properties are thermal resistance, heat capacity, and solar absorbance of the external surface. The particular importance of these properties results from three factors.

(a) High absorptance intensity of solar radiation gives the external surface an impact on the building's thermal properties, with greater effects and importance in deserts than in other regions.

(b) Low ambient vapour pressure makes it possible to achieve indoor comfort with a little ventilation up to a temperature level of about 27-28°C. Having only minimum ventilation during the hot hours of the day keeps the indoor temperature below the outdoor level by late afternoon. Such a reduction in indoor temperature is possible by provision of a proper thermal time constant, which is the combination of thermal resistance and heat capacity, to the building. This phenomenon, for example, occurs in the basement of Yazdi houses where the occupants live in the afternoon.

(c) Large diurnal range of outdoor air temperatures in deserts, together with a selective pattern of diurnal ventilation make it possible to take full advantage of the thermal time constant of the building and to stabilise indoor daytime temperatures at a level well below high outdoor temperatures.

Mud:

The earth is used wet for mud walls; the earth is thoroughly mixed with the water and with short bits of straw. The low thermal conductivity of mud brick shows how this material is better as an insulator in comparison to baked brick or concrete. (Table 5.1) However, mud has some major disadvantages, its resistance to rain, and earthquakes are poor.

Table 5.1 . Comparing the thermal conductivity of some materials. (Source: Koenigsberger. et al. 1973)

Materials	(K) W/mK
Wood chipboard	0.11
Mud brick	0.22-0.32
Stabilised soil blocks	0.50-0.70
Asphalt	0.58
Backed brick	0.71-1.45
Concrete (ordinary)	1.44
Stone limestone	1.53
Stone granite	2.92

Mud Bricks:

They are made of a mixture of earth, water and sometimes-short straw. The mud is rapidly shaped in a wooden mould cast on dry flat ground; it is quickly knocked out to be dried in the sun for several days. The same mud mix as the brick is used for a thick mortar joint when constructing a wall so that the final product will be a homogeneous thick element. However, a combination of mud brick and fired brick is common in masonry structures.

Baked Bricks:

Baked bricks or fired bricks are often made from the same cast as sun-dried bricks but since they shrink in firing they end up smaller. They are used for paving as well as for walls. This material is more often used to pave courtyards than stone, as it is relatively cheaper. Roofs may also be paved for protection against the weather.

Stone:

The stone used in the area close to the foot of the mountains is usually very rough random rubble, as this is the most readily available material. However, in desert area dressed stone is occasionally used for buildings. Pools, stairs, kerbs, and the foot of the walls in the courtyard are sometimes made of dressed stone. As such, it protects the wall where it is most vulnerable to wear and tear in a house.

Plaster:

Walls and roofs are usually plastered inside and out with a mixture of clay, water and short straw. Straw is added to the plaster mixture for strength and elasticity. Lime is occasionally added to the mix where resistance to damp is considered to be important. The resulting rough surface texture of this relatively soft plaster is particularly attractive when the short bits of golden straw in it, are visible on the surface. Hard smooth plaster of limestone finished by a thin layer of gypsum is frequently used internally and produces a finish similar to that of the hard modern plasters common in the modern buildings.

The colour of buildings:

The colour of the walls and the roof has a great effect on the solar impact on the building and its indoor climate, particularly in desert regions where solar intensity is higher than in other regions. Because of the different patterns of solar incidence on the roof and on the walls with different orientations, the importance of colour as a controller of the indoor climate is variable. For the roof, for instance, the influence of colour is maximum. The difference in the maximum surface temperature in summer between a white roof and a black one in a desert area can be about 40˚C. The resulting heat gain to the building interior depends on the thermo physical properties of the layer, but in general it is quite significant. (Mahyari, Ali, 1996)

> "With direct and reflected solar radiation the most intensive sources of heating, the effect of a light external colour in minimising internal day time temperature, is far greater than that of increasing either thermal resistance or capacity, with the added advantage that comfort at night is also improved. But if not whitewashed frequently, the building envelope absorbs enormous quantities of solar energy." (Givoni, 1976).

Materials and Texture of Wind-Catcher:

The materials forming the wind-catcher structure have a determining effect in harmony with the climate. (Particularly because the way of using materials in making a wind-catcher is expensive but is important in maintaining, its contribution to the process of climate control the process of climatic.)

In Bam the wind-catcher façade is plastered with cob; bright colors greatly help the reflection of sun radiation from the wind-catcher surface and its non-absorption by that surface. At the same time, presence of straws inside the mud increases the coarseness of façade texture, which in turn hinders the solar radiation. In "Bushehr Port" wind-catchers, on the other hand, the mortar plaster and plaster of lime and ashes mortar, which is white in color, hinders absorption of the sun radiation and increases its reflection. (Because the climate of "Bushehr Port" is hot and humid and is different from Bam) (Azami, A., 2005).

Main Material of Wind-Catcher Structures:

In Bam: mud-brick or brick together with plaster of clay, straw and timber frames are used because the heat transfer delay time of mud brick is desired.

In "Bushehr Port": plaster and plaster of lime are some traditional materials that cause to prevent humidity penetration into walls of wind-catcher.

These materials are cheap and help in creating temperature balance in the building during day and night.

Features of traditional construction materials in Iran:

The range of Iranian traditional materials used in construction is based upon the local availability, they can be divided to the following categories according to the availability and the features: (a) marble from domestic quarries and from other countries was often used as furniture or mosaic for decoration of interiors and exteriors of religious buildings; (b) natural stone (such as granite) available in abundance and of high quality, served as a load bearing and a decorative material of which ornaments of various kinds were made; (c) in the form of gypsum, stucco as a decoration material for columns, vaults, and domes; (d) wood (pine) served as framing of walls, and long span covers of halls.

The common material for walls of houses that were constructed in recent years was adobe (grizzle) brick – ‘‘hesht’’, with the size of 10, 20, 35 and 40 cm, made from yellow clay of a particular viscosity. The foundation was made as a massive monolithic basis – a mixture of clay, lime, gravel, and water. In seismically active areas, a wooden skeleton reinforced the design.

Modern Iranian constructions are now less dependent on local materials and regional construction basics, but more on the import of any required materials, products and equipment of the construction industry, also attracting professionals from abroad.

The choice of traditional or modern materials should be based on the requirements for constructions with regard to the materials operating conditions such as strength, durability, fire resistance, and seismic stability. If constructions meet the above-mentioned requirements, the choice should be made upon economic feasibility and technical consideration related to the specific conditions of construction, as well as the aesthetic properties of the materials (Abdolbaghi Moradchelleh, 2010).

Shortcoming of Traditional Construction in Iran (especially in hot and dry climate area):

1. Many buildings are constructed by heavy materials; therefore they are potentially dangerous for the people, who live there in the event of seismic activity.
2. They do not have enough resistance against fire, because of frame timbers and straw that used in the structure. (See previous page, main material of wind-catcher structures)
3. These materials are very basic, and they did not use new technology to provide best results of comfortable conditions.

4. Lot of time is required to construct buildings by these methods.

5. People who life in these buildings do not have the most comfortable conditions, especially during the night.

6. Thermal conditions of buildings are not appropriate, especially during the night in the winter.

7. These buildings are not constructed according to building scientific rules.

8. Old materials occupy very high volume of space. (Walls with great thickness)

9. These buildings are not movable

10. These buildings are not flexible

11. These buildings are not multifunctional.

12. The colors are not at the best to provide comfortable conditions for the people, who live in.

Features of New Materials for Optimizing Wind-Catchers, External Envelopes and the Form of Buildings:

After studying the materials of wind-catchers in the hot and dry climate of Iran; it is recommended that new materials with appropriate properties be used to construct wind-catchers and for creating comfort conditions inside buildings. These properties include:

1- The color of the material (exterior layer) should be bright to help the reflection of solar radiation from the wind-catcher surface to reduce its absorption especially in summer, but in winter the color must be change to dark color to much absorption and reduce reflected sun radiation.

   So the materials should have the ability to change color.

2- There is the need for materials with the ability to stock thermal energy of sun during the day and release the energy during the night.

3- The material must be economically cheap and readily available.

4- The appearance of these materials should be compatible with the traditional characteristics in of traditional materials used in that area.

5- The exterior layer of the material must be rough for absorption of thermal energy of sun in the winter and reflection of radiation of sun in the summer.
6- The interior layer should be creased and have some filter for absorbing dust and pollutants in the air.
7- This material should be able to provide appropriate moisturizing inside the buildings.
8- These materials must be light to provide safety conditions after a disaster like an earthquake.

Bam for example, is a city situated in a hot and dry climate, so the use of sprinkler irrigation system to provide comfortable conditions by evaporation is necessary, (digging of well or shaft is not economic and requires lots of time). Also making a shallow pool is not economic and is a cause of water waste.

There are two forms of wind-catcher; therefore new materials and systems for these forms are different and depend on the function and type of wind-catcher.

As a matter of fact, more days during the year are sunny, so most efficient use of solar energy has to be considered. Thus, to design a new system and to create enough shadow the use of photoelectrical cells is recommended.

Some buildings in the near future will be built with smart materials to change the form of the buildings in respect to climate conditions during the day: for instance the form of buildings will change as appropriate in the winter or at night against wind or cold weather and the form will change to another form against warm weather or to sink down in to the earth in the middle of summer or in hot and dry periods, in harmony with the environment.

With these new materials, it should be possible to change the orientation of buildings to provide comfort conditions. For this purpose: (a) Folding architecture and (b) changeable base of buildings could be helpful.

In hot and dry climate, use of Trombe wall with new materials to absorb the energy of the sun in day and emit it during the night is recommended. Also, the Trombe wall should be harmonized with the wind-catcher to provide comfort conditions by matching these two systems together.

Effect of integration of Wind-Catchers with Curve Roofs on Natural Ventilation Performance in Building:

According to the research of Asfour, Omar S. and Gadi, Mohamed B. (2008) different building configurations have been compared before and after the utilization of wind catchers in terms of air flow rate and internal airflow distribution. Utilizing the architectural elements of curved roofs and wind catcher for natural ventilation is an effective strategy and system of ventilation particularly under the undesirable conditions of deep-plan buildings or low reference wind velocities.

Some aspects of new materials and climate - responsible design should include:

Reducing Cooling Loads:

- Building orientation and clustering
- High-reflectivity building materials
- External insulation
- External shading devices
- Windows with low SHGC
- Thermal mass (see below)
- Vegetation (provides shading and evaporative cooling)
- Efficient equipment and lighting to reduce internal heat gains

Regarding Thermal Mass Specifically:

- By itself, it does not reduce the cooling load
- High thermal mass means that it takes longer for the building to warm up, but with a prolonged heat wave, a building with high thermal mass eventually heats up and then will take a long time to cool down
- However, thermal mass will greatly reduce the temperature increase from morning to late afternoon, so if the night becomes cool enough, night air can be used to remove heat from the thermal mass. So it does not build up from day to day (or at least not as much)

To be most effective, thermal mass needs to be combined with:

- External insulation
- Night-time ventilation with cool outside air flowing into the core of the thermal mass (such as hollow concrete slab ceilings or walls in effect, the coolness of the night air is stored and used to keep the building cool during the day); this of course reduces total energy use but also reduces required peak rates of mechanical cooling if there is any, saving on purchase costs for cooling equipment and electrical transformers, and reducing utility charges to meet peak electricity demand
- The traditional materials used to add thermal mass are concrete and stone. Interestingly, phase change materials can be used as well, either as small spheres in regular plaster or in the ventilation air flow. There are waxes that can be designed to melt at 26ºC, absorbing heat in the process and resisting any further increase in air temperature. If the air temperature drops below 26ºC at night, they will refreeze (releasing heat that is taken away with the night-time air flow), ready to absorb heat again the next day. They would be ideal in arid parts of the world (where nights get cold and days are hot)

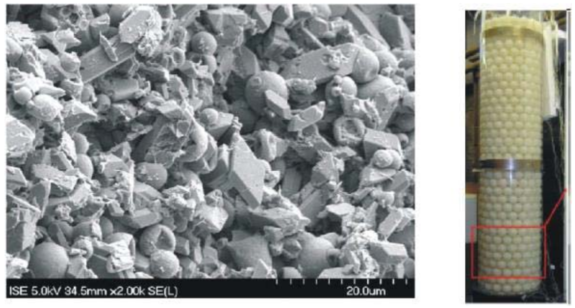

Figure 5.2. (Left) Microencapsulated phase-change material and (Right) spheres containing phase change materials in an air flow pipe. (Source: Schossig et al, 2005, Solar Energy Materials and Solar Cells 89, 297–306, http://www.sciencedirect.com/science/journal/09270248 & Arkar and Medved, 2007, Solar Energy 81, 1078-1087, http://www.sciencedirect.com/science/journal/0038092X)

Chapter VI. Conclusion:

In conclusion, evaporative cooling is very effective in a hot and dry area. The temperature decreases considerably, if there are wind towers and if they are equipped with a water vaporization system. (Source: Optimization of "Badgir (wind-tower)" in Iranian Hot-Arid Region Architecture, Shabestari, Ali Farhadi and Ahmadkhani Maleki, Bahram, 2010).

In conjunction with evaporative cooling and wind towers, further techniques have been used (a) to obtain protection from winter wind (e.g. by the biomimetisme of termite mounds) and (b) to promote summer wind penetration, with consequent further reduction of energy demand for buildings. A sustainable natural ventilation process can also include a system of wind tunnels and air flow through the main building shell to distribute fresh air and provide comfort condition inside the different buildings structures. Also, this system can be conjugated with lighter and stronger construction of the building shell.

In addition, a system based on the use of ventilation chimneys provides for air admission and expulsion. During the night in *summertime*, because of the lower external air temperature, such chimneys produce air-cooling of the chimneys and of the building structures through the stack effect. In *wintertime,* solar radiation on the transparent part of the chimneys of the south façade generates a convective loop, which transfers the heat picked up from the masses of the inner chimneys to the inside the shelter.

The reason for choosing this sort of method is that it is a simple and integrated bioclimatic system, able to obtain a high level of thermal performance that improves the quality of the indoor and outdoor environment, combined with low energy consumption. It satisfies temperature, air and acoustic conditions, and provides completely natural ventilation and is an innovative choice.

:

The newly-found interest for wind-catchers can have a lot to learn from the heritage, cultural and traditional building, but purely traditional solutions seem rather hard to propose, if only because the traditional materials and methods have to be accepted by contemporary architects. The lack of real world model development is one of the factors that currently inhibits the wide application of the wind-catcher technology. So development of a real world model is necessary to improve wind-catcher technology for today and optimize the good results for the buildings in the future.

The discussions presented in this thesis raised the awareness of the importance of the traditional wind-catcher and helped open up possibilities for improving their performance through new methods and materials and by widening the applicability of wind- catchers in the different climate/s conditions through design of new natural passive systems. This thesis explains natural air conditioning systems through looking to the tradition and the trends. Obviously, the Islamic way is to approach major issues such as the use of natural resources through strategies which arise out of the Qur'anic context.

This approach will bring new opportunities for using this old heritage passive cooling system in today's world. Combining traditional knowledge and advanced technology is therefore necessary.

Therefore, a new form of wind-catcher could be based, in the future, on scientific simulations, all the while respecting the Qur'anic principles and the Quranic context. The existence of built examples in different parts of the world provides a starting point for the further research that is necessary to develop practical design guidelines and to develop the features of the management system that will be needed for the design of wind-catchers for all types of buildings under normal conditions. There is no doubt that if the leading architects - both of contemporary architecture and Islamic architecture - realized buildings with wind-catchers, it would have attracted the attention of a much wider public and this valued architectural device would have found a new dimension in the future of architecture.

A model of the design decision sequence is shown on the model on the next page.

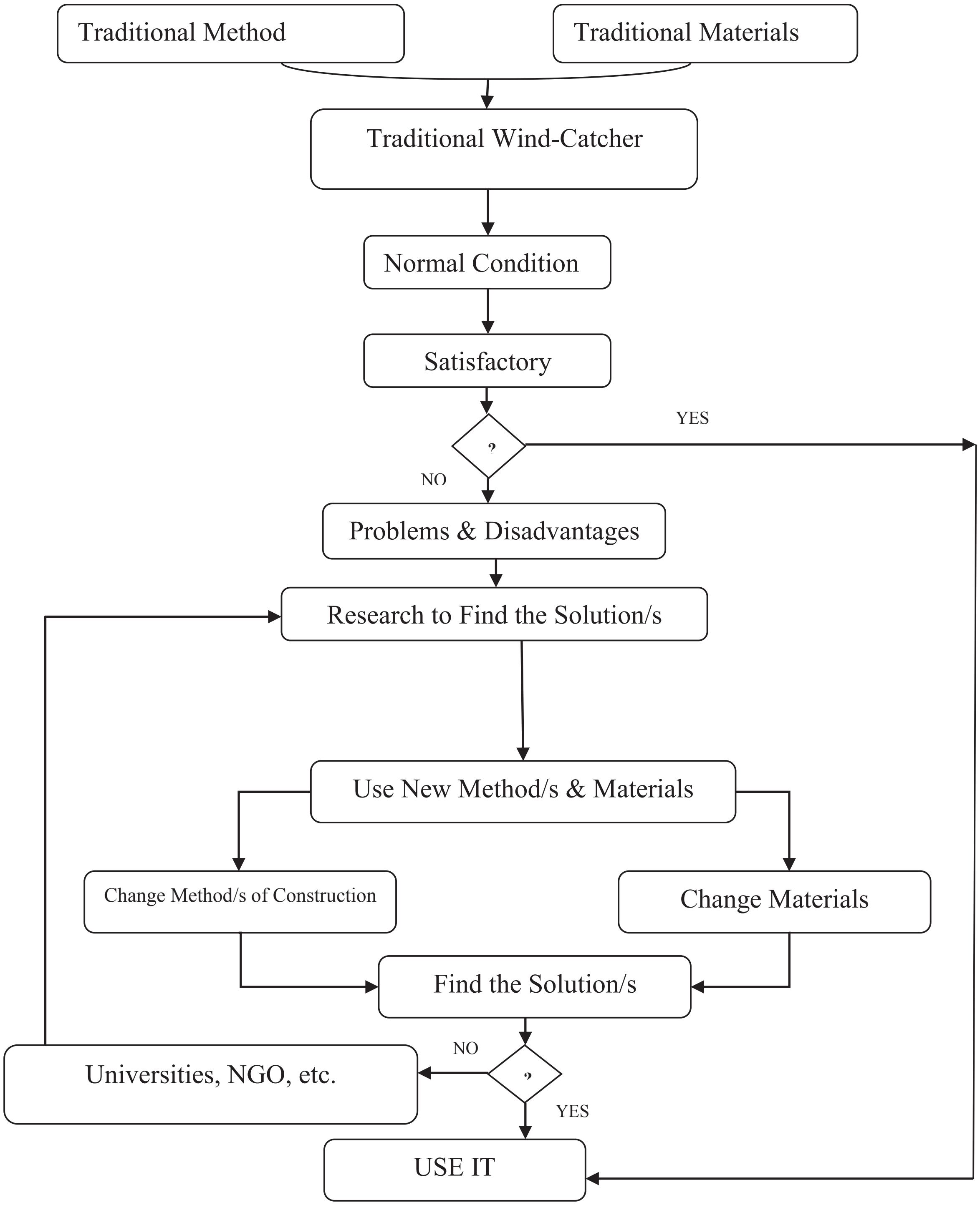
Traditional Method
Traditional Materials
Traditional Wind-Catcher
Normal Condition
Satisfactory
?
YES
NO
Problems & Disadvantages
Research to Find the Solution/s
Use New Method/s & Materials
Change Method/s of Construction
Change Materials
Find the Solution/s
NO
?
Universities, NGO, etc.
YES
USE IT

Figure 6.1. : Diagram of the practical guidelines needed to develop the management system for the design of wind-catchers for all types of buildings, which will be located in the different climate/s, under normal conditions.

References:

A`zami, A., 2005. *Badgir in traditional Iranian architecture.* Santorini, Greece, s.n.

Ali, M., 1997. *Wind catcher.* Sydney: Sudney University.

Anon., 1980. *Bonine, M.E..* New York: Aridity and structure, Desert Housing.

Anon., 2005. *Natural cooling systems in sustainable traditional architecture of Iran.* Santorini, International Conference "Passive and low Energy Cooling".

Anon., 2008. *Wind catcher.* [Online] Available at: www.Flickr.com

Anon., 2010. *Surface water cycle.* [Online] Available at: https://commons.wikimedia.org/wiki/File:Surface_water_cycle.svg

Anon., 2011. [Online] Available at: http://www.hyoomik.com/phi205/wisdom.htm#sophia

Anon., 2011. [Online] Available at: http://www.islam-guide.com/ch3-7.htm

Anon., 2011. [Online] Available at: http://www.esf.edu/efb/turner/termite/gas%20exchange%20wind.html

Anon., 2011. *Eartquake proof.* [Online] Available at: http://www.whatprice.co.uk/building/earthquake-proof.html

Anon., 2011. *Monolithic.* [Online] Available at: http://www.monolithic.com/topics/benefits,

Anon., 2011. *Termite mound.* [Online] Available at: http://www.mountmorelandconservancy.co.za/Bio-Diversity-Mount-Moreland-Conservancy/Termites-Ant-hill.html

Anon., n.d. s.l.:s.n.

Bahadori, M., 1985. An Improved Design of Wind Towers for Natural Ventilation and Passive Cooling. *Solar Energy; vol 35.*

Fath, H., 1986. *Natural Energy and Vernacular Architecture.* Chicago: University of Chicago.

Golany, G. (1983). *Earth-sheltered habitat: history, architecture, and urban design*. New York: Van Nostrand Reinhold.

Gallo C., Salla. M., Sayigh. A., 1988. *Architecture - Comfort and Energy.* s.l.:PERGAMON.

Ghazbanpor, J., 2001. *House Iranian.* Tehran, Iran: s.n.

Ghobadian, V., 1998. *Climatic Analysis of the Iranian Traditional Buildings.* Tehran: Tehran University.

Ghobadian, V., 1998. *Climatic Analysis of the Traditional Iranian Buildings.* Tehran, Iran: s.n.

Givoni, B., 1976. *Man, Climate and Architecture.* Amesterdam: Applied Science Publisher Ltd.

Kasmaee, M., 1980. *Traditional Architecture of Iran and its Relation to its History, Climate and Culture.* Tehran, Iran: Entesharat Khak.

Kasmai, M. A. M., 2003. *Climate and Architecture.* Esfahan, Iran: s.n.

Korb Jaudith, L. K. E., 1998. The architecture of termite mound. *Behavioral Ecology,* pp. 312-316.

L., R., 1978. *Living Better.* s.l.:Writer`s Digest Books.

M.H., G., 1963. *Climate, History of Iran.* s.l.:Cambridge.

Mahmoudi, M., 2005. *Wind tower as a natural cooling system in Iranian architecture.* Greece, s.n.

Michael S. Mamlouk, J. P. Z., 2006. *Materials for civil and construction engineers.* New Jersey: Prentice - Hall.

Mofidi, S., 2008. Analysis on typology and architecture of wind catcher and finding the best type. *Honarhay ziba, vol 36,* p. 29.

Moradchelleh, A., 2008. *Traditions of structural morphology in civil architecture of Iran.* Kiev, Ukraine: s.n.

Omar S. Asfour and Mohamed B. Gadi, 2011. [Online] Available at: http://www.get-sust.com/PDFs/AEDM-Vol2-No4-Asfour-Small.pdf, 2011-02-27

Pamphlet Course, 2010. *Environmental Building Design.* Waterloo: University of Waterloo.

Pyrnia, M., 1981. *Acquaintance with Iran Islamic Architecture.* Tehran: University of Tehran.

Pyrnia, M., 1991. *Islamic Architecture Recognition.* Tehran: University of Tehran.

Roaf, S., 1988. *The Wind Catchers of The Yazd.* London: Oxford.

Roaf, S. e. a., 1982. *Wind Catchers, Living With the Desert.* London, England: Air & Philips.

Smith, P. F., 2005. *Architecture in a Climate of Change.* London: Architecturalpress.

Tavassoli, M., 1974. *Architecture of hot arid climate.* Tehran, Iran: University of Tehran.

Tavassoli, M., 2002. *Urban Structure and Architecture in the Hot Arid Zone of Iran.* Tehran, Iran: s.n.

Trewartha, G. T., 1954. *An Introduction to Climate.* s.l.:McGraw Hill.

Appendix:

Wind data:

Wind data are best presented graphically. Wind roses are one of the most important graphs to analyse the data.

> "Several different types of wind roses can be presented for this purpose. One method presents a separate wind rose (see picture below) for each month (or sometimes one wind rose representing 3 months, i.e. four wind roses representing the four seasons of the year). The length of lines radiating from a small circle is proportionate to the frequency of wind from that direction. Different line thicknesses may indicate wind velocity categories.
> For architectural purposes the most useful form of wind rose is an octagon, with 12 lines on each side, corresponding to the 12 months, from January to December in a clockwise direction, where the length of a line is proportionate to the frequency (% of observations) of wind from that direction in that month. If the winds were evenly distributed, all lines would extend to the outer octagon, which indicates a line length of 12.5%. Small dashes on the inside of the base octagon indicate that there is no wind in that month from that direction.
> The 12 numbers inside the graph give the % of total calm periods for the 12 months. It is usual to give a wind rose for an early morning and one for a mid-afternoon hour. Often two such graphs are shown, one for 9 a.m. and one for 3 p.m. These may be supplemented by a tabulated wind frequency analysis, such as that shown in for one month." (Bureau of Meteorology, Australia, 1988).

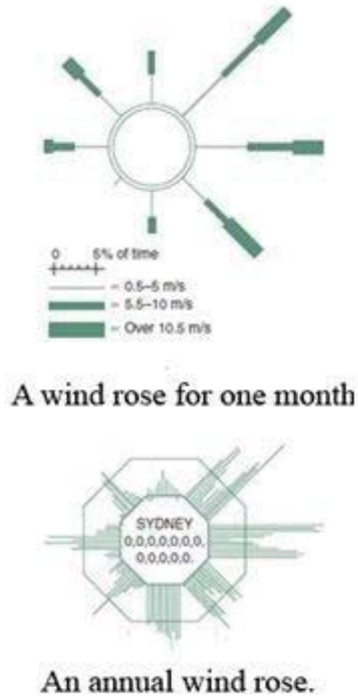

Figure A.1: Wind Rose

Wind-Catcher Formulae:

“Measurement procedures Pressure coefficients:

The external pressure field induced by wind is the most important factor, which influences internal flows in a naturally ventilated structure. In this study, all pressure measurements were referred to the upstream dynamic pressure using the reference velocity in the wind tunnel for the case of uniform wind. The wind pressure coefficient C_p is calculated using the following formula:

$$C_p = \frac{p - p_s}{\frac{1}{2} pV^2 ref}$$

Where p is the surface pressure that was measured with the use of several pressure taps. These pressure taps were neatly placed at apertures and underneath channels of the model. In this equation, p_s is the upstream static pressure and $\frac{1}{2}pV^2ref$ is the dynamic pressure of the uniform wind. Upstream static and total pressures were measured using a pilot–static tube that was placed 16.5 cm upstream of the test model and 12 cm above the wind tunnel floor."(Source: Montazeri, H., Montazeri, F., Azizian, R., Mostafavi, S., 2009, http://www.sciencedirect.com/science?_ob=MImg&_imagekey=B6V4S-4Y5H60C-1-11&_cdi=5766&_user=789722&_pii=S0960148109005394&_origin=gateway&_coverDate=07/31/2010&_sk=999649992&view=c&wchp=dGLzVtb-zSkzk&md5=3e23436ed176a6b2c682afb8d82f56f9&ie=/sdarticle.pdf)

One good example of the Proper shape for Earthquake Building:

Monolithic Domes:

"To improve the lives of people worldwide through the introduction and construction of Monolithic Domes, for personal and public use, those are superior in strength, energy-efficiency and cost control. Some benefits of Monolithic Domes are consisting of:

Low cost and easy-to-build structure designed to for quick construction and easy maintenance, low energy structure minimizes air infiltration, allowing for more efficient heating and cooling; The Monolithic Dome is a micro-energy user. It needs a minimum of energy to maintain a comfortable interior, usually one fourth of that used by other types of structures. In fact, it takes less energy to heat or cool a Monolithic Dome than it does to heat or cool a super-insulated metal building or a conventional house blanketed in an airtight wrap.

In every size and capacity, owners are reporting significant savings in heating and cooling the Monolithic Dome" (Source: http://static.monolithic.com/pdfs/passive_handbook.pdf, 2011-02-27, p.8)

" Building with Monolithic Dome form is a type of building that cause to safe building from natural disasters like hurricanes, tornados, wind and sand storms, earthquakes, and fires;" they have the strength to withstand tornadoes, hurricanes and earthquakes. They are also fire-resistant, rot-proof and termite-proof. That unbeatable strength comes from the concrete and steel used in the dome's

construction and from its rounded shape. Monolithic Domes are the most disaster-resistant structures that can be built affordably.
The Monolithic Dome - is the most disaster resistant building that can be built at a reasonable price. A wind of 250 MPH (used in FEMA 361) pushes with a pressure of 300 pounds per square foot. If the wind speed increases to 300 miles per hour the pressure increases to 404 pounds per square foot (psf). Wind speed of 300 MPH is considered maximum for a tornado. A Force 5 tornado pushes with 4 times the pressure of a Force 5 hurricane. No normal building can withstand that much pressure. Many Monolithic Domes are buried up to 30 feet deep. They must withstand pressured up to 1 ton per square foot (2000 psf). The fact is, the Monolithic Dome is not flat and therefore never can maximum wind push against more than a small area." (Source: http://www.monolithic.com/topics/benefits-strength, 201-02-27)
"It is the most disaster resistant building that can be built at a reasonable price without going underground or into a mountain.
A wind of 70 miles per hour blowing against a 30 foot tall flat walled building in open flat terrain will exert a pressure of 22 pounds per square foot (see sidebars). If the wind speed is increased to 300 miles per hour the pressure is increased to 404 pounds per square foot (psf). Wind speed of 300 MPH is considered maximum for a tornado. It is far greater than that of a hurricane.
Cars can be parked on 100 psf. The side pressure on the building could equal the weight of cars piled 4 high. No normal building can withstand that much pressure. Many Monolithic Domes are buried up to 30 feet deep. They must withstand pressures up to 1 ton per square foot (2000 psf).
As a matter of fact, the Monolithic Dome is not flat and therefore never could the maximum air pressure against it of 404 pounds per square foot be realized. Neither is the concrete only 4,000 psi. It is always much greater. The margin of safety is probably more like three or four.
The Monolithic Dome at Port Arthur, Texas has now been hit by three hurricanes. A hurricane does not exert enough pressure on a dome to be even noticed. As shown above the dome can very easily withstand the stresses of a tornado.
In the following pictures there are some examples of buildings with dome shape in Bam after earthquake" (Source: http://www.istructe.org/EEFIT/files/Bam.pdf, 2011-02-27).

Figure A.2: This adobe 16 m span arch roof of the Henna factory survived (9 EMS) because the load bearing walls were strong and restrained enough to resist movement from lateral loading. The flank wall failed since it was not laterally restrained. (Source: Photo by: H. Darejati)

Figure A.3: This mosque with minarets about 20m tall and vault of 7m span wide 13m tall survived with damage to the false ceiling plaster and structural damage to the minaret with no tiles (Source: H. Darejati)

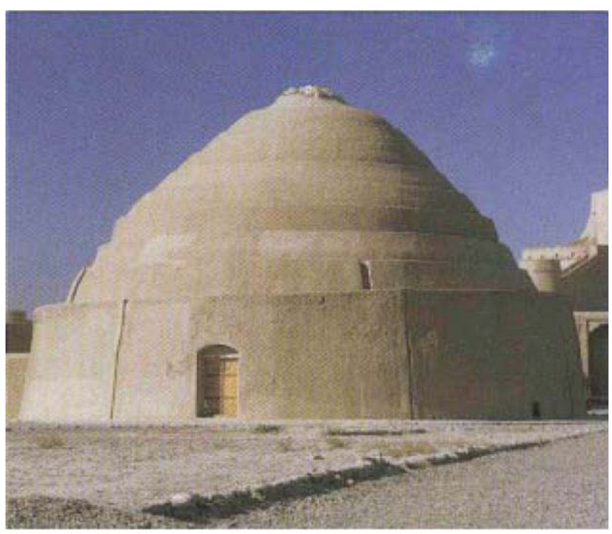

Figure A.4: The northern elevation of the Ice House with reconstructed dome, located on the northern part of the Citadel (Argé Bam). The aerial photographs by James Blair for The

National Geographic Magazine in 1974 show that the dome was not reconstructed at the time of that aerial survey (Source: H. Darejati)

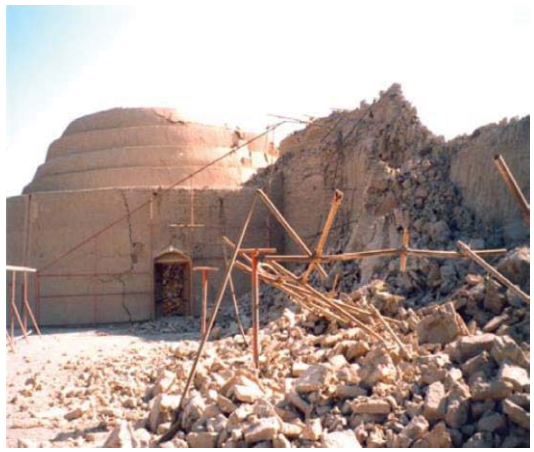

Figure A.5: Southern elevation of the Ice House (Ice maker), after the earthquake. The dome was reconstructed between 1974 and 2003; the original earthen walls survived the seismic forces (9EMS) with a vertical crack near the entrance in spite of the additional loading from the dome (Source: H. Darejati)

The structure of Monolithic Dome:

"A super insulated, thin shell, steel reinforced concrete structure utilizing air formed construction."

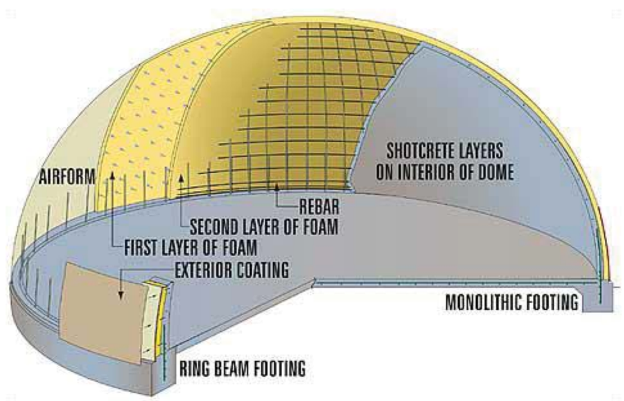

Figure A.6: The structure of Monolithic Dome (Source: http://www.monolithic.com/topics/domes, 1/5/2012)

Ventilation of Dome Monolithic proposed by maker:

"A system that filters the air coming into a structure, as well as the air already in it, is a good idea for any home. So for a person, who lives there, such a system is a must-have. For Monolithic a serious filtering system is necessary. It should design to remove virtually everything harmful from the incoming air and the interior air. This new system provides the clean, fresh air and comfort conditions, which needs for the people.

Some Advantages and Disadvantages of Monolithic Dome:

Debris carried by a tornado could cut the surface membrane. If the debris contained a large timber or metal object, it might be possible if conditions were just right to put a puncture into the dome. But the puncture would be very local and would certainly never cause serious collapse of the dome. Possibly damage to the doors or windows may occur if there was a rapid decompression caused by the tornado. This is disadvantage of Monolithic Dome, but in this research this form of the building is recommended for arid area in south of Iran, where there was not any tornado in the past years.

The forces caused by a major earthquake are considerably less than normal provided for when a dome is designed for nominal vertical loads.

Nuclear fallout is another disaster consideration. It is interesting to note that the only structure left standing near ground zero at Hiroshima was the concrete skeleton of a dome. Certainly the Monolithic Dome would be superior to most buildings if a nuclear fallout condition occurred. Rain would tend to wash the radiation off the building much better than conventional buildings.

The forces caused by wind and earthquake on a concrete dome generally do not control the design. Domes are very strong and durable and in a realistic situation would probably still be standing when all conventional structures had failed.

Generally the Monolithic Dome is quite tall. Radiation strengths are inversely proportional to the square of the distance from the source. The roof of the Monolithic Dome would hold the radiation further from the occupants than many other structures. Also concrete itself is a good absorber of radiation. The concrete Monolithic Dome would greatly reduce the effects of fallout on the occupants.

Note: Dr. Arnold Wilson, retired professor of Civil Engineering at Brigham Young University and Senior Consulting Engineer for Monolithic, is a recognized expert on thin shell concrete construction. Thin shell is the generic name for a Monolithic Dome." (Source: http://www.monolithic.com/stories/building-survivability-the-strength-of-the-monolithic-dome, 2011-02-27)

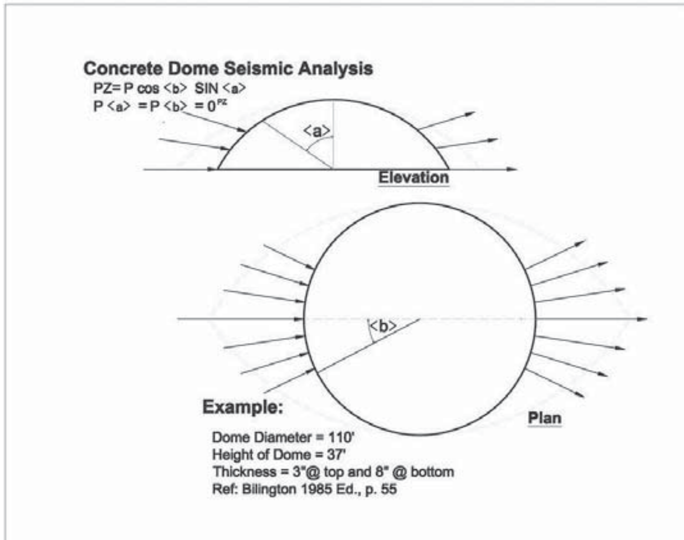

Figure A.7: Concrete Dome Seismic Analysis: From this analysis it is easy to see that earthquake forces do not even approach the design strength of the Monolithic Dome. (Source: http://www.monolithic.com/topics/domes, 1/5/2012)

Figure A.8: Some pictures of Monolithic Domes that are already constructed. (Source: http://www.monolithic.com/topics/domes, 1/5/2012)

Effect of wind on a spherical particle:

"The physical mechanism which leads to aerodynamic drag is as illustrated in Figure A.9.(a) if the particle moves relative to the surrounding fluid, a force in the opposite direction of that relative velocity is exerted by the fluid on the particle. This force is known as the drag that arises from the pressure differences between the frontal region and the wake region of the particle and from the transfer of momentum from the fluid to the particle through molecular motion, namely the viscous effect. There is an equal and opposite force exerted by the particle on the fluid. The force exerted by the flow on the particle is equal to the integral of total stress (or momentum flux) over the surface of the particle."

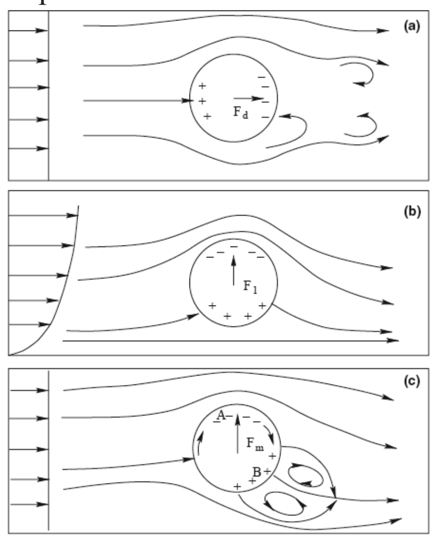

Figure A.9: An illustration of drag, lift and Magnus forces acting on a spherical particle. (a) Aerodynamic drag due to the viscous effect, flow separation and turbulence in the wake region of the particle. Higher fluid pressure on the sphere is indicated positive and lower pressure negative. (b) Aerodynamic lift due to the Bernoulli effect on a spherical particle in a shear flow. The pressure is higher on the lower side of the particle where the fluid velocity is smaller, while the pressure is lower on the upper side, where the fluid velocity is higher. (c) Magnus force due to a combination of the Bernoulli effect and the viscous effect on a spinning particle. On the upper side of the particle, where the particle spins in the same direction as the fluid motion, the fluid velocity is relatively higher and the pressure is relatively lower than on the lower side of the particle, where the particle spins in the opposite direction to the fluid. In these papers wind is a kind of fluid and Monolithic Dome is an example of spherical particle. (Source: Modified from Allen, 1994) (Source: Physics and Modelling of Wind Erosion-Yaping Shao- Springer Inc., ISBN 978-1-4020-8894-0, p.125) “PART: Forces on an Airborne Particle p. 124-129, pp. 292, Physics and Modelling of Wind Erosion-Yaping Shao- Springer Inc. +pictures”

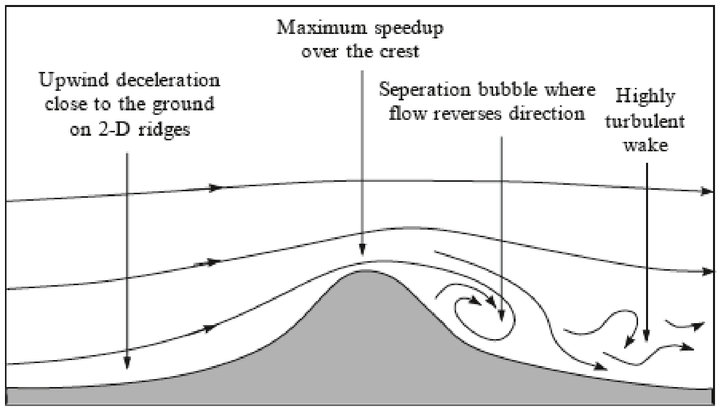

Figure A.10: Basic features of flow over a two-dimensional ridge which is similar to a dome monolithic shelter. (After Finnigan and Brunet, 1995)

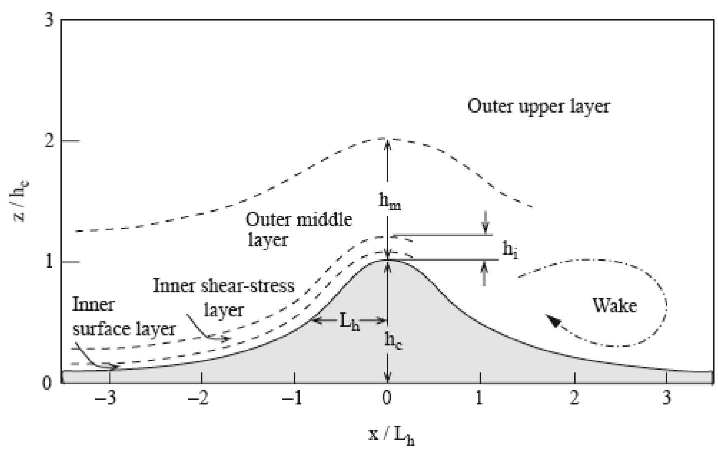

Figure A.11: Conceptual model for flow over a low hill, which is similar to dome monolithic. (Source: Physics and Modelling of Wind Erosion-Yaping Shao- Springer Inc., ISBN 978-1-4020-8894-0, pp. 374)

“The flow is divided into the outer, inner and wake regions. The outer region is further divided into the upper layer and middle layer, and the inner region is further divided into the shear stress layer and the inner surface layer. The wake region exists in the lee side of the hill.” (Source: Physics and Modelling of Wind Erosion-Yaping Shao- Springer Inc., ISBN 978-1-4020-8894-0, p.373-374)