# NATURAL VENTILATION IN BUILDINGS AND THE TOOLS FOR ANALYSIS

By

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A THESIS PRESENTED TO THE GRADUATE SCHOOL
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To my great parents, Dr. Mohammad Ali Mozaffarian and Zahra Zahedi, my lovely brother and sisters, Ramin, Rozita and Roya Mozaffarian
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Natural ventilation is using natural air to condition the interior of a building with minimal mechanical equipment. In other words, it is ventilating the building with natural air. Natural ventilation offers the means to control air quality in buildings, to directly condition indoor air with cooler outdoor air, to indirectly condition indoor air by night cooling of building thermal mass, and to provide refreshing airflow past occupants when desired. Implementing natural ventilation for conditioning can reduce electrical consumption, can recover the valuable building space typically used by all-air mechanical systems, can potentially provide health, comfort, and productivity advantages,  in buildings and increases the efficiency of energy and material resources which are the purposes of a sustainable building, or green building. The objective of this study is to improve the environmental performance of ventilation and temperature control systems in buildings by using natural ventilation instead of mechanical systems. The main focus of this study is natural ventilation through wind. By using a technique for natural ventilation, the outdoor air can be introduced into the building to circulate air. Another primary focus is the selection of software for modeling a building with a natural ventilation system.

# CHAPTER 1
# INTRODUCTION

## Introduction

Studies have shown that it is difficult to ventilate buildings in different climates without using mechanical and/or electrical equipment (McEneaney 2005). While historically all buildings employed natural ventilation, this practice has been disregarded due to developing electrical cooling and heating devices (McEneaney 2005). When the flow of kinetic energy or the buoyancy driven force of the air (convection) is used for ventilation purposes, then this type of ventilation is typically called natural ventilation. This research describes different techniques and designs for natural ventilation in buildings. Some advantages of having natural ventilation include reducing energy and operation costs, better indoor air quality, a healthier and more productive environment (Emmerich et al. 2001).This study focuses on natural ventilation caused by the wind. Review of literature reveals that a traditional wind tower or badgir can be a useful technique for natural ventilation.

## Problem Statement

The use of a wind tower (badgir) on a building without mechanical equipment has not been commonly studied as a solution for natural ventilation. Also, choosing software for natural ventilation in buildings was studied. The case study uses the hot and humid conditions in July in Gainesville, Florida. Humidity inside the case study building was not modeled or estimated for simplicity. The case study indicates that humidity is very likely to be high and outside of comfort parameters (ASHRAE 55).

## Research Objectives

The objective of this study is to improve the environmental performance of ventilation and temperature control systems in buildings by using natural ventilation instead of mechanical systems. Natural ventilation can reduce the electrical consumption of buildings by using natural resources such as wind and solar energy. The main focus of this study is natural ventilation through wind. By using a technique for natural ventilation, the outdoor air can be introduced into the building to circulate air. Moreover, if the air passes over a water reservoir it can reduce the inside temperature of the building, though it is also likely to increase relative humidity. Another primary focus is the selection of software for modeling a building with a natural ventilation system. A case study building, Rinker Hall, School of Building Construction at University of Florida has been modeled with three tools, Autodesk Ecotect, simplified calculations of air change and Computational Fluid Dynamics software. At the end, the result of each tool has been compared, evaluated and a recommendation made.

## Significance of the Study

A sustainable building, or green building is an outcome of a design which focuses on increasing the efficiency of resource use — energy, water, and materials — while reducing building impacts on human health and the environment during the building's lifecycle, through better design, construction, operation and maintenances (Frej 2005). Implementing natural ventilation for conditioning can reduce electrical consumption in buildings and increases the efficiency of energy and material resources. Also, by designing a badgir for natural ventilation in buildings, human health and healthy environment are enhanced. The result of this study determines the potential for natural ventilation and cooling air inside buildings with a minimum usage of electrical air conditioning equipment.

## Limitations of the Study

One of the limitations of this study is choosing user-friendly and precise software for the modeling. In over viewing available programs (Loop DA, AIOLOS, Autodesk Ecotect, Green Building Studio and Computational Fluid Dynamics-CFD) the research becomes challenging. In addition, information and resources on natural ventilation especially about wind tower or badgir as a kind of ventilation are often limited to specific countries like Iran in which it is commonly used.

# CHAPTER 2
# LITERATURE REVIEW

## Introduction

Natural ventilation is ventilation provided by thermal, wind, or diffusion effects through doors, windows, or other intentional openings in the building (ASHARE 62.1 2007).

Historically many buildings in the past used natural ventilation. It is economical and energy efficient to cool the building without using any mechanical equipment. Natural ventilation supplies outdoor air to the interior of the building for ventilation and cooling. Natural ventilation can be substituted for part of a mechanical system through proper design and appropriate building location and use which helps to reduce construction, energy and operating costs. Some benefits of having a naturally ventilated building are to provide indoor air quality and comfort, which leads to healthier and more productive building occupants (McEneaney 2005).

Natural ventilation brings natural elements such as wind, humidity, and warm or cold air through design of building form to let fresh outdoor air in and indoor air out. Some ways of doing this include operable windows, exhaust vents located high in the building, intake vents located low in the building, atria, internal stairwells, ventilation chimneys and small fans (solar powered) and open building plans to facilitate air movement (McEneaney 2005). By reducing the size of mechanical systems, construction cost savings and energy savings due to natural ventilation will occur. Some of the benefits beside energy and cost savings are improving occupant health, quality of life, and productivity. Some studies show that by creating a productive and healthy environment in buildings, patients could make progress more quickly, students can receive a better grade, and residences sell or rent more quickly (McEneaney 2005).

## Definitions of Natural Ventilation

There are different definitions of natural ventilation.

- Ventilation provided by thermal, wind, or diffusion effects through doors, windows, or other intentional openings in the building (ASHARE 62.1).
- The process of supplying and removing air through an indoor space by natural means (Roulet 2002).
- Passively supplying outdoor air to a building interior for ventilation and cooling (Busby).
- Pressure differences between the inside and the outside of the building (UFC 2004).
- Using local wind and temperature differences between the inside and outside of the building to move air through the structure (Chastain 2000).
- Wind and thermal buoyancy as driving forces to create the desired thermal environment and transport away undesired contaminants (Kleiven 2003).
- Providing the “fresh” outdoor air into a building and circulate it in the building or a room to dilute or remove pollutants (Li 2003).
- Based on different definitions of natural ventilation, specific definition of natural ventilation has been used in this study. When the Kinetic energy or the buoyancy driven force of the air is used for ventilation purposes, the type of ventilation is typically called natural ventilation.

## Different Kinds of Ventilation

There are three kinds of natural ventilation systems: wind-driven cross ventilation, buoyancy-driven stack ventilation, single-sided ventilation, stack ventilation with sub-slab distribution, hybrid ventilation and wind-stack driven ventilation (Emmerich et al. 2001).

### Wind-Driven Cross Ventilation

Having ventilation openings on opposite sides of a closed space is wind-driven cross ventilation. Figure 2-1 shows a schematic of cross ventilation in multi-room building which is also called global cross ventilation. In order to have a sufficient ventilation flow, there should be a significant difference in wind pressure between the inlet and outlet openings (Emmerich et al. 2001).

## Buoyancy-Driven Stack Ventilation

Buoyancy-driven stack ventilation will happen based on density differences of cool and warm air. Figure 2-2 shows a schematic of stack ventilation for a multi-room building. By a chimney or atrium, sufficient buoyancy forces will happen. Good design is the way to combine both wind effects and buoyancy effects in stack ventilation schemes (Emmerich et al. 2001).

## Single-Sided Ventilation

In single-sided ventilation, single rooms are ventilated. Figure 2-3 indicates a schematic of single-sided ventilation in a building. Driving forces for single-sided ventilation are relatively small and are highly variable. The least attractive natural ventilation solution happens by single-sided ventilation. This ventilation provides ventilated air for individual offices compared to other kind of ventilation (Emmerich et al. 2001).

## Stack Ventilation with Sub-Slab Distribution

By using in-slab or access-floor distribution of fresh air, greater control of air distribution across the building section is observed. Figure 2-4 shows a schematic of stack ventilation with a sub-slab distribution system (Emmerich et al. 2001).

## Hybrid Ventilation Systems

Hybrid ventilation systems attempt to combine the benefits of both natural and mechanical ventilation in an optimal way. The primary purpose of ventilation is to provide acceptable indoor air quality and indoor temperatures. In natural ventilation, the forces of wind and air density differences are used to move air through the building (Heiselberg 1999, Heiselberg 2000). Hybrid ventilation takes advantage of natural ventilation forces, using mechanical forces only when natural forces are not sufficient. The combination of natural ventilation and modern design techniques, materials and control strategies has great potential (Szikra 2000). This modernized technique for designing new buildings and retrofitting requires more integrated design and construction of buildings, more thermal insulation, reducing non-controlled in filtration and using mechanical ventilation systems with heat recovery. Today higher indoor air quality is required, so mechanical ventilation systems consume considerable amounts of electric energy for fans and heat through the heating coils. It is possible to apply traditional natural ventilation systems. Although it does not provide the acceptable comfort level for the occupants and consumes large amounts of energy to heat the fresh air. So, the solution is a hybrid ventilation system that combines natural and mechanical driving forces. A hybrid ventilation system can be described as a system with a comfortable internal environment using different features of both natural ventilation and mechanical systems at different times of the day or seasons of the year. It is a ventilation system where mechanical and natural forces are combined in a two-mode system. Hybrid ventilation is a two-mode system which is controlled to minimize energy consumption while maintaining acceptable indoor air quality and thermal comfort. The two modes refer to natural and mechanical driving forces. The purpose of its control system is to establish the desired air change rate but lowest possible energy consumption (Heiselberg 1999, Heiselberg 2000).

**Wind-Stack Driven Ventilation**

This method has been used in ancient times in hot climates. Two methods have been used in ancient buildings in Iran: curved-roof air vent systems and wind tower systems. Wind tower systems are as old as 4000 BC. Malkaf or wind-catch was used by ancient Egyptians in the houses of Tal Al-Amarna as well (Allard 1998).

**Wind Catcher or Badgir**

Central Iran has a very large day-to-night temperature difference, ranging from very cool to extremely hot. The air tends to be very dry all day long. Most buildings are constructed of very thick ceramics with extremely high insulation values and thermal mass. Furthermore, towns centered in the desert tend to be packed closely together with high walls and ceilings compared to Western architecture. Maximizing shade at ground level helps lower the temperature in these areas. The heat of direct sunlight is minimized with small windows that do not face the sun. Southern Iran has a very similar climate to Florida's weather. These southern cities are near the Persian Gulf, which has a hot and humid climate. Because of the heat, humidity, and wind in central and southern Iran in summer seasons, wind towers or badgirs have been used and are one of the masterpieces of Iranian engineering. Badgirs have been used to cool the buildings with natural ventilation for centuries since 4$^{th}$ millennium B.C. (Bahadori 2008).

**Different components of badgir:** Badgirs have different parts in different heights. Different parts of the badgir are as follows (Bahadori 2008):

- The roof of the badgir, which is located at the top of badgir in different shapes and sizes.
- The body of the badgir, which is located on the top part of the badgir and has openings in order to capture winds.
- The column of the badgir, which is located on the bottom part of the badgir and conducts wind into the building or water reservoir ("Ab-Anbar") (Bahadori 2008).

Figure 2-5, shows different parts and heights of badgir as it has been explained (Bahadori 2008).

Some cities of Iran such as Yazd, Kashan and Esfahan have daily winds. Badgirs are typically built toward the direction of the winds. Interior walls of badgirs are divided to one, two, four, six and eight divisions. The top part of the badgir (roof of the badgir) is toward the sky and is closed. The bottom part of the badgir is toward the column and the building. Sometimes badgirs conduct the wind toward an "Ab-anbar" (water reservoir) in the building in order to have better cooling. The bottom part of badgirs, or the column of badgirs, has thicker walls than the rest of the badgir (Bahadori 2008).

**Main objective of badgir installation:** The main task of badgir is conducting the outdoor wind into the building and either circulating the air or cooling the building (or both) in order to provide a comfort zone for living or working (Bahadori 2008).

**Badgir and architecture:** South and central regions of Iran have different climates. Each of these climates has its own specific architecture. Building a badgir was one of the most important parts of design in the old architecture of Iran. Many badgirs have been used in different designs and sizes in the buildings to have a better condition inside the building. Badgirs could either be part of the building, sit on top of the roof, or be attached to the building. Badgirs may have been used for beauty and decoration of the home as they were for cooling buildings by natural ventilation (Bahadori 2008).

**Material and color of badgirs:** The materials forming the wind-catcher structure are important. Due to the high fluctuation of temperature between day and night in the hot and dry climate, the badgir usually constructed with mud-brick, becomes cool at night by radiation and convection.

During the day, sun-dried brick walls prevent the heat of the outside air from entering the building. During the cooler night, this kind of material allows the absorbed heat to be released to the inside of the building. The sun-dried brick works as insulation and also as the heating source for buildings (Bahadori 2008). In hot and dry climates like Yazd in Iran, mud-brick or brick together with plaster of cob (clay and straw) are the main materials of the badgir. Mud brick has high thermal mass. The wind-catcher façade in this climate is plastered with cob. Its bright color helps to reflect the sun’s radiation from the wind catcher surface and its non-absorption by that surface. At the same time, the presence of straws inside the mud increases coarseness of façade texture, which hinders the absorption of sun radiation. In hot and humid climates like Bandar

Lenghe in Iran, plasters and lime plasters which have white color are being used. These materials prevent humidity penetration into walls of wind catcher. Their white color hinders sun radiation absorption and increases its reflection (A'zami 2005).

Light colors painted on external surfaces of buildings decrease the daily temperature increase caused by the sun’s radiation. Therefore, it increases thermal stability. *Gatch* plastering is one of the most common plastering used in Iranian architecture. This plastering absorbs solar energy and it has been used on exterior surfaces (Bahadori 2008).

**Height of badgirs:** Heights of badgirs are different based on different climates. Usually, badgir is shorter in hot and dry weather. The height of the badgir affects the temperature of air inside the buildings. In figure 2-6 shows how the temperature of air inside the building depends on height of the badgir. When the height of a badgir is larger, the temperature is higher mainly due to the heat absorption of the column of the badgir in the sun. The taller the badgir is, the better its ability to direct the wind. Typically, the height of badgirs is 5 meter (Bahadori 2008).

**Opening of badgir:** The length of each opening is a minimum of about 20cm. The thickness of the wall between the openings is 8 to 10 cm. Based on these calculations, the builders could have known how many openings were needed. Usually there are more openings to direction of the wind. Also, the last two openings of badgirs are usually closed to increase the effectiveness of the wind’s circulation. There are thin wooden pieces protruding from the openings of the badgir. These wooden pieces are in about every distance of 2-1/4 meters. These wood pieces are not only for strengthening the structure but also to balance the weight (Bahadori 2008). Figure 2-20 shows where the wooden pieces are located in badgir columns.

**Badgir column:** If the badgir is tall, wooden cradling or *gatch*/plaster cradling, framework for supporting a coved or vaulted ceiling, is used every 2 meters. This system starts from the bottom of badgir. Without this system, the wind would enter and leave through the opening in the badgir directly across from its entrance. Usually interior divider walls are diagonal (Bahadori 2008).

**Bottom of badgir:** There are some badgirs which have a small pool or the ab-anbar on the bottom which is connected to the building where the badgir is located. On top of these small pools or ab-anbar, there is a square opening of 1m to 1.5m diagonal and height of 1.5m. Figure 2-7 shows the opening on top of the ab-anbar of a building with a badgir located in Yazd-Iran (Bahadori 2008).

**Roof of badgir:** Badgirs with ab-anbar underneath have usually six to eight interior walls or dividers in order to conduct air to the ab-anbar (Figure 2-8). These kinds of badgirs are usually located in hot and dry climates like Yazd in Iran because in these climates direction of winds changes a lot. Figure 2-9 shows a badgir with four interior wall divisions in a residential building in Yazd, Iran. These kinds of badgirs are usually located in hot and humid climates because in these climates the direction of winds doesn't change a lot. Figure 2-10 shows a badgir with six interior wall divisions. These kinds of badgirs are usually located in hot and humid climates because in these climates the direction of winds changes a lot. The roof of the badgir is usually wooden. The roof is sometimes bowl-shaped to hold water which evaporates to cool the surface. Now, with new technologies, pipes are used in order to expel water outside the building. The tallest badgir of this kind is located in Dolatabad garden in Yazd (Figure 2-11) (Bahadori 2008).

The four directional towers, *chahar-tarafe*, are the most popular wind towers. They have four main vertical shafts divided by partitions. Most of the wind towers in hot and dry regions use this kind of configuration. This kind of the tower is very common and locally is called the *Yazdi Tower* in Yazd (Azami 2005).Figures 2-12 shows different structures that wind towers or badgirs can have. Figure 2-13 shows typical plans of four directional wind tower or badgir. (Azami 2005).

**Orientation of badgirs:** Badgirs openings are located in the direction of the wind. Because wind is the principal driving force for natural ventilation in badgir systems, architects must know the direction of the wind in the specific region in which the building is located in order to design a badgir (Bahadori 2008).

**Sizes of badgir in different climates:** The sizes of badgir roofs depend on varying climates. Flat badgir roofs with a size of 1meter x 1meter and badgir heights of 3-5meters are typical for hot and humid climates (See Figure 2-14) (Bahadori 2008).

Shed badgir roofs with size of 0.5 meter x 0.5meter or 1.2meter x 0.6meter and a height of 1.8 - 2.1meters are typical for hot and dry climates (see Figure 2-15) (Bahadori 2008).

**Detailed structure of wood and plaster in badgir without new technology:** Because plaster did not adhere well to wood, early badgirs in Iran used a thick rope called “Sazoo”. Sazoo was wrapped around the end of wood, which helped the wood adhere to the plaster (Bahadori 2008).

**Badgirs performance during the day:** During the day, hot weather outside meets the body of the badgir which had been cooled from the night before. The outside hot air transfers its heat to the column and walls inside the badgir. In this process, the hot air is cooled in the column of the badgir. The density of the air increases and thus air it flows inside the building and cools the building. Finally, the air leaves the building through the windows, doors and openings. Figure 2-16 shows the circulation of air in badgir during the day (Bahadori 2008).

**Badgirs performance during the night:** During the night, colder outside air comes inside the building through windows and doors. Because cooler air has higher density, it stays on the bottom and the hot air rises. This pressure difference circulates the air causing to cold air come inside the building and cool it. The stored heat from the column of the badgir that is hotter than the ambient air is transferred to the air. Since the hot air has less density, it rises in the column and leaves the building from the openings in the badgir. The cold ambient air replaces this air through the windows and doors of the building. Figure 2-8 also shows the circulation of air in badgir during the night (Bahadori 2008).

**Badgirs in windy condition:** When there is a windy condition, the wind passes through the openings of the badgir, through doors, and through windows. This causes a pressure difference, which helps with the circulation of air inside the building. This pressure difference allows the outside air from various openings to come inside the building and exit through the windows, doors, and other openings of the badgirs which are against the direction of the wind (Bahadori 2008).

**Badgirs with “ab-anbar”:** Badgirs with “Ab-anbar” (water reservoir) system usually are located in places with hot and dry climates, such as in the city of Bam, Iran (Bahadori 2008).

Outside air passes through a channel and evaporates water in the “Ab-anbar” (a small pool underground). Evaporation decreases air temperature and increases the relative humidity of air. Therefore the outside air becomes cooler and circulates throughout the building, cooling the building. Finally, the air leaves the building through the windows and doors. Figure 2-17 shows the stairs and the conducting channel to an ab-anbar underneath a badgir in Yazd, Iran. Figure 2-7 as it has been explained before shows the space underneath a badgir. This badgir located in Yazd, Iran has ab-anbar underneath a holed slab (Bahadori 2008).

There are other badgirs which are called “Kolah Farangy”. These badgirs have dome shapes which have different layers or steps (See Figure 2-18). They have openings covered with nets. These badgirs share the same functions and processes in cooling the building as other badgirs (Bahadori 2008).

**The process of air circulation throughout the building:** Figure 2-19 shows the processes of the circulation of air throughout a building (Bahadori 2008):

- The air enters to the building at the point 1.
- Some of the wind exits at the point 2: Usually it happens for badgirs with only one interior wall divider which is not common.
- Some of the wind passes points 3 to 4 and 5.
- If the point 4, where a control door is located, is closed, all of the outside air passes through points 3 to 4.
- If the point 4 is open, where a control door is located, all of the outside air passes through points 3 to 5 and cools the building.
- In this process, outside air will confront with the air which passes through underground water which is humid. The outside air starts the evaporation process and loses its heat, become cold air and cools the building. Then, air exits the building through windows or doors which are shown in figure 2-10 (Bahadori 2008).

As a result, the building will have natural ventilation without any electrical equipment. Often, underneath the badgir, the temperature can become uncomfortably. So, a room exists underneath the badgir with control doors than can be used to redirect the flow of air (Bahadori 2008).

**Badgirs with new techniques/dampers:** There are places in Iran which the speed of wind is very low. In these places, there are badgirs with wet surfaces called dampers (Figure 2-20). These surfaces have small holes which are wet. There is a pump which directs water from a small pool or ab-anbar to the top of the building with badgir. A fountain is located on top of a clay surface in the top part of the badgir. The water is used to keep the dampers wet. When the wind passes through the small pool or ab-anbar, water evaporates and the air is cooled. Colder air has higher density than the outside air and this causes the circulation of air inside the building (Bahadori 2008).

**Wind tower in Zion National Park visitor center, United States:** Zion National Park Visitor Center applied a wind tower for natural ventilation in United States (See Figure 2-21). The weather condition in this area in summer is hot and dry, in winter is cold and icy. In this building, downdraft cooling towers are the primary cooling system. Cool towers work like a chimney in reverse. Water is pumped onto a honeycomb media at the top of the tower. Ambient air passes through this system evaporating water. Then cooled air, which is denser than the ambient air, falls through the tower under its own weight. Finally, it enters the building. When this natural ventilation system works, no fans are required to cool the building. Windows are strategically placed in the building to relieve hot air. Then, cool air moves through the space. The cool towers enhance energy performance. Also they give the building a unique aesthetic style. These wind towers are inspired by the evaporative cooling effects of the Virgin River slot canyon, which makes Zion famous (Torcellini et al. 2002).

**Mechanical input to the cooling system in Zion National Park visitor center:** The only mechanical input to the cooling system is a pump which circulates water through the evaporative media. This system is useful especially in high ventilation rates in the summer when there are a lot of visitors in the building. Also, when there is a low ventilation rate in the winter and there are fewer visitors. Natural infiltration also provides adequate ventilation during the winter (Torcellini et al. 2002).

The cool towers provide cooling to the main area of the visitor center. Visitors find the towers fascinating as a beautiful architectural element and give them special attention. The interaction of the visitors with the cooling system provides an attractive place that normally would not be achieved with a traditional cooling system. Wind towers operate whenever a traditional single-stage evaporative cooler would operate. When the capacity of the cool towers cannot meet the building cooling loads, the building temperature drifts to the high 70ºF's in summer. To minimize the number of days with high temperatures, the interior mass of the building is cooled by nighttime natural ventilation (Torcellini et al. 2002).

**Results of temperature based on different time and wind speed:** Table 2-1 shows the result of tests from the badgir with dampers in Yazd University in Iran on September, 11, 2003. This result shows that temperature of outside air drops after going through the badgir process. Also, the wind speed drops after the badgir process at a different time of the day. The temperature of the air going to the building is almost constant. This is due to the high heat capacity of the water in the ab-anbar which behaves like a heat sink since it has easy heat transfer with the ambient soil. The soil temperature (ground temperature) is almost constant and does not change significantly day by day or season by season. This fact is used later in CFD modeling. The average of difference temperature is 13.26°C (Bahadori 2008).

## Technologies for Natural Ventilation

### Solar Chimney

A solar chimney is one of the ways of improving natural ventilation in the building. Solar chimneys in buildings help to reduce energy usage, $CO_{2,}$ and pollution in general. The solar chimney has been used for centuries in different places, especially in the Middle East and by the Romans. A solar chimney is a vertical shaft utilizing solar energy to help the natural stack ventilation through a building (Bansal et al. 1993).

The solar chimney consists of a black-painted chimney that absorbs the heat during the day to ventilate the building. There is a suction created at the chimney's base which can be used to ventilate and cool the building. In hot, windless days, a solar chimney provides ventilation.

Badgir is a name which has been used to describe solar chimneys in the Middle East and has been explained in the research (Bansal et al. 1993).

Solar Chimney consists of various parts.

- The Solar Collector Area: On the top part of the chimney or in the entire shaft, there is an area which is called the solar collector area. In order to utilize and retain solar gains, the type of glazing, orientation, insulation, and thermal properties are important.
- The Main Ventilation Shaft: The height, location, cross section, and the thermal properties of the structure have important effect on ventilation shaft.
- The Inlet and Outlet Air Opening: The sizes and locations of where the openings are found have significant outcome (Bansal et al. 1993).

Based on Figure 2-27, this solar chimney provides passive home cooling by allowing air to enter in from the bottom and rise out at the top (Bansal et al. 1993). To have a better result using a solar chimney, its location needs to be higher than the roof level and oriented to the direction of the sun. Using a glazed surface on opposite side of the chimney will cause more heat gain. Openings in the vents in the chimney can be located away from the direction of the wind. By allowing incoming air to pass through underground ducts before entering the building, the cooling effect is maximized (Bansal et al. 1993).

The use of a solar chimney benefits natural ventilation and passive cooling strategies of buildings and reduces energy use, $CO_2$ and pollution. Other benefits of using solar chimneys for improving natural ventilation are to have a better ventilation on hot days in the building, reducing dependence on wind and wind-driven ventilation, improving control of air flow through a building, and helping to have a better choice of air intake, improving air quality, reducing noise levels in urban areas, increasing night time ventilation rates and also minimizing the use of fossil fuel energy ( Bansal et al. 1999).

**Building Characteristics and Openings**

The ventilation rate in a naturally-ventilated building depends on some characteristics such as wind speed, temperature difference between the interior and exterior, the size of the ventilation openings, and the distance between openings. The wind speed and temperature differences cannot be controlled and change based on the location. So, the design and management of a natural ventilation system concentrates more on the placement and sizing of the openings. The following are different openings used in naturally-ventilated buildings.

The size of the openings, the climate of the location and the specific season of the year can control the ventilation rate (Chastain 2000).

**Sizing of Ridge and Eave Openings for Winter Ventilation:** Adjustable eaves and stationary ridge vents had been one kind of ventilation used in cold and temperate regions. They provide ventilation for moisture control and temperature modification (Chastain 2000).

**Ridge Opening:** A continuous stationary open ridge that runs through the entire building is one of the best ways of ventilation. It provides a minimum ridge opening of 6 inches for all dairy buildings up to 30 ft wide and 2 inches of open ridge for every 10 feet of building width for wider buildings (MWPS-7 1995). The spaces between the trusses can be used for eave vents. There should be enough spaces to at least ½ of the ridge vent size (1 in per 10 ft of building width) to let the vent to be open for better airflow during mild winter weather (Chastain 2000).

**Roof Slope:** The roof slope is one of the important factors in designing a naturally ventilated building. It needs a roof with a 4/12 pitch for enough separation distance between the eave and the ridge opening (Chastain 2000).

**Windows:** There are different kinds of window which let natural ventilation pass through. The area of openings can control the amount of airflow which flows. Figure 2-28 shows different window openings. Horizontal pivot windows provide the highest ventilation capacity as shown on the right side of Figure 2-28. Horizontal pivot windows have more ventilation capacity than center vertical pivot windows. Casement windows and pivot windows have the same advantages and the difference is casement windows are open to strong blast of the wind. With bay windows, pressure differences can be localized (Iannone 1999).

**Passive Cooling Systems:** Applying passive cooling techniques is one of the most important parts in designing a building. Saving energy and reducing pollution are some of the environmental and economical benefits (Iannone 1999). Some of these passive cooling techniques are as follows:

Architectural methods: the domed roof, vaulted roof, ventilated roof, high roof and double roof. Ventilated roofs include the naturally-ventilated, advanced naturally-ventilated, micro -and artificially-ventilated roof (Iannone 1999).

**Domed and Vaulted Roof:** This kind of roof has been used usually in hot and dry regions. There is a small opening at the top of these roofs. The material of these roofs are made from locally-available material such as stone or brick masonry and covered with a plaster finish. The opening of the roof is an escape path for hot air and for ventilation. Curved roofs reflect more radiation than flat roofs. Since thermal stratification causes hot air to gather within the building in space under the roof, a significantly comfortable feeling will be created at the floor level (Sanjay 2008).

**Curved Roofs:** Curved roofs absorb more diffuse radiation than the flat roofs but the amount of beam radiation is as same as flat ones. Curved roofs with an opening on top are more energy efficient in hot arid climatic conditions for natural ventilation (Sanjay 2008).

**Ventilated Roofs:** There are naturally ventilated, artificially ventilated and micro-ventilated roofs. Ventilated buildings are structures that have hollow walls and roofs through which a certain amount of air-flow is maintained. The air-flow is regulated in a way that minimum heat is transferred to or from the building interior and exterior (Sanjay 2008).

**Naturally Ventilated Roofs:** Wind pressure can ventilate the buildings naturally. Then, an air flow will drive to cool the building. Mechanical energy will not be used. During daytime, the air gap performs as an extra insulating layer in the ventilated building. The insulation layer of air has lower temperature in ventilated building than a typical building surface. Even though, the air flow velocity in the gap is lower than the ambient wind speed. Part of the daytime heat gain transfers to the air in the gap. Because of natural convection, the air flowing through the gap renews this air. Therefore, inside wall/roof surface won't warm up. This technique has been traditionally used in buildings centuries ago (Sanjay 2008).

**Artificially Ventilated Roofs:** The air flow in artificially ventilated roofs is due to forced convection. Mechanical methods for example blower, induced draught fans are some of forced convections. In the process of flowing air through air gaps, the temperature of room air reduces. So, the room air will become more comfortable and better (Sanjay 2008).

**Advanced Naturally Ventilated Roofs:** Internal sources of heat can warm the air and drives the air flow. So, when there is internal source of warmth including at night, airflow can be assured at all times (Sanjay 2008).

**Micro-Ventilated Roofs:** Roofs with small sized thickness ducts are micro-ventilated roofs. There are two layers of terracotta tiles with small thickness in between. Terracotta tiles are made from clay and molded in the form of tiles. Ducts have been created by the two layers obtained by continuous opening along the eaves course (inlet) and along the ridge course (outlet) or even by insertion of special ventilation tiles. The air flows into these duct. The thickness of air duct can be 4 to 6 centimeter. When the air duct thickness increases, the energy saving increases (Sanjay 2008).

**High Roof:** Historical buildings have been marked by high roofs. In buildings with high roofs, warm air collects at the top and cool air remains at the floor level. Therefore, at the floor level, the air temperature is in a comfortable zone (Sanjay 2008).

**Double Roof:** In this kind of roofs, there are two roofs or ceilings with an air gap between. There are usually two concrete ceilings one above the other with an air gap in between. The air gap performs as a thermal resistance between the first roof, exposed to the heat of direct sun, and the second slab below (Sanjay 2008).

## Advantages of Natural Ventilation Systems

Advantages of natural ventilation are as follows.

- Removal of mechanical air handling systems.
- Reducing cooling energy consumption.
- Eliminating the use of fan power required.
- Providing quantitative health, comfort, and productivity advantages.
- Providing qualitative advantages of ‘fresh air’ in the minds of most occupants.
- Having better control of their environments and less restrictive comfort criteria.
- Reducing significant fraction costs of conventional mechanical ventilation systems in commercial buildings.
- Eliminating the large spatial requirements that conventional mechanical systems demand.
- Avoiding the duct cleanliness dilemma, and its attendant costs (Emmerich and Stuart Dols 2001).

## Comparisons between Natural and Mechanical Ventilation

There are more benefits to have natural ventilation than mechanical ventilation. Some of these benefits are cooling energy savings, better comfort, productivity and occupant health. The following are some comparisons between using mechanical and natural ventilation in buildings.

### Cooling Energy Savings and Limits of Applicability

Natural ventilation can pay costs of cooling, the associated energy costs and carbon dioxide emissions. Based on where the building is located, this cost can change because of different building's thermal performance (Emmerich and Stuart Dols 2001).

### Occupant Health, Comfort and Productivity

Based on research in both European and North American countries, there are lower symptoms in the naturally ventilated buildings compared to mechanically ventilated and air-conditioned buildings (Mendell et al. 1996). Natural ventilation systems can provide more healthful, comfortable, and productive environments than mechanical systems. Architects have accepted natural ventilation as one of several objectives of high quality sustainable design (Emmerich and Stuart Dols 2001).

### Duct Cleanliness and Filtration

Duct cleanliness and building air quality are intimately linked (Limb 2000). Natural ventilation systems can solve this problem by replacing ductwork with habitable spaces that serve to direct naturally-driven airflows (Emmerich and Stuart Dols 2001).

### Fan Power

Natural ventilation can be accomplished by either natural means or mechanical means. In Cooling the building mechanically, fans become one of the mechanical means which use a significant amount of the energy (BRECSU 2000). By comparing to different mechanical cooling systems, naturally ventilated buildings in the United Kingdom offset from 20 kWh/m$^2$ to

60 kWh/$m^2$ of fan energy consumption annually for cooling purposes, approximately \$1.70/$m^2$ (\$0.16/$ft^2$) to \$5.20/$m^2$ (\$0.48/$ft^2$) annually in energy costs. As a result, these savings account for approximately 15 % of total energy consumption in U.K. office buildings (Heikkinen and Heimonen 2000).

**HVAC Equipment Cost and Space Requirements**

HVAC equipment cost and space requirements mechanical heating, ventilating, and air conditioning equipment often are one of the large cost of construction of new buildings and the renovation of existing buildings. These costs may be expected to range from 35 % to 45 % of construction costs in larger office and institutional buildings (Emmerich and Stuart Dols 2001). Consequently, by replacing or at least reducing mechanical systems for ventilation and cooling one of the potentially quite large cost savings can be saved (Emmerich and Stuart Dols 2001).

Mechanical air handling equipment including fans, filters, heating and cooling coils, vertical distribution shafts and ducts, horizontal distribution duct networks, dampers, supply diffusers and return grilles consume vast amounts of space. Therefore, mechanical equipments consume about 20 % to 40 % of the total volume of the building. Natural ventilation systems recover much of this volume as occupied space for the spatial interior of the building. This recovered space (volume) may be used for formal architectural objectives or for daylight distribution (Emmerich and Stuart Dols 2001).

**Ambient Air Quality**

Another important issue in natural ventilation systems is the impact of ambient air quality. Typical natural ventilation systems do not use filtration. The filtration in mechanical ventilation systems does not remove all contaminants from the outdoor air. It generally includes some form of particle filtration. Natural ventilation helps improve indoor air quality. Also, it can control indoor humidity and airborne contaminants which are health hazards. So, the acceptability of having a better ambient air quality in natural ventilation systems must be considered (Emmerich and Stuart Dols 2001).

## Disadvantages of Natural Ventilation Systems

- Lack of heat recovery capabilities (Emmerich and Stuart Dols 2001).
- Difficult to control when natural driving forces are small (Emmerich and Stuart Dols 2001).
- Lack of filtration capabilities particularly urban, with high outdoor particle and gaseous contaminant concentrations (Emmerich and Stuart Dols 2001).
- Unable to control humidity especially in hot and humid climates (Bahadori 2008).

## Desiccants

Controlling moisture has always been challenging for engineers. Controlling moisture in hot humid climates is even more challenging. Desiccants are one of the materials which can be used to control moisture. To achieve optimum use of this material, temperature and humidity play an important role. The dew point is the most useful combined measure of temperature and humidity. Dew point is the temperature at which the water vapor content of the air is at saturation. The dew point varies with the amount of water in the air. A desiccant will absorb the water vapor in the air and lower the humidity. Figure 2-22 illustrates the absorption rate and the absorption capacity of different desiccants. Figure 2-22 also shows how much each desiccant has a tendency to absorb water also effectiveness of each desiccant at different temperatures and extreme water vapor concentrations. There are different desiccants such as montmorillonite clay, silica gel, molecular sieve, calcium oxide and calcium sulfate (Lavan 1982).

### Montmorillonite Clay

Montmorillonite clay is a naturally occurring absorbent. This material has been created by drying magnesium aluminum silicate. This clay will successfully regenerate for repeated use at very low temperatures without significant corrosion or swelling. This clay is inexpensive and also its effectiveness within normal temperature and humidity is high (Lavan 1982).

**Silica Gel ($SiO_2$ * $H_2O$)**

This is the most commonly used desiccant which has been made from sodium silicate and sulfuric acid. Its pores have an enormous area which will absorb and hold water. Silica gel is very proficient at temperatures below 77°F (25°C). It loses its absorption capacity when temperatures begin to rise. One of the best benefits of silica gel is its noncorrosive and non-toxic nature (Lavan 1982).

**Molecular Sieve (Synthetic Zeolite - $Na_{12}Al0_3SiO_{212}XH_2O$)**

Molecular sieve has an internal absorptive surface area of 700 to 800 sq m per g. Because of its unique structure, molecular sieve does not absorb moisture as much as silica gel or clay as temperatures rises. Molecular sieve is high in cost per unit (Lavan 1982).

**Calcium Oxide (CaO)**

Calcium oxide has a moisture absorptive capacity of not less than 28.5% by weight. The unique feature of this material is that it will absorb a much greater amount of water vapor compared to other materials. It is most effective where there is a high concentration of water vapor (Lavan 1982).

**Calcium Sulfate ($CaSO_4$)**

Calcium sulfate is an inexpensive material which is created by the controlled dehydration of gypsum. It is chemically stable, non-decomposed, non-toxic and non-corrosive (Lavan 1982).

**Calculations for Amount of Desiccants**

To determine the amount of desiccant to be used in the building, the calculations below is required (Lavan 1982).

Amounts of desiccant required = K x V

K = 0.161 (in gal.) or 0.0007 (in cu. in.) or 1.2 (in cu. ft.)

V = the volume (in gal., cu. in. or cu. ft.).

For calculating how much desiccant is needed, follow the steps below:

(1) Calculate the volume of the building in cu. ft.

(2) Determine the unit of desiccant required by using the formula above.

(3) Select the type of desiccant that meets your needs according to Table 2-3.

**Desiccant in Commercial Buildings**

Desiccant systems have been used over the last 15 years as a component of HVAC systems in commercial buildings. There has been an improvement and benefits in buildings with desiccant component. More recently, active desiccant systems are used for ventilating systems. Desiccants which are solid are more common to use for commercial buildings (ASHRAE 1999). Places like supermarkets and refrigerated warehouses, which all contain refrigeration systems, air become cool more effectively when most of the building's moisture load is removed by an active (heat-reactivated) desiccant system. Active desiccants remove water from process air by adsorption which can apply by using wheels like Figure 2-23. These wheels dry the air with heat from natural gas. Dehumidification by adsorption provides enormous capacity compared to cooling-based dehumidification. A desiccant wheel only needs to dry the incoming fresh air, rather than drying all the air circulating through the restaurant. This keeps installed costs to a minimum which is very beneficial for commercial buildings.

**How to Use Desiccants**

One of the most common ways of using desiccants in an air stream is to embed the material into a lightweight honeycomb shaped matrix formed into a wheel. Supply air passes through one section where water vapor is absorbed by the desiccant. Then the wheel rotates slowly into a second air stream which is known as the reactivation air. The air dries the desiccant and carries the moisture out of the building (ASHRAE 1999).Figure 2-23 illustrates how the system works.

### Advantages of Desiccants

Active desiccant wheels dry deeply and achieve good control of humidity. The quantities of moisture which can be removed by active desiccant wheels depend on (ASHRAE 1999):

- Air temperature and moisture of entering air
- The type and quantity of desiccant
- The depth of the wheel
- The surface area of the honey comb
- The velocity of air moving through the wheel
- The speed of wheel rotation

Commercial desiccant wheels are usually set between 180°F and 225°F (82°C and 107°C).

When the moisture from the supply air has been removed, the temperature of the supply air is higher. By transferring from latent heat to sensible heat, the temperature of the supply air rises 80% to 90%. The amount of energy or heat which has been released by a material or object is latent heat. Potential energy in the form of thermal energy or heat is sensible heat (ASHRAE 1999).

### Disadvantages of Desiccants

Active wheels require heat input in order to dry the desiccant which adds to operating cost. Desiccant systems add to initial cost (ASHRAE 1999).

## Design Suggestion for Hot and Humid Climate

### Double-skin Facade Configuration

Other design suggestion for hot and humid climates is the double-skin façade configuration. Double-skin facades have different layers or skins: construction, external, intermediate and inner skin. The external and internal skins can be made of single or double glazed glass panes of float glass or safety glass. At the intermediate space, there is an adjustable sun shading device for thermal control. There are different double skin constructions such as Box Window facade, Shaft-box facade, Corridor facade and Multi-story façade (Wong et al. 2006).The performance of the double-skin facade depends on the ventilation means. The modes of ventilation could be either natural or buoyancy driven, forced or mechanically driven and mixed which is both natural and forced driven. This technique can be used in different climates like Florida as well (Wong et al. 2006).

### Benefits of Double Skin Facade

There is a significant energy saving when natural ventilation is applied through the use of the double skin façade (Wong et al. 2006). Computational Fluid Dynamic models have been used in order to find a new type of double-skin facade configuration which provides a better indoor thermal comfort in the hot and humid climate (Wong et al. 2006).

## Natural Ventilation Analysis and Design Tools

This section presents a summary of the currently available tools for designing and analyzing natural ventilation systems in buildings. Outputs of some of these tools will be compared. Tools with easy access and better detailed result will be chosen for research methodology.

### LoopDA – Natural Ventilation Design and Analysis Software

The Loop Equation Design Method has been proposed for sizing ventilation airflow components of natural and hybrid ventilation systems. While the approach has been demonstrated on a limited basis, the method has been automated in order to better evaluate its reliability under a more controlled, less error-prone, environment. A computer program developed by National Institute of Standards and Technology that implements the Loop Equation Design Method of sizing which are the openings of naturally ventilated buildings. The tool, referred to as LoopDA for Loop Design and Analysis, is included with an existing multi-zone analysis tool. LoopDA provides the designer of natural ventilation systems with an environment in which to perform and document the process of designing the opening sizes of natural ventilation systems and analyzing the system behavior under a variety of operating conditions. The LoopDA program provides an example of its application to the design of a naturally ventilated building and describes needs for future enhancements to the tool to increase its usefulness within the design community (Dols and Emmerich 2003).

The *Loop Equation Design Method* consists of the following eight steps (Dols and Emmerich 2003):

- Lay out the global geometry and multi-zone topology of the natural ventilation flow loops for each zone of the building.
- Identify an ambient pressure node and additional pressure nodes at entries and exits of each flow component along the loops.
- Establish design conditions: wind pressure coefficients for envelope flow components, ambient temperature, wind speed and direction, and interior temperatures; evaluate ambient and interior air densities.
- Establish first-order design criteria and apply continuity to determine the objective design airflow rates required for each natural ventilation flow component.
- Form the forward loop equations for each loop established in step 1 above by systematically accounting for all pressure changes while traversing the loop.
- Determine the minimum feasible sizes for each of the flow components by evaluating asymptotic limits of the loop equation for the design conditions.
- Develop and apply a sufficient number of technical or non-technical design rules or constraints to transform the under-determined design problem defined by each loop equation into a determined problem.
- Develop an appropriate operational strategy to accommodate the regulation of the natural ventilation system for variations in design conditions.

**AIOLOS Software**

It is software which calculates the airflow rate, energy consumption and number of hours of overheating in natural ventilation configurations. This tool can be used for design purposes or simply for a deeper insight into mechanisms involved in natural ventilation (Allard 1998).

The following possibilities are offered by AIOLOS Software (Allard 1998):

- Calculation of the global airflow rates in simulated zone.
- Calculation of airflow rate through openings in the building
- Sensitivity analysis for examination of the impact of specific parameters on natural ventilation
- Find the best process of appropriate opening sizes for receiving best airflow rates.
- A thermal model for evaluating the impact of different natural ventilation strategies on thermal behavior of the building.

These calculations can be done for a short time period (a number of days) or an extended time period (up to a year). This tool helps the user the possibility of fast evaluation of the climate in the region, which the building is located. Results are in tabular or graphical form. Statistical treatment is possible for a better understanding of the results (Allard 1998).

This AIOLOS software has been used for hot and humid climate conditions like Florida (Andrade 2000).

The following information can be established from a model made by AIOLOS software (Andrade 2000):

- Climatic conditions for a given model.
- The use of natural ventilation for cooling buildings.
- The air circulation through the building.

Based on results, critical paths for air circulation through the building and the most suitable characteristics for the architectural components are determined (Andrade 2000).

The application of the simplified model will produce recommendations, in each step of an iterative process, leading, for example, to the redesign and relocation of ventilation ducts, inlet and outlet grilles, doors, windows, ventilated roofs or to the replacement of materials or constructional systems not compatible with thermal comfort optimization, by natural means. The solutions defined by the simplified decision model will be, at the end, validated by comparing them to the solutions defined by the direct simulation with a building physics tool (Andrade 2000).

AIOLOS software will be used mainly to calculate airflows, energy consumption and number of hours of overheating. Vortex software will be used to characterize patterns of air circulation through the internal spaces of the building and also in the immediate external environment (Andrade 2000).

**Autodesk Ecotect**

Autodesk Ecotect is an industry leading building analysis program which allows designers to work in 3D and apply the tools necessary for an energy efficient and sustainable future. Ecotect is a complete building design and environmental analysis tool that covers the broad range of simulation and analysis functions required to truly understand how a building design will operate and perform (ecotect.com website).

**Ventilation and airflow in Autodesk Ecotect**

Ecotect allows generating both the geometry and analysis grids for export directly to computational fluid dynamics (CFD) tools such as NIST-FDS, FLUENT and WinAir4. After the calculations in these tools are complete, it is then possible to import results back into Ecotect for display within the context of the original model. Figure 2-24 and 2-25 show the building with CFD analysis and results (ecotect.com website).

**Prevailing winds**

By using data in the hourly weather file, Ecotect can overlay wind speed and direction directly on top of the current model, making it especially relevant to natural ventilation and wind shelter strategies. Then, this plot can also show temperature, humidity and rainfall, over any date and time range (ecotect.com website) as shown in figure 2-26.

**Disadvantage of Ecotect for natural ventilation**

The analysis routines in Ecotect do not show detailed air-flow and ventilation information.

**Green Building Studio**

Autodesk Green Building Studio enables architects to quickly calculate the operational and energy implications of early design decisions. The Autodesk Green Building Studio web service automatically generates geometrically accurate, detailed input files for major energy simulation programs. Green Building Studio uses the DOE-2.2 simulation engine to calculate energy performance and also creates geometrically accurate input files for Energy Plus. Green Building Studio web service users are able to eliminate redundant data entry and dramatically reduce the time and expense traditionally associated with whole-building energy simulation analysis (energy.gov website).

**Input of green building studio**

Minimum manual inputs required from end users are 'building type' and 'zip code'. Users may specify additional input parameters to the extent they have been enabled in the BIM/CAD program's Graphical user interface. All other simulation variables supplied by the Autodesk Green Building Studio web service may be viewed and edited in other DOE-2.2 or gbXML compatible applications (energy.gov website).

**Output of green building studio**

Outputs for each design scenario modeled include:

- Estimated Energy and Cost Summary (annual, lifecycle)
- Annual carbon footprint specific to region and utility mix
- Renewable energy potential (photovoltaic and wind)
- Weather data summary and user defined graphics
- Building and site specific natural ventilation potential
- US EPA Energy Star comparison
- Water and day lighting preliminary analysis for LEED
- Energy End-Use Charts
- Building Summary of construction areas, equipment capacities, etc.
- gbXML file for import to Trane TRACE 700 or other gbXML-compliant tools
- DOE-2.2 file for import to eQUEST
- Energy Plus IDF file for editing and running in Energy Plus
- VRML file

**Advantages of using Green Building Studio**

Autodesk Green Building Studio reduces time and cost of building design and lifecycle management processes. Major benefits include (energy.gov website):

- Enables hourly whole building energy, carbon and water analyses much earlier in the design process.

- Reduces design and analysis costs, allowing more design options to be explored within budget.

- Compression of early design time, speeding project time to completion.

- Accelerates analysis for LEED compliance.

**Simplified Calculations of Air Change**

Data can be established from a psychrometric chart in order to do calculations for air change. A psychrometric chart is a graph of the physical properties of moist air at a constant pressure which often equated to an elevation relative to sea level. The chart graphically expresses how various properties relate to each other (see Figure 3-26). The thermo physical properties found on most psychrometric charts are (Wikipedia 2009):

- Dry-bulb temperature (DBT) “is the temperature of air measured by a thermometer freely exposed to the air which is shielded from radiation and moisture. In construction, it is an important consideration when designing a building for a certain climate” (Nall 2004). It is typically the x-axis, the horizontal axis, of the graph. The unit for temperature in psychrometric chart is Fahrenheit.

- The thermodynamic wet-bulb temperature (WBT) is a thermodynamic property of a mixture of air and water vapor. When a volume of air is cooled adiabatically to saturation by evaporation of water into it, all latent heat will be supplied by the volume of air. The temperature of an air sample that has passed over a large surface of liquid water in an insulated channel is the thermodynamic wet-bulb temperature. This thermodynamic wet bulb temperature will become saturated (100 percent relative humidity) by passing through a constant-pressure, ideal, adiabatic saturation chamber. Meteorologist and others may use the term "isobaric wet-bulb temperature" to refer to the "thermodynamic wet-bulb temperature". It is also called the "adiabatic saturation temperature". The thermodynamic wet-bulb temperature is plotted on a psychrometric chart. The value indicated by a simple wet-bulb thermometer often provides an adequate approximation of the thermodynamic wet-bulb temperature. For an accurate wet-bulb thermometer, the wet-bulb temperature and the adiabatic saturation temperature are approximately equal for air-water vapor mixtures at atmospheric temperature and pressure (VanWylen and Sonntag 1973).

- The dew point is that temperature at which a moist air sample at the same pressure would reach water vapor saturation. The dew point is also called a saturation point. The dew point is associated with relative humidity. A high relative humidity indicates that the dew point is closer to the current air temperature. Relative humidity of 100% indicates that the dew point is equal to the current temperature and the air is maximally saturated with water. When the dew point stays constant and temperature increases, relative humidity will decrease (VanWylen and Sonntag 1973). Figure 3-19 shows dew point in different temperatures.

- Relative humidity (RH) is the ratio of the mole fraction of water vapor to the mole fraction of saturated moist air at the same temperature and pressure. RH is dimensionless, and is usually expressed as a percentage. Lines of constant relative humidity reflect the physics of air and water which are determined via experimental measurement. Relative humidity of 100% indicates that the dew point is equal to the current temperature and the air is maximally saturated with water (VanWylen and Sonntag 1973).

- Humidity ratio is also known as moisture content, mixing ratio, or specific humidity. Humidity ratio is the proportion of mass of water vapor per unit mass of dry air at the given conditions (DBT, WBT, DPT, RH, etc.). It is typically the y-axis, the vertical axis, of the graph. For a given dew point, there will be a particular humidity ratio for which the air sample is at 100% relative humidity. Humidity ratio is dimensionless, but is sometimes expressed as grams of water per kilogram of dry air or grains of water per pound of air (Liddell and Scott)

- Specific enthalpy symbolized by *h*, also called heat content per unit mass. It is the sum of the internal heat energy of the moist air including the heat of the air and water vapor within. In the approximation of ideal gases, lines of constant enthalpy are parallel to lines of constant wet-bulb temperature. Enthalpy is given in joules per kilogram of air or BTU per pound of air (Liddell and Scott)

- Specific volume, also called inverse density, is the volume per unit mass of the air sample. The units are cubic meters per kilogram of air. Other units are cubic feet per pound of dry air (Liddell and Scott)

**Computational Fluid Dynamics-CFD**

Based on the contextual complexity of the physical phenomena and the needs of controlling indoor comfort, Computational Fluid Dynamics, CFD, is needed for natural ventilation system designs. The first applications of CFD were in the 1970s in building science. These codes have been used in designing natural ventilation systems in buildings. Simplified models can be used starting from the early stages of the design process, because the necessary calculating data are limited to only a few essential parameters. It has been examined the application of CFD to predict passive airflows in buildings driven by internal heat sources and more recently assisting wind flows. CFD is based on little design steps, which are related to indoor environmental quality. It is possible to start from a simplified geometry and modify its form by little or single variations until arriving at a topologically correct ventilation system (Iannone 1999). FLUENT package could provide detailed air temperature, air velocity, contaminant concentration within the building or outdoor spaces. Based on long computational time and excessive computer resource requirements, the application of CFD for natural ventilated building have been limited (Wang and Wong 2006).

Numerical flow mechanics (computational fluid dynamics – CFD) is increasingly used for the solution of technical problems related to flows. At the Institute for Micro Process Engineering, the CFD software FLUENT is used along with the mesh generator GAMBIT. Use of the former software allows for the development and optimization of a variety of microstructure devices. No prototype has to be constructed and tested in a time- and cost-consuming manner.

In order to simulate any flow, well known fluid momentum equations called “Navier-Stokes (N.S) equations” should have been solved within the computational domain. These equations are the non-linear equations that obtained from the momentum balance across the sample fluid control volume. The N.S equations in physics are one of the most complicated differential equations that govern physical phenomena. Since there is no analytical solutions for these equations for the complex geometries typically the N.S equations are solved numerically. The aforementioned solution is sometimes called Computational Fluid Dynamic (CFD) simulation. There are many commercial packages exist in order to solve N.S equations. A well known commercial package is FLUENT. This package has been used in this study to solve N.S equations as well as energy equation (FLUENT user manual 2006).

## Summary

When the kinetic energy or the buoyancy driven force of the air is used for ventilation purposes, then this type of ventilation is typically called natural ventilation. Some of the benefits of natural ventilation beside energy and cost savings are improving occupant health, quality of life, and productivity. Based on the literature review, the wind tower (badgir) has been chosen as the possible technique for natural ventilation without mechanical equipment that is examined in the case study. This technique has benefits for green buildings/sustainable buildings which will be discussed in the results and conclusions. This technique adopts environmental energies such as wind for better natural ventilation. This technique had been used in mostly Middle East and other countries for centuries and it can be beneficial in new buildings. Different tools for analyzing natural ventilation have been researched to select the approach. Based on the literature review, Autodesk Ecotect, simplified calculation for air change by using psychrometric chart, and FLUENT package have been chosen as tools to model natural ventilation with a badgir. The use of the tools and their effectiveness will be discussed in the results section.

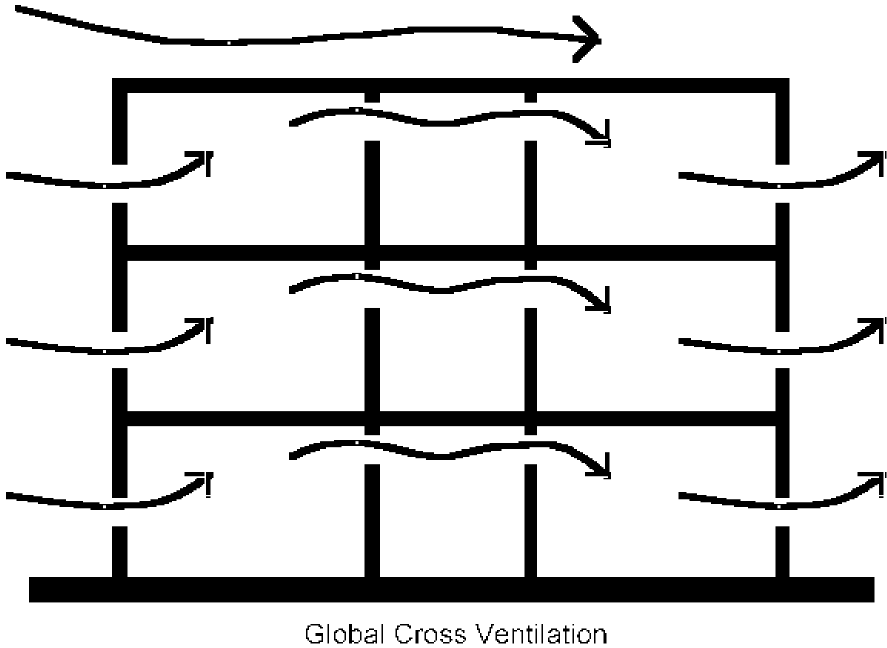



Figure 2-1.  Schematic of wind-driven cross ventilation (Source: Emmerich, Stuart Dols 2001).

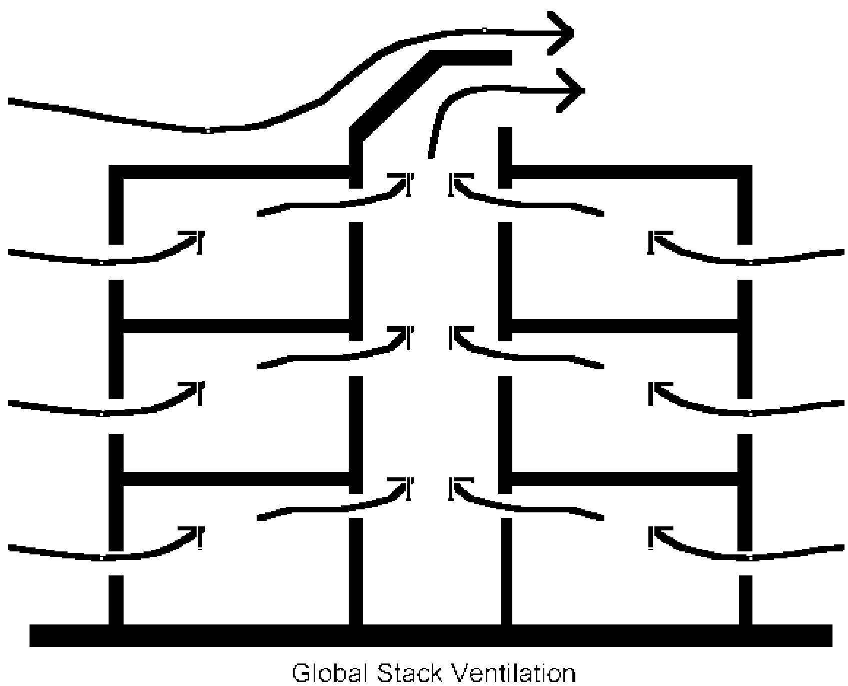



Figure 2-2.  Buoyancy-driven stack ventilation (Source: (Emmerich et al. 2001).

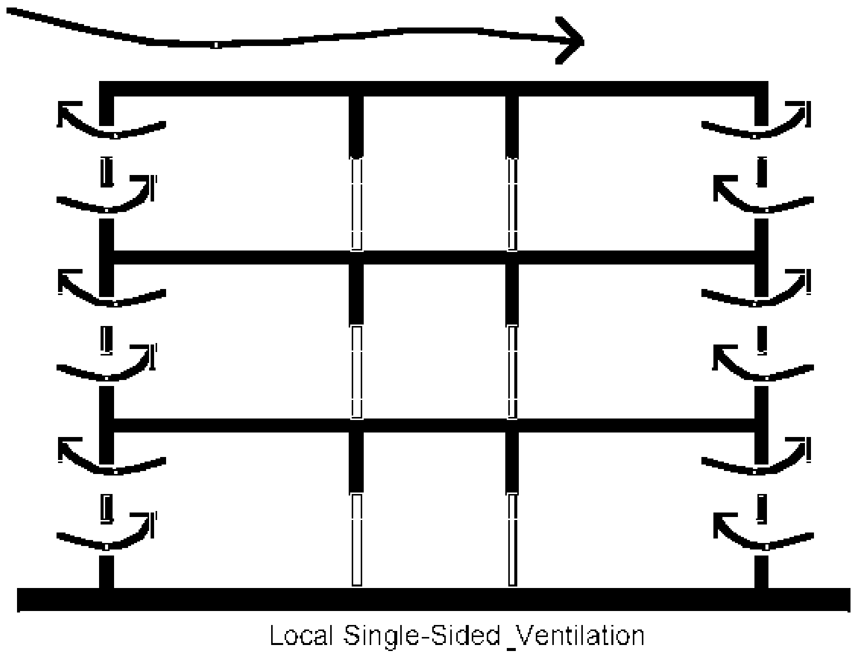



Figure 2-3. Schematic of single-sided ventilation (Source: Emmerich, Stuart Dols 2001).

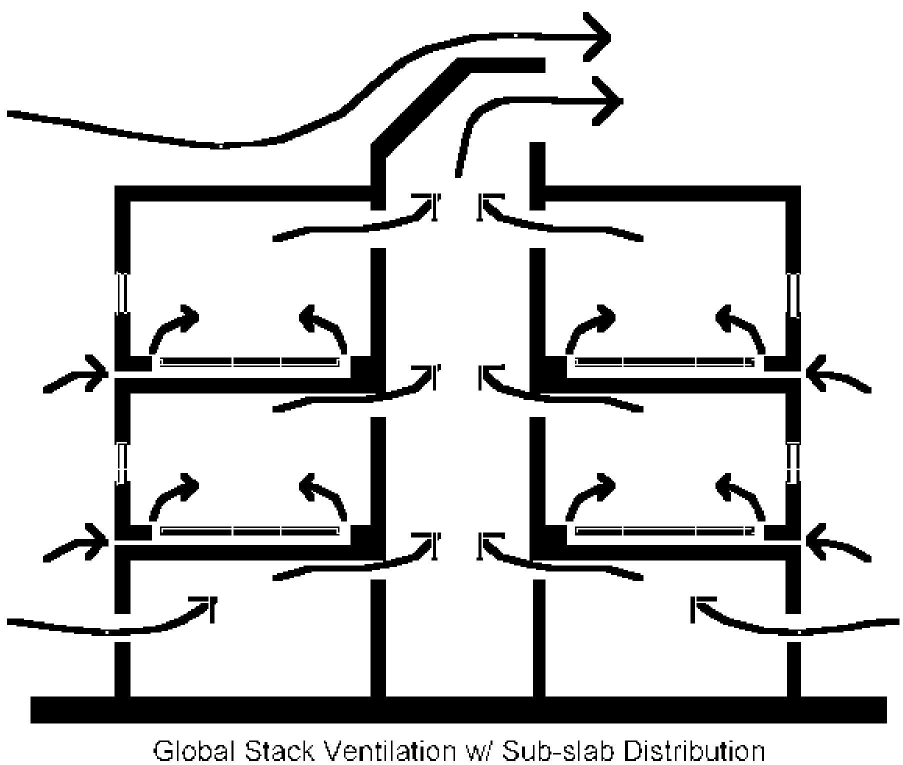



Figure 2-4. Schematic of stack ventilation with sub-slab distribution (Source: Emmerich, Stuart Dols 2001).

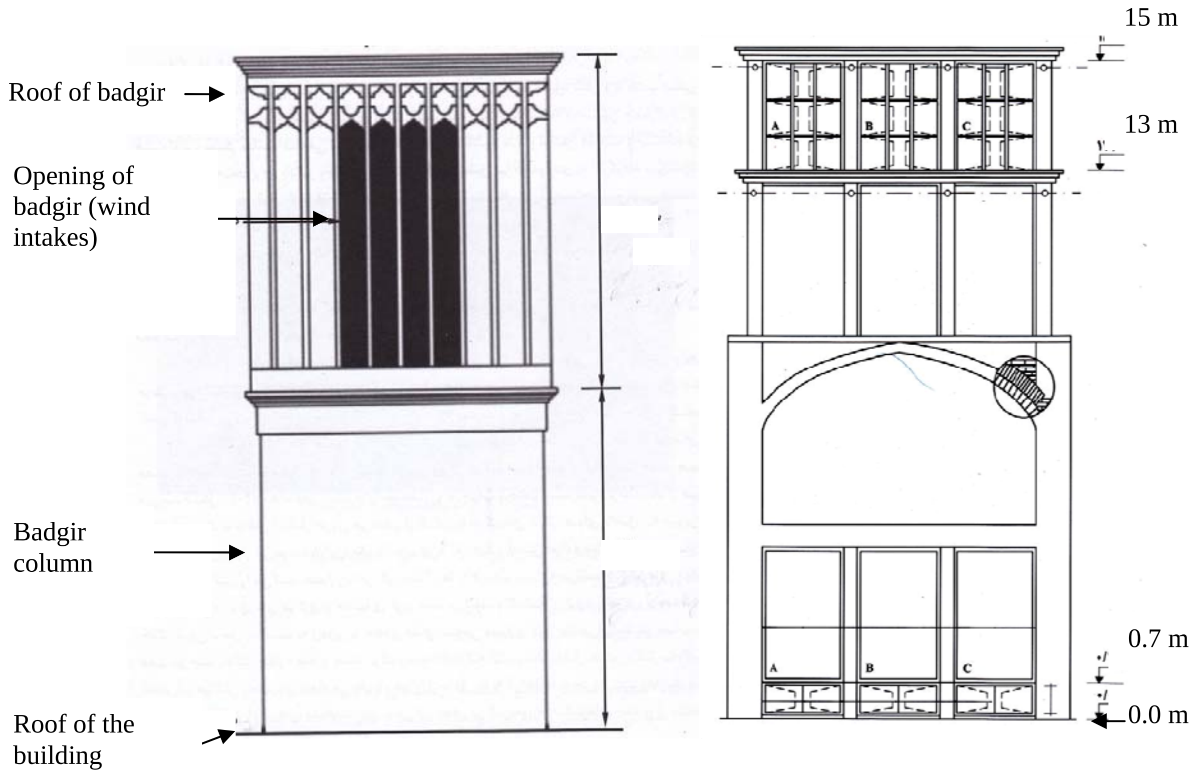



Figure 2-5. Different parts of badgir (Source: Bahadori 2008).

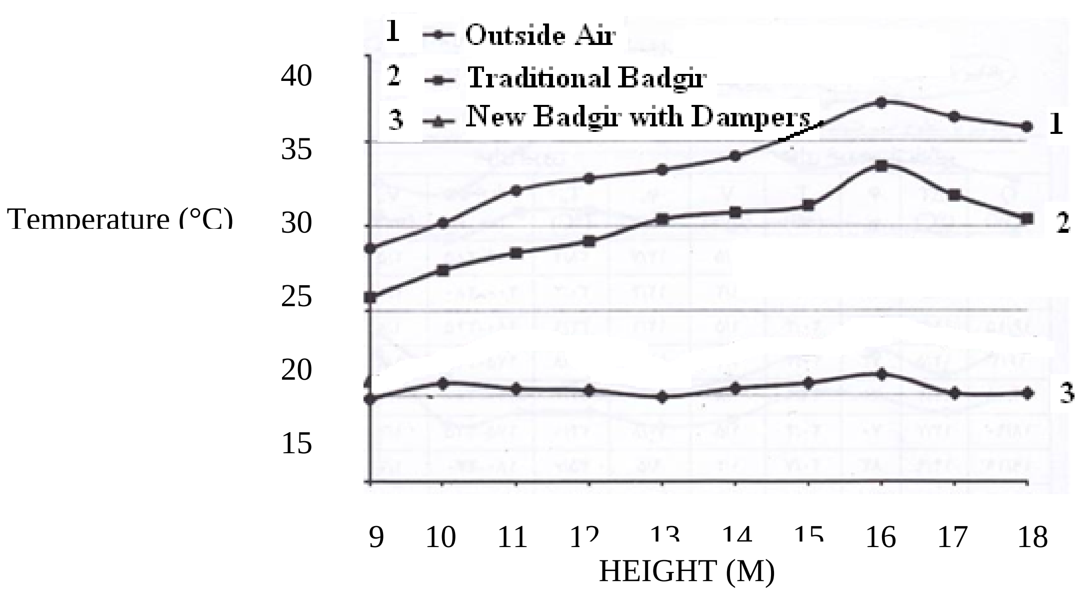



Figure 2-6. Comparison between inside temperature (°C) and height of badgir (m) of Yazd University in Yazd, Iran, year 2003 at 3:00 pm for 10 days period (Source: Bahadori 2008).

Figure 2-7. Space under badgir which has water reservoir (ab-anbar) located under holed slab. (Source: Romina Mozaffarian).

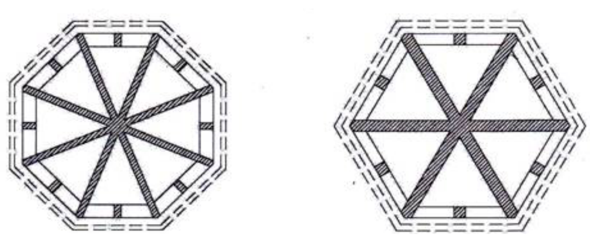


Figure 2-8. Plan of badgirs with six and eight interior wall dividers (Source: Bahadori 2008).

Figure 2-9. Badgir with four interior wall dividers (Source: Romina Mozaffarian).

Figure 2-10.  Badgir with eight interior wall dividers (Source: Romina Mozaffarian).

Figure 2-11.  Badgir in Dolat-abad in Yazd, Iran (Source: Romina Mozaffarian).

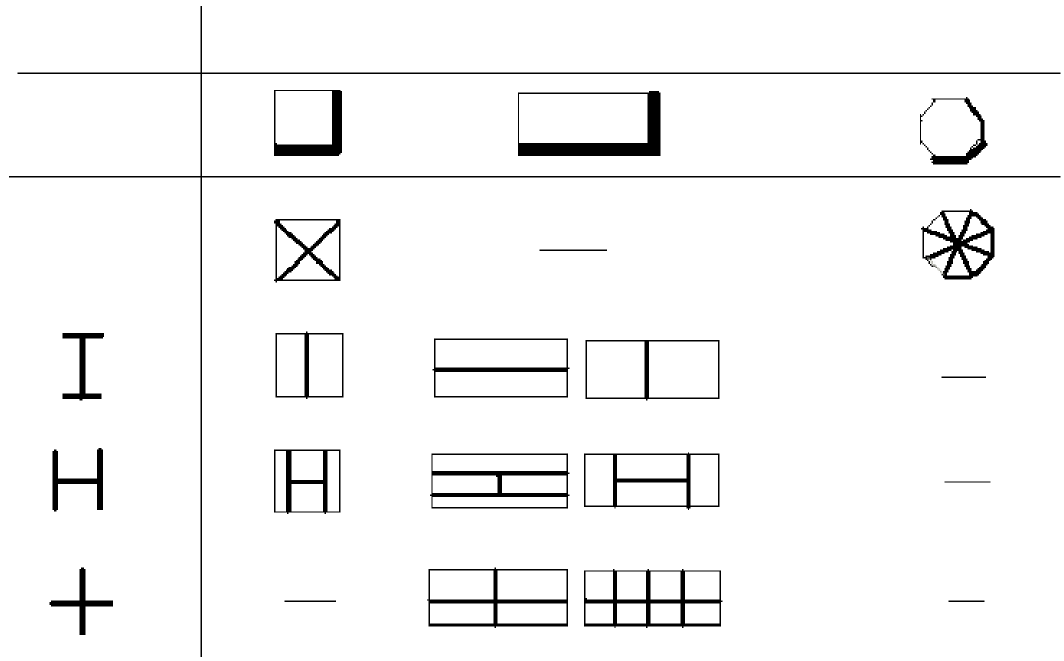


Figure 2-12.  Plan views of different wind towers (Source: Azami 2005).

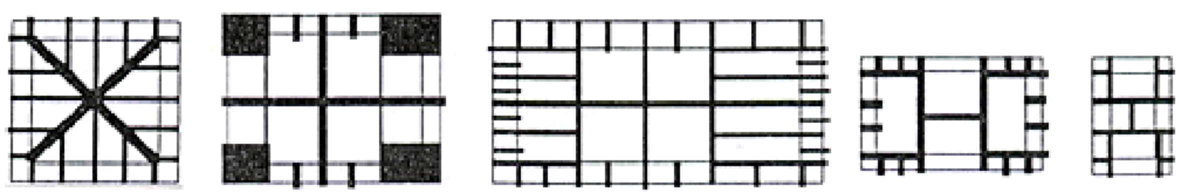


Figure 2-13.  Typical plan of four directional wind towers (Source: Azami 2005).

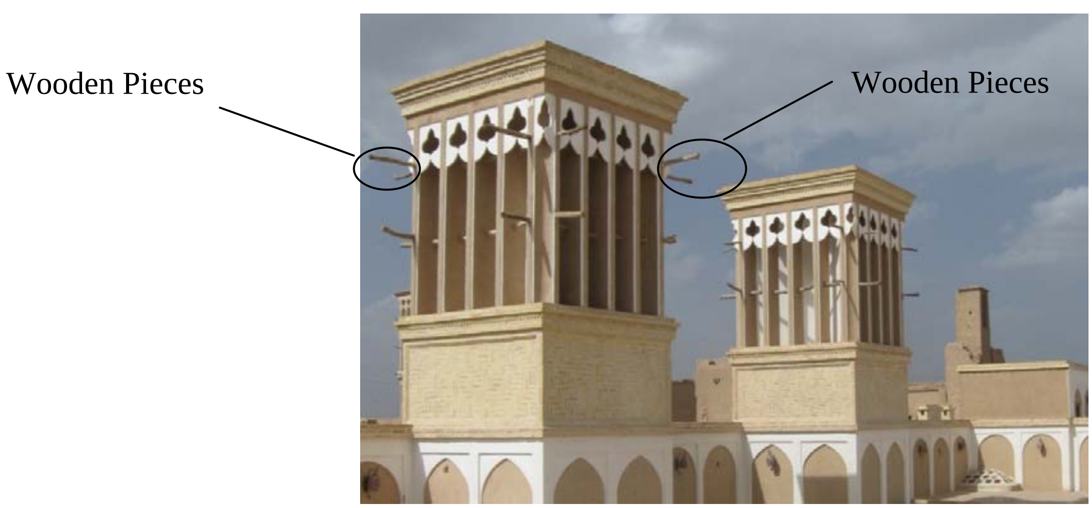



Figure 2-14.  Flat badgir roof in Yazd, Iran (Source: Romina Mozaffarian).

Figure 2-15.  Badgir with shed roof in Yazd, Iran (Source: Romina Mozaffarian).

Dashed Line: - - - Circulation of air during night time
Solid Line: ―― Circulation of air during day time

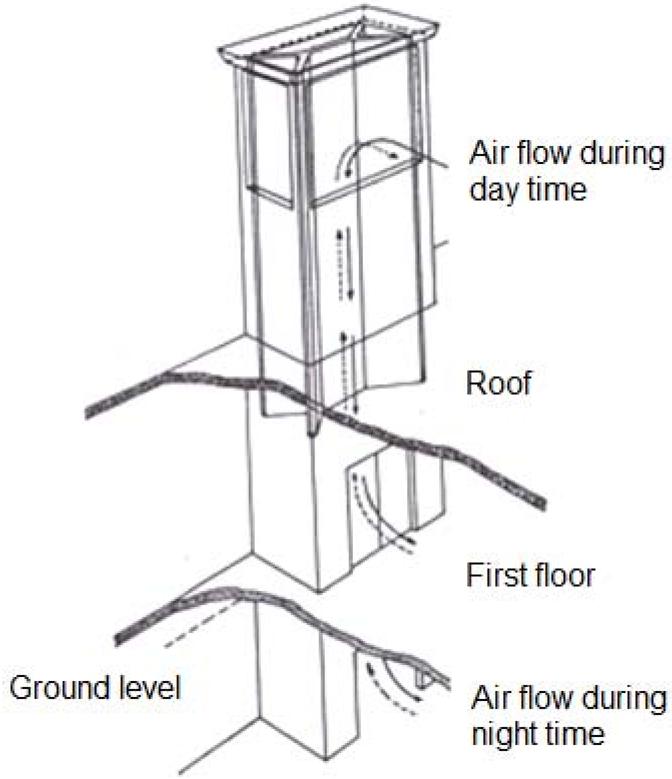



Figure 2-16.  Circulation of air during the day and night (Source: Bahadori 2008).

Figure 2-17. Stairs under badgir columns to water reservoir (ab-anbar) (Source: Romina Mozaffarian).

Figure 2-18. Modern badgir or “Kolah Farangy Badgir”in Tabas, Iran (Source: Bahadori 2008).

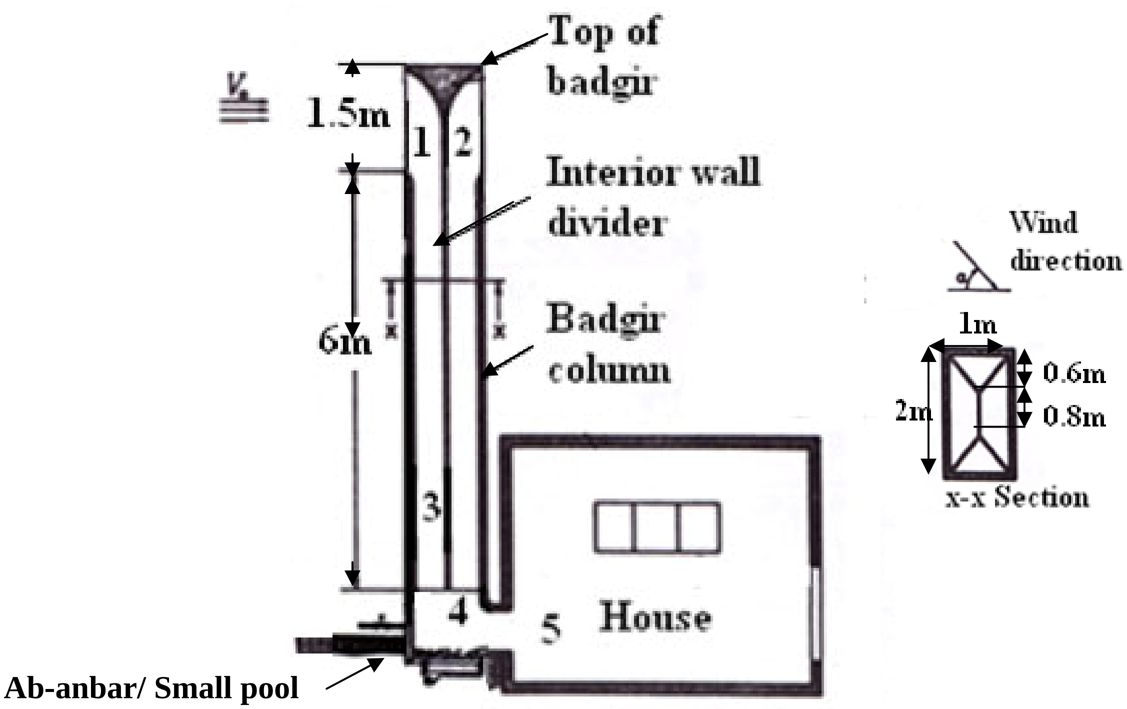



Figure 2-19. Circulation of air through a building with badgir (Source: Bahadori 2008).

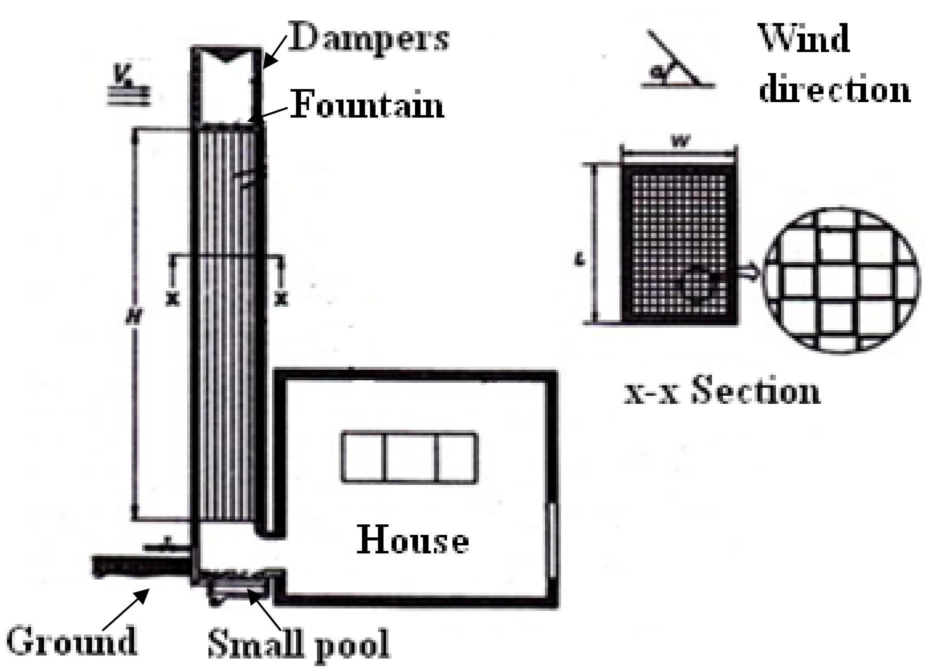



Figure 2-20. Section of badgir with dampers and small pool underneath (Source: Bahadori 2008).

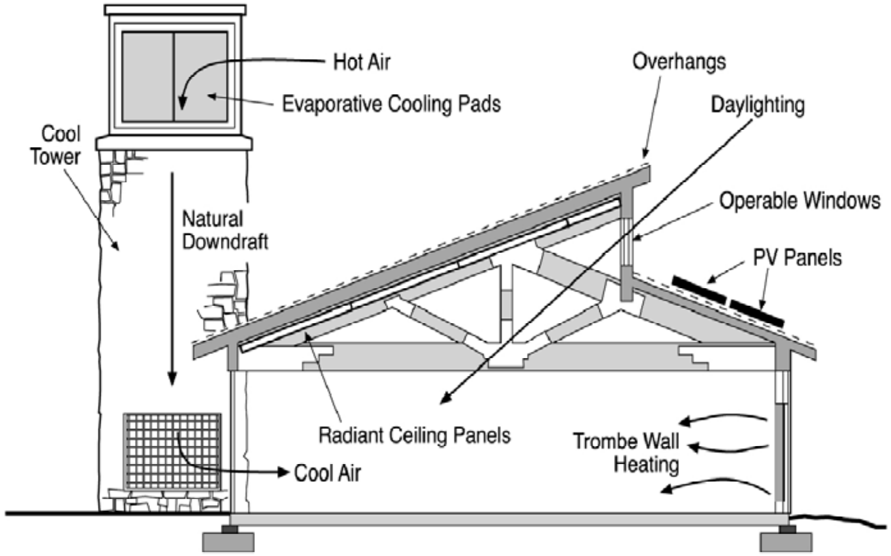
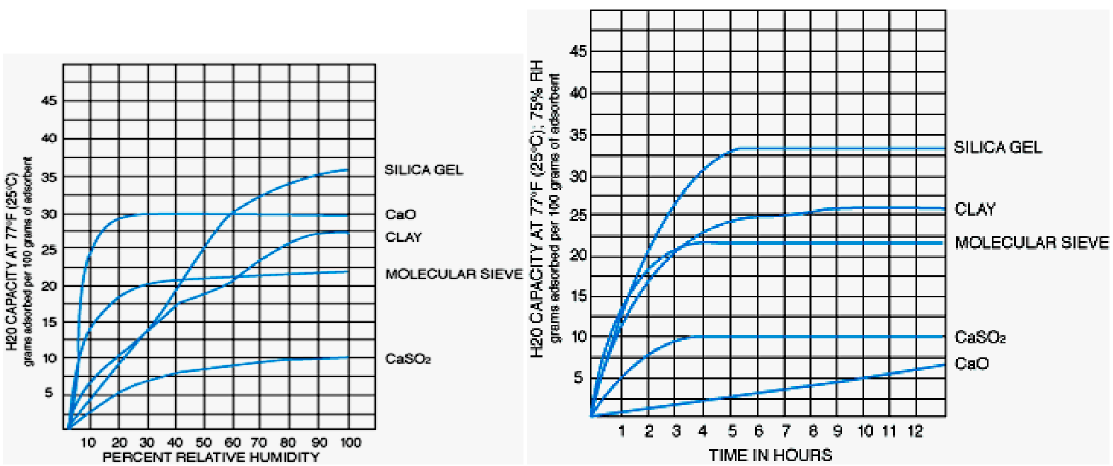



Figure 2-21. Cross section of a building in Zion National Park visitor center (Source: Torcellini et al. 2002)




(a) (b)

Figure 2-22. (a)Comparisons between percentage of relative humidity and water capacity in different desiccants, (b) Comparison between time in hours and water capacity of different desiccants (Source: Lavan 1982).

Table 2-1. Temperature and wind speed of outside air and badgir air (Source: Bahadori 2008 and modified by Romina Mozaffarian)

| **Cooled Air Entering the Building from Badgir** | | **Outside Air/Ambient Air** | | **Difference of Temperature °C** | **Hour** |
|---|---|---|---|---|---|
| **Temperature °C** | **Wind Speed m/s** | **Temperature °C** | **Wind Speed m/s** | | |
| 19.8 | 1.5 | 28.7 | 2.5 | 8.9 | 9 |
| 20.7 | 1.2 | 30.2 | 2.1 | 9.5 | 10 |
| 20.4 | 1.5 | 32.1 | 1.8 | 11.7 | 11 |
| 20.3 | 1.4 | 32.8 | 1.8 | 12.5 | 12 |
| 19.9 | 1.8 | 33.3 | 2.1 | 13.4 | 13 |
| 20.4 | 1.5 | 34.1 | 1.7 | 13.7 | 14 |
| 20.7 | 1.4 | 35.6 | 1.7 | 14.9 | 15 |
| 21.2 | 1.3 | 37.2 | 1.8 | 16 | 16 |
| 20.1 | 1.2 | 36.4 | 1.6 | 16.3 | 17 |
| 20.1 | 1.4 | 35.8 | 1.9 | 15.7 | 18 |

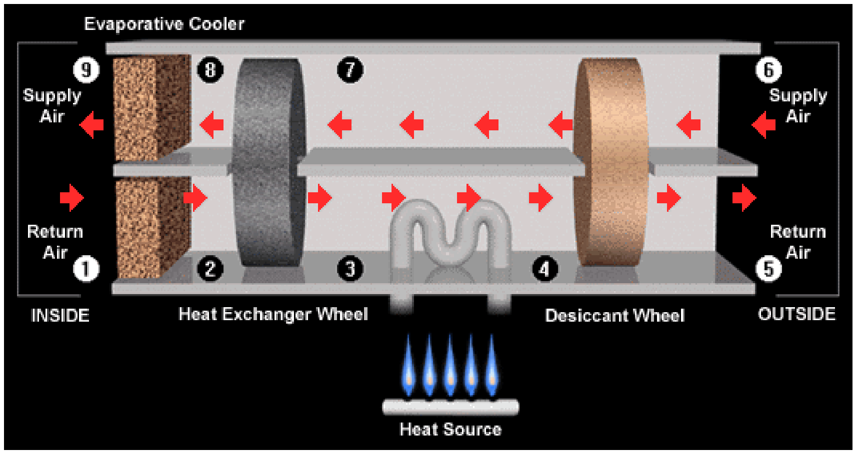



Figure 2-23. Evaporative cooler (Source: ASHARE 1999).

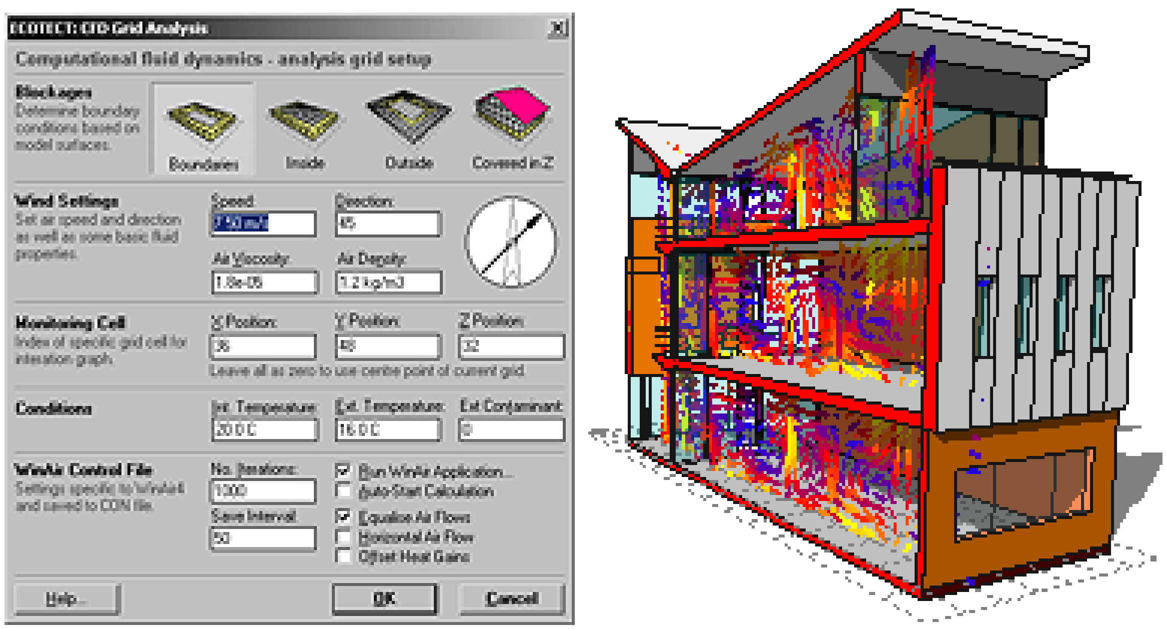



Figure 2-24. CFD model (Source: Ecotect website).

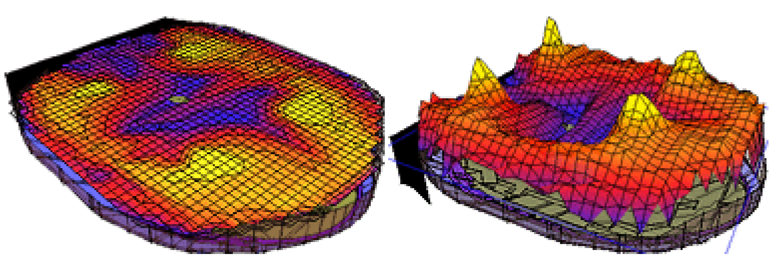


Figure 2-25. CFD model (Source: Ecotect website).

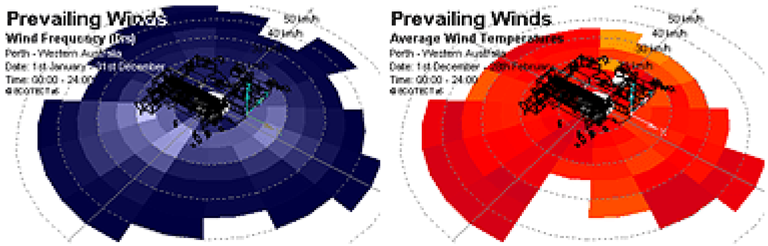




Figure 2-26. Plots of prevailing winds from weather data, showing annual wind frequency and speed (left) and summer wind temperatures (right)(Source: ecotect.com website).

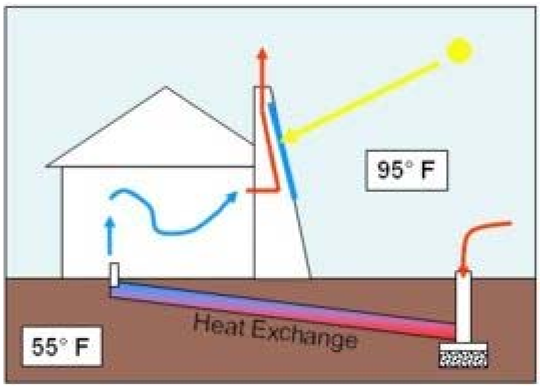




Figure 2-27. Solar chimney (Source: Bansal and Mathur 1993).

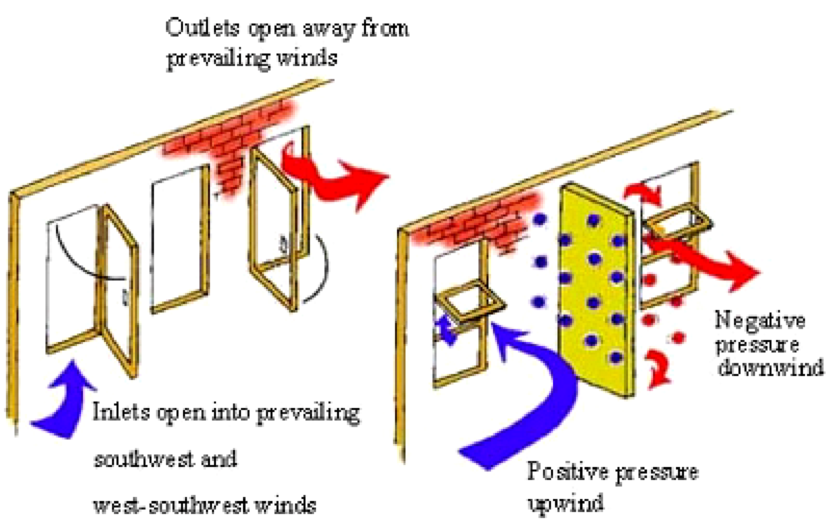




Figure 2-28. Window openings (Source: Bansal and Mathur 1999).

# CHAPTER 3
# RESEARCH METHODOLOGY

## Introduction

The purpose of this study is to improve the environmental performance of building ventilation and temperature by using a wind tower (badgir). Badgirs can reduce the electrical consumption of the buildings. The main focus of this study is on natural ventilation caused by winds. By using a badgir, outdoor air can be introduced into a building to circulate air. Secondly, tools for modeling a building with badgir are examined. Autodesk Ecotect, a psychrometric chart, and FLUENT packages are tools which were selected to study natural ventilation in a case study building, namely Rinker Hall in the School of Building Construction at the University of Florida. These three tools have been compared and evaluated. In this model, we are assuming that wind will pass through a water reservoir, which in Florida can be the natural underground water, to reduce temperature. The hottest month of the year, July, has been selected for the study.

## Wind Tower or Badgir as a Specific Kind of Ventilation Design

Based on the literature review, the wind tower or badgir has been chosen as one of the best techniques for natural ventilation in buildings. Badgirs have not been applied commonly in buildings for natural ventilation in United States. In wind tower or badgir, no mechanical conditioning system is used. Natural ventilation caused by wind is one of the main forces used in badgirs. By designing a badgir, the outdoor air can be introduced into the building to circulate air and ventilate the building. When visiting the city of Yazd, in Iran in March 2009, it became obvious to me that a badgir is really a masterpiece of engineering which works efficiently even now without any mechanical equipment. The weather in Yazd was not windy in March, but the badgir system was cooling the building well. There was a room under the tower of badgir with three doors to control circulate the cool air when needed.

## Analytical Tools for the Examination of Natural Ventilation with a Badgir

After reviewing possible analytical tools for examining natural ventilation of a building with badgir, three tools, Autodesk Ecotect, simplified calculation based on psychometric chart and the FLUENT package, have been chosen. These tools are either user friendly, low cost, or considered to be the state of the art.

### Autodesk Ecotect Process

The following data are information given in Autodesk Ecotect program for modeling a building in Atlanta climate. The Atlanta climate was the closest climate to Gainesville and was selected.

### Inputs Required for Autodesk Ecotect are as following.

- Three Dimensional View of the building: Specific dimensions can be given to model the building. Figure 3-1 is the model of Rinker Hall, school of Building Construction at University of Florida with approximate dimensions in Autodesk Ecotect Program. This figure shows a three dimensional view of the building in this software.
- Location Data and Wind Data: Figure 3-2 shows wind frequency in different hours. The chart on the right corner shows different hours of the day in the Atlanta, Georgia climate zone.
- Hourly Data: Figure 3-3 shows monthly diurnal average of different temperatures in twelve months of year.
- Give information to calculate thermal analysis. Hottest day of July/02 has been chosen for this study.

### Simplified Calculations Based On Psychrometric Chart

By using a psychrometric chart, the air temperature of the badgir's intake can be found. We assume that the temperature inside the building is approximately close to the temperature of the ambient air passing through water resorvoir/ab-anbar/small pool. This temperature can be directly extracted from the psychrometric chart as follows.

## Input of Psychrometric Chart

### Average Temperature

Average temperature is the average of the high and low temperatures.

Based on Table 3-1, maximum temperature in July in Gainesville, Florida is 90.9 °F (32.72°C) and minimum temperature in July in Gainesville, Florida is 70.8 ° F (21.55°C). The daily average temperature is as followed:

$$\text{Average Temperature in July} = \frac{90.9 + 70.8}{2} = 80.85\ °F\ (27.14\ °C)$$

### Relative Humidity

The relative humidity is a percentage measure of the amount of moisture in the air which is compared to the maximum amount of moisture that air can hold at the same temperature and pressure. Based on data from the National Oceanic and Atmospheric Administration, Table 3-2 indicates relative humidity (%) for selected city, Gainesville, FL. For Rinker Hall, a relative humidity of approximately 60% has been chosen, which is the afternoon relative humidity in Table 3-1. Based on Table 3-2, relative humidity, the afternoon humidity, in one of the most humid times of the year, July is 60%.

### Dew Point

Dew point is that temperature at which a moist air sample at the same pressure would reach water vapor saturation. Relative humidity of 100% indicates that the dew point is equal to the current temperature and the air is maximally saturated with water. Based on Figure 3-4, psychrometric chart, the average dew point, is as follows:

$$\text{Average Dew point Temperature based on Psychometric result in July} = \frac{61.5 + 79.5}{2} =$$

70.5 ° F (21.38 °C)

The above temperature is close to the water temperature in the main water reservoir, Ab-anbar. If the water reservoir is big enough, the water temperature would not change drastically during a 24-hour period.

**Air Change Calculation**

Volumetric flow rate = Wind speed (m/sec) $\times$ Cross sectional area of badgir ($m^2$)

Since average wind speed in Gainesville, FL is 2.5 m/sec and cross sectional area of badgir is 9 $m^2$ (3 m $\times$ 3 m).

Then, at each second 2.5 m/sec $\times$ 9 $m^2$ =22.5 $m^3$air is coming into the building.

Therefore, in 1 hr, 22.5 $m^3$air $\times$ 3600=81000 $m^3$air is coming into the building

Volume of Rinker Hall, School of Building Construction is 18,000 $m^3$.

Therefore, the amount of the fresh air coming into the building in 1 hr is:

$$\frac{Voulme\ of\ \frac{Air}{hour}}{Voulme\ of\ Space} = \frac{81{,}000\ \frac{\mathrm{m^3}}{\mathrm{h}}}{18{,}000\ \mathrm{m^3}}$$ = 4.5 volume of air per hour.

## FLUENT Package

FLUENT package is another software used to obtain information about natural ventilation in a building. The computational domain is divided into 87,037 small elements (so called mesh) to solve Navier-Stokes equations in each of these small elements. This simulation computationally is costly. The computation was performed on a 2.61 GHz desktop computer and the results converged after 8 hours. FLUENT package has been used to find the temperature of the building with and without the badgir details. In FLUENT package, the assumption is the wind passes over water reservoir before coming to the building for simplify. This temperature of the air flowing into the building after passing the water has been used as the last boundary condition. Therefore, the value of 70.5° F (21.38 °C) which had been calculated from psychrometric chart is imposed at the badgir's intake in FLUENT package.

In order to calculate information in CFD Package, the following data needed to be considered for FLUENT packages.

**Input of FLUENT Package**

- **Average temperature:** Average Temperature is the average of the high and low temperatures. Data in table 3-1 has been collected from NOAA for Gainesville, Florida. Month of July has been selected for FLUENT package process. Table 3-1 shows the maximum temperature is in July which is 90.9°F(32.72 °C) and minimum temperature in July which is70.8°F (21.55 °C).

- **Wind speed:** Wind speed shows the movement of air in an outside environment. Figure 3-5 shows different directions of wind in Florida. Figure 3-6 indicates wind direction in different months in St. Augustine Beach. St. Augustine Beach, FL is the selected city to get information for wind speed since it is the closet city to Gainesville, FL. Figure 3-6 shows the average wind speed (m/s) throughout the year. Average wind speed in July is used for FLUENT package.

- **Boundary condition:** The Navier-Stokes (N-S) equations are the fundamental differential equations of the movement of fluid. Boundary conditions need to be defined in order to solve Navier-Stokes equations. Therefore, the value of velocity in all of the boundaries should be defined. In order to solve any differential equations, some boundary conditions and/or initial conditions need to be defined. The same role applies for Navier-Stokes equations. In order to solve N.S equations, all velocity should be defined at all boundaries. Boundaries in the Rinker Hall CFD model translates as any limits of our computational domain that separate the computational domain from the ambient. The effect of the ambient on our computational domain is defined at the boundaries. Therefore, all of the walls are the boundaries of our domain. The open areas such as open doors and/or the badgir are another type of boundary. The well-known "No-Slip" boundary condition has been applied on all of the walls. This boundary condition implies that the velocity of the fluid close to the walls should be the same as the velocity of the wall (in this case the velocity of the wall is zero because all of the walls are stationary). Because all of the openings are exposed to the ambient air, the pressure at the doors (specifically the open doors) is assumed to be atmospheric pressure (100,000 Pascal). The velocity of the flow at the badgir is set to be the average velocity of the wind in July. The opening of the badgir should be designed perpendicular to the wind to be able to collect all of the kinetic energy of the wind.

- **Flow field:** The flow field is the velocity component at each point. Each point also has its own static pressure that is calculated.

- **Computational domain:** Computational Domain is the area in which N-S equations are solved. Here, the interior area of the building and badgir serve as the computational domain. The computational domain is the Rinker Hall School of Building Construction building at the University of Florida. The feasibility of installing a badgir in order to reduce electricity consumption of the building has been studied. The goal of this research is to find if the installation of a badgir in the Rinker Hall School of Building Construction is able to provide cooling for the building. In this study, using the Computational Fluid Dynamic (CFD) method, the building, as is and without the badgir, is compared to the building in which the badgir is implemented.

- **No slip boundary condition:** This condition is imposed for three components of velocities: X velocity, Y velocity and Z velocity. This makes evident that all the velocity components at the wall have to be zero.

- **Barometric pressure:** Barometric pressure, also called air pressure or atmospheric pressure, is the pressure exerted by the weight of air over a given area of Earth's surface. Barometric pressure is measured by an instrument called a barometer. Low pressure areas have less atmospheric mass above their location, whereas high pressure areas have more atmospheric mass above their location. Similarly, as elevation increases there is less overlying atmospheric mass, so that pressure decreases with increasing elevation (Mechtly, E. 1973). Figure 3-7, shows a fifteen-year average mean sea-level pressure in the world map. In this figure, MSLP stands for mean sea level pressure, JJA stands for June, July, August and DJF stands for December, January, February months.

- **Openings:** There are three existing doors and openings located in Rinker Hall, School of Building Construction. FLUENT package recognizes these doors as openings where their pressure value is set as atmospheric pressure.

- **Pressure outlet boundary:** Pressure outlet boundary condition has been imposed at the doors. In other words, $P$ at the doors is atmosphere pressure.

- **Heat flux and temperature boundary condition:** The 1000 $w/m^2$ heat flux boundary condition is imposed on the south wall and roof. The 1000 $w/m^2$ value is the typical sunshine heat flux in Florida. The temperatures of other walls are set to be equal to ambient air temperature. FLUENT solves flow field (Navier-Stokes equation) for these boundary conditions. FLUENT calculates temperature, velocities and pressure in the computational domain.

- **Solar heating load:** In northern Florida, the sun shines from south, east and west. When sun rises from east, the west and south walls and the roof of the building are absorbing solar energy. At noon, the sun shines vertically to the top of the building and heats the roof and the south walls, while during the evening the roof, east, and south walls absorb the solar energy. The study shows that the sun which shines on the west and east walls was neglected because the walls are exposed to the sun's rays for only a short period of the day. In the state of Florida, the maximum solar energy hitting the ground is about 1000 $Watt/m^2$. This is assumed that the skies are clear. The average solar energy can be calculated by integrating the solar radiation during the day. The average solar energy was used as the heat flux boundary condition on the roof and the south walls. Though there are many simplifying assumptions in this study, the results allow an understanding and confirm the effectiveness of the implementation of the badgir.

## Badgir Model Information in FLUENT Package

Rinker Hall, School of Building Construction at University of Florida, is a model for FLUENT package. The dimensions of the building have been obtained from the floor plan of the building. Figure 3-8 shows the dimension of a model used in FLUENT package in meters. For simplicity, educated assumptions were used in the model. Figure 3-9 shows computational domain (Rinker Hall) and the elements that have been used in this study.

There are some assumptions which have been considered in this study. Assumptions are as follows:

- Interior walls: The interior walls have been neglected in this study.
- Openings: It was assumed that there are 3 open doors in this building and the opening at the badgir.
- Velocity components: All velocity components are set to be zero at the walls. At the inlet of the badgir the velocity is set to be equal to the wind velocity.
- Pressure: The pressures for the doors are set to be as atmospheric pressure.
- Air Temperature at badgirs: In FLUENT package, it has been assumed that the badgir's intake already passes through water reservoir/ab-anabar which is underground water in Florida for simplicity of the model. Therefore, the value of 70.5° F (21.38 °C) has been imposed at the badgir's intake in FLUENT package.
- Boundary condition: Since the energy equation is coupled with the momentum equations (N.S), the boundary conditions for the energy equation have to be defined in all of the boundaries.
- Heat flux: The heat flux at the roof and the south wall set to be as the average heat flux of the sun during the summer.
- Temperature: The temperature of the other walls is set to be equal to ambient temperature.
- Direction of Sun: The Rinker Hall School of Building Construction at the University of Florida is an example of a building in hot and humid climate. Sun shines from south west in Florida. In the CFD model, the sun shines toward the roof and the south walls of the building. Shades are therefore on north side of Rinker Hall. In order to design a badgir;

precise information about the wind speed at the certain time (daily average or monthly average) must be extracted from statistical weather data.

- Height of badgir: In order to design the height of the badgir tower, it is important to know the arrangement of nearby buildings as well as surrounding tall trees. Since tall trees or buildings may dissociate the wind speed and power, tower's height should be taller than the neighbor buildings or trees. The entrance of the badgir should be located perpendicular to the average wind direction to collect the maximum amount of air possible.

- Dimensions of badgir: The speed of the air inside the building should be in the certain range to produce comfort airflow for people. According to ASHARE, the velocity of $0.5 < V < 2$(m/s) is acceptable (ASHARE 1999). As a result, we will continue our design based on 2.5 (m/s) winds in the main corridor. We will assume that this speed of the wind in the main corridor would maintain the comfort Velocity limits in the hall and smaller rooms. This assumption helps us to design the badgir entrance dimensions using continuity equation. In fluid mechanics, continuity equation (conservative of mass) applies on a control volume which may have many inlets and outlets. Continuity equation says that the amount of mass entering a domain should be equivalent to the amount of mass leaving control volume.

- Mathematically, continuity equation assuming a constant density of air can be express as:

- $A_1V_1=A_2V_2$

- Where, $A_1$ is the cross sectional area of the badgir intake.

- $V_1$ is the wind speed entering badgir which can be found from the statistical weather data at the certain times.

- $A_2$ is the cross sectional area of the main corridor (10.8 $m^2$).

- $V_2$ is the desired air speed in the main corridor which is 2.5(m/s), as discussed before.

- Solving Eq. 1 for the unknown badgir intake cross sectional area:

- $$A_1 = {}^{A_2V_2}\!/_{V_1}$$

- So,

- $$A_1 = {}^{10.8(m^2)\times 2(m/s)}\!/_{2.5(m/s)} = 8.64(m^2)$$

This is a rough estimate of the cross sectional area of the badgir.

Since the area to perimeter of square is the maximum for arbitrary rectangular, the most effective shape of the badgir is square. In order to have 8.64 $m^2$ cross sectional area, the dimension of the badgir should be almost $3(m) \times 3(m)$.The height of the badgir tower above the roof assumed to be 6 m.

The schematic of the badgir is shown for any initial assumptions.

Figure 3-10 shows the dimensions and wind speed assumptions for badgir Model in FLUENT package. Figure 3-11 shows the floor plan of Rinker Hall which was used in the CFD Model. Figure 3-12 is the picture of the entrance of the Rinker Hall School of Building Construction.

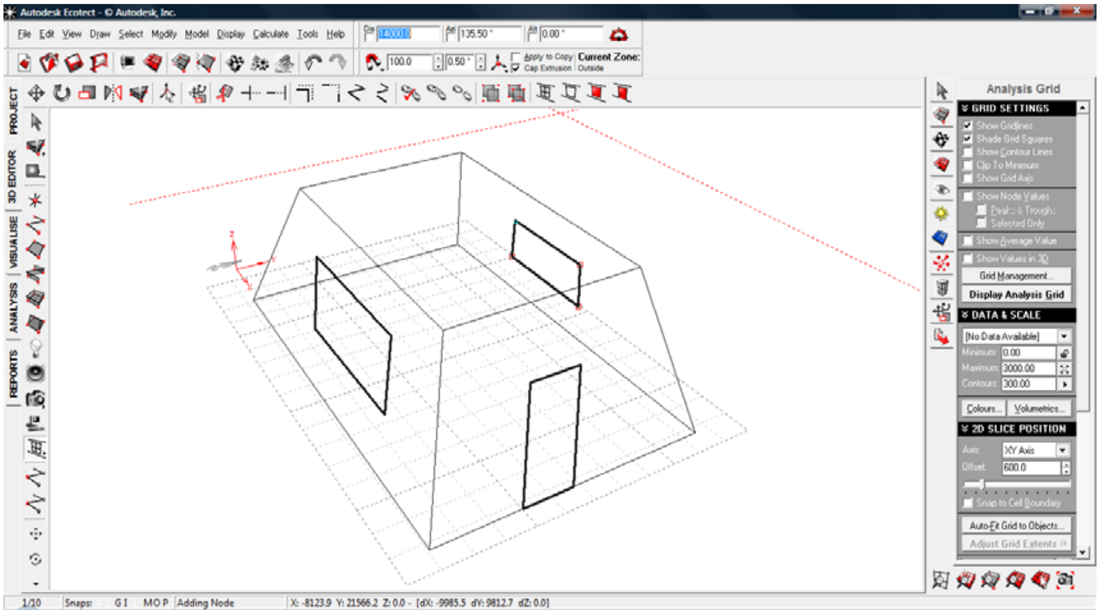



Figure 3-1. Three dimensional view of a simplified Rinker Hall in Ecotect Software (Source: Romina Mozaffarian).

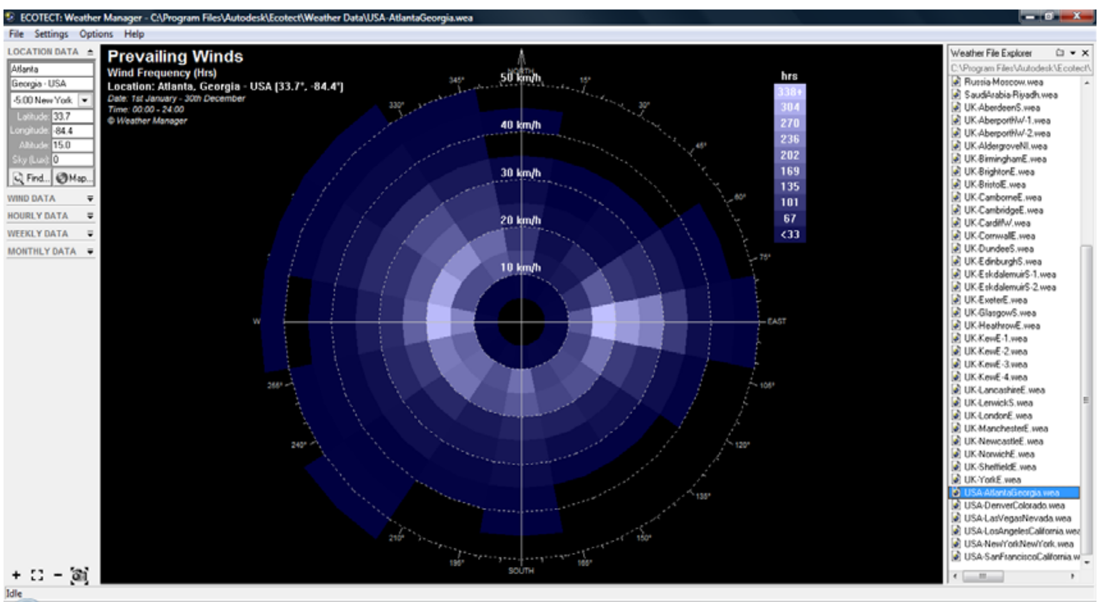



Figure 3-2. Locational Data and Prevailing winds (Source: Romina Mozaffarian).

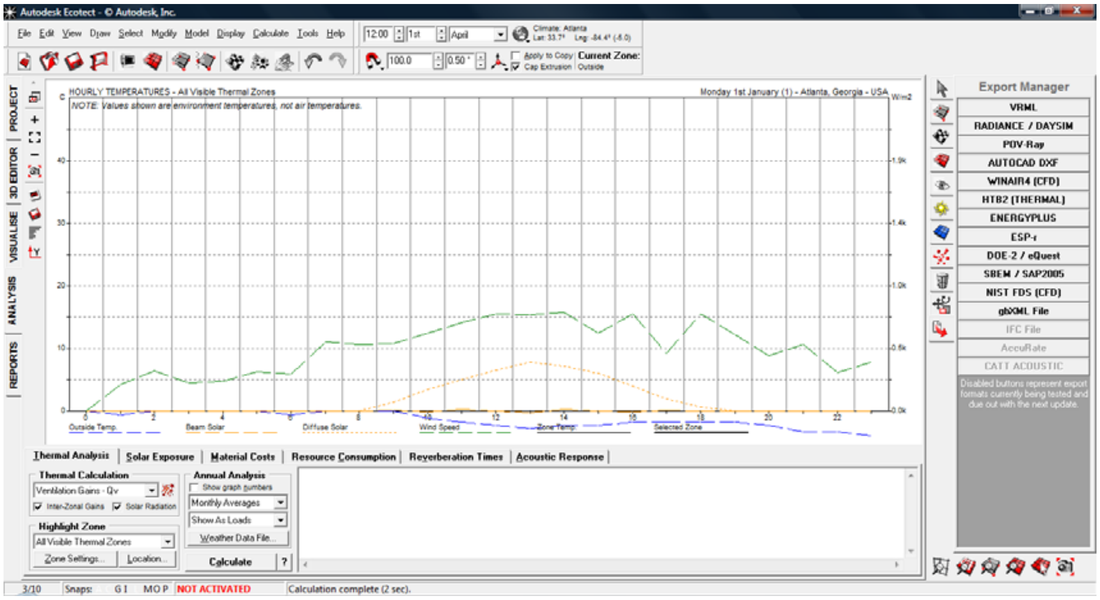


Figure 3-3. Hourly temperatures (Source: Romina Mozaffarian).

Table 3-1. Maximum and Minimum Temperature in Gainesville, Florida (Source: National Oceanic and Atmospheric Administration 2001and modified by Romina Mozaffarian)

| Normal Daily Temperature (°F) Gainesville, FL | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| YRS | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | ANN |
| 30 | 66.2 | 69.3 | 75.1 | 80.4 | 86.5 | 89.9 | 90.9 | 90.1 | 87.4 | 81 | 74.4 | 68.1 | 79.9 |
| 30 | 42.4 | 44.7 | 49.9 | 54.7 | 62 | 68.4 | 70.8 | 70.6 | 68.1 | 59.2 | 51.1 | 44.4 | 57.2 |

Table 3-2. Average Relative humidity (%) (Source: NOAA 2001 and modified by Romina Mozaffarian)

| FLORIDA | Years | | JAN | | FEB | | MAR | | APR | | MAY | | JUN | | JUL | | AUG | | SEP | | OCT | | NOV | | DEC | | Annual | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M= Morning<br>A= Afternoon | M | A | M | A | M | A | M | A | M | A | M | A | M | A | M | A | M | A | M | A | M | A | M | A | M | A | M | A |
| GAINESVILLE (%) | 18 | 18 | 90 | 60 | 90 | 56 | 91 | 53 | 91 | 51 | 91 | 50 | 88 | 56 | 89 | 59 | 90 | 60 | 96 | 64 | 93 | 61 | 93 | 60 | 91 | 62 | 91 | 58 |

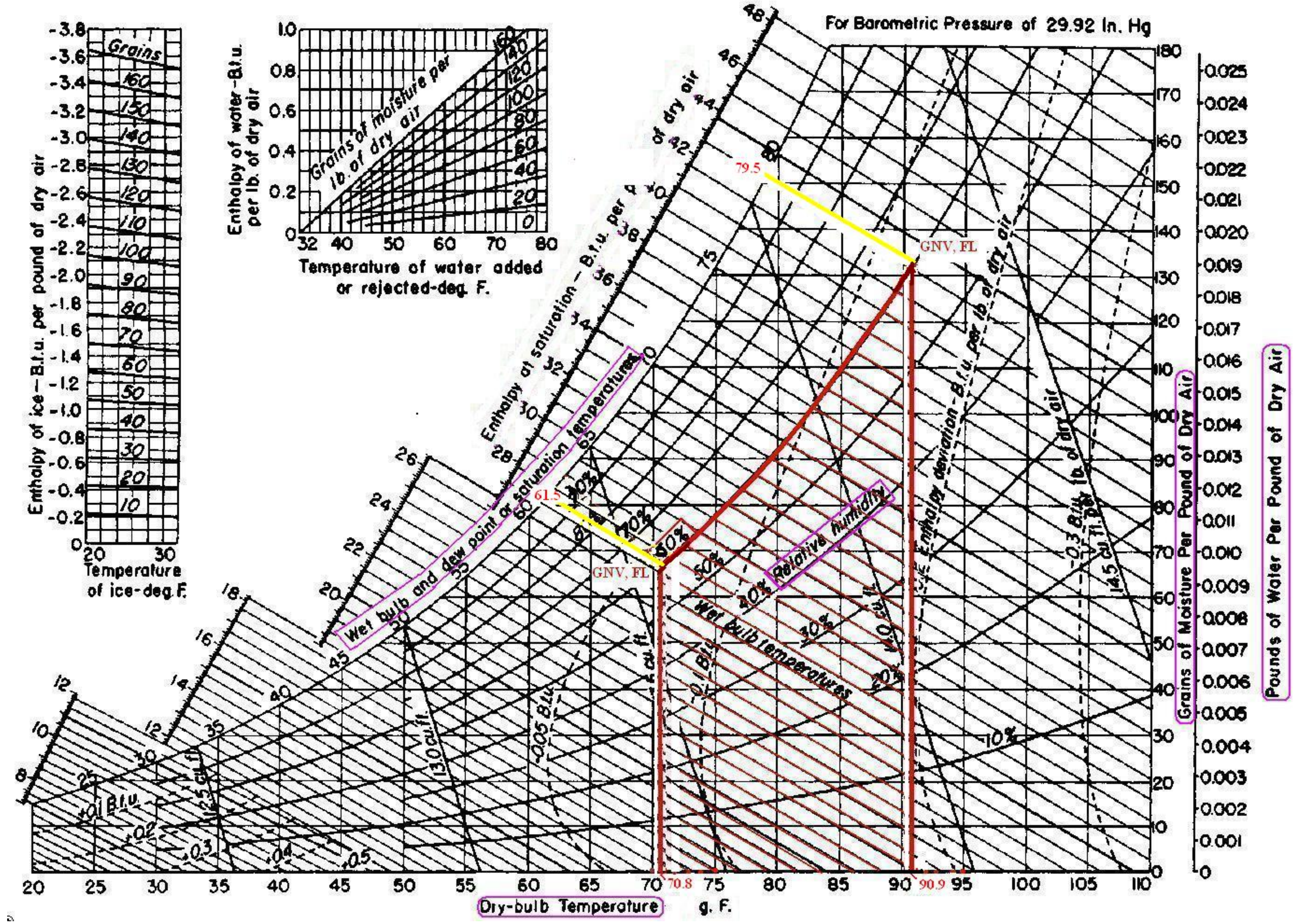



Figure 3-4. Psychrometric chart (Source: truetex.com website and Modified by Romina Mozaffarian).

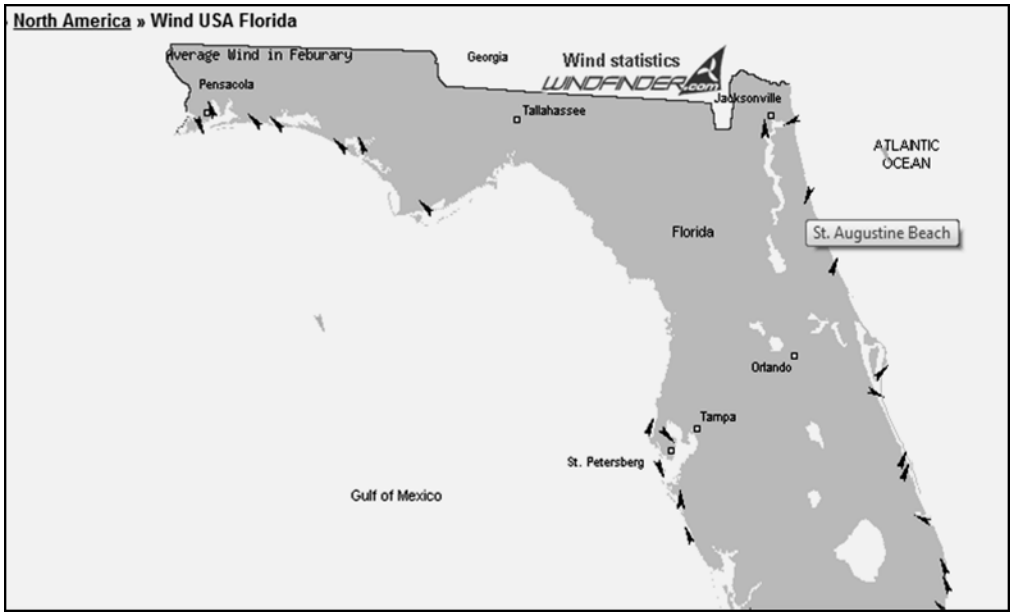



Figure 3-5. Wind directions state(Source: windfinder websit).

St. Augustine Beach (AUGUSTIN)

Stats based on observations taken between 10/2006 - 1/2009 daily from 7am to 7pm local time.

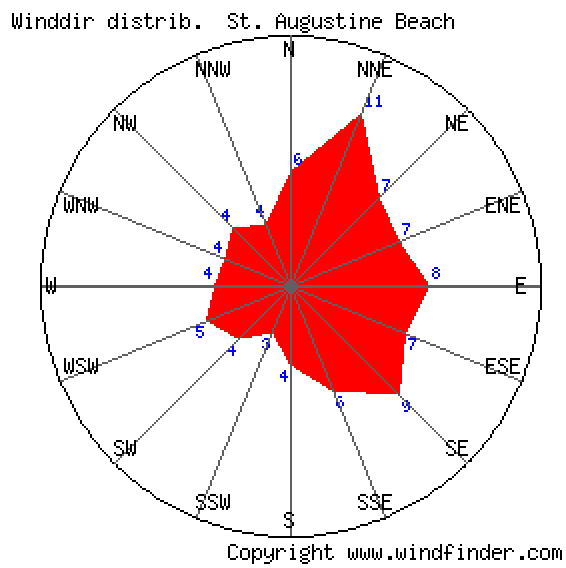
| Month of year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | SUM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10 | 11 | 12 | 1-12 |
| Dominant Wind Dir. | | | | | | | | | | | | | |
| Wind probability > = 4 Beaufort (%) | 34 | 34 | 40 | 46 | 56 | 37 | 17 | 28 | 55 | 51 | 44 | 29 | 39 |
| Average Wind Speed (kts) | 9 | 10 | 10 | 11 | 12 | 9 | 8 | 9 | 12 | 12 | 11 | 9 | 10 |
| Average Air temp. (°C) | 16 | 17 | 18 | 20 | 24 | 26 | 28 | 28 | 27 | 24 | 19 | 18 | 22 |
| Select Month (Help) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Year |
| Wind direction Distribution (%) |  | | | | | | | | | | | | |



Figure 3-6. Wind direction local(Source: windfinder website).

Table 3-3. Wind Speed (m/s) (Source. windfinder website)

| FLORIDA | YRS | JAN | FEB | MAR | APR | MAY | JUN | JUL | AUG | SEP | OCT | NOV | DEC | ANN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| GAINESVILLE (m/s) | 23 | 6.8 | 7.3 | 7.6 | 7.1 | 6.7 | 5.9 | 5.5 | 5.2 | 6 | 6.1 | 6.2 | 6 | 6.4 |

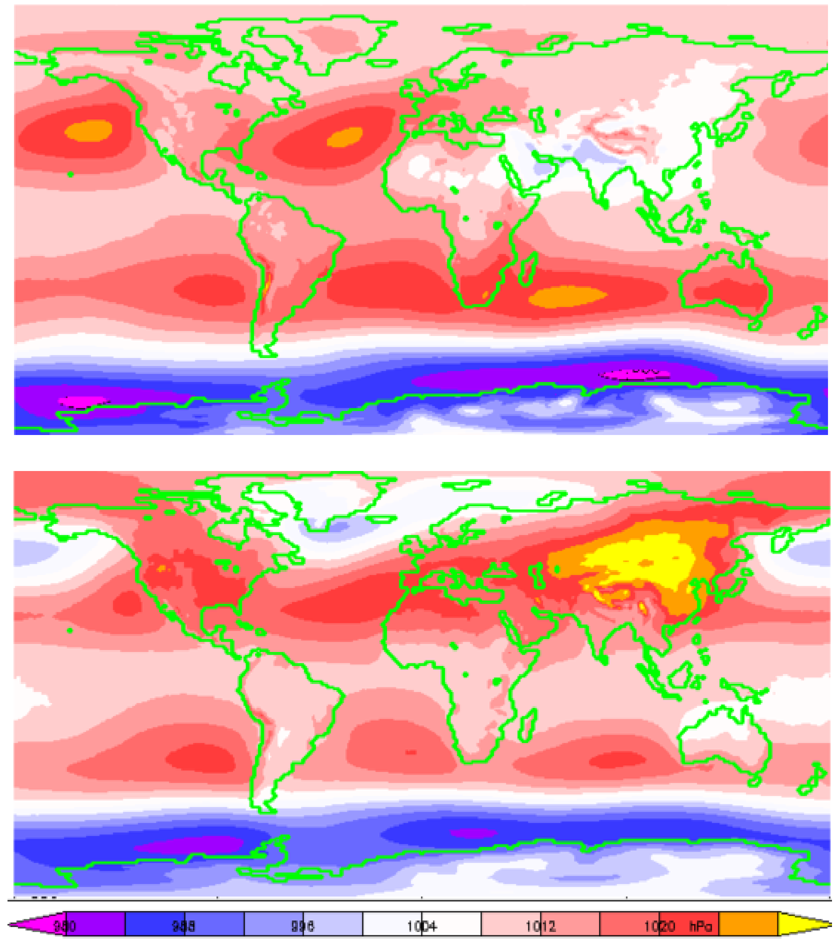



Figure 3-7. 15 year average MSLP (mean sea level pressure), JJA (June, July, and August) and DJF (December, January and February) months (Source: William M. Connolle).

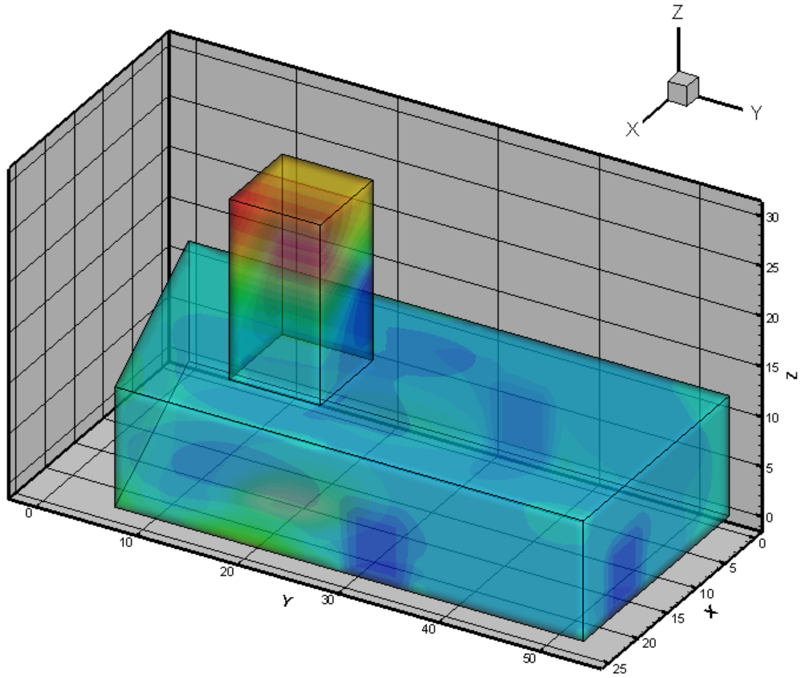



Figure 3-8. Rinker Hall model in meter in FLUENT package (Source: Romina Mozaffarian).

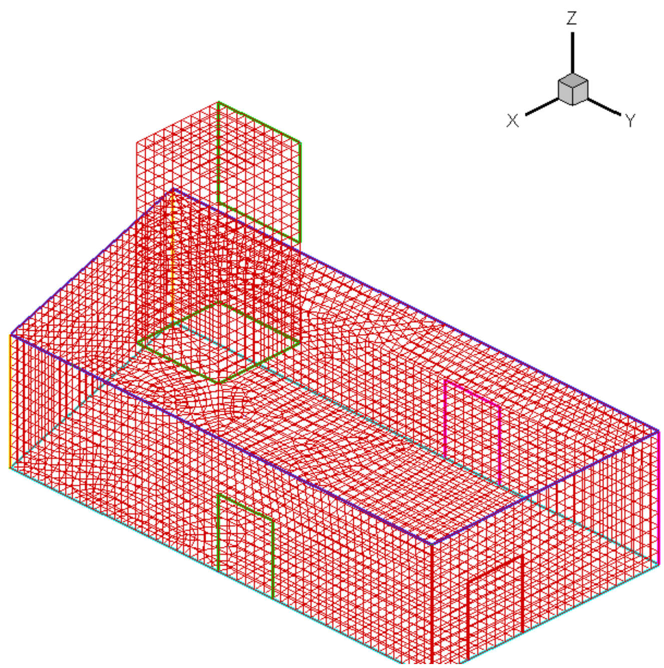



Figure 3-9. Computational domain (Rinker Hall) and the elements that were used in this study (Source: Romina Mozaffarian).

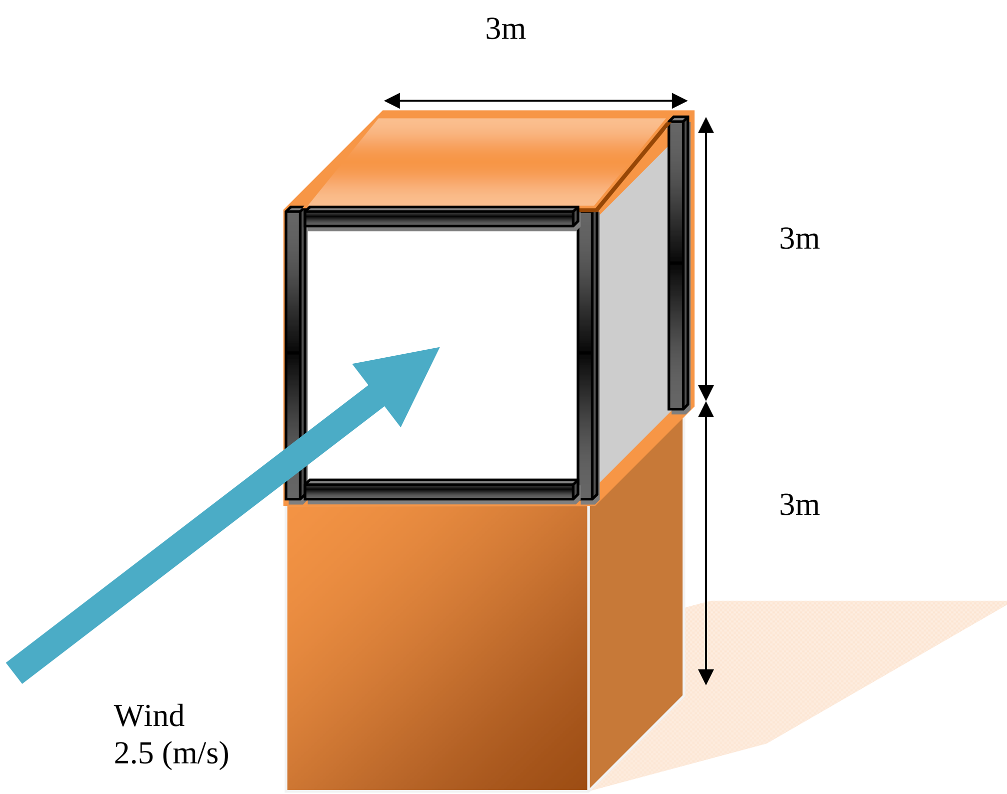



Figure 3-10. Badgir (Source: Romina Mozaffarian).

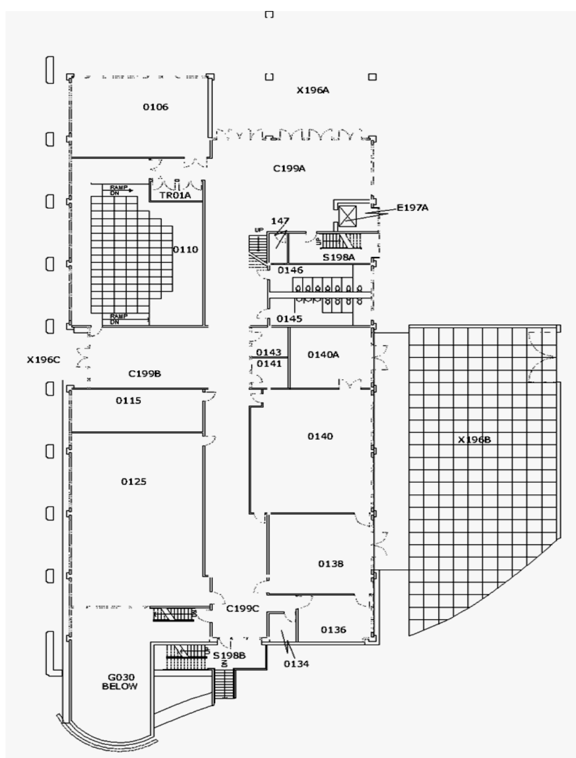



Figure 3-11. Rinker Hall first floor plan (Source: Roya Mozaffarian).

Figure 3-12. Rinker Hall main entrance (Source: Roya Mozaffarian).

## CHAPTER 4
## RESULTS AND ANALYSIS

### Introduction

Based on the literature review and methodology, information regarding badgir has been summarized in Table 4-1. Table 4-1 is the result of information for designing a badgir in hot and dry climate and hot and humid climates. This information is based on researches of typical badgirs in Iran. The dimensions of opening in badgirs need to be calculated based on square feet of a building.

### Similarities between Wind Towers/Badgirs of Buildings in United States and Middle East with New Techniques

Wind tower in Zion Park is an example of applying badgir in United States. In this building, honeycomb media is located at top of the tower. Water pumps in this system, and then evaporates. Since evaporated air is denser than ambient air, it drops through the tower and enters the building. This cool air cools the building. This system is very similar to the buildings with badgir and dampers which are located in Yazd, Iran as well.

In badgirs with dampers in Iran, there is a pump which directs the extra water from small pool or ab-anbar to top of the building. A fountain located on top of clay surface on top part of badgir use the extra water and keeps the dampers wet. When the air gets wet through dampers, evaporates and gets cool. Colder air has higher density than outside air and this causes circulation of air inside the building. Air enters to the building and cools the building (Bahadori 2008).

### Benefits of Badgirs in Green Building/Sustainable Building

The following are the benefits of having badgirs in green buildings.

- Cooling the building without using any electrical equipment (natural ventilation).
- Having natural lighting through the openings of the badgir.

- Using the cold space underground for storing food instead of a refrigerator, especially in winte.

- Using natural materials like adobe, dried mud bricks for building badgirs for high heat storage capacities and for sustainable building.

**Autodesk Ecotect, Simplified Calculation and FLUENT package**

Three tools, Autodesk Ecotect, simplified calculation from psychrometric chart and FLUENT package, were used to find a tool for analyzing a building with a badgir. The results of Autodesk Ecotect are not detailed for a specific building with specific dimensions. Also, Autodesk Ecotect's output is not detailed for natural ventilation of a building with badgir. Simplified calculation based on psychrometric chart is not as detailed as a FLUENT package. It has an approximate result without considering facts such as wind speed and temperature of walls of buildings. In FLUENT package the temperature of walls and wind speed are considered for boundary conditions. The following are the results of Autodesk Ecotect, simplified calculations from psychrometric chart, and FLUENT package.

**Autodesk Ecotect**

- The results of given information to Autodesk Ecotect software are as follows.

- Monthly diurnal averages: Figure 4-1 shows Monthly temperature, beam solar, diffuse solar, wind speed and zoned temperature are being shown in different colors.

- Weekly Summary: Figure 4-2 shows weekly average temperature. Different colors of temperatures indicate different temperatures.

- Monthly Rainfalls: Figure 4-3 shows rainfalls in different months of years in mm.

- Comparisons of Different Wind Data: Figure 4-4 shows wind data in average wind frequency, average wind temperature, average relative humidity and average rainfall throughout a year.

- Monthly Wind Data: Figure 4-5 shows wind frequency in all different months.

- Daily Data: Figure 4-6 shows hourly operational profile from 1st day of January to 31st of December. It shows the result of temperatures, relative humidity, direct solar radiation, diffuse solar radiation, average wind speed outdoor, average cloud cover and average daily rainfalls in different hours of day.

- Weekly Data: Figure 4-7 shows weekly data of average temperature, maximum outdoor temperature, minimum temperature, relative humidity, direct solar radiation, diffuse solar radiation, average wind speed, average cloud cover and average daily rainfall.
- Data for Strongest Wind in Hourly Data: Figure 4-8 shows monthly Diurnal averages in different temperatures in a year. By looking at the figure, in month of July highest temperature, relative humidity, direct solar, diffuse solar are being graphed.
- Thermal Comfort: Figure 4-9 shows thermal comfort in mean radiant temperature.
- Export the model to CFD, DOE-2, gbxml and DXF files.

## Simplified Calculations of Air Change

Based on the methodology reviewed in the previous chapter, the daily average temperature in Gainesville, Florida in July, the temperature of air passing through water reservoir, and the air change rate has been calculated. Based on these, we are assuming that the building with the badgir has an indoor air temperature of 70.5°F (21.38 °C), which is the temperature of the air passing through water reservoir/ab-anbar. Also, we are assuming a building without a badgir has a temperature of daily average temperature of ambient air in Gainesville, Florida in July which is 80.85°F (27.14 °C). The difference between these two temperatures is 10.35°F (-12.03 °C). The result shows a building with badgir has a lower temperature than a building without badgir. The humidity is not being considered.

Result of temperature difference = 80.85° F- 70.5° F= 10.35° F (-12.03 °C)

## FLUENT Package

### Results of Building with Badgir

In Figure 4-10(a, b), contours of the velocity and the flow streamlines in the building are depicted. This figure shows that the wind is entering the badgir with a velocity of 2.5(m/s), the average velocity of the wind in Gainesville, July. Then the wind circulates in the building and leaves the building from the open doors. It can be seen that when the wind entering into the badgir due to the growth of the boundary layers at the wall, the mean velocity of the wind increases to 4.5 m/s (see Fig.4-10(a)). This may not be good since the wind speed under the badgir would be greater than the comfort speed. However, if this wind was distributed in the whole building using ducts and dampers, a more uniform flow in the building could be attained. It should be considered that the badgir would not work if the doors or windows are kept closed since the flow of air coming into the building should have a way to go out. Therefore, in order to have an effective badgir, either doors should be kept open all the time or openings or vents connecting to the outdoors have to be included in the design.

Figure 4-11 (a, b) shows contours of the pressure and streamlines of the flow in the building (Fig. 4-11.b is another view of Fig. 4-10.b). In this figure it can be seen that when the wind enters the badgir (see Fig. 4-11.b), it hits the other wall of the badgir and makes a high pressure region of 14 kilopascal (see Fig. 4-11.a). The low pressure of 0 and -1 kiloPascal at the doors can be noticed in Fig. 4-11.a. Since the pressure at the doors is set to atmospheric pressure, the zero gauge pressure can be noticed at those regions. Figure 4-11.a is more advanced computation model if all interior walls take into the account. The pressure drops in the building due to the existence of barriers such as interior walls.

Figure 4-12 shows the contours of the temperature which is the most interesting variable in the building. In order to be able to model the buoyancy effect in the flow field, the air assumed to have the properties of an ideal gas. Therefore the density of air is decreasing with increase in temperature according to the ideal gas equation of state. All of the temperatures scales in Figure 4-12 are in Kelvin. Figure 4-12 clearly shows that the roof has the highest temperature since the heat flux of sun is coming from the roof. However, it is interesting to note that the roof temperature has a maximum value far from the badgir column. This indicates that since the air flow is slow far from the badgir column, there is not enough flow to remove heat from the roof.

By integrating the temperature over the volume and dividing it to the volume of the building the average temperature of air inside of the building with the badgir has been found. The average temperature for a building which uses a badgir is 296.0450 K° (or 73.4 °F or 23 C°).

As we have mentioned before, the simulation assumes that the air has already passed through an ab-anbar that acts like a heat sink to the ground with an almost constant temperature and the air temperature has already reached to dew point temperature. Experimentally this condition can be achieved by wetting walls of the badgir as has been mentioned in literature review.

If we want to compare two buildings with and without a badgir, the average temperature in the building seems to be the best criteria. Even though humidity comparison is also important, the effect of the temperature on human comfort is not as important as humidity.

**Results of Building without Badgir**

In order to model the building without the badgir, the same geometry and boundary conditions have been considered and the only difference is that the intake of the badgir is replaced with a wall. Since the wall (no slip boundary condition) does not let air flow penetrate into the building, there would be no external flow for air circulation. In another words, the only driving force in the building without badgir is the buoyancy force of the air. This means that, for example, the density of air in the vicinity of the hot walls is decreasing and this fact produces a buoyancy force that moves this part of the air upward.

Figure 4-13(a, b) depicts the contours of the pressure and one slice of the temperature in the building without badgir. This figure (4-13.a) shows that the contours of the pressure are uniformly lies on each other. In fluid mechanics this type of flow configuration is called stratified flow. Since there is no external wind, flow velocities are small compared to the flow inside of the building with the badgir. Since the buoyancy force of the hot air is upward, it can be seen that the maximum pressure is at the highest part of the building in the badgir column and roof. Figure 4-13.b shows that the air in vicinity of the roof is hotter than other parts mainly due to the heat transfer from the hot roof into the building.

Figure 4-14 (a, b) shows the contours of the temperature and the flow streamlines and the x-velocity counters on a slice of the building without a badgir. Figure 4-14.b shows a complicated pattern of flow of air. However, this configuration of flow field is the result of buoyancy force. In Fig. 4-14.b it can be seen that roof temperature is high mainly due to the sun. The roof temperature is uniform in this figure since the flow movement is slow in this building while with the badgir (Fig. 4-12) showed a large variation in roof temperature.

By integrating the temperature over the volume and dividing it into the volume of the building the average temperature of air inside of the building without a badgir has been found. The average temperature for a building without a badgir is 307.7 K° (94.46 °F or 34.7 C°).

Table 4-1. Requirements for typical badgirs in different climate regions

| Weather Conditions | Hot and Dry Climate | Hot and Humid Climate |
|---|---|---|
| **Cross section of badgir** | Square<br>Rectangular<br>Hexagon<br>Octagon | Square |
| **Size of the roof** | 1.64 ft x 2.62 ft<br>2.30 ft x 3.60 ft<br>1.64 ft x 0.50 ft<br>3.94 ft x 1.97 ft | 3.28 ft x 3.28 ft |
| **Height of badgir** | 5.91 ft-16.4 ft | 9.84 ft-16.4 ft<br>More than 16.4 ft |
| **Roof shape of badgir** | Flat | Flat<br>Shed |
| **Size of each Opening of badgir(Minimum)** | 7.9 Inches | 7.9 Inches |
| **Wall divider between each opening of badgir** | 3.1 Inches -3.9 Inches | 3.1 Inches -3.9 Inches |
| **Wooden cradling** | Every 6.56 ft | Every 6.56 ft |
| **Orientation of badgir** | Direction of wind | Direction of wind |
| **Material of badgir** | Mud-brick<br>Brick with Plaster of cob(clay and straw) | Plaster/<br>Lime Plaster |

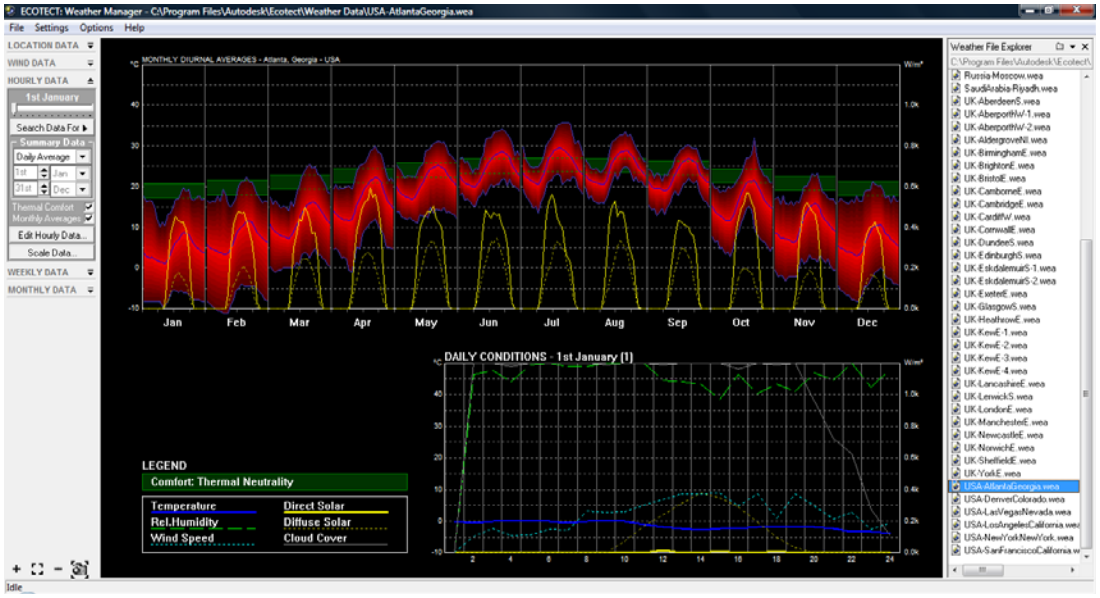


Figure 4-1.  Monthly diurnal averages (Source: Romina Mozaffarian).

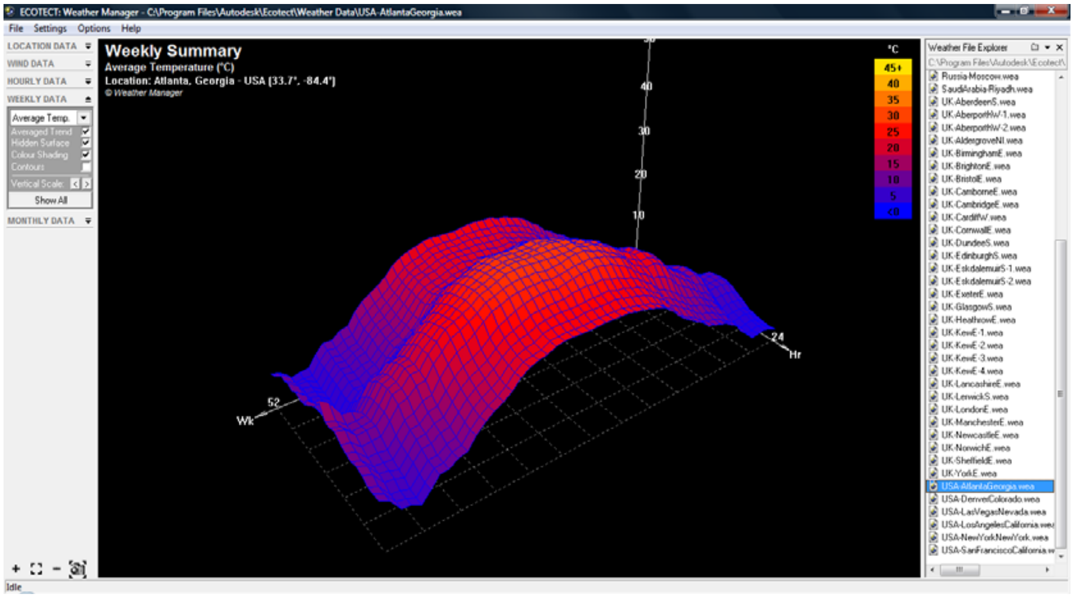


Figure 4-2.  Weekly summary (Source: Romina Mozaffarian).

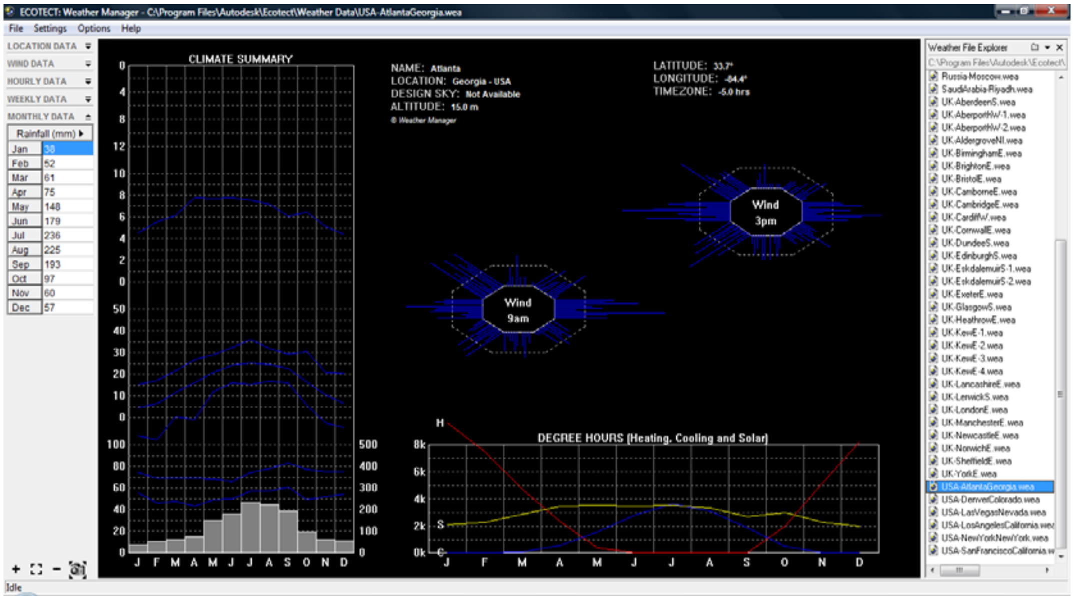



Figure 4-3. Monthly rainfalls (Source: Romina Mozaffarian).

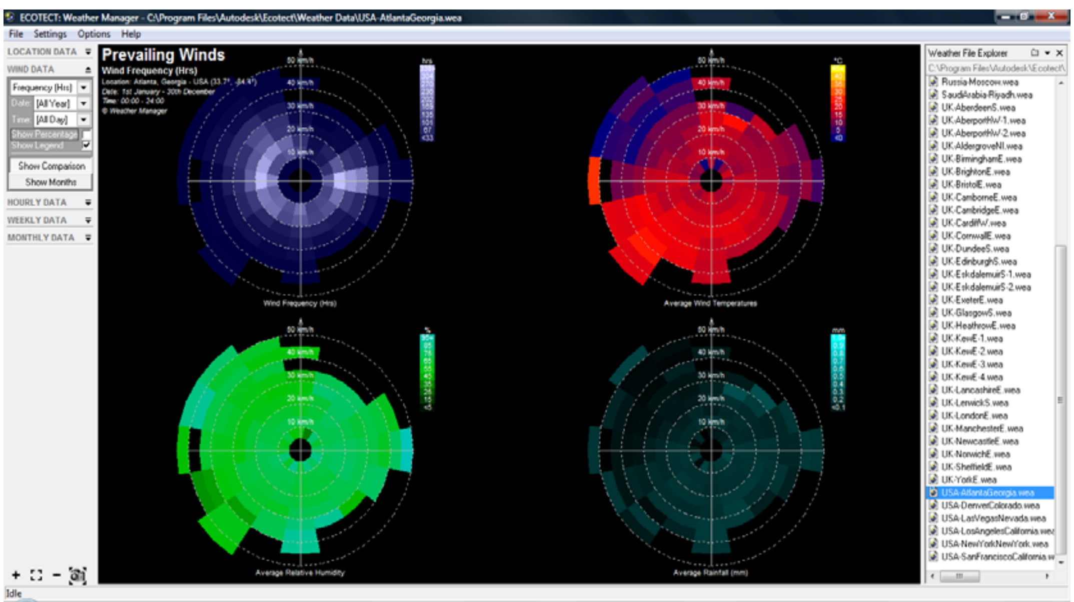



Figure 4-4. Prevailing winds (Source: Romina Mozaffarian).

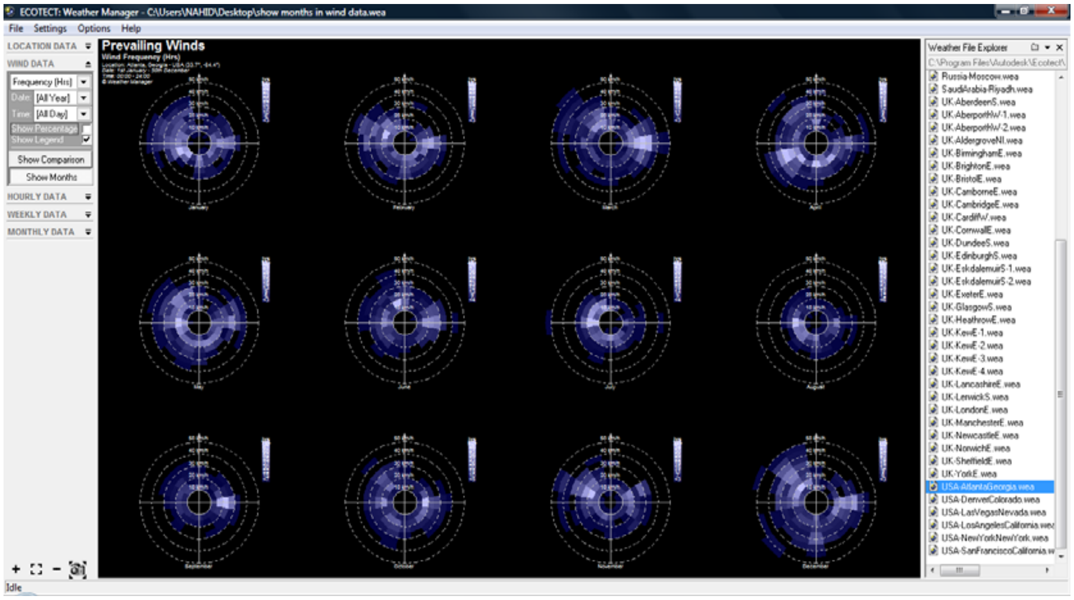



Figure 4-5.  Prevailing winds (Source: Romina Mozaffarian).

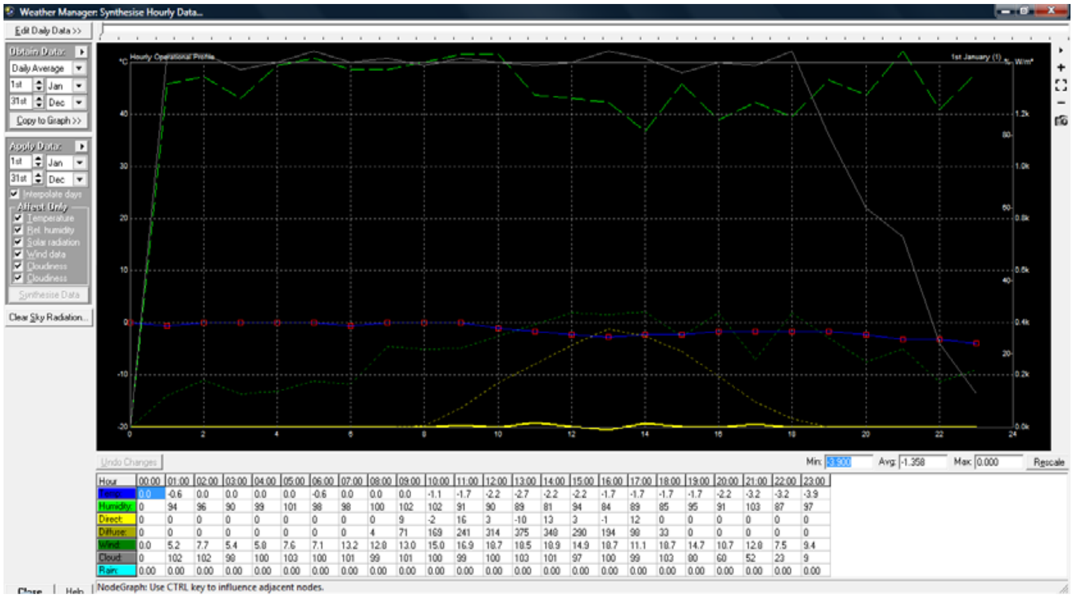



Figure 4-6.  Hourly operational profile (Source: Romina Mozaffarian).

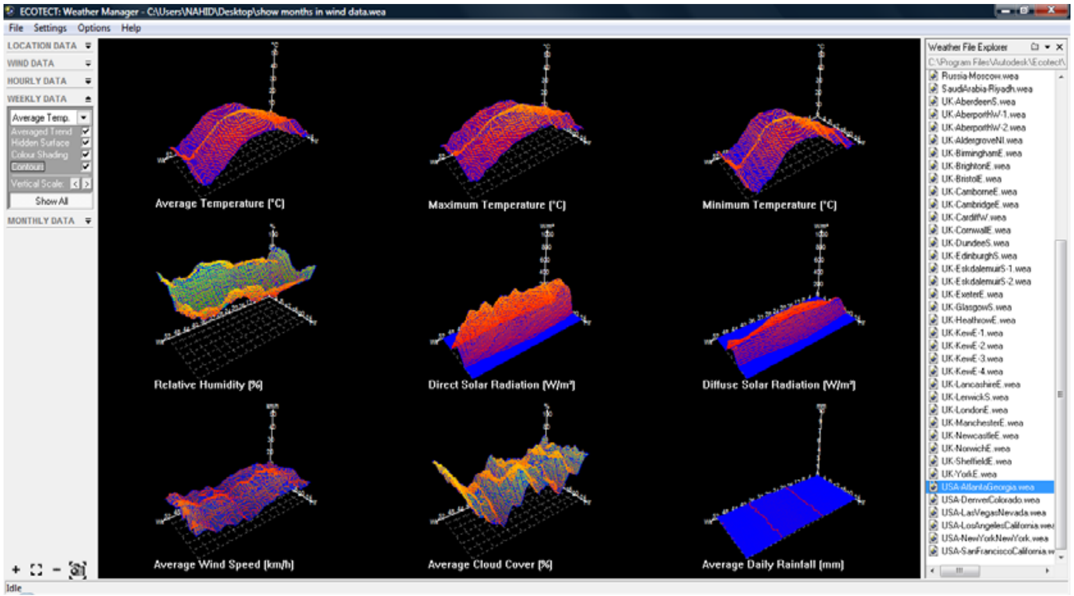



Figure 4-7. Weekly data (Source: Romina Mozaffarian).

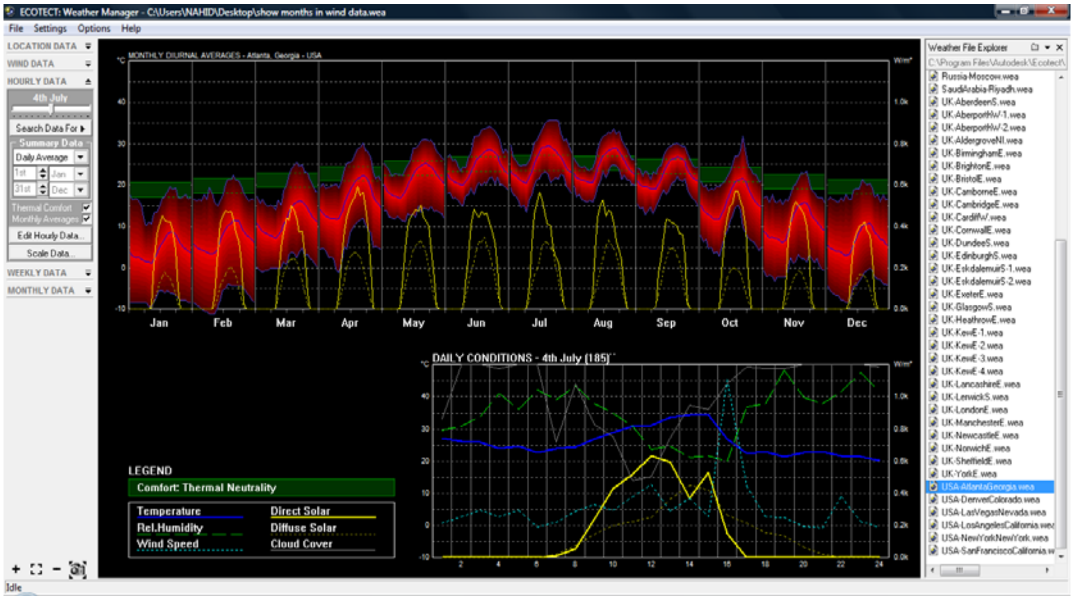



Figure 4-8. Monthly diurnal averages (Source: Romina Mozaffarian).

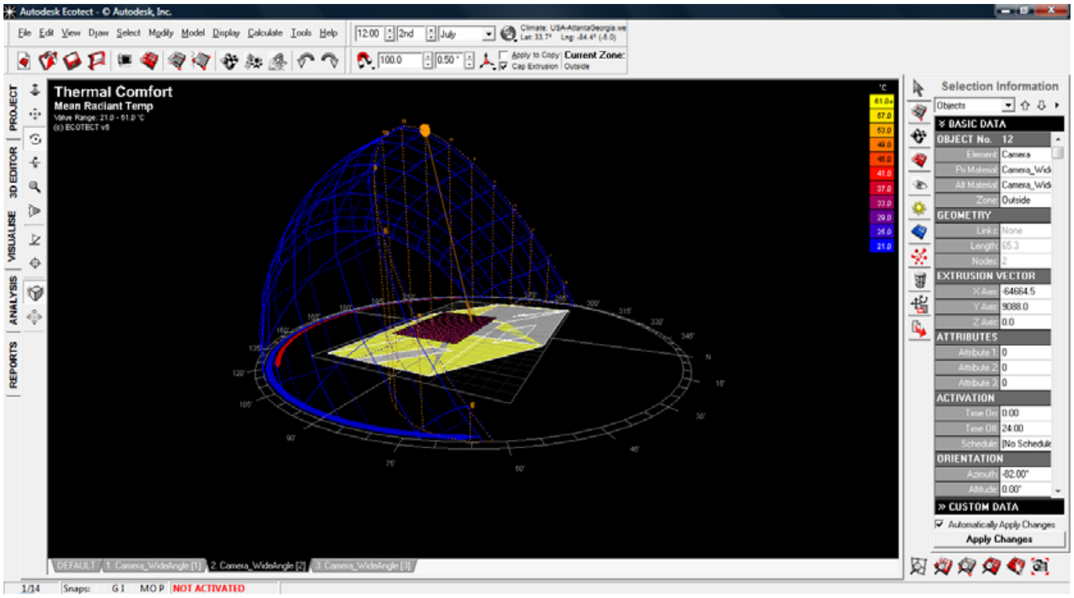



Figure 4-9. Thermal comfort (Source: Romina Mozaffarian).

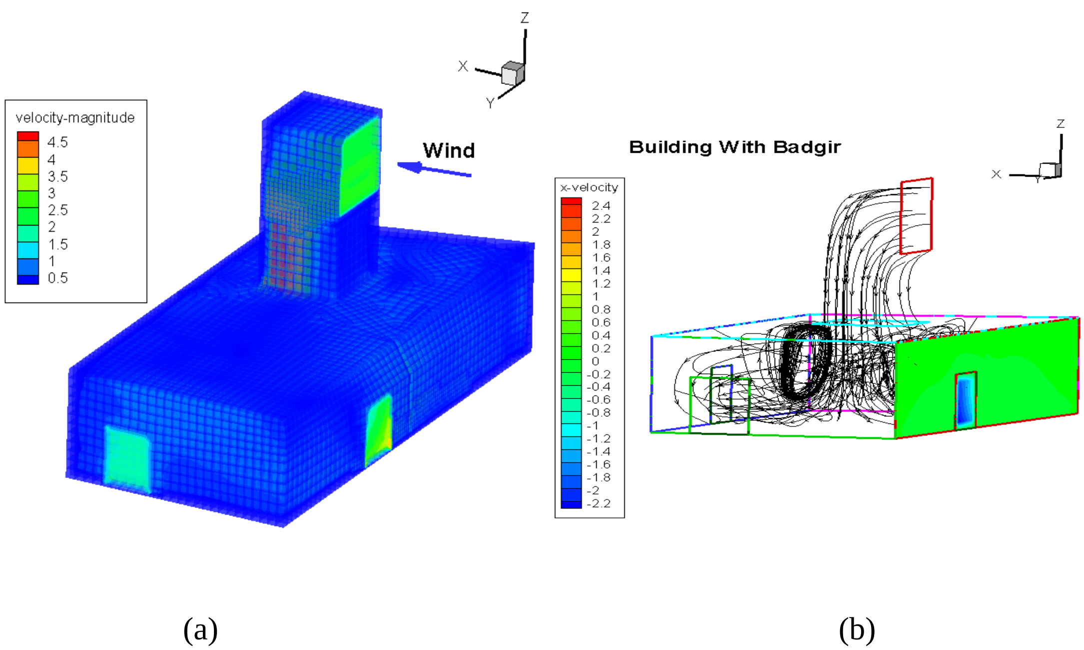
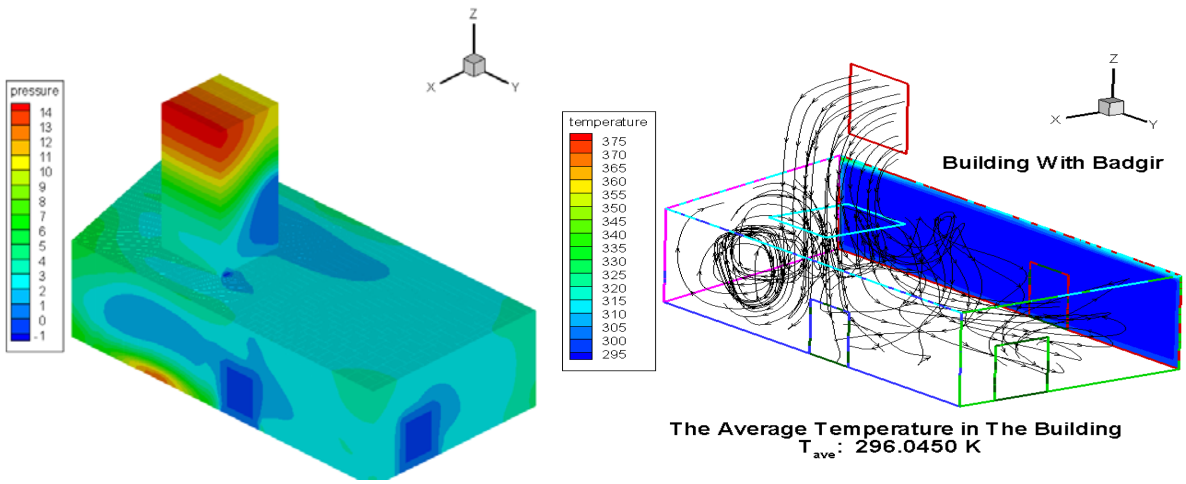



Figure 4-10. Velocity contours of the building with Badgir (a). Streamlines of the air flow (b) (Source: Romina Mozaffarian).




(a) (b)

Figure 4-11. Static Pressure contours of the building with badgir (a). Streamlines of the flow (b) (Source: Romina Mozaffarian).

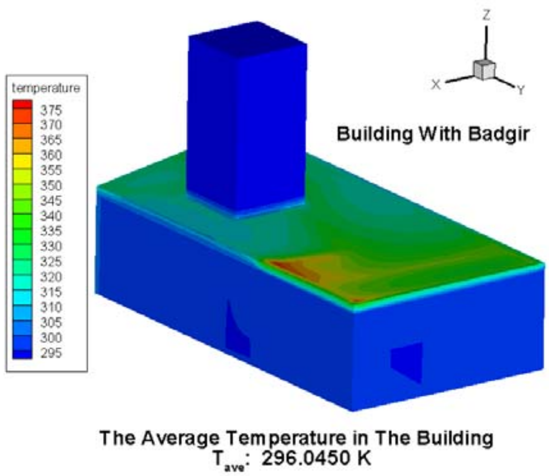
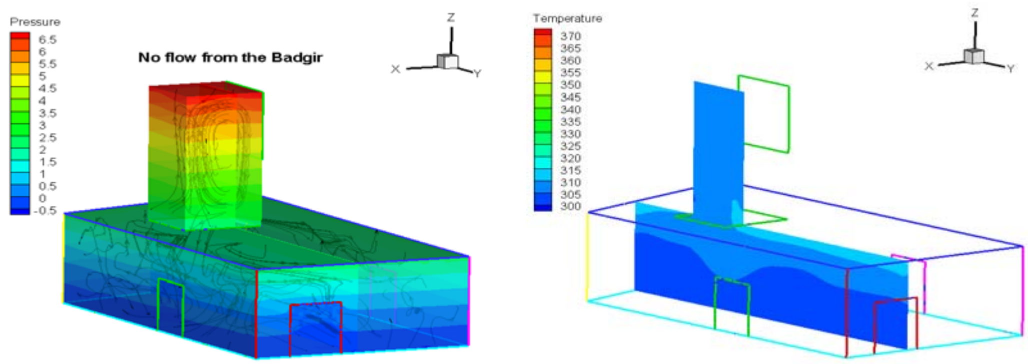
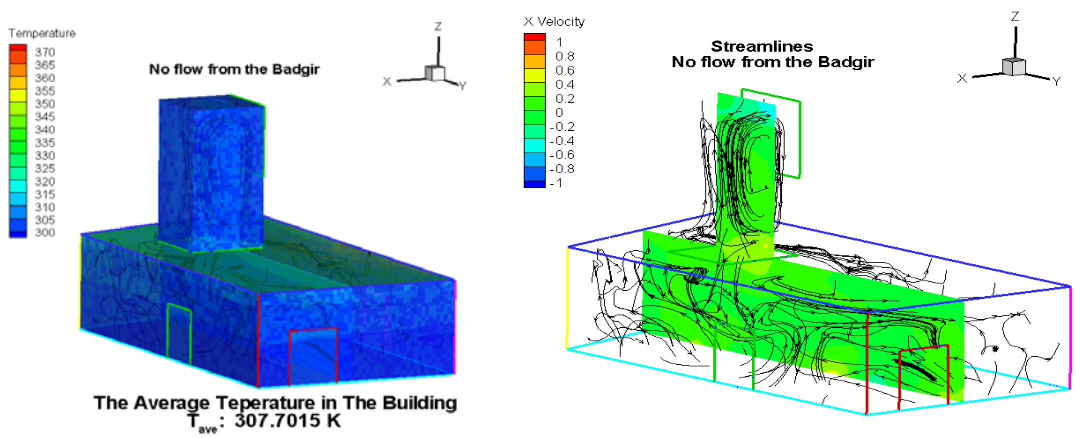



Figure 4-12. The temperature contours in the building and the volume average of the temperature in the building with badgir (Source: Romina Mozaffarian).




(a) (b)

Figure 4-13. The pressure contours in the building (a) and the temperature counters in one slice of the building without badgir (b) (Source: Romina Mozaffarian).




(a) (b)

Figure 4-14. The temperature contours in the building (a). Streamlines and x-velocity counters in one slice of the building without badgir (b) (Source: Romina Mozaffarian).

# CHAPTER 5
# CONCLUSIONS

When the kinetic energy or the buoyancy driven force of the air is used for ventilation purposes, the type of ventilation is typically called natural ventilation. There are many different configurations which exist in order to create effective natural ventilation. This study focuses on natural ventilation caused by outdoor winds. In other words, the kinetic energy of wind is used to circulate air inside of the building. There are specific design requirements requiring consideration in the design of a badgir in any building. Badgirs are made up of three parts, the roof, the body, including openings, and the columns of the badgir. Table 4-1 is the result of information for designing a badgir in hot and dry climate and hot and humid climates. This information is based on researches of typical badgirs in Iran. The dimensions of opening in badgirs need to be calculated based on square feet of a building. Based on the literature review, the following are recommendations for designing and constructing badgirs in United States.

The components of badgirs are the roof, the opening of badgir and column of badgir.

Based on literature, in hot and dry climates in United States, interior wall dividers are square (4 interior walls), rectangular (4 interior walls), hexagon (6 interior walls) and octagon (8 interior walls). Figure 2-14 shows the badgir with six and eight interior wall dividers. Figure 2-15 shows four interior wall dividers. Based on literature, in hot and humid climates, commonly four interior wall dividers are suggested in United States. Height of badgirs can change based on different climates. Height of badgirs in hot and dry climates is 9.84 ft to 16.4 ft, 5.91 ft to 6.89 ft. Height of badgirs in hot and humid climates are usually 9.84 ft to 16.4 ft or even taller than 16.4 ft. The taller the badgir is, the ability to direct the wind increases. Adobe/cob/mud brick was one of the main materials in badgirs structure which was available locally in ancient countries like Iran. Adobe is a natural building material made from sand, clay, and water, with some kind of fibrous or organic material (sticks, straw, dung), which is shaped into brick using frames and dried in the sun. Using natural materials that are available locally is one of the concepts of sustainable building or green building. Natural materials such as brick and adobe brick that have high heat storage capacities are being suggested to be used to construct buildings with badgir in hot and dry climate regions. These materials have high heat absorption capacity (Biket 2001). The opening of badgirs between each wall divider which had been shown in Figure 2-5 is 7.9 inches which can be applied for badgirs in United States. 3.1inches to 3.9 inches are the dimension of wall divider between each opening of badgir. These are approximate dimensions which can be changed based on the dimensions of badgirs. Directions of badgirs depend on direction of winds. Direction of winds in each region is different which has to be considered before designing a badgir in a building in United States. Badgirs in hot and humid climates like Florida can use the natural water underground as a water reservoir to cool the building. In hot and dry climates like Nevada, a small pool can be designed underground to pass the air over and reduce the temperature of outside air.

Three tools, Autodesk Ecotect, simplified calculations based on the psychrometric chart, and a FLUENT package, are used to find the best tool which can give a best result for natural ventilation of a building with badgir. The FLUENT package is the most detailed and precise tool.

The result of Ecotect did not have the capability to provide comparative temperature data. The simplified air change model shows that the average indoor temperature of a building with a badgir is about 10.35° F (-12.03 °C) cooler than a building without a badgir. Results of the FLUENT package shows that the average indoor temprature of a building with a badgir in Gainesville is almost 11.7 °C (53.06°F) (according to Fig. 4-12 and Fig.4-14), lower temperature than a building without badgir. The reported results are rough estimates which include the main features of the flow field and temperature. Even though the results are hopeful, it must be considered that there were many simplified assumptions applied in these simulations. In order to have a more realistic comparison, future studies must be conducted in further detail.

Recommendations for future studies are:

1. The ab-anbar can be included in the simulation. In this study, the effect of the ab-anbar is explicitly extracted from the psychrometric chart and the obtained air condition is used for the badgir intake.
2. The effect of the interior walls can be included into the simulation. In this study, interior walls were neglected.
3. Transient simulation can be performed by imposing variable wind speed and sun heat flux in 24 hrs. In this study the maximum sun heat flux and wind speed were used in the simulation.
4. Performance of the badgir can be compared to many other configurations that can be employed for natural ventilation. For example, the coupling of solar chimney in order to drive air and underground water for cooling proposes can be used.
5. Badgir can be compared with other type of green technologies. For example, the performance of the badgir can be compared to the commercial solar chiller performance for cooling proposes.
6. In the most advanced study, the series of the badgir as the flow driver, desiccant for dehumidification, and the ab-anbar for cooling with the coupling of solar panels in order to dry wet desiccants can be studied and the implementation cost can be compared to the commercial HVAC systems or solar chillers.

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## BIOGRAPHICAL SKETCH

Romina Mozaffarian was born in Tehran, Iran. She enjoyed at a young age and continues to enjoy artwork, oil-painting, and pencil drawings. She studied computer engineering at the University of Tehran (Azad University), and she maintained an intense interest in mathematics. After moving to the United States in 1999, she chose to combine her interest in art and math by studying architecture. She received her Associate in Arts degree from Miami Dade Community College in 2003. She continued her major at Florida Atlantic University and received her professional bachelor's degree in architecture degree in 2006. During the three years spent studying at Florida Atlantic University, she also worked at architectural firms to gain experience. Her interests and experience led her to pursue study in building construction. She then began graduate school in building construction at the University of Florida, continuing to work for architectural firms in Gainesville, Florida. Later, she began teaching as a teaching assistant for a graphic communications in construction course at the University of Florida. Romina Mozaffarian received her master of science in building construction in the summer of 2009. Then, she plans to begin working for a construction company to apply her knowledge of both construction and architecture.