WIND-CHIMNEY

Integrating the Principles of a Wind-Catcher and a Solar-Chimney to Provide Natural Ventilation

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by
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TITLE: **WIND-CHIMNEY**

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Ventilation

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Abstract

This paper suggests using a wind-catcher integrated with a solar-chimney in a single story building so that the resident might benefit from natural ventilation, a passive cooling system, and heating strategies; it would also help to decrease energy use, CO₂ emissions, and pollution. This system is able to remove undesirable interior heat pollution from a building and provide thermal comfort for the occupant.

The present study introduces the use of a solar-chimney with an underground air channel combined with a wind-catcher, all as part of one device. Both the wind-catcher and solar chimney concepts used for improving a room's natural ventilation are individually and analytically studied.

This paper shows that the solar-chimney can be completely used to control and improve the underground cooling system during the day without any electricity. With a proper design, the solar-chimney can provide a thermally comfortable indoor environment for many hours during hot summers. The end product of this thesis research is a natural ventilation system and techniques that improve air quality and thermal comfort levels in a single story building. The proposed wind-chimney could eventually be designed for use in commercial, retail, and multi-story buildings.

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Chapter 1

Introduction

This thesis proposes using the principles of a basic wind-catcher integrated with a solar chimney to provide natural ventilation and generate cooling air by using underground pipes in one-story spaces in the Los Angeles area. By proposing this system, the author's goal is to help reduce the use of energy and to benefit from a healthier, natural cooling system that has been offered to us for free.

There have been many experimental studies completed worldwide recently featuring natural ventilation and heating systems. Historically, many cases have been cited wherein application of a natural ventilation system should be a requirement and not a choice, given the cost of operating such mechanical systems, the pollution and fumes produced, and the development of arising health issues.

Wind-catchers have been used over centuries in many regions around the world, especially in hot and dry climates, as a means to provide passive cooling and natural ventilation. These old wind-catchers are usually tall structures, in different shapes and styles, which are attached to the roof of a building. People in regions where wind-catchers are popular have been generating necessary ventilation in this manner for centuries. Figure 1.1

By integrating wind-catchers into underground water canals or reservoirs, in some cases they were even able to cool the air to freezing temperature; by doing so, they could keep their food and provisions preserved for months. These wind-catchers in

particular were used in an environment with existing prevailing wind. But in a windless climate where no significant wind exists, the use of a solar chimney became a good configuration to implement natural ventilation in buildings. A solar chimney is basically a vertical shaft that heats up by solar power and enhances the natural stack ventilation throughout a building.

FIGURE 1.1: AN IMAGE OF WIND-CATCHERS (Yazd, Iran)

Source: Wikipedia 2011

In this paper, the author gives a basic history of wind-catchers, along with descriptions of how each system has been working for many years. This paper specifically studies the solar chimney, with the support of scientific experiments by others.¹ A literature search was conducted to find fundamental supporting information on wind-catchers, solar chimneys and their structures. Through analysis and experimental studies, the possibilities of designing a wind-catcher in a one-story space were evaluated.

Several interviews with mechanical, structural engineers were conducted to familiarize the author with the structure and mechanical criteria of a wind-catcher. The

¹ M. Maerefat, A.P. Haghighi, Passive cooling of buildings by using integrated earth to air heat exchanger and solar chimney (Tehran: Tarbiat Modares University, Tehran, 2008)

author identified, as well, how wind-catcher and solar-chimney technology could be applied to create the desired air quality environment. A framework was developed for evaluating the extent to which the proposed wind-chimney can satisfy the range of developmental experiences that a well-ventilated system should provide. The author also proposed design solutions applicable to wind-chimney components.

A combination of both systems—a wind-catcher integrated with a solar chimney that works with an underground cooling system—is proposed in this paper as a concept for a ventilation system in a one-story residential building. The first chapter serves as an introduction to the objectives and rationale of wind-catchers and solar chimney research. In chapter two, the principles of air movement by pressure differential and convection are explained; chapter three covers the physical and characteristics of the wind-catcher and the history behind it. Chapter four covers and describes several case studies of integrated Solar Chimney (SC) and the earth to air heat exchanger (EAHE). In Chapter five, a study model is represented to validate the results of the previous chapters and to determine the feasibility of a solar chimney system with the aid of a wind-catcher.

Chapter 2

Principles of Air movement

In this chapter, the principles of air movement are discussed. Environmental temperature is one of the most critical factors governing human comfort and survival; air movement plays a big role in cooling down the body temperature in hot or humid conditions.

The human body undergoes a physiological reaction when exposed to uncomfortable thermal conditions. The Vaso-Motor control center,² which is located in the medulla oblongata in the brain, regulates the vascular shunt mechanism. This basically redistributes blood during exercise and while at rest, accordingly. Regulated by the Vaso-Motor control center, the blood flow increases and the body loses excess heat in a warm environment. Furthermore, immediately outside the range of Vaso-Motor control when the temperature rises above 75°F, perspiration increases heat loss through the latent heat of evaporation.³ However, the air in contact with the skin soon becomes saturated, and evaporation stops. In order for evaporation process to continue and the human body avoid sweating due to comfort level requirement, this air must be removed mechanically using fans or an Air Conditioning (AC) system, or naturally by air movement. Natural air movement can be applied through two principles: Pressure Differential or Convection.

² "What is the Vaso-Motor Control ", Wiki Answers, accessed December 2011, <http://wikianswers.com>

³ Jens Pohl, Building science: concepts and application (Chichester, England: Wiley-Blackwell, 2011), 22.

2.1 Air movement by Pressure Differential

When wind velocity varies it produces a pressure differential, which causes air movement from a higher air pressure zone to a lower pressure zone. This is based on the Bernoulli theory and it's called "Venturi action," which explains that when the velocity of a moving fluid increases the pressure decreases.

When air is directed into the larger end of the funnel-shaped tube, which opens to a side tube in figure 2.1.1, it accelerates as it passes through, owing to the reduced open area through which the same volume of air must pass in the same period. This increased airspeed lowers the pressure in the airstream at A, with respect to the atmospheric pressure at B in the lower part of the side tube. Thus air is drawn up the side tube by the pressure difference, which is proportional to the square of the velocity. This concept can be used in a variety of ways to provide steady streams of air through buildings.⁴

FIGURE 2.1.1: FUNNEL-SHAPED TUBE DIAGRAM

Source: Fathy 1986

⁴ Hassan Fathy, *Natural Energy and vernacular Architecture: Principles and examples with reference to hot-arid climates* (Chicago: University of Chicago press. 1986)

Based on the same principle, when the air flows over a building it produces a zone of low pressure on the leeward side and a higher pressure zone on the windward side.

This produces a steady airflow due to the suction through the leeward side opening.

Figure 2.1.2

FIGURE 2.1.2: A SECTION SHOWING AIR MOVEMENT IN THE BUILDING CAUSED BY PRESSURE DIFFERENTIAL

The good example of a system that runs with pressure differential is a wind-catcher. A wind-catcher is a duct mounting above the building and has an aperture toward the prevailing wind. Figure 2.1.3; this device catches the cooler air above the building and brings it inside. Therefore, a window or a door that acts as a wind-escape is needed to ensure that ventilation occurs.

FIGURE 2.1.3: AN IMAGE OF A WIND-CATCHER

Source: Kavandi 2007

The basic wind-catchers design follows the same principle of using air that is drawn in by the pressure differential, which can create a constant flow. Figure 2.1.4

FIGURE 2.1.4: A CROSS SECTION OF A SPACE SHOWING THE PERFORMANCE OF A BASIC WIND-CATCHER

Figure 2.1.4 shows that when the air flows over a building it creates a higher air pressure on the windward side of the wind-catcher. Due to the lower air pressure on the

other side, air moves from the higher pressure to the lower pressure region and generates an air movement.

2.2 Air movement by Convection:

The tendency of a liquid or gas to cause less dense object to float or rise to the surface is called buoyancy.⁵ Because of the difference in density between cool air and warmer air, warm air tends to move upward and escape due to its lower density. This air movement, called convection, can lead to a stack effect driven by buoyancy.

As long as there is a continuous source of heat and a considerable amount of cool air available, a constant stream of air is produced. The higher the temperature difference and the height of the building, the greater the buoyancy force and stack effect will be. This leads to greater air movement. The constant natural cooling system used in the courtyard homes in hot-arid regions in Middle-East is a good example of producing air movement by convection.

In these hot and dry areas, most residential homes have a courtyard that is located in the center of the house and is usually surrounded by several rooms. Inhabitants of these regions have learned to close their doors to the outside and open them toward their courtyards. In the evening, since the air temperature drops due to re-radiation of heat to the sky, warm air in the courtyard rises and is replaced by cooled night air from above, which starts cooling the courtyard and surrounding rooms. Figure 2.2.1; This cool air gathers in the courtyard in layers and eventually moves into the surrounding rooms.

⁵ "Buoyancy," Encarta Encyclopedia, accessed October 2011, [www. Encarta Encyclopedia.com](http://www.Encarta.com)

FIGURE 2.2.1: A SCHEMATIC GRAPH SECTION OF AIR CHANGE BY CONVECTION IN HOMES WITH CENTRAL COURTYARD

Another example of this natural cooling system, which works by convection, is the combination of courtyard and garden area together. The courtyard stays cool until later afternoon because it's shaded by surrounding walls. In the same time, the garden area that is more exposed to the sun warms up. This warmed air moves upward and will be replaced by the cool air coming from the courtyard. In the past, residents used to place a seating area between the courtyard and the garden called a Mashrabia. People in these regions used this Mashrabia room in summer season. Due to the air movement from the courtyard side to the garden area, the Mashrabia usually stays cool for several hours.

Figure 2.2.2 shows a cross section of this courtyard and garden area.

FIGURE 2.2.2: A CROSS SECTION OF HOMES WITH COURTYARD AND GARDEN, SHOWING THE AIR MOVEMENT BY CONVECTION

Another example of air movement by convection is shown in figure 2.2.3

This cross section of a house in Zavareh (located at the northeast of Isfahan Province, next to the central desert area in Iran) shows how the summer living area in this house could stay cool by convection.

FIGURE 2.2.3: A CROSS SECTION OF A HOUSE IN ZAVAREH, IRAN

Source: Tavassoli, 1973

Chapter 3

Wind-catcher

3.1 History of the Wind-Catcher

FIGURE 3.1.1: AN IMAGE OF A WIND-CATCHER

Source: JimSim, Travepod.com 2009

The wind-catcher has been used for centuries to provide natural ventilation in buildings. It's not quite clear who invented the very first wind-catcher, but different types of wind-catchers have been seen in many different places in the world, from ancient Egypt in the houses of Tal Al-Amarna and in the pharaonic house of Neb-amun (which dates from the nineteenth dynasty in 1300 B.C.), to the Middle East and Europe.

Wind-catchers were originally built in hot-arid areas, where prevailing winds exist and the air is free from moisture. In these regions, a mounted wind-catcher above

the building is usually facing prevailing wind in order to catch and induce the cool air inside the building.

In hot-dry regions, it is not possible to use an ordinary window for the dual purposes of light and ventilation. If using windows to provide air movement or natural ventilation, windows need to be smaller in size to create enough air velocity, which, in turn, reduces the natural daylighting. Therefore, a separate ventilation system, like the wind-catcher, was designed to provide air movement while windows were designed to serve just the purpose of natural daylighting. Based on the geographic location, wind-catchers come with different designs and styles. They are designed in different heights and numbers of opening, from one-sided to eight-sided in some cases.

3.2 Designs and Types of the wind-catcher

3.2.1 One-sided wind-catcher

One-sided wind-catchers are usually used in the regions where air blows in one specific direction. It only has one duct or passage facing prevailing winds to induce air directly inside. It is usually designed with a higher tower to catch the air from above, since the air in higher elevation is free from dust and it is cooler. As this air needs to leave the room, exhausted segments, like windows and doors, are required. Figure 3.2.1.1

FIGURE 3.2.1.1: A CROSS SECTION GRAPH OF A ONE-SIDED WIND-CATCHER SHOWING AIR MOVEMENT BY PRESSURE DIFFERENTIAL

3.2.2 Two-sided wind-catcher

A two-sided wind-catcher has a shaft with the top openings on two opposite sides and a dividing panel that goes along the length of the shaft to direct the cool air down to the seating area. In this type of wind-catcher air enters from one side, ventilates the room, and escape from the other side. If the air incident angle is more than 0° in the forward side of wind-catcher, short-circuiting occurs (Chapter 4, page 35). Short-circuiting causes the air to enter from the windward side opening and leave through the leeward side without a chance to circulate the building. Figure 3.2.2.1

FIGURE 3.2.2.1: A CROSS SECTION OF A TWO-SIDED WIND-CATCHER

3.2.3 Three-sided wind-catcher

In this type of wind-catcher, the windward side is usually larger than the other sides to catch the most of the prevailing wind. Figure 3.2.3.1 shows a three-sided wind-catcher, located in the town of Tabas, Iran.⁶ In this wind-catcher, the windward side is wider than the other sides, with more outlets (or apertures) to capture as much prevailing air as possible. The wind speed increases as it enters through the curved shape of the inside outlets.

⁶ Mahmood Tavassoli, Architecture in the hot arid zone. (Tehran, 1973)

FIGURE 3.2.3.1: A CROSS SECTION AND PERSPECTIVE OF A THREE-SIDED WIND-CATCHER

Source: Tavassoli 1973

3.2.4 Four-sided wind-catcher

This type of wind-catcher can be seen in the regions where wind does not have a specific direction. This type is designed to capture the air from all directions. Figure 3.2.4.1 shows a floor plan and section of a water reservoir in the town of Naeen, Iran. In this building there are two, four-sided wind-catchers designed to catch the prevailing air from all four directions. An eight-sided wind-catcher has been placed above the water reservoir to act as an exhaust segment and release the warmed air into eight different directions outside of the building.

FIGURE 3.2.4.1: AN IMAGE OF A WATRE RESERVOIR

Source: Tavassoli 1973

FIGURE 3.2.4.2: A FLOOR PLAN OF WATRE RESERVOIR

Source: Tavassoli 1973

FIGURE 3.2.4.3: A CROSS SECTION OF A WATER RESERVOIR
Tavassoli 1973

3.3 Functions of the wind-catcher

A wind-catcher operates based on three methods:

The first method is used in the basic wind-catcher, as it is explained in chapter 2, and works based on pressure differential. This method is used in combination with courtyards in several cases and brings the air directly into buildings, but it does not cool the air. Instead, it depends on the air speed to provide a ventilation effect.

In the second method, the opening face of a wind-catcher is away from prevailing wind. When wind blows over this wind-catcher, it creates lower air pressure on the windward side. Since the air pressure inside the building is higher than the outside, the tendency of higher pressure air traveling to the lower pressure region causes the air to be

drawn upwards. The wind-catchers using this method are usually combined with an underground water canal. In figure 3.3.1, the hot air is drawn down into the canal and is cooled by coming into contact with the cold earth. The cold water in the water canal helps the air become even cooler. This cool air is then drawn upward through the wind-catcher and ventilates the entire building.

FIGURE 3.3.1: A CROSS SECTION OF WIND-CATCHER INTEGRATED WITH AN UNDERGROUND CANAL

Source: (Wikipedia) Bailey 2009

This method of wind-catcher integration with underground canal has been used by Persians since 400 BC to store ice in the summer time. They called this ice storage Yakhchal. A Yakhchal⁷ is a large underground space, made of very thick walls and a special mortar that is heat and water resistant. Figure 3.3.2 As a Yakhchal is usually connected to wind-catchers and has access to an underground water canal, it can become very cold, down to the freezing temperature.

⁷ "Yakhchal," Wikipedia the Free Encyclopedia, accessed March 2011, <http://en.wikipedia.org>

FIGURE 3.3.2: AN IMAGE OF A YAKHCHAL

Source: Wikipedia 2011

3.3.1 Solar Chimney:

The third method is when a wind-catcher functions as a solar chimney in an environment with no significant wind or available water. A solar chimney, which creates a pressure gradient, is a vertical duct or passage employing solar energy to heat up the air. Figure 3.3.1.1. Thus, the air rises through the passage as a result of convection. This convection of heated air is able to improve the natural ventilation of buildings and create passive cooling and natural ventilation.

FIGURE E 3.3.1.1: A CROSS SECTION OF A BASIC SOLAR CHIMNEY

FIGURE 3.3.1.2: A CROSS SECTION OF A BASIC SOLAR CHIMNEY INTEGRATED WITH AN UNDERGROUND PIPE

The solar-chimney component can be integrated with an underground pipe(s). If the incoming air goes through an underground pipe, the cooling effects can be significantly increased. Figure 3.3.1.2 shows that when the solar chimney warms up by solar radiation, while the warmed air is trying to escape through the solar-chimney duct, it will be replaced by cooled air coming from the underground channel.

Chapter 4

A Case Study

In this chapter, the author is using an experimental study that has been performed by a group of mechanical engineers in Tarbiat Modares University in Tehran, (M. Maerefat, A.P. Haghighi, Passive cooling of buildings by using integrated earth to air heat exchanger and solar chimney, 2008, Renewable energy 35 (2010) 2316-2324)⁸ to understand and evaluate the performance of a solar- chimney using an underground air channel application.

4.1 Experimental study of integrated Solar-Chimney (SC) and earth to air heat exchanger (EAHE). Figure 4.1.1

In order for this system to function and provide the desired indoor natural ventilation, it depends on outdoor temperature, solar radiation, solar chimney and underground pipe dimensions, and cooling demand.

⁸ Maerefat, Passive cooling of buildings by using integrated earth to air heat exchanger and solar chimney.

FIGURE 4.1.1: A SCHEMATIC DIAGRAM OF AN INTEGRATED EARTH TO EARTH TO AIR HEAT EXCHANGER AND SOLAR CHIMNEY

Source: Marefat and Haghighi 2008, Renewable energy 2011

A Parametric study is performed to find the effects of the geometrical dimensions of the solar chimney and EAHE and outdoor environmental conditions. Figure 4.1.1 shows the schematic diagram of this model.

The following dimensions and specifications are used in this schematic model: The size of the room is 13'W x 13'L x 10'H and has a minimum cooling demand of $Q = 116$ W. The size of solar chimney is 3'W x 1'L x 13'L and the solar chimney inlet size is 15"W x 15"L. The underground pipe is made of PVC measuring 82' in length, 0.4" thick and a diameter of 1'-7" in diameter; the pipe is placed 1' below the soil surface. These dimensions have a significant effect on the cooling load, which is evaluated here. In this study, the EAHE outlet and the solar chimney inlet are placed in the opposite wall from each other. The outdoor air temperature is 93°F.

4.1.1 Performance of the system at various cooling demands and solar radiation.

Table 4.1 shows how this system performs under various amounts of solar radiation and cooling demands. The results show that few solar chimneys integrated with couple of EAHE pipes can generate an acceptable range of indoor comfortable temperature. According to table 4.1, in order to provide cooler indoor temperatures, longer and more numerous cooling pipes are recommended. For example, in the cooling demand of 116 W and solar radiation of 600 W/m^2 , if the length of the underground pipe is 82 feet, with one solar chimney and one underground pipe, this system is able to provide an indoor comfort temperature of 83°F while the outside temperature is about 93°F .

Cooling demand (W)	Solar Radiation W/m ²	Length of each EAHE m (f)	ACH ---	Room Air Temp °C (°F)	Number of SC	Number of EAHE
116	400	25 (82f)	6.34	28.53 (83.3)	2	1
	600		4.03	28.14 (82.6)	1	
	800		5.06	28.31 (82.9)	1	
	1000		5.84	28.44 (83.1)	1	
200	400	25 (82f)	6.30	29.35 (84.4)	2	1
	600		3.56	28.73 (84.4)	1	
	800		4.81	29.35 (84.8)	1	
	1000		5.65	29.33 (84.7)	1	
400	400	30 (98f)	5.69	29.92 (85.8)	2	1
	600		7.90	30.15 (86.2)	2	
	800		3.88	29.51 (85.1)	1	
	1000		4.87	30.62 (87.1)	1	
600	400	40 (131f)	4.67	28.27 (82.6)	2	1
	600		7.21	30.42 (86.7)	2	
	800		3.09	27.77 (81.9)	1	
	1000		4.00	29.02 (84.02)	1	
800	400	40 (131f)	5.20	28.13 (82.6)	3	2
	600		4.21	27.64 (81.7)	2	
	800		5.33	29.03 (84.2)	2	
	1000		6.27	30.14 (86.2)	2	

(The outdoor temperature is 93°F)

TABLE 4.1: THE EFFECTS OF LENGTH OF EAHE ON THE SYSTEM PERFORMANCE

Source: Source: Marefat and Haghighi 2008, Renewable energy 2011

4.1.2 Performance of the system at various solar absorber lengths.

The dimensions of the solar chimney's inlet and the area of the solar chimney affect the velocity of the flow to some extent but, 1) the surface area of the solar chimney, which absorbs solar power to provide a stack effect and 2) the cooling surface area of the underground pipes, which helps to remove heat from the air flow to the soil, have major performance effects on the system. To increase the cooling effect of surface area of EAHE pipes, the diameter and length of the pipe should be increased.

Table 4.2 shows that by increasing the length of the solar chimney, the area of absorber increases and higher ventilation flow will be generated. But a higher ventilation rate generates higher indoor temperatures; therefore, more of the underground pipes will be required.

Cooling demand (W)	Absorber length m (f)	ACH ---	Room Air Temp °C (°F)	Number of SC	Number of EAHE
116	3.0 (9.8f)	4.40	28.53 (83.3)	1	1
	4.0 (13f)	5.83	28.14 (82.6)	1	1
	5.0 (16f)	7.06	28.31 (82.9)	1	1
	6.0 (19f)	8.18	28.44 (83.1)	1	1
800	3.0 (9.8f)	2.36	29.35 (84.4)	2	3
	4.0 (13f)	5.10	28.73 (84.4)	2	3
	5.0 (16f)	6.62	29.35 (84.8)	2	3
	6.0 (19f)	8.29	29.33 (84.7)	2	3
800	3.0 (9.8f)	3.12	29.92 (85.8)	3	5
	4.0 (13f)	3.05	30.15 (86.2)	2	4
	5.0 (16f)	3.51	29.51 (85.1)	2	5
	6.0 (19f)	3.84	30.62 (87.1)	2	6

(Outdoor temperature is 93°F and solar radiation is 1000 W/m²)

TABLE 4.2: THE EFFECTS OF THE SOLAR ABSORBER LENGTH ON THE SYSTEM PERFORMANCE

Source: Marefat and Haghighi 2008, Renewable energy 2011

4.1.3 The effects of EAHE length on system performance

Table 4.3 shows, in the outdoor temperature of 104°F and cooling demand of 800 W, with the absorbed solar radiation of 400 W/m² and the EAHE length of 49 Feet, the acceptable cooling temperature cannot be provided. But in the same condition, if the EAHE length increases from 49 feet to 82 feet and with a set of two solar chimneys and six underground pipes (which is a total of 82 x 6= 492 feet of pipes), the system is able to provide a temperature of 84°F, which is 20°F lower than the outside temperature.

Cooling demand (W)	Outdoor air temp °C (°F)	Solar Radiation W/m ²	Length of each EAHE m (f)	ACH ---	Room Air Temp °C (°F)	Number of SC	Number of EAHE
116	40 (104)	400	15 (49)	3.47	29.68 (85.30)	4	10
			25 (82)	6.02	29.72 (85.40)	3	2
			35 (115)	5.17	27.00 (80.60)	3	2
			45 (148)	5.79	28.61 (83.40)	3	1
116	40°C=104°F	1000	15 (49)	3.47	29.87 (85.70)	2	9
			25 (82)	6.49	28.72 (83.60)	1	3
			35 (115)	4.65	28.77 (83.70)	1	1
			45 (148)	3.56	29.33 (79.30)	1	1
800	40°C=104°F	400	15 (49)	Thermal	comfort can not	be	provided
			25 (82)	3.14	29.00 (84.20)	3	5
			35 (115)	4.54	29.50 (85.00)	3	2
			45 (148)	4.27	27.00 (80.60)	3	2
800	40°C=104°F	1000	15 (49)	Thermal	Comfort can not	be	provided
			25 (82)	3.35	29.38 (84.40)	2	6
			35 (115)	7.42	29.52 (85.10)	2	3
			45 (148)	5.59	29.26 (84.60)	2	2

(The outdoor temperature is 93°F)

TABLE 4.3: THE EFFECTS OF THE EAHE LENGTH ON THE SYSTEM PERFORMANCE

Source: Marefat and Haghighi 2008, Renewable energy 2011

4.1.4 The effects of EAHE diameter on the system performance.

Table 4.4 shows, in the optimal diameter of 19 inches, minimum numbers of pipes and solar chimneys are required.

Cooling demand (W)	Outdoor air temp °C (F°)	Solar Radiation W/m ²	Diameter of EAHE (m),(f)	ACH ---	Room Air Temp °C (°F)	Number of SC	Number of EAHE
116	40 (104)	400	0.3 (1)	4.30	29.9 (85.90)	4	10
			0.5 (1.6)	6.02	29.72 (85.40)	3	2
			0.7 (2.3)	3.01	29.89 (85.80)	3	2
			0.9 (2.9)	4.76	29.98 (85.90)	3	1
116	40 (104)	1000	0.3 (1)	5.07	27.70 (82.00)	2	9
			0.5 (1.6)	6.49	28.72 (84.00)	1	3
			0.7 (2.3)	8.67	29.96 (85.90)	1	1
			0.9 (2.9)	7.85	29.80 (85.60)	1	1
800	40 (104)	400	0.3 (1)	Thermal	comfort can not	be	provided
			0.5 (1.6)	3.14	29.00 (84.20)	3	5
			0.7 (2.3)	4.43	29.86 (85.70)	3	2
			0.9 (2.9)	Thermal	comfort can not	be	provided
800	40 (104)	1000	0.3 (1)	Thermal	Comfort can not	be	provided
			0.5 (1.6)	3.35	29.38 (84.40)	2	6
			0.7 (2.3)	3.21	29.31 (84.70)	2	3
			0.9 (2.9)	3.71	29.94 (85.80)	2	2

(The outdoor temperature is 104°F)

TABLE 4.4: THE EFFECTS OF THE EAHE DIAMETER ON SYSTEM PERFORMANCE

Source: Marefat and Haghighi 2008, Renewable energy 2011

4.1.5 The effects of environmental conditions, including solar energy and outdoor temperature, on the system performance. Table 4.5

Cooling demand (W)	Outdoor air temp °C(°F)	Solar radiation (W/m ²)	ACH ---	Room Air Temp °C (°F)	Number of SC	Number of EAHE
500	40 (104)	100	3.28	29.61 (85.30)	5	3
		500	5.16	31.13 (88.00)	3	3
		900	4.83	31.40 (88.50)	2	3
500	45 (113)	100	3.01	30.92 (87.60)	6	4
		500	4.30	31.12 (88.00)	3	4
		900	4.02	31.27 (88.20)	2	4
500	50 (122)	100	3.05	31.02 (87.80)	6	6
		500	3.45	31.62 (88.90)	3	5
		900	3.06	31.52 (88.70)	2	5
1000	40 (104)	100	4.98	30.51 (86.90)	8	6
		500	4.10	31.95(89.50)	2	2
		900	3.63	30.69 (87.20)	2	4
1000	45 (113)	100	4.15	30.00 (86.00)	8	6
		500	3.27	31.15 (88.00)	3	5
		900	3.00	30.90 (89.40)	2	5
1000	50 (122)	100	4.18	31.95 (89.50)	8	7
		500	3.05	31.98 (89.60)	3	6
		900	3.15	31.53 (88.70)	3	12
1500	40 (104)	100	5.20	31.36 (88.40)	8	4
		500	3.29	30.61 (87.00)	3	5
		900	3.00	30.35 (86.60)	2	5
1500	45 (113)	100	3.95	31.00 (86.00)	9	9
		500	3.62	31.70 (89.00)	4	9
		900	3.17	31.60(88.60)	3	12
1500	50 (122)	100 500 900	Thermal comfort		Can not be	provided

TABLE 4.5: THE SYSTEM PERFORMANCE AT DIFFERENT INDOOR AND OUTDOOR TEMPERATURES

Source: Marefat and Haghighi 2008, Renewable energy 2011

Increased solar intensity causes stronger stack effect and higher ACH. As a result, fewer solar chimney ducts are needed to direct the cool air through the air pipes and balance the pressure decline. Due to the higher ACH caused by solar intensity, indoor air temperature increases as well, and, in order to create a thermal comfort condition, more air pipes or EAHEs are required. Conversely, when the outdoor temperature increases, the stack effect decreases and more solar chimney ducts are required for air movement and ventilation.

These results show that even with a warmer outdoor temperature of 113°F and lower solar radiation of 100 W/m², this system can provide an almost comfortable indoor condition of 86°F and 4 ACH with the aim of 8 solar chimneys and 6 EAHE pipes. If the outdoor temperature rises to over 122°F and cooling demand increases to 1500 W, the thermal comfort can not be provided and the solar chimney cannot generate a stack effect.

4.1.6 Conclusions

This study shows that the proposed passive solar ventilation system, which is connected to underground air pipes, can create a natural air movement to provide comfortable thermal conditions. The amount of solar radiation, the outdoor temperature, and the arrangement and dimensions of the solar chimney ducts and air pipes are crucial to the performance of this system.

As the results show, using taller solar chimneys to absorb more solar radiation means that fewer solar chimneys will be required. However, because taller solar chimneys create thermal discomfort, more underground pipes will be needed to cool the airflow and provide a comfort level. Based on the study of pipe's diameter, an optimum

diameter of 19 inches will give the minimum required number of solar chimneys and EAHEs.

Also, this study found that a length of more than 65 feet should be used to provide the ideal thermal comfort conditions. The study shows that when the outdoor temperature is higher than 113°F, creating passive thermal comfort conditions becomes difficult, but, with proper configuration, even in temperatures as high as 122°F and a poor solar intensity of 100 W/m², the system can still provide desirable conditions.

4.2 Two-sided wind-catcher performance evaluation

Another experimental study was done to investigate the performance of a two-sided wind-catcher. This experimental study was performed by a group of mechanical engineer students in Yazd University in Yazd, Iran, (H. Montazeri, F. Montazeri, R. Azizian and S. Mostafavi, 2008, Renewable energy 35 (2010) 1424-1435).⁹

This type of wind-catcher is divided internally into two ducts as explained in chapter 2, page 13. In this experimental study, two one-sided wind-catchers were attached back-to-back to create a two-sided model. An open-circuit wind tunnel was used to generate airflow into the building and create pressure coefficients around all surfaces of the wind-catcher. The amount of airflow was then measured in various wind angles. In addition, the CFD (computational fluid dynamics) stimulation was used to not only evaluate the pressure coefficient distribution and airflow around and inside the wind-catcher, but also to assess the accuracy of the measurement results.

⁹ H. Montazeri, F. Montazeri, R. Azizian, S. Mostafavi Two sided wind-catcher performance evaluation using experimental, numerical and analytical modeling, (Yazd: University of Yazd press. 2008)

FIGURE 4.2.1: ISOMETRIC VIEW OF THE TWO-SIDED WIND-CATCHER MODEL

Source: Montazeri, Azizian and Mostafavi 2008, Renewable energy 2010

The most important factor that affects the internal ventilation and airflow is the external air pressure produced by wind. The wind pressure coefficient C_p is calculated based on this formula: $C_p = \frac{P - P_s}{\frac{1}{2}\rho V^2_{ref}}$, where p is the surface pressure that was measured with the use of several pressure taps. These pressure taps were neatly placed at apertures and underneath channels of the model. In this equation, p_s is the upstream static pressure and $\frac{1}{2}\rho V^2_{ref}$ is the dynamic pressure of the uniform wind. Upstream static and total pressures were measured using a pitot-static tube that was placed 16.5 cm upstream of the test model and 12 cm above the wind tunnel floor.¹⁰ Figure 4.2.2

¹⁰ Montazeri, Two sided wind-catcher performance evaluation using experimental, numerical and analytical modeling.

FIGURE 4.2.2: TWO-SIDED WIND-CATCHER MODEL WITH PRESSURE TABS, PITOT AND STATIC TUBES

Source: Montazeri, Azizian and Mostafavi 2008, Renewable energy 2010

The results showed that the two-sided wind-catcher's performance depends on the pressure coefficients and that these coefficients change with the wind direction angle. When the wind angle increases, the pressure coefficient drops; its minimum amount is at a 90° angle. The pressure coefficients, however, remain uniform on the leeward side of the wind-catcher. Another problem with increasing the wind angle is the possibility of short-circuiting, Short-circuiting causes the air to enter from windward side opening and leave through the leeward side without entering the building. Increasing the air incident angle causes short-circuiting in the wind-catcher system and, if the angle continues up to 60° , no airflow will circulate inside the building and almost all the air from the windward side will escape through the leeward side. Figure 4.2.3

FIGURE 4.2.3: TOP VIEW OF THE PASSING FLOW AROUND THE WIND-CATCHER FOR DIFFERENT WIND ANGLES

Source: Montazeri, Azizian and Mostafavi 2008, Renewable energy 2010

Chapter 5

The proposed Wind-Chimney and its goal

The data and results from the experimental studies in the previous chapters show that both the solar chimney and the wind-catcher individually are able to provide enough natural ventilation in the summer to provide indoor thermal comfort, if properly applied and designed. Thermal comfort is not just dependent on air temperature alone, but is also affected by heat conduction, convection, radiation, and evaporative heat loss. The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) has listings for suggested comfortable temperatures and airflow rates in different types of buildings and different environmental circumstances. For example, the suggested comfortable temperature in summer in a single office with occupancy rate of 0.1 per square meter and an air velocity of 0.18 m/s is between 74° and 77.9°F.

As explained in chapter 2, page 4, when the temperature rises above 75°F, perspiration increases heat loss through the latent heat of evaporation. The air in contact with the skin becomes saturated, and evaporation stops. In order for the evaporation process to continue and for the resident to avoid sweating, this air should be removed and ventilated by mechanical systems or natural air movements.

The goal in this chapter is to provide an acceptable indoor thermal comfort by integrating the solar chimney and wind-catcher systems together; as calculated in page

36, a minimum amount of 2-3 ACH and a temperature between 75° and 80°F meets the thermal comfort requirements for the building space proposed here.

The proposed wind-chimney will be placed in a one-story building space in the Los Angeles area. In Los Angeles, the average highest temperature throughout the year is 85° F in the month of August¹¹ (Table 5.1); the highest recorded temperature was 112°F in 1990, but in this proposed wind-chimney, the system performance is evaluated under the annual highest temperatures at 85° F condition.

TABLE 5.1: THE AVERAGE TEMPERATURE RANGE IN LOS ANGELES

Source: <http://rssweather.com> 2011

The Los Angeles building is considered to be a 500-square-foot residential space with the dimensions of 25'W x 20'L x 10' H and a window of 5'W x 5'L. This proposed

¹¹ Climate in Los Angeles County, " Average Temperature Range, accessed December 2011, <http://rssweather.com>

system has three main components: 1) a wind-catcher component 2) a solar chimney component and 3) an underground pipe component. The underground pipe is 65' long with a diameter of 18". These dimensions were chosen based on the previous studies in order to help the system perform most efficiently. Figure 5.1

FIGURE 5.1: A SCHEMATIC PLAN OF PROPOSED WIND-CHIMNEY

FIGURE 5.2: A SCHEMATIC SECTION OF PROPOSED WIND-CHIMNEY

The solar chimney panel is facing south at a 59° angle to get the most of solar energy radiation (details in page 40) and the wind-catcher opening is facing toward the

direction of prevailing wind in Los Angeles, which is from WSW in summer months according to national weather service forecast.¹² Table 5.2

CALIFORNIA PREVAILING WIND DIRECTION													
STATION	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	ANN
LOS ANGELES	E	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	WSW	E	WSW

TABLE 5.2: DIRECTION OF PREVAILING WIND IN LOS ANGELES
Source: WESTERN REGIONAL CLIMATE CENTER DATA 2011

5.1 Option 1: Wind-Catcher Component.

FIGURE 5.1.1: A CROSS SECTION OF THE PROPOSED WIND-CHIMNEY USING THE WIND-CATCHER COMPONENT

Figure 5.1.1 shows that the system works similar to one-sided wind-catcher as it explained in Chapter 3, page 12. The incident angle of the wind, outdoor temperature and the wind speed play important roles in this component; in this option the amount of

¹² " Wind Direction," Western Regional Climate Center, accessed December 2011, <http://www.wrcc.dri.edu/htmlfiles/westwinddir.html>

cooling load and the minimum required ACH for the proposed space and the provided amount of ACH by the wind-catcher component is calculated.

5.1.1 The total amount of cooling load and the minimum ACH requirement for the proposed space. To measure the cooling load (disregarding solar radiation) of the space in Btu/hr, given the following condition:

The space volume: $25'W \times 20'L \times 10'H = 5000$ cubic feet (cu.f)

The space area: $25'W \times 20'L = 500$ square feet (s.f)

The windows area: $5'W \times 5'W = 25$ s.f

The wall area: $2 \times (25' \times 10') + 2 \times (20' \times 10') = 900$ s.f

The total net wall area: Wall area – Window area = $900 \text{ s.f} - 25 \text{ s.f} = 875 \text{ s.f}$

The recommended U-value (heat transmission) of the wall is $0.085 \text{ Btu/hr} \times \text{s.f} \times ^\circ\text{F}$

The recommended U-value of the window is $0.45 \text{ Btu/hr} \times \text{s.f} \times ^\circ\text{F}$

The recommended U-value of the roof is $0.065 \text{ Btu/hr} \times \text{s.f} \times ^\circ\text{F}$

(There is no heat gain through the floor)

The outdoor temperature is 85°F and indoor temperature is 75°F

The heat gain through the walls, the floor and the roof is based on following formula:

$$Q = \text{Heat Gain} = U \times A \times \Delta T^{13}$$

U = (coefficient of heat transmission)

A = (area)

ΔT = (outdoor and indoor temperature difference)

$$Q_{\text{wall}} = 0.085 (U_{\text{wall}}) \times 875 (\text{wall area}) \times 10 (\text{temperature difference}) = 744$$

$$Q_{\text{window}} = 0.45 (U_{\text{window}}) \times 25 (\text{window area}) \times 10 (\text{temperature difference}) = 112$$

¹³Pohl, Building science: concepts and application.

$$Q_{\text{roof}} = 0.065 (U_{\text{roof}}) \times 500 (\text{roof area}) \times 10 (\text{temperature difference}) = 325$$

$$Q_{\text{wall}} + Q_{\text{window}} + Q_{\text{roof}} = 744 + 112 + 325 = 1181 \text{ Btu/hr}$$

$$Q_{\text{total}} = 1181 \text{ Btu/hr} = \text{Total heat gain}$$

To calculate the amount of air change per hour based on thermal loads, the following Formula,¹⁴ (this formula was suggested by Alper Erten, a mechanical engineer from Buro Happold Consulting Engineers group in Culver city, ca in July 2011) is used:

$$\text{Required air exchange rate, CFM (cu.f/m)} = \text{Total load (Btu/h)} / (1.08 \times \Delta T)$$

$$\text{CFM (cu.f/min)} = \text{Btu/h} / 1.08 \times (\Delta T)$$

$$\text{CFM} = 1181 \text{ Btu/hr} / 1.08 \times (10^\circ\text{F}) = 109$$

The required air change per hour (ACH) is:

$$109 (\text{cu.f/min}) \times 60 (\text{min/hr}) = 6540 (\text{cu.f/hr}) / 5000 (\text{CF}) \text{ room volume} = \mathbf{1.3 \text{ ACH}}$$

Therefore, an ACH of at least 2 is required for this space to keep the average indoor air temperature at 75°F while the outdoor temperature is at 85°F.

5.1.2 The provided amount of ACH by the wind-catcher component.

The amount of air change per hour is calculated to make sure the system is able to provide enough air movement to occupants. To determine the number of ACH occurring in the proposed building, using only the wind-catcher component with the vent area of 1' x 1' and prevailing wind speed of 7mph = 616 ft/min in Los Angeles area¹⁵ (Table 5.2), the amount of air volume that goes through the vent area per minute is:

$$\text{Air velocity (ft/min)} \times \text{vent area (s.f)} = \text{cu.f/min}$$

$$616 (\text{ft/min}) \times 1 (\text{s.f}) = 616 \text{ cu.f/min} \text{ and the number of air changes per hour is:}$$

¹⁴ Alper Erten, (Buro Happold Consulting Engineers 2011)

¹⁵ "Wind Speed," National Climate Data Center, accessed December 2011, <http://lwf.ncdc.noaa.gov/oa/climate.html>

616 cu.f/min x 60 min/hr = 36,961 cu.f/ hr

36,961 cu.f/ hr / 5000 cu.f (room volume) = **7 ACH.**

DATA THROUGH 2002	YRS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
LOS ANGELES AP, CA	54	6.7	7.4	8.1	8.5	8.4	8.0	7.9	7.7	7.3	6.9	6.7	6.6

TABLE 5.3: AVERAGE WIND SPEED IN LOS ANGELES

Source: National Climate Data Center 2011

As the above results show, in this proposed system when the air velocity is 7 mph, and the vent area is one square feet in a 500 square feet residential space, about 7 air change per hour occurs, which is more than what is needed in this proposed building space based on the required amount of at least 2 ACH.

5.2 Option 2: In this option, using two components—a wind-catcher and a solar-chimney without an underground pipe—is analyzed. In Figure 5.2.1, air enters the building due to the pressure differential and escapes through the solar chimney component. In this case, the entire system works like a two-sided wind-catcher, as explained in chapter 3, page 12. Similar to option 1, the system is able to provide 7 ACH, which is more than is required.

FIGURE 5.2.1: A CROSS SECTION OF THE PROPOSED WIND-CHIMNEY USING THE WIND-CATCHER AND SOLAR- CHIMNEY COMPONENTS

5.3 Option 3: In this option, using two components—a solar-chimney and an underground pipe—is analyzed. It is important to note that a wind-catcher alone does not cool the air; it only ventilates it. Therefore, when the outdoor temperature is very warm, the wind-catcher component is not able to bring the temperature down. In warmer conditions, the solar chimney component can work as an outlet to remove the warm air from inside and replace it with the cooler air coming from underground pipes. When only the solar chimney and underground pipe components are used, the wind-catcher component can be closed up by an operable cap, as shown in Figure 5.3.1

**FIGURE 5.3.1: A CROSS SECTION OF THE PROPOSED WIND-CHIMNEY
USING THE SOLAR CHIMNEY AND UNDERGROUND CHANNEL
COMPONENETS**

This solar chimney consists of a black-painted chimney or a solar panel on top to absorb the maximum amount of solar radiation. If using a solar panel system to absorb solar radiation, it should always face southerly in the northern hemisphere and northerly in the southern hemisphere in order to get the most of solar radiation. The solar panel should be tilted horizontally at a degree equal to the latitude, plus 15 degrees in winter or minus 15 degrees in summer, according to The United States Department of Energy. The following formula can be used to gain an additional 3-5% of more solar energy efficiency:¹⁶

¹⁶ U.S. Department of Energy, A Consumer's Guide to the California Solar Initiative Statewide Intensives for Solar Energy Systems, Accessed August, 2011, <http://www.energy.ca.gov>

Solar panel tilted angle = Latitude $\times$ 0.9 + 29° in winter

Solar panel tilted angle = winter angle - 52° in summer

The Latitude in Los Angeles is 34°, therefore the best tilted angle for the solar panel is $34 \times 0.9 + 29^\circ = 59^\circ$.

The amount of cooling loads in the proposed space is **Q = 1181 Btu/hr = 346 W**

According to Table 4.1 (chapter 4, page 24), if the cooling load is about 400W and the solar panel produces a solar radiation of 800 w/m³, in order to bring the temperature from 93°F down to 85°F and provide the ACH of 3.88 with one solar chimney and one EAHE, the system needs an EAHE of at least 98 feet.

In this proposed solar chimney component, in order to provide the required amount of 2 ACH for the proposed space under the cooling load of 346 W, the length of underground pipe needs to be at least 98 feet. And in some cases, for example, Table 4.3 In chapter 4-page 26, if the cooling demand increases to 800W and the outdoor temperature rises to 104°F with a length of 49 foot for the underground pipe, thermal comfort cannot be provided unless the underground pipe length increases to 82 feet and three solar chimneys and five underground pipes be installed, to provide an ACH of 3.

The proposed solar chimney with the optimal tilted angle of 59° for the solar panel (to absorb adequate amount of solar energy) and a pipe length of 98 feet in an 85°F temperature condition in Los Angeles is able to provide 4 ACH in the space, bringing the indoor temperature down to 77°F. This system performance is dependant on solar radiation of at least 800 w/m³. If the same system is absorbing less solar radiation, for example about 400 w/m³, with the same pipe length of 98 foot, in order for the system to

provide 4 ACH, two solar chimneys will be needed instead of one to bring the inside temperature down to 75°F. Table 4.1, page 24.

According to the Table 4.1 in chapter 4, page 26, when the cooling demand is 116 W and solar radiation is 600 W/m², using 82 feet underground pipe, one solar chimney and one underground pipe, the system provides 4 ACH and brings the indoor temperature to about 11°F lower than outside temperature. For instance, if the outdoor temperature is 93°F, the solar chimney can bring it down to 81°F, which is a relatively comfortable temperature. But if the outdoor temperature is about 104°F, according to chapter 4, Table 4-3, not only will the solar panel need to absorb more solar energy (about 1000 W/m²), but also a longer underground pipe (about 115 feet) will be needed to gain the required ACH of 4 and to bring the temperature down to 83° F. In order for solar panel to absorb more solar energy, the surface of solar panel should be increased.

In chapter 4, Table 4-4 shows that when the outdoor temperature is 104°F and the solar radiation is 1000 W/m², one solar chimney and nine underground pipes are needed in order to provide 6.45 ACH and bring the room temperature down to 84°F. Under these circumstances, if the cooling demand is 800 W, under a solar radiation of 1000 W/m², thermal comfort cannot be provided unless the diameter and number of pipes increases significantly.

Finally, in the severe cases of hot temperature (122°F) described in chapter 4, Table 4.5 and under a cooling demand of 1500 W, even if solar radiation varies from 100 to 900 W/m², thermal comfort cannot be provided; a back up cooling system, perhaps, will be needed.

5.4 Option 4: In this option all three components of wind-catcher, solar-chimney and underground pipe is applied. If all three components of the system become active and operable, the system is still able to work and provide ventilation. As a matter of fact, it would probably work more efficiently than just using the solar chimney and underground pipe components in option 3. As mentioned in option 3, if the cooling demand increases, the system needs longer pipes or more solar chimney towers and underground air pipes to provide cooling effects; therefore, by activating the wind-catcher component, the required amount of ACH can be met and longer and more pipes and SCs' are not necessary. Although, when the outdoor temperature is higher than 104°F, activating the wind-catcher component does not help to cool the air down and the system needs to be configured with a longer pipe or/and more solar chimneys. Other limitations of applying all three components at the same time is the possibility of short-circuiting between the air coming from the wind-catcher and solar chimney components and the air escaping from these two components. Figure 5.4.1

FIGURE 5.4.1: A CROSS SECTION OF THE PROPOSED WIND-CHIMNEY USING THE SOLAR CHIMNEY AND UNDERGROUND CHANNEL COMPONENT

Conclusions:

The studies on this proposed wind-chimney show that this system can operate well and provide an adequate natural ventilation and thermal comfort based on the climate condition in the Los Angeles area. This system can be a viable alternative to expensive and inefficient air conditioning systems; it could also reduce energy use, noise levels in urban areas, and pollution and it can be successfully applied and retrofitted into existing and new structures.

The performance efficiency of this proposed system depends on:

1) The amount of solar radiation, outdoor temperature, arrangement, dimension of the solar-chimney and the wind-catcher components and positioning of the air pipes.

The Tables (1-4 through 5-4) in Chapter 5 showed how these elements play a crucial role in the system performance.

Although the system can provide thermal comfort as long as the temperature does not exceed 120°F, acceptable conditions were also noted even though the ideal temperature configuration was exceeded by 2 °F

2) The pressure coefficient that changes when a wind incident presents itself at an angle to the open side of the wind-catcher component. This angle should be at 0° to 30° toward the prevailing wind (chapter 4, page 32). With more than a 0° Angle, the system still performs, but not as efficiently. If this angle increases to a 60° angle, then a severe short-circuiting would happen in the system.

Further Study:

This thesis is assumed to be positioned in the Los Angeles area at highest temperature of 85°F. Further study can analyze the reaction of the system in more severe climates, where there is not enough sunlight to generate solar radiation nor is there significant wind to operate the wind-catcher.

The use of solar radiation as a heating alternative has NOT been discussed in this thesis. Further study can determine that the heat generated from a solar panel can be used for heating purposes of a given space.

It is assumed that the structure is a one story single residential building and that adjacent buildings are the same height. This assumption might affect results. Subsequent study can evaluate the effect of other adjacent, taller buildings or commercial towers and their affect on prevailing winds and the wind-catcher system. System performance should be further gauged when there are multiple rooms or floors needing to be simultaneously ventilated.

The study model in this thesis was created to evaluate a wind-chimney and its operational performance characteristics. However, it was not used to evaluate or optimize toward a design solution. Further study may be focused on design aspects of this system.

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