NATIONAL TECHNICAL UNIVERSITY OF ATHENS
SCHOOL OF ARCHITECTURE

Augmenting traditional wind catcher with combined evaporative cooling system and solar chimney

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AZAM NOROOZI

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SUPERVISOR: PROFESSOR YANNIS S. VENERIS

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AZAM NOROOZI

Augmenting traditional wind catcher with combined evaporative cooling system and solar chimney

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Thesis Committee: Yannis S. Veneris

Georgios Kallos

Elias Zacharopoulos

The Ph.D. Proposal has been examined and approved on …2012……

Yannis Veneris (Professor)

Georgios Kallos (Professor, National & Kapodistrian University of Athens)

Elias Zacharopoulos (Professor)

Kostas Moraitis (Professor)

Anastasios Stamou (Professor)

Flora-Maria Bougiatioti (Assistant Professor)

Mathaios Santamouris (Professor, University of South Wales)

……………………………

Azam Noroozi

School of Architecture

National Technical University of Athens

Abstract

Wind catchers are one of the oldest cooling systems in Hot-Dry regions that are employed to provide sufficient natural ventilation in buildings. The optimal adequacy of the wind catchers has been constrained in the suitable wind speed, which causes them to be inefficient at times and in areas with low wind speed. A four-directional wind catcher equipped with two evaporative cooling parts (wetted blades and adjustable opening pads) and a solar chimney was proposed in this study. A prototype of the proposed wind catcher has developed to analyze the performance of the system. Theoretical analysis of the wind catcher was carried out and a set of experiments were organized to validate the results of the obtained models. Moreover, a numerical simulation investigated the ventilation performance of the solar chimney. The results showed when the pad was closed, the maximum value of cooling load was achieved at the wind speed of 3(m⁄s). In addition, at the wind catcher heights of 2.5 and 3.5 m and the wind speeds of lower than 3(m⁄s), the cooling loads approximately doubled by employing closed-pad mode. Compared with the open-pad mode, the closed-pad mode has shown better results, when the wind speed was low. The airflow rate at the no-wind condition and solar radiation of 1000 (W/m2) was eventuated around 0.021 (kg/s), if applying the evaporative cooling system. Consequently, the combined system increases the mass flow rate of the air by several times in the low wind speed compared that without the solar chimney.

ΠΕΡΙΛΗΨΗ

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I would also like to thank my family: my husband, to my son and daughter, and to my father and mother for supporting me spiritually throughout writing this thesis and my life in general.

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Nomenclature

RH	Relative Humidity	dimensionless
DBT	Dry-Bulb-Temperature	°C
$\boldsymbol{T_a}$	Dry-Bulb-Temperature of ambient air	°C
$\boldsymbol{T_{wb}}$	Dry-Bulb-Temperature of ambient air	°C
$\boldsymbol{T_t}$	air temperature after the pads	°C
$\boldsymbol{D_P}$	thickness of the straw	cm
$\boldsymbol{v_i}$	Air velocity through the pad	m/s
$\boldsymbol{C_\rho\ \omega}$	specific heat of the air	J/(kg K)
$\boldsymbol{h_g}$	enthalpy of the saturated vapor at the air temperature	
$\boldsymbol{B}$	area of the walls	m^2
$\boldsymbol{I}$	solar beam on the walls	W/m^2
$\boldsymbol{\dot{m}}$	mass flow rate	kg/s
$\boldsymbol{\dot{m}_a}$	mass flow rate of the wind entering the wind catcher	kg/s
$\boldsymbol{C_p}$	specific heat of the humid air	J/(kg K)
$\boldsymbol{H_O}$	convection heat transfer coefficient of ambient air	W/(m^2 K)
$\boldsymbol{L_v}$	latent heat of the evaporation	J/g
$\boldsymbol{h_D}$	mass transfer coefficient	g/(m^2 s)
$\boldsymbol{A_m}$	wetted surface of the column	m^2

$\boldsymbol{w_c}$	humidity ratio of the saturated air at the desired temperature	dimensionless
$\boldsymbol{w_a}$	humidity ratio of the inner airflow	dimensionless
$\boldsymbol{h_i}$	inner convection heat transfer coefficient of the air	W/(m^2 K)
$\boldsymbol{F}$	friction coefficient of the conduit	dimensionless
$\boldsymbol{L}$	length of the conduit	m
$\boldsymbol{D}$	hydraulic diameter of the conduit	m
$\boldsymbol{C_{PW}}$	pressure coefficient of wind	dimensionless
$\boldsymbol{Z}$	height of the wind catcher	m
$\boldsymbol{V_W}$	wind velocity	m/s
$\boldsymbol{T_O}$	outlet temperature of the wind catcher	°C
$\boldsymbol{R}$	gas constant for air	J/(kg K)
BWK	Cold Desert Climate	
$\boldsymbol{C_p}$	pressure coefficient	
$\boldsymbol{Q_c}$	Evaporative cooling loud	kW

Greek Symbols

η	efficiency of the straws	
ω	humidity ratio of the air	kg/kg
α	wall absorptivity	decimal

Acronyms

IPCC	Intergovernmental Panel on Climate Change
WCS	Wind Catcher System
HVAC	Heating, Ventilation and Air Conditioning
CFD	Computational Fluid Dynamics
WCIECS	Wind Catcher Integrated with Evaporative Cooling System
WCISCS	Wind Catcher Integrated with Solar Chimney System
PEC	Psychometric Energy Core
DECT	Down-Draft Evaporative Cool Tower

Chapter 1

Introduction

Problem Statement

Climate change and global warming are among the top critical issues in today's world. Human influence on the climate system is apparent, and today the emissions of greenhouse gases are at its highest level in human history. It is becoming increasingly evident that human activities have an impact on the environmental balance of our planet [1].

Energy consumption, especially the burning of fossil fuels, is currently one of the main factors contributing to climate change. The impact of energy consumption is not limited to environmental effects. It also impresses the world economy and human comfort. Primary energy consumption includes transport, the built environment, and power generation [2]. Energy used in buildings accounts for about 40% of the global energy production, most of it comes from non-renewable sources. Building energy consumption accounts for 33% of total annual carbon dioxide emissions, which contributes significantly to climate changes [3, 4].

A study by Larsen shows, people averagely spend about 90% of their time inside the building, which highlights the importance of focusing on maintaining a good and healthy environment [5]. The negative effect of the world population growth and the rapid urbanization in urban area have led to a sharp increase in environment pollution which have profound impacts on human health. Consequently, it is urgent to reduce the environmental impacts of the built environment [6].

Hot and dry climate zones are known for extreme hot weather in summer and little rainfall all year that lead to a dry condition. The primary concern in Hot-Dry regions is thermal comfort. During hot seasons climate plays an essential role in the building performance and its energy consumption. The conventional design solutions for maintaining thermal comfort mostly considers mechanically driven ventilation and air-conditioning systems. Building heating, ventilation, and air-conditioning systems(HVAC) account for almost half of the energy consumption in buildings [3]. The high demand for these systems will dramatically increase greenhouse gas emissions.

Before the invention of modern mechanical systems, consequent of harsh climatic conditions in hot and dry areas, people had to build their houses with some ingenious strategies, which based on minimum energy consumption [7]. These strategies are the use of renewable energy(solar energy, wind, the earth thermal reservoir, and water), energy recovery and demand-control and energy efficient technologies without environmental pollution [8]. Those can be considered in building design for ventilation, cooling, and heating to preclude the use of fossil fuels.

Passive systems can be considered as a viable and efficient strategy for the concept of sustainable building, because one of the goals of sustainable design is the comfort of the residents. There are various passive cooling methods to provide excellent thermal comfort and high indoor air quality with low energy consumption (see figure 1.). Two essential techniques in the vernacular architecture of this climate have been passive cooling and natural ventilation [9].

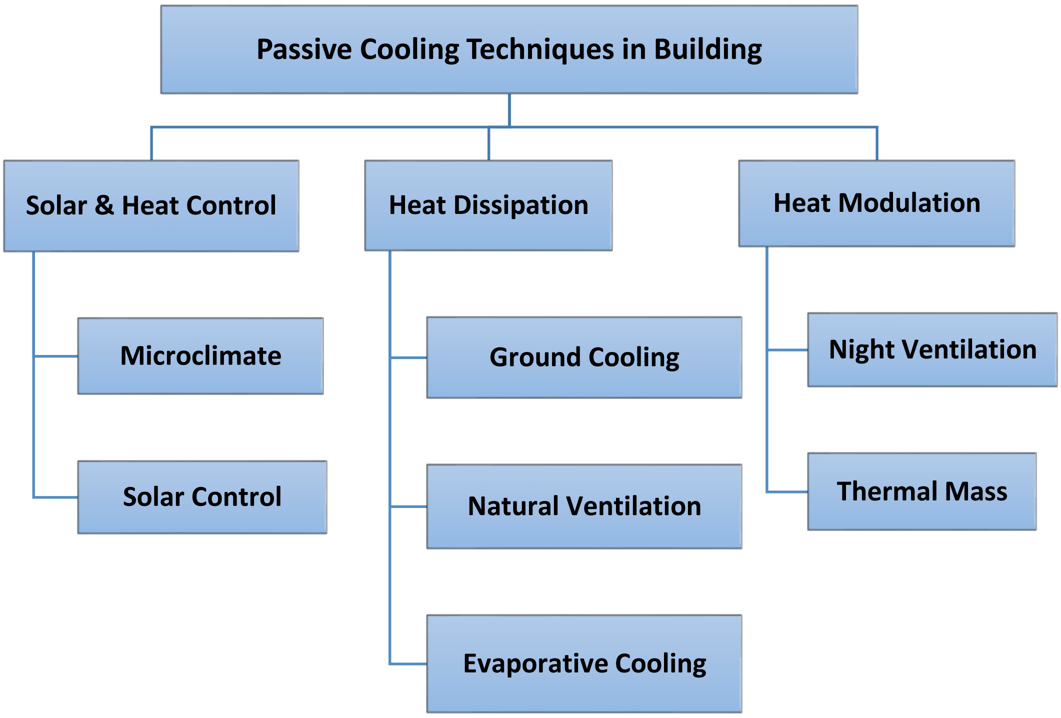

Figure 1.Different passive cooling methods for energy efficient buildings [10].

One of the essential building elements in the Hot-Dry climate which was used for cooling and natural ventilation is wind catcher. Wind catchers have been used as a traditional strategy of vernacular architecture in the Middle East countries such as Iran, Egypt, Jordan, Kuwait, and the UAE, under Hot-Dry and Warm-Humid conditions. The local climate, geographical conditions and the social position of the residents defined some design parameters in traditional wind catchers such as materials, construction, height and number of openings [11].

Wind catchers requires a driving force to operate. The first force is external wind and the second force due to the naturally occurred difference in temperature is buoyancy effect. Some researches show that external wind force provides 76% more, internal ventilation than buoyancy effect [12]. Consequently, the traditional system is mostly applied for heat dissipation rather than supplying ambient cool air through the system, the use of cooling equipment in the channels only leads to energy dissipation.

Moreover, when there is not adequate external airflow, the stack effect is negligible. Therefore, system efficiency is low which causes the wind catcher to be inefficient at times and areas with low wind speed [13].

Aim and Scope

This research focuses on a combinatorial construction of passive and low energy strategies in the four-sided wind catcher system (WCS). The proposed wind catcher tries to improve the performance and reduce some of the problems and limitations of conventional and traditional wind catchers to reduce energy consumption in the buildings located in the Hot-Dry regions. The suggested system has changed traditional solutions along with new considerations.

The primary goal of this project is increasing the contribution of buoyancy force in the wind catcher performance. The system is equipped with a solar chimney structure and evaporative cooling features to improve the ventilation and cooling potential under hot and dry climatic conditions.

The secondary goals of this research include:

i. Developing an evaluation framework which comprehensively considers the quality of the evaporative cooling feature in the simple prototype.
ii. Investigating the mechanism of solar chimney structure in combination with the wind catcher using CFD[1] software.

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[1] Computational Fluid Dynamics

Structure

The structure of the thesis is organized as follows:

In chapter 1, the introduction states the problem, aim, and scope of the research as well as the structure of the thesis.

Chapter 2 extensively describes climatic elements, climatic classifications and the notions of thermal comfort. Moreover, it briefly outlines the design strategies and elements in a Hot-Dry climate. The final part of this section focuses on wind catchers in detail.

Chapter 3 reviews literature on the studies of the wind catcher in three parts. The studies of the components optimization of traditional wind catchers and existing research of two combined systems (WCIECS)[2] and (WCISCS)[3] are presented. The pros and cons of the existing wind catchers are investigated to identify the expectations of the new designed system and originality of the work.

Chapter 4 describes the proposed system and its components. The working principles, the system response in different environmental conditions, are expressed.

Chapter 5, evaluates of the proposed model. An analytical model, and an experimental model assess the efficiency of the evaporative cooling of the system. The CFD software gives an overview of the role of the solar chimney in structure functioning.

Chapter 6 presents results and discussions of the assessments.

Finally, chapter 7 draws a conclusion and future works.

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[2] Wind Catcher Integrated with Evaporative Cooling System

[3] Wind Catcher Integrated with Solar Chimney System

Chapter 2

Basic Definitions

Climatic Elements

Climate was an issue that had been studied by the ancient Greek philosophers and geographers. This word has been derived from the Greek word *Klima* meaning “slope,” referring to the variation in received sunshine on Earth’s surface, which is due to the regular changes in the Sun’s angle of inclination upon a spherical Earth. Climate can be perceived as a local environmental conditions including, temperature, humidity, solar radiation, wind, rain and so on [14].

Climate is different from weather. Weather is a result of daily atmospheric conditions at a particular place and time, while climate is the result of average weather conditions in a specific place. The most significant of climatic elements that make up both weather and climate are as follows:

(A) Ambient temperature

(B) Solar radiation

(C) Air humidity

(D) Precipitation

(E) Wind

Ambient Temperature

Ambient temperature is the temperature of air in a shady enclosure. It is usually determined in degree Celsius (ºC). Temperature is a significant factor in determining the weather, because it influences or controls other elements of the weather. At a specific site, temperature fluctuates depending on factors such as wind, shading, the presence of water body, sunny condition, etc.

Solar Radiation

Solar radiation is the radiant energy received from the sun. It shows the intensity of sun rays falling per unit time per unit area (watt per square meter (w/m^2)). Geographic location, orientation and season, time of day, and atmospheric conditions influence the collision rays on a surface.

Solar radiation plays an essential role in the structure of traditional architecture. In the warm climates, the smallest amount radiation that penetrates the building is noticeable.

Humidity

Humidity states the amount of water vapor in the atmosphere. There are three main measurements of humidity: absolute, relative and specific. Relative humidity (RH) is calculated by the ratio of the mass of water vapor in a specific volume of moist air at a given temperature, to the mass of water vapor in the same volume of saturated air at the same temperature [15]. RH is expressed as a percentage and has no units.

Precipitation

It can appear in all of its forms such as drizzle, rain, sleet, snow, etc. The amount of precipitation is usually defined in millimeters (mm).

Wind

Wind is the horizontal movement of the atmosphere that is the result of the horizontal differences in the air pressure. Indeed, wind is the movement of air from high pressure to low pressure. The main influencing factors are differential heating of land and water mass on the earth’s surface, solar radiation and rotation of the earth. Wind speed is a significant design factor for architects. Windsocks are used to show the direction and Anemometers record the speed in (km/h) or meters per second (m/s).

Climatic Classifications

The ancient Greeks proposed the first climate classification scheme. They divided Earth’s surface into five zones based on the intensity of sunshine; a torrid zone, two temperate zones, and two frigid zones [16]. There are three basic types of classification systems; empirical, genetic, and applied. According to the empirical classification system, the climate is classified by observable features (e.g. temperature, precipitation). On the other hand, some observable features (e.g. the frequency of air mass invasions, the influence of orographic barriers, the influence of particular wind, and pressure belts) make a genetic classification. Finally, the applied classification systems can solve specific problems. In the following, a type of climatic classifications is introduced that is significant in the architectural design process.

Köppen Climatic Classification System

The most widely used climatic classification system is that of Wladimir Koppen (1846-1940) in its various modified forms. This system is one of the empirical classification systems which is utilizes monthly temperature and precipitation data. Moreover, it includes the relationship of climate with the vegetation. According to this scheme, the world has five climatic groups with 13 sub-division. Five main climatic groups are:

- A (Tropical Moist Climates)
- B (Dry Climates)
- C (Mesothermal or mid-latitude mild)
- D (Microthermal or mid-latitude cold)
- E (Polar)

Hot-Dry Climatic Regions

Hot-Dry desert climates extend in two belts between latitudes 15°, 30° N, and S. The condition of the Hot-Dry climate is as follows:

There are two seasons, one hot season and a cooler one. In the hot season, Dry-Bulb-Temperature (DBT) maximum ranges are around 43-49°C. Moreover, DBT are in more cooling season around 27-32° C. Due to being away from the body of water, the temperature range between night and day is high. Minimum nightly temperatures are around 24-30°C and 10-18°C in hot and cooler seasons respectively.

Relative Humidity (RH) varies from 10 to 55%. Precipitation is slight and variable. Although flash storms may occur, several years droughts are usual. Sky conditions are normally clear, with limited luminance, which may be further reduced by dust storms.

White dust haze may cause high glare and luminance. Solar radiation is strong. However, long wave re-radiation releases heat at night into the cold sky. Winds are usually local and turbulent.

In a Hot-Arid region, low humidity and lack of clouds cause a high-temperature difference between day and night. High day temperatures and rapid night cooling may cause materials to fracture. The major problems in hot and dry climate are the limited water resources and green spaces caused by hot days, low humidity, the intensity of solar radiation and stagnant air (lack of airflow) at low altitude.

Thermal Comfort

Climate is defined as the condition of the atmosphere at a particular location over a long period of time. It depends on the temperature, humidity, solar radiation, wind, rain. Because a climate contains many different aspects, this study investigates only the aspects of the indoor thermal condition.

One of the main goals of building construction is to create a comfortable living space. Although architecture focuses on many other aspects, thermal comfort cannot be undermined. The air temperature is perhaps the most noticeable climatic element related to the built environment experienced by the resident. Therefore, it is a matter of concern as a climatic element for human comfort [14].

Indoor environment, the heating, indoor air quality, light, and noise affects health, productivity, and comfort of the occupants. Recent studies have shown that improved air quality in the indoor environment would be expected to rise complacency and the productivity of work [17]. The satisfaction of residents from the quality of the indoor environment largely depends on indoor thermal condition. Comfort is the condition of mind which expresses satisfaction with the environment. The comfort temperature is a function of the air temperature and the mean radiant temperature [18].

Thermal comfort in an indoor area is related to the heat exchange between the human's body and the environment. Moreover, it depends on the individual's metabolism, the nature of the activity engaged in, and the body's ability to adjust to a range of ambiance [19].

Macpherson identified six factors that affect thermal comfort in the building as follows:

- Indoor temperature
- Relative humidity
- Mean radiant temperature
- Air velocity
- Clothing level
- Metabolic rate

Thermal comfort can be achieved in different contribution of each individual parameter as well as their combinations with other parameters. There are other aspects of building services which affect the comfort of occupants. In buildings where the occupants control their environment, variability may result from people adjusting conditions to suit themselves which affects the comfort of other occupants. The results of some surveys show the indoor thermal comfort related to the outdoor climate. Moreover, time is the main factor in comfortable temperatures. The rate of change of time is typically quicker than weather seasonal fluctuations but longer than the momentary fluctuations that occur in the surrounding microclimate [20].

Many scientists worked on different designs for climatic models so that each has positive points for architectural performance. In different stages of architectural design, two groups of these models apply [21].

1) Defining Comfort Conditions
   a) Fanger thermal equation
   b) Adaptive model
2) Design Strategy Models
   a) Building bioclimatic charts
      i) Olgyay bioclimatic chart
      ii) Givoni bioclimatic chart
   b) Mahoney model

The energy used in the thermal comfort of buildings, includes ventilation, heating and cooling systems accounts for more than 60% of the total energy consumption in buildings.

Various factors have different thermal effects. The commonly factors found in conventional design are air temperature and air humidity. It affect only 6% and 18% of our understanding of thermal comfort, while the temperature of surrounding surfaces and the air velocity account for 50% and 26% of thermal comfort perceptions, respectively.

Therefore, the wind and the sunlight in Hot-Dry regions play an essential role in achieving thermal comfort. As, they were two major factors in the design of the traditional architectural elements that helped provide comfortable conditions for habitants in this climatic.

Natural ventilation

Natural ventilation is the process of supplying fresh air and removing stale air that can reduce the costs of the building construction and operation, and energy consumption. It is one of the fundamental methods in the energy-efficient design of buildings that can play a significant role in ventilation and cooling in consequence of improving indoor air quality and providing adequate thermal comfort in certain climates.

In natural ventilation of a space, wind pressure and stacks effects cause the circulation of air. Different building elements such as window, wind catcher and solar chimney are used for natural ventilation.

Principles and elements of natural ventilation

Natural ventilation is the use of natural forces to help and guide the movement of air through the building [8]. Natural ventilation originates from two natural forces, pressure differences created by the wind around the building; and temperature differences or both as driving forces.

1. Wind Driven Ventilation

In nature, wind is used as motive force for providing ventilation. The flow of the wind on a building face will produce a positive pressure on the windward side and a relative negative pressure on the leeward side. This pressure difference, as well as, the pressure differences inside the building will drive airflow. (See figure 4)

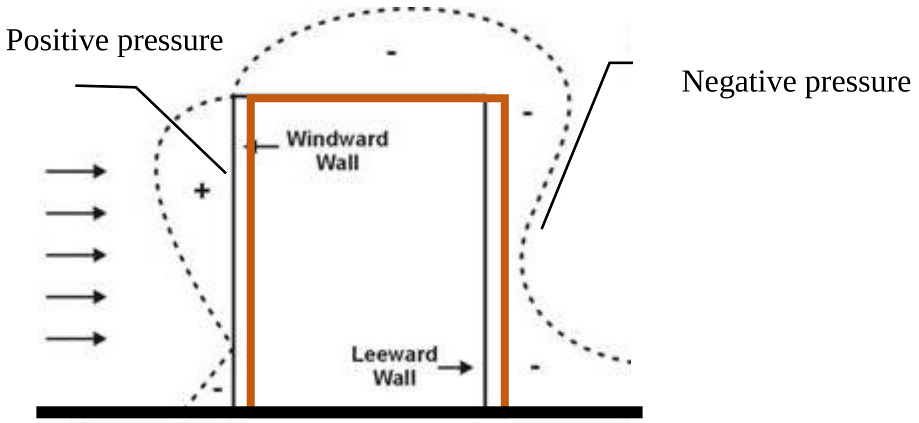


Figure 2. Pressure pattern on around the building.

There are many factors which play an active role in capturing the wind and providing ventilation in the building. The building shape becomes a crucial factor that can create wind pressures, which causes the air to flow through the openings of the building. The other factors include the following:

- Building orientation and location, so that the windward wall is perpendicular to the summer wind.
- Window typologies and operations;
- Types, shape, and size of openings;
- External elements and urban planning.

2. Stack Ventilation

Temperature differences between the inside and outside of buildings cause stack effects. When the inside building temperature is higher than the outside, warm indoor air will rise and exit thus being replaced by cooler, denser air from below. It can be induced by temperature or by humidity. On hot summer days with no wind, the relatively stable airflow, naturally occurs by the stack effect. Moreover, because airflow does not rely on the pressure and direction of the wind, there is greater control in locating the air intake. The inlets should supply air from the low level in the room. The outlets should be located across the room and at a high level.

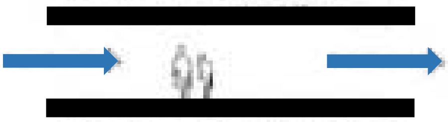
Types of natural ventilation are due to wind and buoyancy through cracks in the building envelope or purposely installed openings.

a) Single-Sided Ventilation:

Limited to zones close to the openings. Single-sided ventilation is driven by wind-induced turbulence (buoyancy can also contribute), and the depth of the space that can be adequately ventilated is limited.

b) Cross-Ventilation:

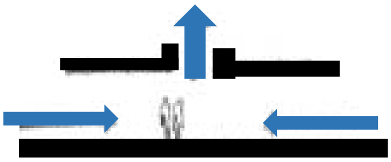
Cross Ventilation is driven by wind. The depth of the building ventilation is limited. Buildings utilizing the stack ventilation principle are characterized by two or more openings on opposite walls -covers a more extensive zone than the single-sided openings.



c) Stack Ventilation:

Stack ventilation is mainly driven by buoyancy (wind can also contribute) and can ventilate deep plan buildings. Buildings utilizing the stack ventilation principle are

characterized by ventilation openings in the façade [22].



Historical Design Strategies and Climate-Responsive Building Elements in Hot-Dry Climate

In traditional buildings, climate has a significant effect on the design of sustainable living spaces. Before the advent of the industrialization, humans have utilized some innovative strategies to provide thermal comfort in Hot-Dry climates [23].

Hot days with low humidity are the principal problem in Hot-Dry areas. High temperatures during the summer months increase energy demand for cooling systems in buildings. Increasing energy consumption leads to higher emissions of air pollutants and greenhouse gases [2].

In most countries, there are excellent examples of vernacular architecture, as well as, many contemporary architects by embracing some of the principles of climatic design, have created interesting examples of low energy buildings adapted to the climate.

The purpose of this section of the study is to introduce traditional climate-responsive building elements in Hot-Dry regions and their functions. Therefore, the physical aspects of the climatic and vernacular architecture have been focused on. Mofidi [24] has introduced some architectural aspects, derived from the analysis, in the Hot-Dry climate, which included the essential design strategies. The analysis of the cases demonstrates some similarities and contrasts in elements and principles that are different in history and culture but being similar in climate. Taleghani et al. [7] introduced natural climatic strategies and then, categorized these characteristics into three levels: a) macroscale, b) medium scale, and c) microscale. These levels described the performance of the strategies. Moreover, they focused on points that can be learned from past experiences to improve energy consumption patterns in contemporary architecture. Maleki [25] has demonstrated the usage of traditional architecture in a Hot-Arid climate of Iran as a sample of sustainable architecture. He has described and illustrated some essential building elements in Hot-Dry regions. Figure2 illustrates some architectural strategies and elements in the Hot-Dry climate are stated.

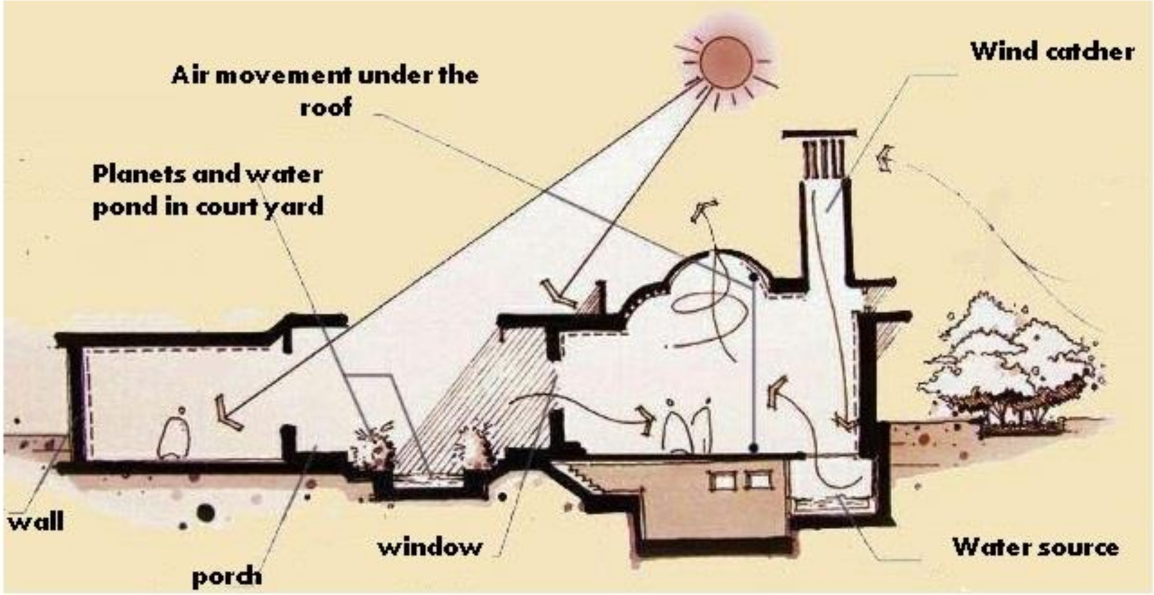


Figure 3. The schematic view of climate-responsive building elements in Hot-Dry regions

Introverted Building and Courtyard

The most popular element of traditional buildings which was intended to create a better inhabitable microclimate was the courtyard. It is basically an atrium in many shapes and spatial layout. The courtyard has been a social space with an environment function, planned to increase daytime cooled spaces. Commonly, there was a sunken courtyard with some plants and a shallow pond to produce fresh and cool place for inhabitants by evaporative cooling. The diffusion of water through the canal into the courtyard floor, made of porous stone, contributed to the effect of evaporative cooling. The deep courtyards with high walls have minimized the hours of direct sunlight during the daytime, created a suitable place for summer [26]. Shading and increasing RH have influenced the comfort condition of the yard. Courtyards have been used for thousands of years and are common architectural features in many areas including the Middle East and the Mediterranean. It is a common natural ventilation and cooling technique that improves comfort conditions by modifying the microclimate around the building [8] (Figure 3). Table 1. shows the solutions of a courtyard for comfort conditions.

Figure 4. A courtyard of a traditional house located in Yazd, Iran

Table 1. How courtyard responded to climatic conditions

	comfort functions	**solutions**	**climatic elements**
Courtyard	• Day time cooling • Increase ventilation • Increase relative humidity • Minimizing hours of direct radiation	• Dimension of walls • Orientation of courtyard • Utilizing evaporative cooling • Plants • Shallow pond, Fountain	• Solar radiation • Air movement • Humidity

Porch

The porch is a unique space in traditional architecture, with one side entirely open, typically to a courtyard [7]. The porch was utilized to improve privacy and security as well as to control the entry of light for the spaces that didn't have direct light, while natural ventilation was induced by windows that open to the porch. The location of the porch is usually on the south side of courtyards with the open side of the room facing to the north [27]. Table 2 presents the solutions of the porch for comfort conditions.

Table 2. How porch acted to climatic conditions

	comfort functions	**solutions**	**climatic elements**
Porch	• Filtering direct radiation • Increase ventilation	• Orientation of porch • Dimensions • Windows	• Solar radiation • Air movement

Wind Catcher

One of the significant climate-responsive building elements of Hot-Dry climate which was used for cooling and natural ventilation is Wind-catcher. A wind towers or a wind catcher is small tower with a height between 5 to 33 m raised on the roof of a building. It acts as a cooling system to provide favorable ventilation and a pleasant interior environment utilizing the widely available renewable energy of wind [28]. A wind catcher needs a driving force to operate where the first force is buoyancy effect, resulting from naturally occurred temperature difference. The second force is the external wind [29]. The flow of the wind on the internal blades of the wind catchers will produce a positive pressure on the windward side, while the leeward openings meet a negative pressure. Therefore, like a ventilation system the hot and polluted air is drawn out [30]. It should be mentioned, that in the past architectural construction has taken advantage of masonry blocks and thicker walls and roofs to prevent the fast heat transfer from exterior to interior of the building or vice versa.

Wind catcher was used for improving natural cooling in two ways-displacement, and evaporative cooling. Evaporative cooling is a natural phenomenon that occurs when moving air passed over a water surface as clay jars, porous pottery, and wetted straw [26, 31]. The wind catchers were in many different sizes, directions and heights, due to the specific breeze flow related to environmental areas. Generally, their location in the building plan was determined based on the four main geographical directions or according to wind power and direction [32]. A wind catcher comprises a chimney, stalk, catgut, chain, and shelf. Table 3 shows the solutions of wind catcher for comfort conditions.

Table 3. How wind catcher operated to climatic conditions

	comfort functions	**solutions**	**Climatic elements**
Wind catcher	• Cooling • Ventilation • Increasing relative humidity	• Orientation of opening • Tower height • Materials • Water surface	• Solar radiation • Air movement • Humidity

Roofs in the Shape of Domes and Vaults

One of the types of the roof in Hot-Dry regions is the dome which has been as the covering roof for mosques, water reservoirs, and shopping centers. This strategy was commonly employed for closed and semi-opened spaces [24]. Having the convex and unbalanced surface would create a different impact angle of the sunbeam on the dome. Moreover, since a portion of the ceiling always remains in the shade during morning and/or afternoon times, it will benefit more from self-shadowing. The surface form of the roof also increases contact surface with the outdoor winds. The distance between the dome and the floor causes the accumulation of warm air under the dome that improves the effectiveness of the thermal insulation. On the other hand, the curved shape of the dome helps to increase solar reflectance and thermal emittance during the night which can result in a better cooling performance. Table 4 indicates the solutions of a roof for comfort conditions.

Table 4. How roof responded to climatic conditions.

	comfort functions	solutions	climatic elements
Roof	• Improving night cooling • Improving the effectiveness of the thermal insulation	• Convex form • Unbalanced surface • Material	• Solar radiation • Air movement

Wall

In arid regions, there are significant diurnal temperature fluctuations within the hot seasons. Walls, in traditional buildings, were made of mud, clay brick or a blend of mud plaster, straw, and mud with high thickness. Due to its thickness and material characteristics, a wall would absorb heat from 9 AM to 12 AM from solar radiation then the heat would penetrate the building until the pre-dawn hours. This strategy was applied to increase the time-lag and to retain some heat for nighttime warming.

The extensive thickness of the walls, approximately one meter, led to improve the thermal insulation, subsequently made the walls to work as a thermal barrier and avoid thermal emittance to the interior during the day. Therefore, a large portion of the absorbed heat transfers to the ambient by radiation and convection. Consequently, the walls provide enough comfort for residents. Table 5 shows the solutions to a wall for comfort conditions.

Table 5. How wall acted to climatic conditions.

	comfort functions	solutions	climatic elements
Wall	• Loses the heat through transferring • Thermal insulation • Delays the heat transfer from outside to inside (thermal lag)	• Thickness of wall • Materials	• Solar radiation

Window

The primary purposes of a window were the entrance of daylight, ventilation, and views. In the Hot-Dry climate, windows were mostly applied for ventilation [33]. Windows would often be divided into smaller parts by thick wooden frames which provided more control of light by an edge around the window as a canopy in different sizes. The glass part was reduced in size and was made with the least glass because glass is not a good sound and heat insulator [26]. Moreover, in traditional houses of Hot-Dry climate, the window glass was designed in different colors and ornaments. Windows with colorful glass provide enough sunlight, block the intense sunshine, and create beautiful patterns in the room. The fact that clear glass and other non-opaque materials have relatively less solar transmission insulation value with very little loss of heat energy. Colored panes have provided further diffusion of light as well as privacy in buildings [33].

Windows with latticework and screen are one of properties of the climate-responsive traditional buildings. They allow the air and light to enter through a filtered rate with the consideration of increasing privacy for the residents. These could be constructed from metal, stucco and what is typical of the local structure. Latticework was also often made of wood, especially in residential sites, e.g. 'Moucharaby' and 'Orsi'. Table 6 presents the solutions to the window for comfort conditions.

Table 6. How window reacted to climatic conditions.

	comfort functions	**solutions**	**Climatic elements**
Window	• Control of solar radiation • Ventilation	• Size • Breaking of window • Canopy • Colorful glass • Lattice work	• Solar radiation • Air movement

Wind Catcher in Detail

Wind is the movement of air or gusts from high-pressure areas (highs) to low-pressure areas (lows). Spatial differences in the density of the atmosphere make air movement above the Earth's surface. Earth's surface consists of water, and land mass, which their absorption of solar radiation is not equivalent [34]. Winds can be affected by the interaction of global, and regional patterns created by the sun's differential heating effect on land, forest, and water, and more locally, by topography.

As mentioned, wind plays an essential role where as it is a significant factor in architectural structures in the Hot-Dry regions [28]. Architects consider the effect of wind on thermal comfort through convection or ventilation, and air penetration in interior spaces.

Figure 5. A four-sided wind catcher located in Yazd, Iran

At ancient times, wind catchers were used similarly to the modern air conditional systems in warm and dry areas. The date of the earliest historical evidence of a wind catcher related to the fourth millennium BC, a simple example of it is found in a house on the southern slopes of the Alborz Mountains in the northeastern part of Iran. Wind catcher couldn’t be used in the regions where were vulnerable to sand-storms and warm winds even in valleys [7].

Wind catchers have been used in countries with Hot-Arid climates for centuries. They have been on top of ordinary houses and water cisterns as well as mosques [25]. A wind catcher consists of a tower that seems like a chimney with one end in summer living quarter of the house, and its top at a certain height on the roof. It was used to provide natural ventilation and passive cooling for the interior spaces of buildings by convection and evaporation of renewable energy of wind [28]. It led the suitable wind into the living environment for the modifying of the heat and the adjustment of the temperature in terms of thermal comfort [35].

In Hot-Dry regions, it is necessary to increase humidity rate. The airflow initially passed through a stone pond and fountain, and then entered the building, which resulted in transferring moisture to other building spaces. In some places, wetted mats or thorns were placed inside the wind catcher to enhance the humidity and coolness of the airflow. In these areas, the hot weather had the potential effect of causing water to evaporate quickly in turn develop cooling in the living spaces and relative humidity in the air, thereby reducing the heat and drought [31].

Generally, the orientation of the wind catcher is based on the four main geographical directions as well as, wind power and the prevailing wind direction [32].

This system had different names in different countries, as it was called “Baud-Geer” in Iran and “Malqaf” in Arab countries. Malqaf was a bidirectional wind catcher which was normally combined with another architectural element known as “Salasabil” that was a wavy marble plate linked to a source of water [36].

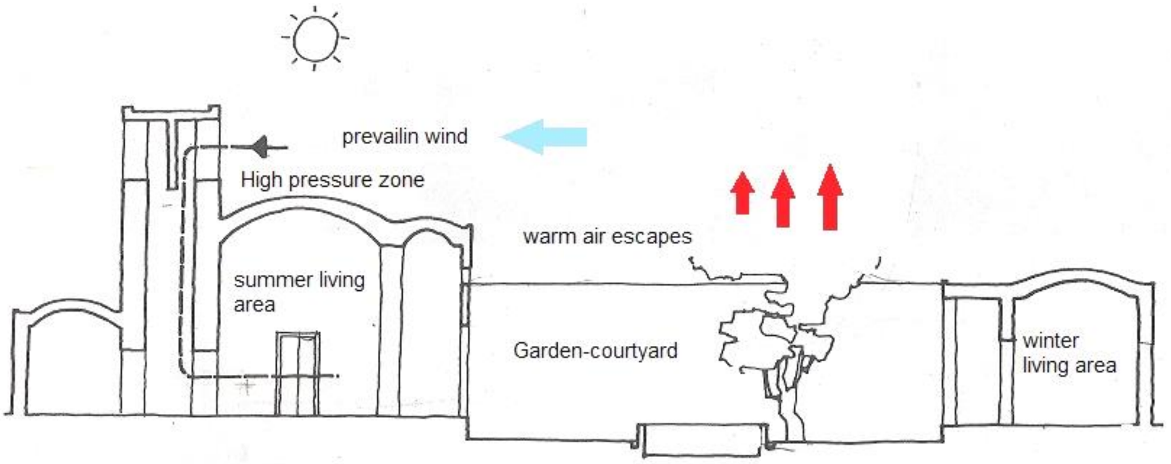


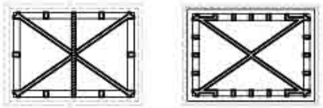
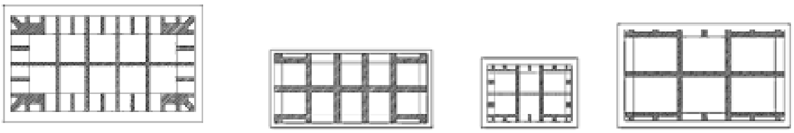
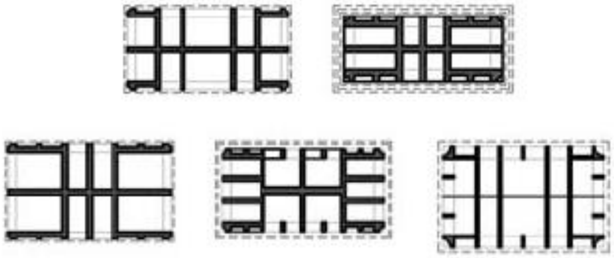
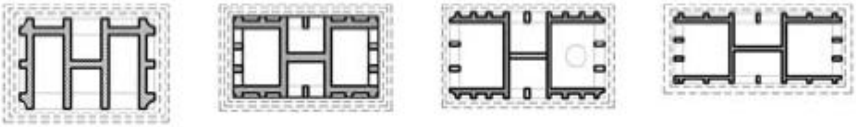
Figure 6. A cross section of air path in conventional wind catcher [37]

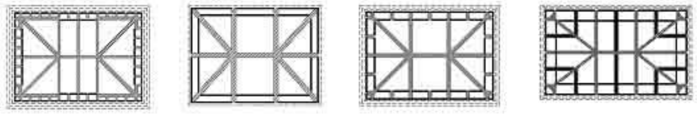
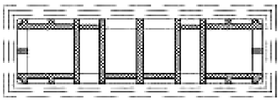
Wind catchers had diverse designs that have roots in the personal experience of architects, the suitability, wealth and social status of homeowners. The height of the tower, the passage section of the air, the location and number of openings, and the placement of the tower accordingly varied to suit its cooling performance [38].

A conventional wind catcher consists of a cabinet, shaft and blades. Cabinet is the head part of wind catcher which includes airflow transmission duct. Further, shaft is located between the cabinet and the roof. Bricks and adobes elements which divide wind catcher opening into smaller opening are blades.

The blades are raised in two main and subsidiary partitions within the shaft. Parapets as main blades continue to the center part of the shaft. As regards the subsidiary blades are the wind catcher s wings. [39], [28]. The role of the blades is not only to divide the wind catcher to smaller shafts and increase the air motion cause of buoyancy effect, but also to meet the structural requirements of the system. Blades are placed in columns in different shapes (See table 7).

Table 7. Typology of wind catchers with oblong plan [28]

	Blades form	Cross plan
1	Wind catchers with X form of blades	
2	Wind catchers with + form of blades and equal canals	
3	Wind catchers with + form of blades and different canals	
4	Wind catchers with H form of blades	

5	Wind catcher with K form of blades	
6	Wind catcher with I form of blades	

The Different Kinds of the Traditional Wind Catcher

In different reviews, several types of the wind catchers categorized that based on their tower height, cross-section, number of openings, orientation and also their position on the building plan.

In addition to the type, wind catchers have been designed using different forms and plans such as circle, octagon, polygon, square and oblong. There was almost no triangular form and only rare cases of wind catcher with a circular plan have been observed [28].

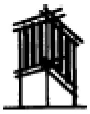
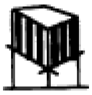
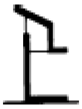
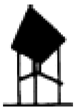
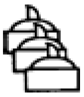
Location of wind catcher on the building plan varies. There were three main strategies regarding to the location of wind catchers:

1. Placing the structure behind the parlor adjacent to the courtyard
2. Placing it on the northern portion of the parlor
3. Constructing it at one corner of the courtyard having no direct relation with the

Parlor [40]

Table 8 summarizes the main characteristics of wind catcher based on the climate zone.

Table 8. Comparing various wind catcher in the Middle East according to different climatic zones [40]

	 Iran's arid zone	 Persian gulf	 Iraq	 Egypt	 Pakistan	 Afghanistan
Climatic zone	Hot and dry	Hot and humid	Hot and dry	Hot and dry	Hot and humid	Dry and semi hot
Air direction	Northeast	Breeze	Northwest	Northwest	Southwest	North
Shape of cross section	Square/ rectangle Six-, eight-sided	Square	Rectangle	Rectangle	Square	Square
Average dimensions (m)	0.5 × 0.8 0.7 × 1.1	1 × 1	0.5 × 0.15 1.20 × 0.60	–	1 × 1	1 × 1
Height (m)	3–5	3–5	1.80–2.10	One story above roof	5 and above	1.5 from roof
Direction according to the airblow	Diagonal	Diagonal	Ordinary	Ordinary	Diagonal	Ordinary
Ceiling of the Baudgeer	45° slope	30° slope	45° slope	30° slope	45° slope	30° slope
Ventilated spaces	Dinning plus basement	Dinning plus others	Only basement	Dinning plus one room	All rooms	All rooms
Airblow	Multi-sided	Multi-sided	One-, two-sided	One-sided	One-sided	One-sided
Evaporative cooling	Sometimes	Never	Sometimes	Sometimes	Never	Never

Moreover, wind catchers have usually various openings in terms of the wind direction. In cities where the suitable wind blows from a specific direction, the air trap has been kept open in one direction and closed at the all other sides [7].

1. *One-sided wind catcher*
2. *Two-sided wind catcher*
3. *Three-sided wind catcher*
4. *Four-sided wind catcher*

Working Principles of the Traditional Wind Catchers

Extensive research has been carried out using CFD and full-scale tests on different types of wind catchers to determine the forces that contribute to the airflow through the system. The wind catcher's performance was affected by wind speed, temperature difference, location and number of openings in the building. There were two driving forces to operate. The first force was the external wind and the second force was buoyancy effect due to the difference in temperature.

Wind Catcher Function According to Buoyancy Effect

When wind speed is almost zero, induced air movement results from differential buoyancies of warm and cool air inside the building. In these circumstances, the wind catcher acts according to the temperature difference. During the day, because the sun hits on the southern face of it, the internal and external walls absorb a lot of heat, so the air temperature inside the wind catcher increases and goes upward. This creates a vacuum inside the living area and takes the cool air from the courtyard into it. Moreover, the existing air in the northern ducts is drawn [29]. On the contrary, during the night, the air outside become cold, and the cold air moves downward. The heated adobe walls of the wind catcher cool off at night. The similar reaction of the walls related to the construction produces a vacuum in the open space of the courtyard. This produces air circulation through the wind catcher resulting in the natural ventilation of the home.

Wind Catcher Function According to External Wind

When there is minimal wind outside, the performance of a wind catcher is more governed by the difference in air pressure. The higher density of the air on the surface exposed to wind makes the air pressure positive, while pressure is negative in the leeward opening [29, 30]. Figure 7 shows how this difference of pressure creates air traction and suction in the wind catcher.

There were two ways for natural cooling of the wind catcher; displacement, and evaporative cooling. Evaporative cooling is a natural phenomenon that occurs when moving air passes over a wetted medium or water source. Evaporative cooling technique is beneficial in hot and dry areas because the temperature considerably reduces and the moisture level increases [26]. Generally, evaporative cooling in traditional architecture was used in two ways. The first way rely mostly of landscaping system. The airflow that passes through rows of trees, water fountains, and above ponds, springs, or wet cover becoming cool and make the space cooler.

The second way was the use of a wind catcher, in which the circulated air cooled down when the wind passed upon the water pond or through the moist walls [34].

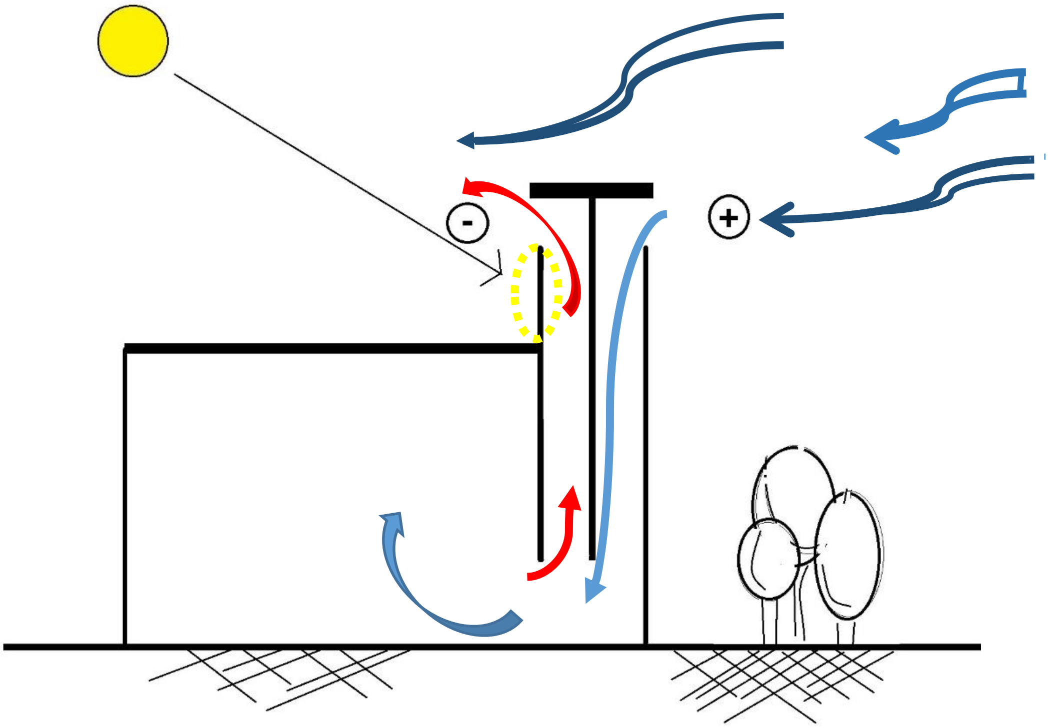


Figure 7. Traction and suction in wind catcher

Chapter 3

Literature Review

The objective of this section is to review and provide comprehensive literature on wind catcher systems for space cooling and ventilation. Considering the goals objectives of this research, the literature review results are categorized into three different groups to achieve better conclusions.

Review on the Studies with Emphasis on Components Optimization of Traditional Wind Catchers

Several researchers have analyzed various designs of wind catchers.

Montazeri et al. [38] have investigated numerically, analytically, and experimentally the operation of a two-sided wind catcher. Results demonstrate that the maximum performance is achievable when air incidence angle is closer to 90°. At this incident angle, the wind catcher efficiency increases approximately 20% more compare to the zero incidence angles.

Elmualim et al. [41] have carried out empirical and computational fluid dynamics (CFD) simulations to evaluate the performance of square and circular section wind catchers for natural ventilation applications in buildings. The results indicated that the performance of the system depends mainly on the speed and direction of the dominant wind. Moreover, the outcome shows that the efficiency of the four-sided wind catcher is much higher than the circular one in the same wind speed. Furthermore, it agrees with Montazeri findings. Montazeri [42] has examined the ventilation performance in wind catchers with a different number of openings, in order to evaluate how the number of openings affects the hydrodynamic reaction of wind catchers. The experimental wind tunnel, smoke visualization testing and computational fluid dynamic (CFD) were modelled. It illustrated that the number of openings was the main factor in the performance of wind catcher systems. In addition, a rectangular system could provide a higher efficiency compare to a circular plan.

Dehnavi et al. [43] have studied the effect of physical properties of square wind catchers on their performance and found the optimum characteristics of square wind catchers for best performance. Likewise, they have found the most efficient in the form of a squared wind catchers with the crossed blades.

Ghadiri et al. [44] have surveyed the wind catcher elements in the traditional architecture based on their physical characteristic and parameters. They used ANSYS Fluent software for simulation, which showed the impact of different square wind catcher’s plan geometry on the indoor ventilation rate. The results indicates that the ventilation rate in the cross form of the blades is higher compare to other investigated geometries.

In another research, they [44] have investigated four-sided wind catcher performance using a numerical method. In this study, CFD simulation was utilized to determine the effect of height on the ventilation rate of the wind catcher room. Based on the research findings, the height of the wind catcher influences the ventilation rate, wind speed, and volume flow velocity at the different opening ratios of the wind catcher.

Mahdavinejad et al. [45] have evaluated the YAZDI-wind catcher[4] function using an analytical model and a simulated case study as well as theoretical modelling. The results show that YAZDI wind catcher with four openings has a positive performance throughout the year.

Zarandi [28] has assessed typology of the wind catchers by the physical analyzing of the thermal behavior of conventional wind catchers in Yazd . She has analytically and numerically studied 53 conventional wind catchers with an optimum operation and recorded their specifications. Results illustrate the general characteristics of wind towers with optimum performance.

Masrour et al. [46] have examined the air circulation in the traditional wind catchers and buildings. They have compared the mass flow rate of intake air into the wind catcher and building at various wind speeds and directions during the day. The research results can be used for designing better wind catchers with higher performance.

Sarjito [47] has investigated the wind catcher geometry to define the optimum geometry of a wind catcher. All simulations were carried out using ANSYS CFX; Moreover, other researches have been carried out by Yavarinasab and his colleague [48]. They have investigated and analyzed the relationship between some important factors of wind catchers such as length,

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[4] one of the traditional wind catcher types in Iran.

width and height as well as the area of the room associated to it. In two separate studies, the effect of the shape of the wind catcher’s roof on its performance has been studied.

Dehghan et al. [49] revealed that the geometry of wind catcher’s roof and the approaching wind direction strongly influence the flow pattern, the internal pressure field and induced airflow rate inside the wind-catchers. Moreover, Esfeh et al. [50] have investigated experimentally and theoretically the influence of wind speed and direction on the ventilation capacity of one-sided wind catchers, which were constructed with flat, inclined or curved roofs. The results indicate that wind catcher with curved roof performed better in the test than other types of wind catchers.

Review on the Studies of the Wind Catcher Integrated with Evaporative Cooling System (WCIECS).

Bahadori is a pioneer in research on wind catchers, who was involved in many researches related to wind catchers and their efficiency for almost 40 years. He has introduced two new designs of the wind catchers including wind catchers with wetted columns and wetted surfaces. Bahadori et al. [40] examined the new designs of wind catchers theoretically and experimentally and compared their performance to the conventional wind catchers. Results show that both new designs performed better than the conventional wind catchers. Furthermore, it identifies the strengths and weaknesses of each of the systems in different environmental conditions.

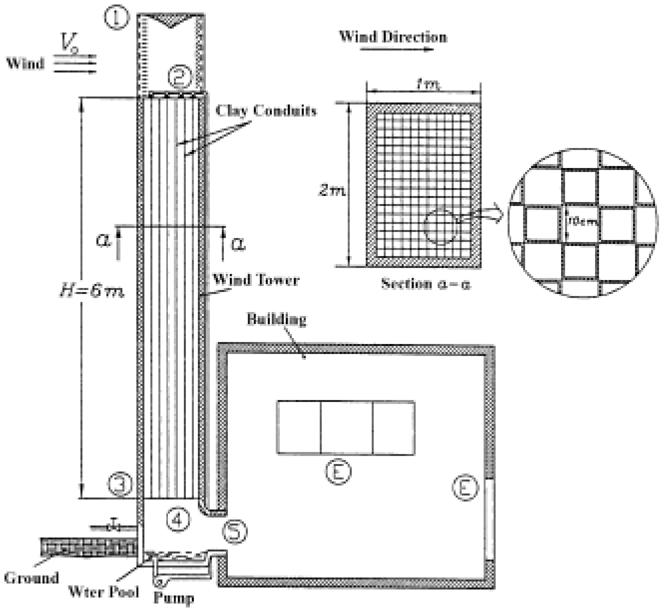


Figure 8. Cross-section of a wind catcher with wetted column [40]

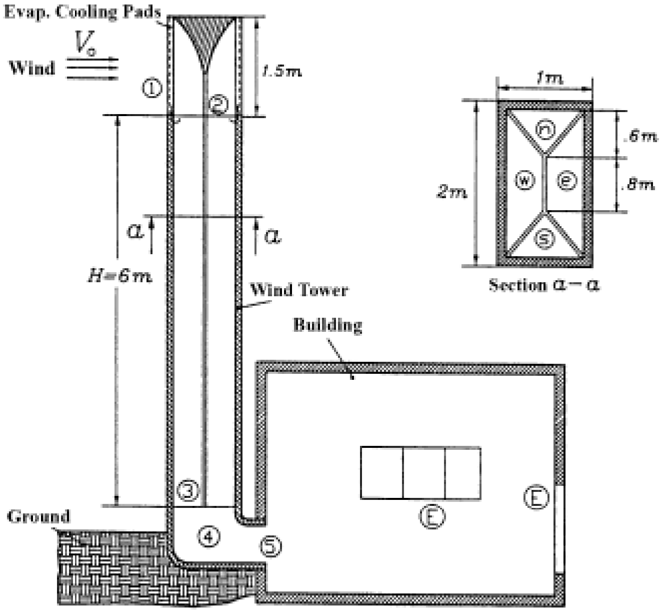


Figure 9. Cross-section of a wind catcher with wetted surfaces[40]

In a thesis conducted by Elzaidabi [51] an indirect evaporative cooler system has been constructed by combining a modified wind catcher and a diamond-shaped psychometric energy core (PEC) unit. This work evaluated the proposed systems for different parameters such as wind velocity, fan velocity, and water flow rate numerically and experimentally. Results show that the system has had good performance with over 80% cooling capacity.

Pearlmutter et al. [52] have presented a multi-stage down-draft evaporative cooling tower (DECT). In this system, water spraying in the upper part of the tower makes the dry ambient air cooler. Then the cool air which is now heavier moves to the bottom of the tower and mixes with other air stream in the secondary inlet and the mixture is cooled by evaporation. In addition to the theoretical analysis, the paper depicts experimental findings on temperature reduction, water consumption, and cooling output.

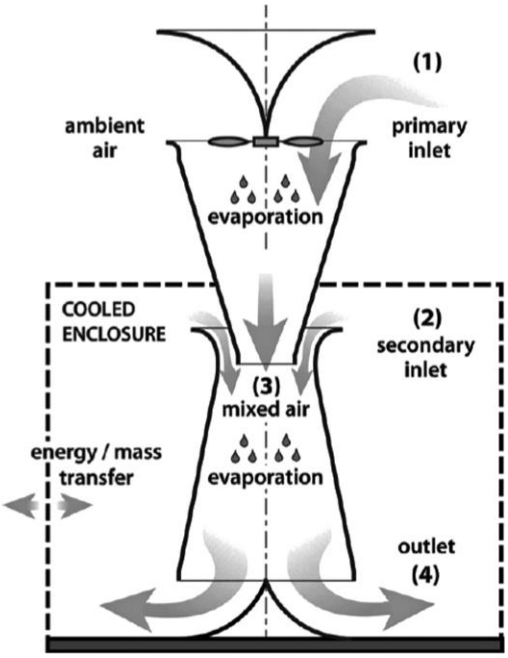


Figure 10. multi-stage down-draft evaporative cooling tower Model [52]

Kalantar [53] has experimentally and numerically studied the cooling performance of a wind catcher with water sprayers system on the top of system in a hot and dry region. It signifies the important effect of the evaporative cooling in the hot and dry region because the temperature decreases considerably if the system is embedded in the wind catcher.

Saffari et al. [54] have carried out a numerical study on the wind catcher consisting of wetted curtains hung in the tower. In another research, Haghighi et al. [55] have evaluated the performance of a wind catcher that was coupled with shower cooling system to meet thermal comfort conditions.

Engelmann et al. [56] have tried to simulate a typical office building to investigate the potential of different ventilation and cooling strategies. They demonstrate that active cooling provides good thermal comfort in warm and hot climates with high and fluctuating cooling loads. Amer et al. [57] reviewed the recent developments of the concerning evaporative cooling technologies that could potentially meet adequate cooling comfort, reduce environmental impact and lower energy consumption in buildings. The review has been conducted to cover direct evaporative cooling, indirect evaporative cooling and combined direct-indirect cooling systems.

Some other researchers have been accomplished on the utilization of evaporative cooling in the different segment of a wind catcher.

Janajreh et al. [58] have suggested the wind catcher potential for providing occupants comfort conditions under trans-evaporative cooling. The wind that captured by wind-catcher is impregnated with moisture which consequently causes reducing the temperature and increasing the density of the air.

Goudarzi et al. [59] have designed and fabricated a new design of wind catcher constructed from a four quadrant peak rooftop, nozzles, and turbines. They found that numerical results agree well experimental results.

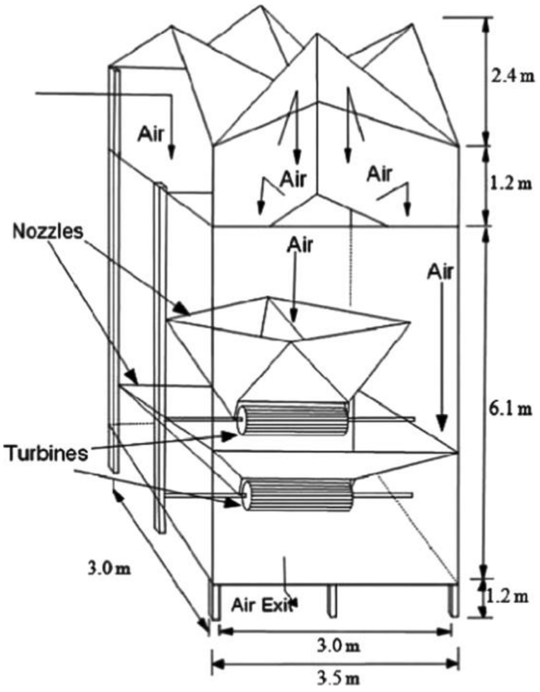


Figure 11. Goudarzi et al. a new design of wind catcher constructed from a four quadrant peak rooftop, nozzles, and turbines [59]

Review on the Studies of the Wind Catcher Integrated with Solar Chimney System (WCISCS).

Wind catcher with the proper absorption of outside airflow and directing it to the indoor space acts as a passive natural ventilation system. In recent years, natural ventilation has been recognized as a method of saving energy in buildings. Installation of one heat source inside any wind catcher facilitates the movement of airflow due to buoyancy effect. Based on a study carried out by a group of scholars on the thermal comfort of residents of three buildings, it was revealed that there is a negative relationship between thermal comfort and having a strong heat source such as strong solar radiation [36]. However, the result of smoke visualization and CFD simulation showed that installation of a heat source improves the performance of wind catcher, particularly at lower wind speeds [60].

Sanchez et al. [61] analyzed and optimized the aerodynamics of wind catchers and wind-extractors and also the geometry of their elements by using computational fluid mechanics. They presented a simple model as a result of their work. Wind extractor utilizes wind energy to induce airflow by centrifugal action. Centrifugal force created by rotating vanes, in turn, creates a low-pressure zone, which draws the fresh air from outside and replaces polluted air/hot air continuously.

Elmualim [62] investigated the effect of the airflow control mechanism and the heat source inside rooms on wind catcher performance. Therefore, experimental wind tunnel and smoke visualization testing and CFD modelling were conducted. The result showed that the performance of the wind catcher depends significantly on the speed and direction of the wind. Furthermore, there is a decrease in internal temperature compared to the external in the presence of heat sources.

Some studies have investigated the integration of solar chimney into a wind catcher. A solar chimney essentially is a solar air heater, which is designed to the maximum gain of solar energy and thereby maximize the air movement. Bansal et al. [63] proposed a system comprised of a wind catcher and a solar chimney. They indicated for low air velocities, the effect of the solar chimney is substantial in promoting natural ventilation.

Maerefat et al. [64] have proposed using a system consisting of a solar chimney and an evaporative cooling cavity. The research has studied the system's ability to meet the thermal requirements of residents and the effects of main geometric parameters on system performance.

The findings show that the system can make good indoor air condition under different conditions.

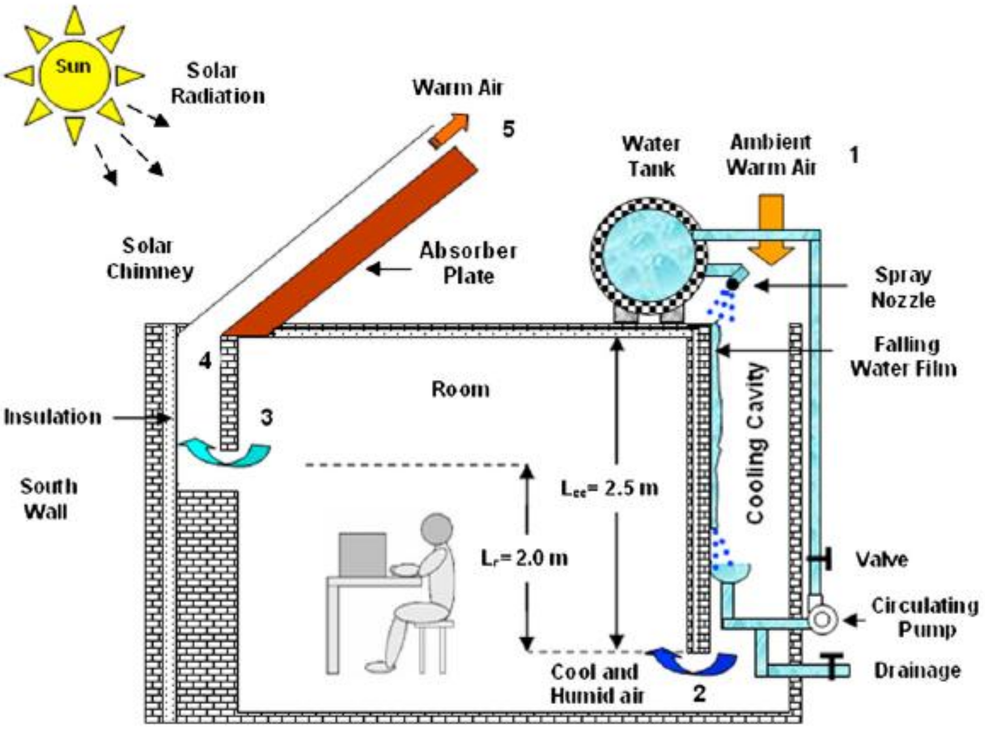


Figure 12. Schematic diagram of solar chimney and cooling cavity [64]

Tavakolinia in her thesis has introduced the use of a solar-chimney with an underground air channel combined with a wind-catcher to create thermal comfort for inhabitants. The end product improves air quality and thermal comfort levels in a single story building, while the system reduces energy use, CO2 emission, and pollution [37].

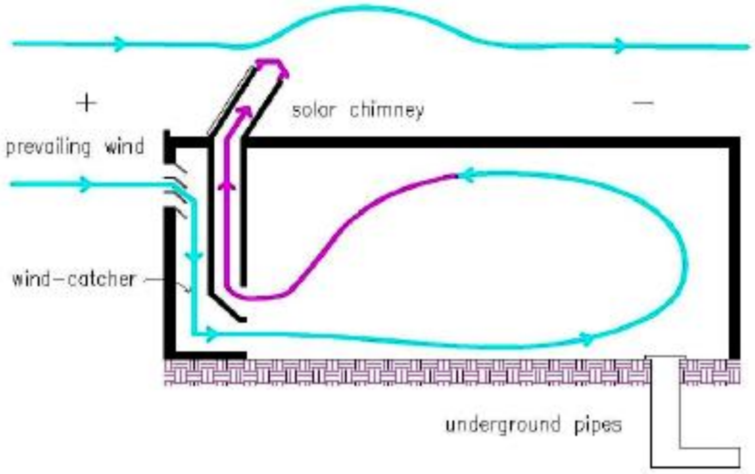


Figure 13. A cross section of the proposed wind- chimney [37]

Abdallah et al. [65] have developed the integration of direct evaporative cooling tower with a solar chimney multi-zone thermal ventilation model. The findings show that the system caused an acceptable decrease in indoor temperatures. Moreover, they numerically investigated the effect of solar chimney parameters on wind catcher parameters as a second phase of the new integrated model. The result indicates that the performance of the system is very high in the hottest days of the year [66].

Mahdavinejad and Khazforoosh [67] have presented a pattern in which combination of wind catcher and chimney in one of Kashan(Iran) house for optimum ventilation efficiency so that the energy efficiency will be increased.

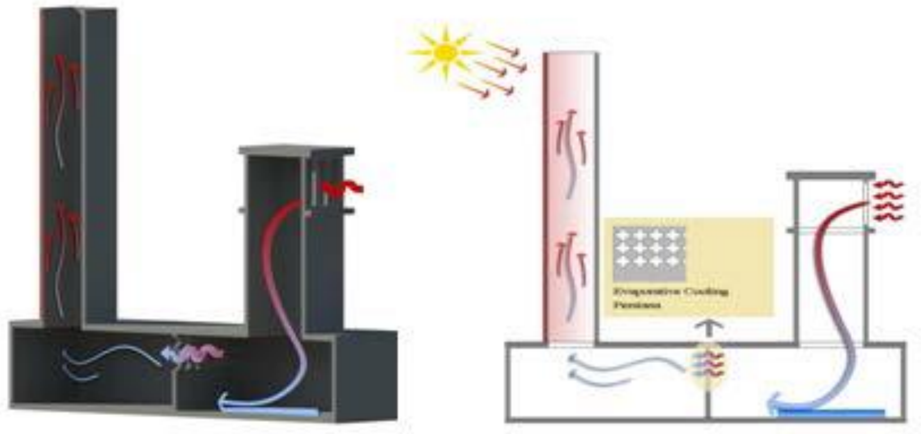


Figure 14. The proposing pattern mechanism by Mahdavinejad and Khazforoosh [67]

Dehghani-Sanij et al. [68] have designed a new wind catcher that can rotate and set itself in the direction of maximum wind speed. As a part of system, a solar chimney is installed in another part of the building. The proposed design of wind towers can help to save energy. These wind towers can be used in most countries, especially in developing countries. The use of these wind towers reduces greenhouse gas, CO2 emission, and air pollution.

Ansar et al. [69] performed various simulations on a combinatorial wind catcher-solar chimney system for a closed dwelling space. They revealed that substantial air motion could be attained within the closed region with such a combination. The solar chimney in such a system was found to be most effective for average heat flux on the absorber and lower ambient air velocities, while at higher ambient wind velocities, the main contribution for air current within the room was from the wind catcher.

The Pros and Cons of the Existing Wind Catchers

Sustainable architecture is seeking to minimize the negative environmental impacts of buildings, as well as increasing efficiency in the use of materials and energy. In the countries at Hot-Dry regions, due to harsh conditions and lack of access to modern heating and cooling system in ancient times, the architects had to rely on natural energies to achieve comfort [32]. The strategies used in traditional architecture are consistent with the concepts of sustainable architecture because these strategies have an approach to minimize energy consumption and improve thermal comfort.

Wind catchers as traditional natural ventilation systems have been utilized to provide acceptable indoor conditions and maintain a healthy and comfortable living space, rather than using conventional mechanical ventilation. The controlling of the climatic influences on the building is the most critical part of the construction and design. Most votes in several surveys show strong sings of dissatisfaction with internal conditions from a mechanically controlled environment. Some studies have made clear that the operating of the mechanical system which completely separated from the outdoor environment, can even be far from comfort and health [70]. Moreover, natural ventilation has been a unique method for reducing energy consumption and cost [38].

Wind catchers have been used for cooling buildings using substitution with cool air instead of warm air. The system has used clean and fresh air at roof level compared to low-level windows. Furthermore, it can be combined with evaporative cooling to accelerate the cooling process.

Despite all the advantages of using wind catchers, some researchers have questioned the use of wind catcher because insects and dust can easily enter. This aspect is critical in Southeast Asia and Africa where the Dengue and Malaria diseases kill thousands of people every year.

Driven-flow to direct the air through the building in most modern and traditional wind catchers are the natural forces of wind pressure and stack effect as resulting from air buoyancy, which occurs due to temperature and moisture difference in indoor to outdoor. However, as noted above (see section Working Principles of the Traditional Wind Catchers), when there is wind, the wind catcher is more applicable for heat dissipation rather than supplying ambient cool air as an internal air suction. When there is not adequate external airflow, the stack effect is negligible. As a result, the system 's efficiency is lowered which causes the wind catcher to be inefficient at times and areas with low wind speed [36]. These conditions are also present in most newly designed systems.

On the other hand, in Hot-Arid climate, the ambient air is usually hot and dry; there is often dust and sand in it that makes the unprocessed air insufferable [71]. In traditional wind catchers, airflow through the surface of the water, such as porous pots, and ponds was used to improve the natural cooling and air conditioning. Lack of control over the water evaporation process was the major drawback of the system.

In the courtyard, as a traditional strategy in the hot and dry climate, the presence of trees, ponds and tall walls, made the air cool and moist. Placing a courtyard near the wind catcher has increased its efficiency and helped to improve structure performance. Due to the declination of size in the housing structure, the courtyard is incompatible to modern architecture.

In the case of the proposed modern systems, in addition to the issues outlined above, and from an architectural point of view, some of them have a little resemblance to the traditional constructions that lead to a reduction in visual communication with the former ones. A survey of the literature reveals that the acceptable level of indoor comfort and savings in energy is based on the wind catcher integrated with evaporative cooling system. Furthermore, wind catcher and solar chimney were placed in two separate parts of the building as two different concepts, consequently, not united.

Originality

The wind and the sunlight in Hot-Dry regions were two major factors in the design of the traditional architectural elements that helped provide comfortable conditions for habitants in this climatic [72].

Scholars debated the importance of the two driving forces in wind catcher- wind and buoyancy effect- some emphasize the first force as the primary motive of passive ventilation, while others emphasize the second force. Several of them have proposed buoyancy effect and the difference in the density of the air in inside and outside as the main force of passive ventilation in the structures. Meanwhile, others have shown the effectiveness of these two forces equally.

Test results using computational fluid dynamics have showed the ventilation efficiency of the system by external wind is 76% more than the buoyancy effect [73]. The study on four-sided wind catcher indicates that at 61.5 % of the wind incidence angles, the exhausting air to outdoor, is more than the sucked air from outside, although the proportion rates of the two flows are approximately equal to each other at other angles. [13]. Consequently, when there is wind, the wind catcher is more in a traditional mode as an internal air suction.

Moreover, their studies have suggested that the installation of a window could provide additional external winds and could increase the internal air conditioning by 47% compared to only relying on buoyancy force. The optimal speed occurs when there is a window to strengthen the wind effect and a heat source to enhance the buoyancy effect [36].

However, in Hot-Dry areas, the windows need to be small to reduce absorbed solar radiation. Therefore, a separate ventilation system, passive or mechanical devices, could be an application to provide air movement while windows just have served natural daylight purpose [37].

A conventionally wind catcher is an internal air suction for the dissipation of the heat, rather than supplying ambient cool air, the applying of cooling equipment inside the system only leads to energy loss. The system attempts to increase the contribution of the buoyancy effect to wind pressure in the blown airflow into the building.

Considering those two presented approaches:

1) The air passes through the wet pad units hanged in the air inlet opening which leads to a reduction in temperature and an increase in density of the air that subsequently results in the downward movement as the buoyancy effect [74].
2) In some conduits that are solar chimney, intensifying the buoyancy force cause the hot air to rise and leave the conduit. Then the fresh cool air is replaced through other channels. However, the only source for fresh air supply are the channels of the wind catcher.

The wet blades section are used to increase the evaporative cooling capacity of the system. Moreover, to improve performance at the various wind incidence angles, the wind catcher is designed in four-sided shape and the pads units, around the vertical axis, can be rotated.

Chapter 4

Proposed Wind Catcher

Wind catchers are one of the oldest cooling systems that are employed to provide sufficient natural ventilation in buildings. This study proposed a four-sided wind catcher. The performance of the designed system was evaluated using two methods with the help of a laboratory scale model.

Wind Catcher Description

The designed device is a four-directional wind system that was equipped with two evaporative cooling parts (wetted blades and adjustable opening pads), supplemented with a solar chimney structure. The construction has a foursquare cross-section, and its dimensions have been determined using the results of the previous studies conducted by Bahadori at al. and Yavarinasab [40, 48]. Figure 15 illustrates the main components of the proposed system.

Wind Catcher Components

It comprises of a head, which is the upper part of the structure and includes a flat roof, some openings on four sides and hinged evaporative cooling units, two air outlets, solar absorber plates and grid screen mounted to prevent insect entry. The hinged pads operate like a filter. Likewise, the water sprayers which placed on the top of pads in intended to soak them. The hinged pads can be positioned in two different modes, opened and closed, using an ON/OFF switch in a swinging motion.

The column, the middle part of the wind catcher, consists of some ceramic parapets which are located in the middle of the base of the column and extended to top of structure in the shape of "H". Inside main conduits, there is a wetted blades section with vertical cloth curtains. Blades are erected from the bottom of the heat and is extended to the air distribution window. Water spraying pipes designed to sprinkle water on the curtains. The excess water is collected in a container located at the bottom of shaft and will be recirculated in the system.

Moreover, two small conduits that located between warm air outlets of the room and the air outlets in the head act as a solar chimney. A window, which deploys at the lower end of the column, distributes the fresh and cold air (comes from the wind catcher) into the building. Other windows, on top of it, exhaust polluted air through of chimney to out.

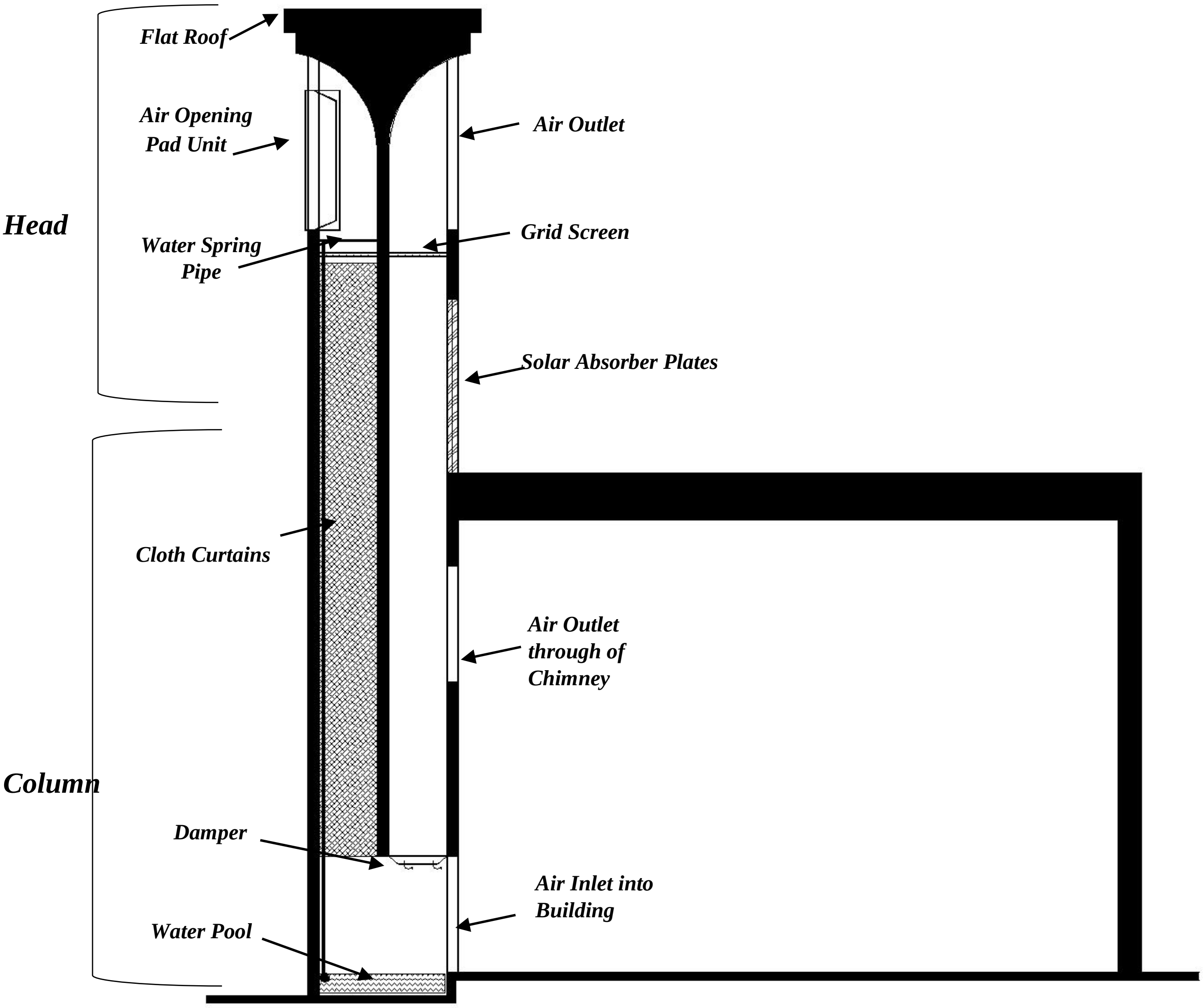


Figure 15. The components of the proposed wind catcher

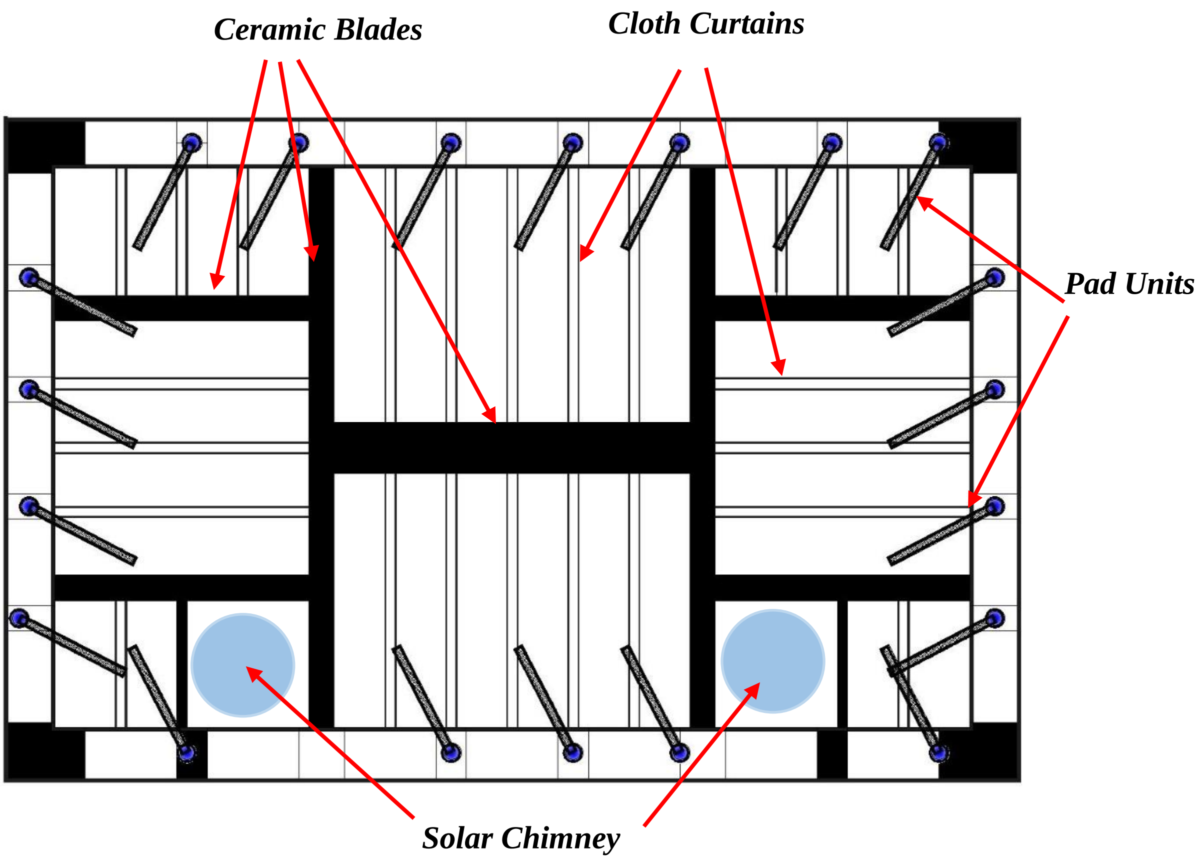


Figure 16. The plan of the proposed wind catcher

Using wind catchers is generally considered as a smart way of utilizing wind energy directly in a building, which has provided thermal comfort and passive ventilation for building inhabitants in the Hot-Dry climate [43, 75]. In presence of a desirable wind speed, wind catcher acts as a ventilator in which the fresh air is taken into the building and the hot and polluted air discharged based on wind pressure [29]. Indeed, wind speed is the most dominant driving force for moving the air through the conduit. The proposed system attempts to augment the efficiency of the system using integrated parts and structure in which blown airflows into the building, while the wind speed is low.

The water nozzles, which installed on the top of the pad unit and the blades section is intended to make them wet. Moreover, it increases the driving force of the buoyancy effect. The concept works based on the absorption of the relatively large amount of energy needed for evaporation of water from the air in the vicinity of the wetted surface. This action leads to a reduction in temperature and an increase in density of the air that subsequently results in the downward movement of the fresh air through the wind catcher [76].

The pad unit and the blades section support the system to retain a balance between the two essential parameters of evaporative cooling and ventilation to provide thermal comfort. Evaporation cooling is a passive cooling system, which is one of the most effective methods and known for creating thermal comfort in the hot and dry climate in the old architecture [77]. In this technique, as a physical phenomenon, the heat of air is used to evaporate water that results in air temperature reduction. It can be efficient in a dry climate where increasing air moisture content can improve the occupant's comfort [77].

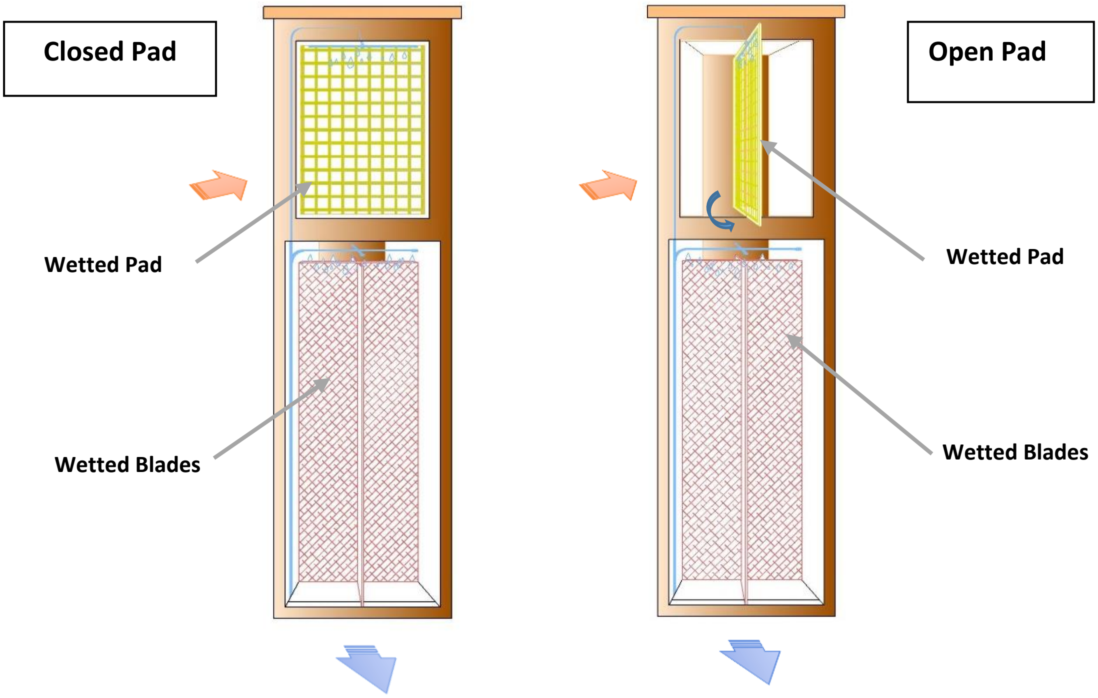


Figure 17. The schematic view of the proposed wind catcher with open and closed pad

The traditional wind catchers were a combination of the air inlets and outlets. Therefore the chimneys were considered as a part of the wind catchers in the past [39]. Some disparate conduits, made by blades in wind catcher, at a given time work as fresh air inlet duct. The other channels operate to exit polluted air based on the chimney effect, as the environmental conditions change, the flow pattern will reverse [28].

The chimney effect is based on the principle that air density decreases with an increase in temperature. Depends on the sunlight direction, the airflow is heated in the conduits located on the side and flows upward. The difference in temperature between the interior and exterior parts and between different regions creates different pressures and result in air currents [25]. Due to the mass and heat capacity of the materials used in current and traditional wind catchers, the amount of cooling energy stored is relatively small. This amount of energy cannot meet the cooling needs of a hot day.

A solar chimney essentially is a solar air heater, which is designed to maximize the absorbance of solar energy and thereby the air movement [78]. As air is a transparent fluid, it cannot be directly heated by solar radiation. Therefore, a solar chimney must contain a solar absorber; a surface made of a material which absorbs solar radiation, and allows solar heat to be transferred to the air using convection. This converts solar energy (heat) into kinetic energy (motion) of air [77]. Solar collectors can be used as aids to promote stack effect ventilation and wind catcher performance in times or areas of little wind speed [8, 63].

Chapter 5

Evaluation of the Proposed Wind Catcher

In the Hot-Dry climate, high temperature during hot seasons, diurnal temperature fluctuations, as well as intense sunlight and relative drought influence the climatic specifications. Since the thermal comfort depends greatly on the variable characteristics, the wind catcher could play a decisive role in providing comfort to the inhabitants by cooling the air and increasing the relative humidity of the building space without letting the sunlight to enter.

The proposed wind catcher system intended to address the residents' thermal comfort needs better. In order to analyze the performance of the system, a simplified prototype based on the principles of the proposed system was developed. The pad unit and the blades section that acts as evaporative cooling techniques and a solar chimney which intended to improve ventilation are two main mechanisms that have been integrated into the design of wind catcher. This simple model was evaluated in two stages, including performance evaluation of the evaporative cooling system as well as the analyzing the effect of including a solar chimney presence within a wind catcher.

Modeling of the Proposed Wind Catcher

Prototype Description

The prototype had a height of 2.5 m, cross-section of 0.40 × 0.20 m, including the input conduit and the air outflow conduit (solar chimney), with the air openings extended 0.40 m above the device. Table 9 depicts other dimensions of the wind catcher.

Figure 18. The metal structure of the model before installing the wall

The walls were constructed from a 6 mm thick polycarbonate plate with its outer surfaces covered by a shiny aluminum sheet to minimize solar radiation absorption. Inside the input conduit, there is a blade section with a cross (+) shape configuration which was made up of four gunny sack curtains with a width of 0.10 m and length of 1.80 m.

Figure 19. The blade section with plus shape and gunny screens

A 1 cm thick straw layer, constructed as a pad, was installed in the air inlet opening.

Figure 20. Constructed pad is installed in prototype wind catcher

Drip tubing is used to spray water on the pad and the blades.

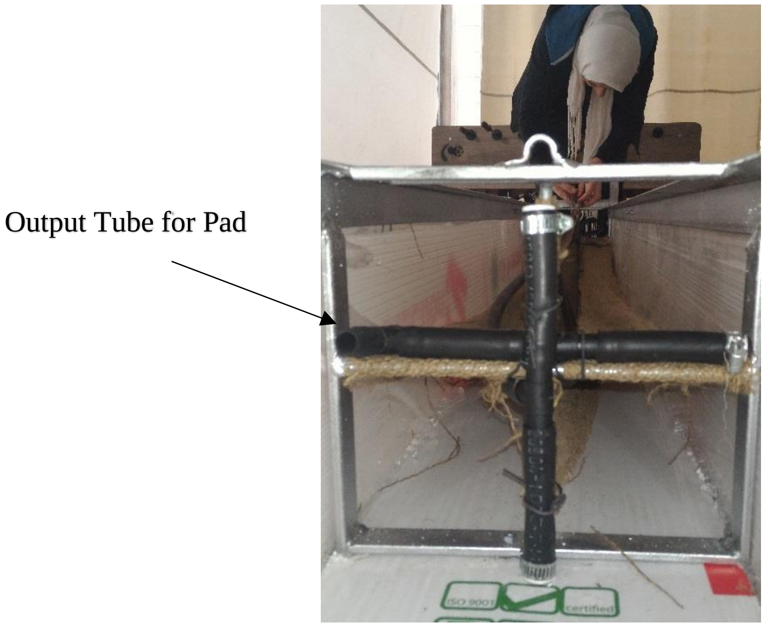


Figure 21. Drip tubing mounted on blades

A window, which deploys at the lower end of the system is the outlet of system. Moreover, the opening in south is blocked by a panel, therefore the structure can operate as a one-sided wind catcher. Table 9 summarizes the geometrical specifications of the system.

Table 9. Geometrical specifications of the prototype system

S. No.	Geometry	Measurement
1	Area of wind catcher opening in north	0.1*0.4 =0.04 m^2
2	Area of wind catcher opening in south	0.1*0.4 =0.04 m^2
3	Room inlet opening area	0.16*0.15 =0.024 m^2
4	Length of the collector (glazing)	0.25 m
5	Breadth of the collector	0.1 m
6	Area of chimney opening (inlet from room)	0.16*0.15=0.024 m^2
7	Height of wind catcher	2.5 m
8	Dimensions of wind catcher plan	Inlet channel with plus blades shape) 0.2*0.2 m Outlet channel (chimney) 0.1*0.2 m

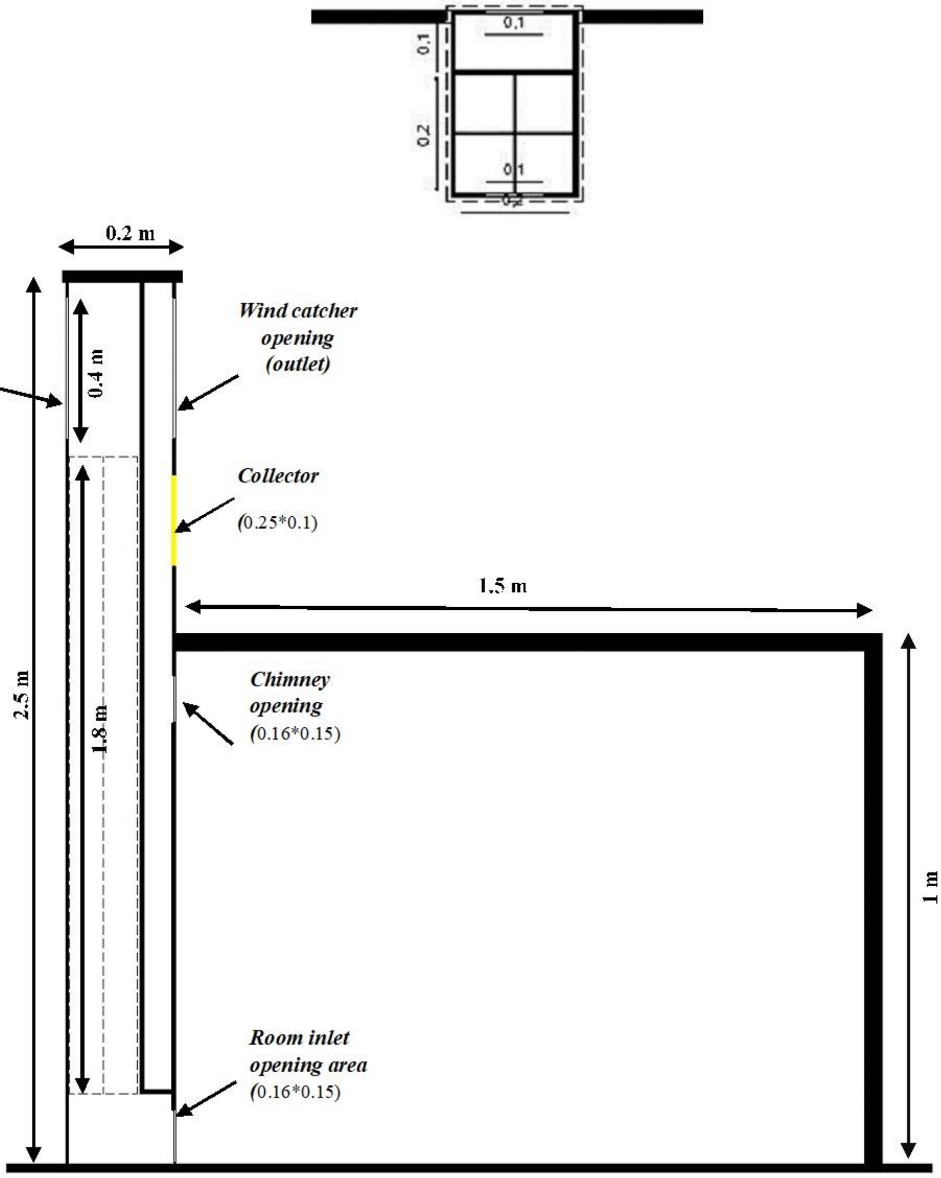


Figure 22. A simplified longitudinal section of wind catcher and room

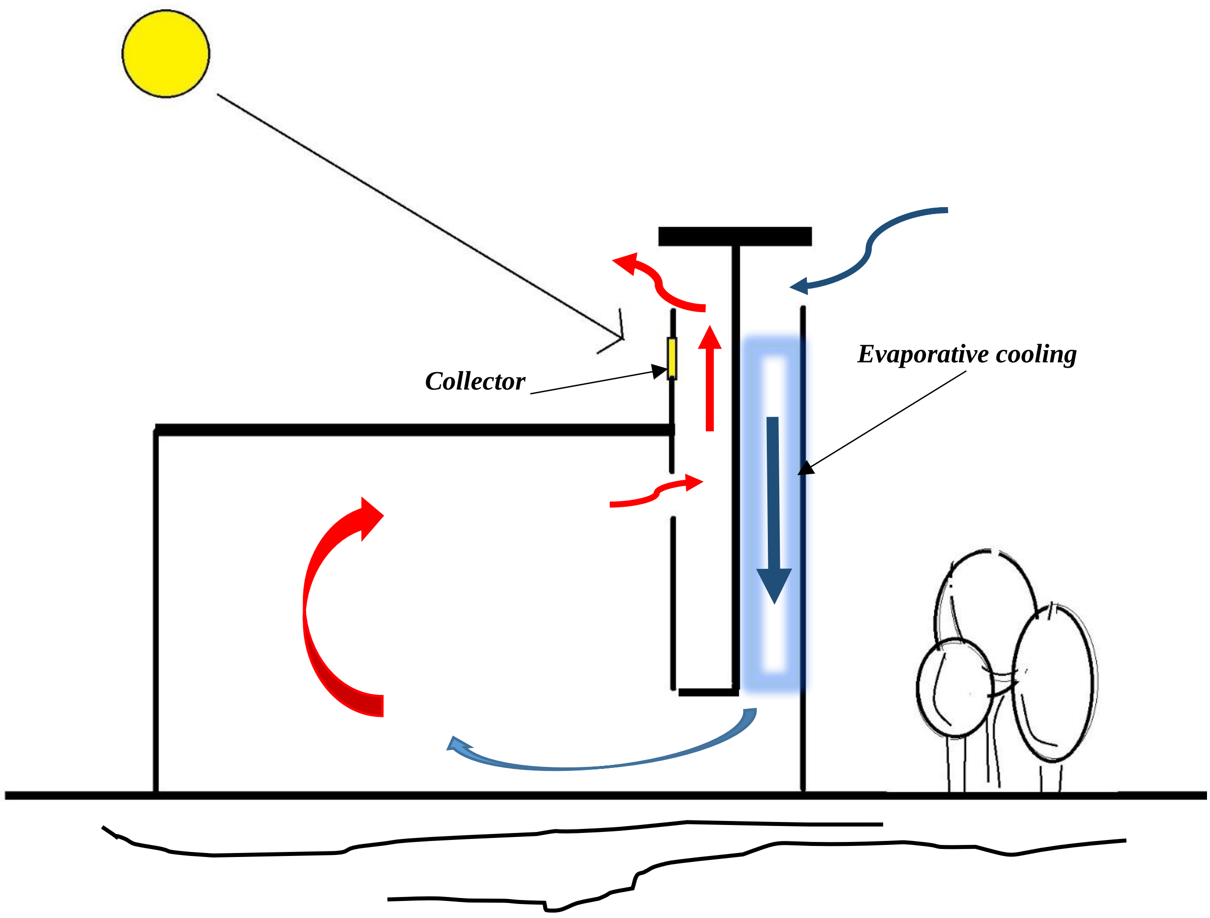


Figure 23. Schematic diagram of the prototype wind catcher performance

Evaluation Method of the Evaporative Cooling System

Wind catchers cause natural cooling in two ways, displacement and evaporative cooling [54]. Evaporative cooling can be generated naturally when an airflow passes through a wetted medium or a water source. In the assembled structure, the pad unit and the blades section are soaked up with water spray and enhance natural cooling.

Analytical Modelling

An analytical modelling has established to assess the temperature and humidity variations of the airflow rate through the constructed wind catcher. Inlets opening is located at the top of the system in north orientation. Moreover, in this section the solar absorber plate is removed, as well as, the inlet openings on the other sides are blocked. Considering this assumption the system acts as a one-sided wind catcher. A window, which deploys at the lower end of the column is the outlet of system.

When the pad is closed, the air passes through the wetted straw, and the water evaporation reduces the temperature and increases the relative humidity (RH) of the flowing air. On the other hand, when the pad is open, the entering airflows parallel to the pad. So, the pad acts like a screen.

The temperature drop of the air when passing through the wetted straw is obtained by the following expression [79].

$$T_t = T_a - \eta(T_a - T_{wb}) \tag{1}$$

where η is the efficiency of the straws, T_a and T_{wb} are respectively dry and wet bulb temperatures of ambient air (°C), and T_t defines the air temperature after the pads (°C). The efficiency of the pad depends on the thickness of the straw (d_p) in centimeter and airspeed through the pad (v_i) in meters per second as the equation

$$\eta = f(v_i) + L(d_p)$$

$$f(v_i) = \begin{cases} -0.02325V_i + 0.899 & v_i < 1\text{m/s} \\ -0.0452{V_i}^4 + 0.26{V_i}^3 - 0.635{V_i}^2 + 0.57774V_i + 0.714 & v_i > 1\text{m/s} \end{cases} \tag{2}$$

$$L(d_p) = \left[0.04631 - 1.444 * 10^{-3} d_p\right] \ln \frac{d_p}{2.5} \tag{3}$$

Since the evaporative cooling by the pad is assumed to be an isenthalpic process, the humidity ratio (ω) of the air behind the pad is given by the following expression

$$(\omega)_t = \frac{C_p T_a + (\omega h_g)_a - C_p T_t}{(h_g)_t} \tag{4}$$

where C_ρ is the specific heat of the air (J/(kg K)), T is the dry air temperature, ω is the humidity ratio of the air (kg/kg), and h_g is latent heat. t and a refer to the interior and exterior airflows, respectively.

In the second part, the entering air passes through the conduits. To determine temperature and RH variations of the air inside the conduit, its height is divided to smaller parts (with a length of 0.5 m) in which the wall and ambient temperatures, solar radiation, and wind speed were assumed to be constant. According to the trial and error method, the changes in the length of fewer than 0.5 meters are negligible. When the pad is open, it operates like the screens inside the conduit. A similar calculation has been considered for the open pad. Therefore, it assumed as the first part of the conduit unit.

The energy balance equation for each part of the column can be written as [80, 81].

$$\begin{gathered} I_s \alpha b_s + h_o b_s (T_a - T_s) + I_e \alpha b_e + h_o b_e (T_a - T_e) + h_o (b_w + b_n)(T_a - T_n) \\ + \dot{m}_a C_p (T_{in} - T_{out}) = \dot{m}_v L_v \end{gathered} \tag{5}$$

where b is the area of the walls (m^2), I is solar beam on the walls (W/m^2), α is the wall absorptivity (decimal), $\dot{m}_a$ is the mass flow rate of the wind entering the wind catcher (kg/s), C_p is the specific heat of the humid air (J/(kg K)), h_o is convection heat transfer coefficient of ambient air (W/(m^2 K)). L_v is the latent heat of the evaporation (J/g) and the subscripts *s*, *e*, *w*, and *n* refer to the south, east, west, and north walls of the wind catcher, respectively.

The rate of the water vaporization is calculated by [82].

$$\dot{m}_v = h_D A_m (w_c - w_a) \tag{6}$$

where h_D is the mass transfer coefficient (g/(m^2 s)), A_m is wetted surface of the column (m^2), w_c is the humidity ratio of the saturated air at the desired temperature. w_a is the humidity ratio of the inner airflow. Mass transfer coefficient can be expressed as

$$h_D = \frac{h_i}{C_\rho} \tag{7}$$

where h_i is the inner convection heat transfer coefficient of the air (W/(m^2 K)) which was given by Equation (8).

$$h_i = 2.8 + 3v_i \tag{8}$$

Finally, the cooling load calculated the various parts of the column as

$$Q_c = \dot{m}_a C_p (\Delta T) \tag{9}$$

To obtain the air velocity inside the wind catcher, we use the expression [40, 79, 83].

$$f \frac{L}{D} \frac{V_i^2}{2g} + \Delta P_p = \frac{1}{2} C_{pw} \rho V_w^2 + \frac{gZ\rho}{R} \left[\frac{1}{T_o} - \frac{1}{T_a} \right] \tag{10}$$

where *f*, *L*, *D*, C_{pw}, *Z*, v_w, T_o, and *R* respectively show the friction coefficient of the conduit (dimensionless), length of the conduit (m), hydraulic diameter of the conduit (m), the pressure coefficient of wind (dimensionless), height of the wind catcher (m), wind velocity (m/s), outlet temperature of the wind catcher (°C), and the gas constant for air (J/(kg K)). ΔP_p stands for pressure drop in the opening pad which has been calculated using the empirical expression

$$\Delta P_p = \begin{cases} 1.029 v_i d_p^{0.755} & v_i < 1m/s \\ 4.9(0.1885 v_i^4 - v_i^3 + 2.091 v_i^2 - 1.42 v_i + 0.4056) d_p^{0.755} & v_i > 1m/s \end{cases} \quad (11)$$

Experimental Procedure

In order to evaluate the performance of the system under real operating conditions, as well as to validate the obtained analytical expressions, a set of experiments were carried out during the month of May 2017 at the campus of Bozrgmehr University, located at Qaen (33°43′36″ N and 59°11′04″ E) a small city at east side of Iran. According to Köppen and Geiger, this climate has been classified as a cold desert climate (BWk). The average temperature in the warmest month of the year is 27.6 °C.

Since the wind speed was mostly fluctuating during the test period, a blower (Pars200 modle, Parskhazar co., Tehran, Iran) with an adjustable rotary speed was utilized to provide a constant air velocity inside the wind catcher’s conduit in north orientation. The tests were conducted at three increasingly levels of wind velocity through the conduit (1, 1.5 & 2.5 m/s). Moreover, the wetted pad is fixed at closed mode during the tests.

Five temperature sensors (SMT160 moled, Tika co., Tehran, Iran) were used to measure temperatures of the inlet (opening is placed at the top of the system in north orientation), outlet (located at the bottom of device), and outer surfaces of the walls of the wind catcher as well as ambient.

The sensors were connected to a personal computer through a temperature transmitter (TM 1323 model, Tika co., Tehran, Iran). A solar power meter (TES 1333 model, TES co, Taipei, Taiwan) was utilized to measure solar radiation intensity on the south and east walls. Relative humidity (RH) of ambient air, the inlet, and the outlet of the wind catcher were determined using RH sensors (SUN-25H model, SUNWARD co., Tehran, Iran). Each test was conducted in a time frame from 9 a.m. to 3 p.m. The data were recorded at 30 min time intervals during the day. Tables 10 to 12 show the reported weather data on through three days.

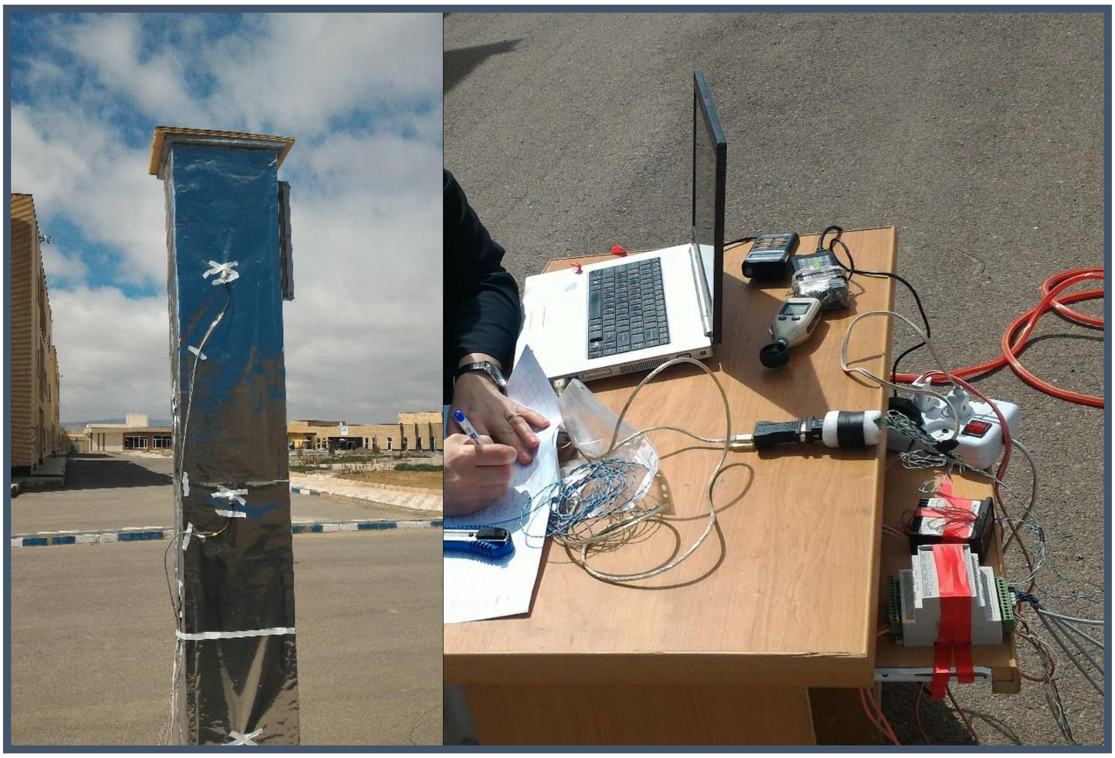


Figure 24. The sensors were connected to a personal computer by means of a temperature transmitter

Table 10. Reported weather data for the first day

Time	T_a(°C)	T_s(°C)	T_e(°C)	T_n(°C)	V_W(m/s)	V_i(m/s)	I_s(W/m2)	I_e(W/m2)	RH
09:00	27.00	29.60	29.40	26.20	2.5	1	520	612	14
09:30	27.60	30.00	29.70	26.90	2.3	1	588	587	14
10:00	27.90	30.50	30.30	27.40	2.9	1	633	566	13
10:30	28.40	30.90	30.60	28.00	3.1	1	694	546	13
11:00	29.00	31.30	30.80	28.50	2.5	1	734	532	13
11:30	29.60	31.30	31.10	28.90	3.3	1	785	458	12
12:00	30.00	31.40	31.30	29.30	3.4	1	805	365	12

12:30	30.60	31.20	30.50	30.00	4	1	810	279	12
13:00	30.80	31.60	29.80	30.20	3.7	1	807	197	12
13:30	31.10	31.80	29.20	30.90	4.5	1	777	142	11
14:00	31.20	32.10	28.90	30.70	4.8	1	750	87	11
14:30	30.90	31.70	28.10	29.50	5.2	1	635	55	11
15:00	30.00	31.20	27.80	29.30	5.9	1	570	0	12

Table 11. Reported weather data for the second day

Time	T_a(°C)	T_s(°C)	T_e(°C)	T_n(°C)	V_W(m/s)	V_i(m/s)	I_s(W/m2)	I_e(W/m2)	RH
09:00	26.80	28.90	28.80	26.30	2.2	1.5	513	597	15
09:30	27.20	29.10	28.90	26.70	2	1.5	570	567	15
10:00	27.45	29.10	29.20	27.30	2.5	1.5	620	504	15
10:30	27.90	29.40	29.70	27.80	3.2	1.5	630	429	14
11:00	28.30	29.60	30.10	28.15	3.3	1.5	685	358	14
11:30	28.80	30.00	30.60	28.50	3.2	1.5	720	286	14
12:00	29.50	30.50	29.80	28.85	3.5	1.5	778	220	13
12:30	30.20	30.60	29.50	29.30	3.8	1.5	798	190	13
13:00	30.70	31.30	28.90	29.90	3.4	1.5	802	136	13
13:30	31.00	31.80	28.20	30.50	4.2	1.5	806	75	12
14:00	30.90	31.80	28.10	30.20	4	1.5	790	40	12
14:30	30.40	31.25	27.70	29.70	4.6	1.5	745	0	12
15:00	30.20	31.00	27.50	29.20	5	1.5	603	0	12

Table 12. Reported weather data for the third day

Time	T_a(°C)	T_s(°C)	T_e(°C)	T_n(°C)	V_W(m/s)	V_i(m/s)	I_s(W/m2)	I_e(W/m2)	RH
09:00	27.60	29.9	29.8	27	3	2.5	525	622	14
09:30	28.20	30.6	30.2	27.5	3.5	2.5	600	605	13
10:00	28.25	31.05	30.4	28.2	2.9	2.5	368	580	13
10:30	28.55	31.6	31	28.9	3.2	2.5	706	565	13
11:00	29.30	31.9	31.3	29.1	2	2.5	758	541	12
11:30	29.80	32.2	31.4	29.7	2.5	2.5	809	477	12
12:00	30.20	31.7	31.8	30.2	1.5	2.5	820	384	12
12:30	30.90	31.8	30.9	30.7	3.1	2.5	835	293	11
13:00	31.20	32.15	30.2	31	4	2.5	810	219	11
13:30	31.40	32.7	29.3	31.5	5	2.5	780	162	11
14:00	31.80	32.1	28.5	31.3	4.8	2.5	755	95	11
14:30	31.20	31.8	28.2	30.4	4.2	2.5	660	35	12
15:00	30.60	31.3	27.8	30.1	6.3	2.5	580	0	12

Experimental Validation

To verify the obtained expressions, the results of the models were compared with those of experiments using the Pearson correlation coefficient (r), the root mean square deviation (e) and the mean absolute error (MAE) criteria which were determined as [84, 85]

$$r = \frac{N\sum X_i Y_i - (\sum X_i)(\sum Y_i)}{\sqrt{N\sum X_i^2 - (\sum X_i)^2}\sqrt{N\sum Y_i^2 - (\sum Y_i)^2}} \tag{12}$$

$$e = \sqrt{\frac{\sum (e_i)^2}{N}} \tag{13}$$

And

$$MAE = \frac{1}{N}\sum e_i \qquad (14)$$

Where $e_i = \left[\frac{X_i - Y_i}{X_i}\right]$, Xi and Yi are respectively the ith theoretical and empirical data; and N is the number of observations.

The Analysis of the Presence of the Structure of a Solar Chimney

One of the passive ventilation methods is the use of a solar chimney that provides ventilation for adjacent spaces with the help of renewable solar energy and uses the effect of a chimney in an air channel. In this system, the airflow is created by the buoyancy force. That is, the hot air rises and leaves conduit, replacing the fresh cold air instead.

This section studies the effect of the solar chimney on the ventilation performance of the prototype wind catcher in a hot and dry climate. The airflow in the sample has two paths. In the wind catcher section, the airflow moves downward by creating a negative float. The positive airflow through the solar chimney causes a moving upward. Therefore, it creates a comfortable interior in terms of temperature and humidity by placing the appropriate cooling evaporation systems at the air inlet (located at the wind catcher section).

Computational Fluid Dynamics (CFD) Simulation

CFD is a computer-based tool design to numerically solve a wide range of fluid mechanics problems for discretized building spaces. CFD modelling techniques are more useful in determining the internal thermal and flow characteristics inside a building, which is more critical when it comes to the more detailed design of the ventilation system to ensure uniform flow distribution and to avoid local discomfort areas associated with stale air [86]. Masses of studies on solar chimneys have been conducted using CFD method and showed that the existing CFD models predict velocity and temperature profiles along with other flow characteristics accurately [87].

Many researchers have proposed different methods to investigate wind catcher’s performance. One of them is CFD-based programs which have more advantages compare to others and offer a comprehensive report of the airflow. Elmualim and Awabi [41, 62] proposed a CFD model which utilizes CFD simulation to validate laboratory measurements of C_p (pressure coefficient) in windward and leeward quadrant of a square wind catcher at normal incidence. They achieved good agreement (1% error) in windward and a less successful result (77% error) in leeward side. Li and Mak [88] compared their CFD simulation results with wind tunnel measurements of Elmualim et al. in a square wind catcher with a length of 500mm. Consequently, a good agreement was reached between the two results. The performance of a circular wind catcher is evaluated by Su Riffat [89] using the CFD model demonstrating. Hughes et al. [90] used CFD to model a 1000mm wind catcher in order to predict a net flow rate. They compared the wind tunnel experimental result of Elmualim and Awabi, and the results showed a 20% error.

Ghadiri et al. confirmed The CFD simulations with detailed wind tunnel experiments. The results demonstrated that CFD simulation is a reliable method for wind catcher study, but it is less accurate in prediction of models with non-vertical wind directions [91].

Kaiser et al. reviewed different analysis of wind catcher designs and cooling methods. They suggested that the CFD techniques in use were suitable [92]. Due to the factors mentioned earlier, CFD modelling is chosen to optimize the solar chimney design herein.

Development of the Numerical Model

Numerical simulations on the steady state airflow due to pressure/thermal gradients, the influence of various structural parameters and, the weather conditions were carried out using the customized CFD solver Fluent of ANSYS Workbench. FLUENT employs an unstructured control volume mesh with triangular meshes on the surface of the geometry. The total number of elements was 840000. The grid independence test was done.

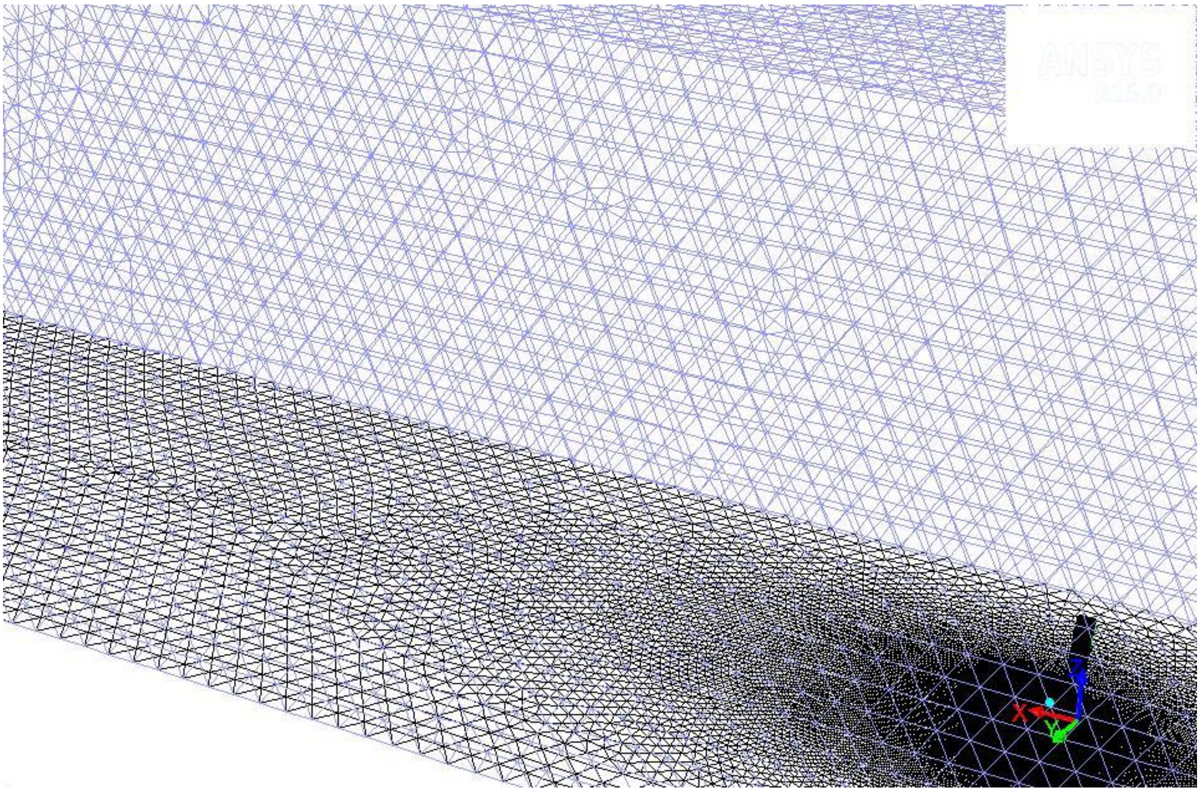


Figure 25. The view of mesh design of wind catcher model with triangular meshes on the surface of the geometry

The underlying assumptions for the CFD simulation include a three dimensional, fully turbulent, non-isothermal, and steady-state incompressible airflow. The industry standard for turbulence simulation is the k–ε turbulent model that was used for modelling of buoyancy-driven because of its robustness at a relatively low computational cost. The following equations govern the air motion for incompressible turbulent flow:

1. Continuity equation
2. Momentum equation
3. Energy equation

These equations for incompressible fluid flow can be respectively expressed as follow:

$$\nabla.\vec{V} = 0 \tag{1}$$

$$\frac{\partial \vec{V}}{\partial t} + (\vec{V}.\nabla)\vec{V} = -\frac{1}{\rho}\nabla p + \vartheta\nabla^2\vec{V} + \rho\vec{f} \tag{2}$$

$$\rho C_p\left[\frac{\partial T}{\partial t} + \left(\vec{V}.\nabla\right)T\right] = k\nabla^2 T + \varphi \tag{3}$$

where $\vec{V}$ is the velocity vector (m/s), $\vec{f}$ is the total body force per unit mass (N/kg), ρ is the specific mass (kg/m^3) and ϑ stands for kinematic viscosity of the fluid (m^2/s), T and k respectively stand for temperature (K) and thermal conductivity (W/mK), and φ, the viscous dissipation, is expressed as:

$$\varphi = (\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x})^2 + 2\left[(\frac{\partial u}{\partial x})^2 + (\frac{\partial v}{\partial y})^2\right] \tag{4}$$

where u and v are respectively the x- and y- components of velocity (m/s).

The default convergence criterion in FLUENT is 10^{-6} for the energy equation and 10^{-3} for all other equations. When the set convergence criterion is met, the iteration process is complete.

Boundary Conditions

The simulation consisted of a simple model room space with the size of 1.5*1.25*1m (length, width and height) has been combined with a one-sided wind catcher and a solar chimney. Figure 22 shows the geometry of the structure in details. The room attached to wind catcher is a closed room without any openings. Wind catcher is placed in length.

The chimney is a glazing collector at a constant temperature. The other side walls of the solar chimney are insulated, hence adiabatic. The walls of the dwelling space are assumed not to take part in heat transfer so that the solar chimney is solely responsible for the thermal buoyancy effects on air. Moreover the infrared radiation of the room walls is ignored.

The dimension of the domain was 5 times the height of wind catcher for the front and lateral of the domain based on recommended guidelines in CFD [93-95] and above the wind catcher, the height was just set at the same measurement. Behind the wind catcher the height was set (outflow direction) at least 15 times which would allow the flow to develop. Inlet velocity boundary condition is imposed on the inlet of the computational domain, while pressure exit boundary condition is imposed far downstream at the rear. No-specified shear boundary conditions at the side faces and the top face of the computational domain ensure the velocity gradients are non-existent at the sides and top.

The influence of the internal gains (occupants, equipment) and heat gain through walls were not investigated in this work. All walls of the dwelling space were assigned no-slip boundary condition for airflow.

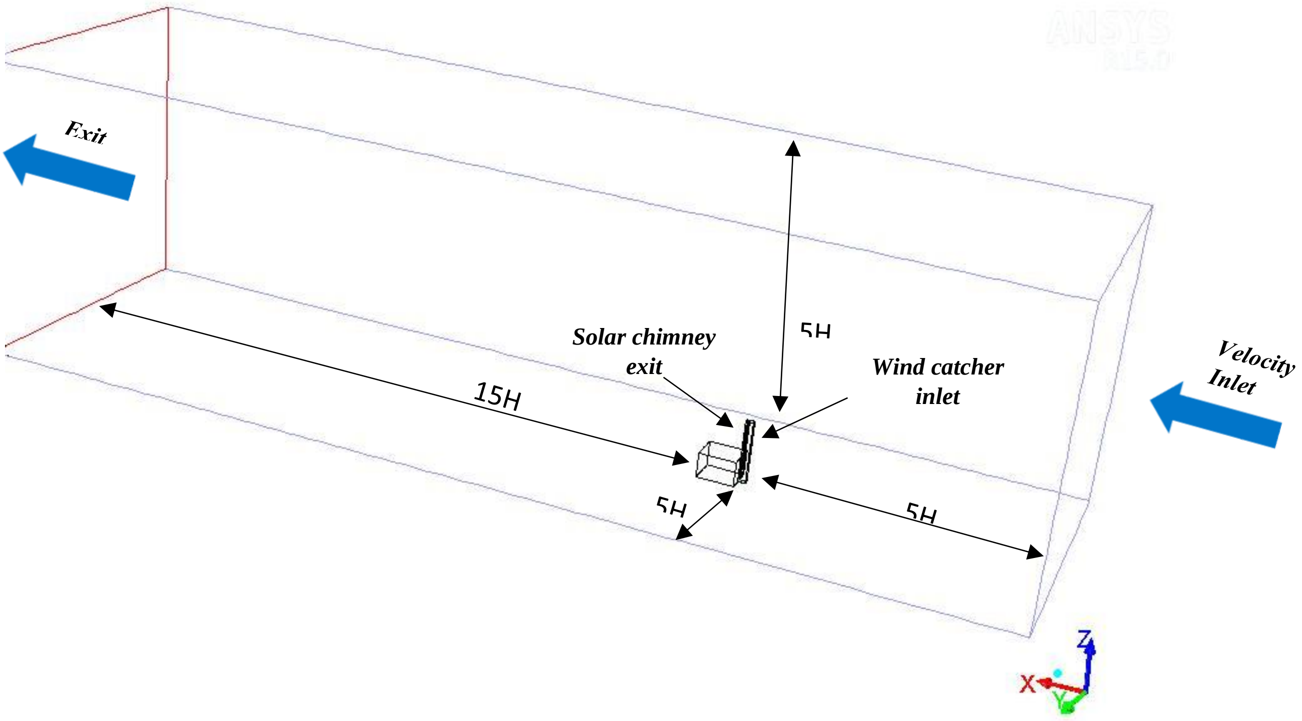


Figure 26. Schematic view of computational domain and boundary conditions for simulations on the combinatorial system

Simulation Method

In this study, also CFD simulations were accomplished to evaluate the effect of the influx of solar radiation amount on volume flow rate and air velocity at the entrance of the room. Different inlet air velocity ((the wind speed in inlet opening) (0, 3, 5 $^{m}/_{s}$)), and also the effect of increasing solar radiation on the capability of the combinatorial system are considered. A set of simulations was carried out with two different specified values for solar radiation, i.e., I = 0 and 1000 $^{W}/_{m^2}$ a normally incident on the absorber plate. These values of heat flux were imposed as boundary conditions on the absorber plate which heat flux is a result of the solar radiation on the glazing surface (collector). There are two modes that depend on the presence or absence of the evaporative cooling load ($Q_c = 0.5kW$). The inlet air temperature is fixed at 30 °C (Based on experimental work). Airflow distribution in the room is color coded and related to the CFD color map then used to obtain the simulation results in all cases as it was judged to give acceptable results taking into consideration the limitation of the studies (cost, time and computer capabilities).

Chapter 6

Results and Discussion

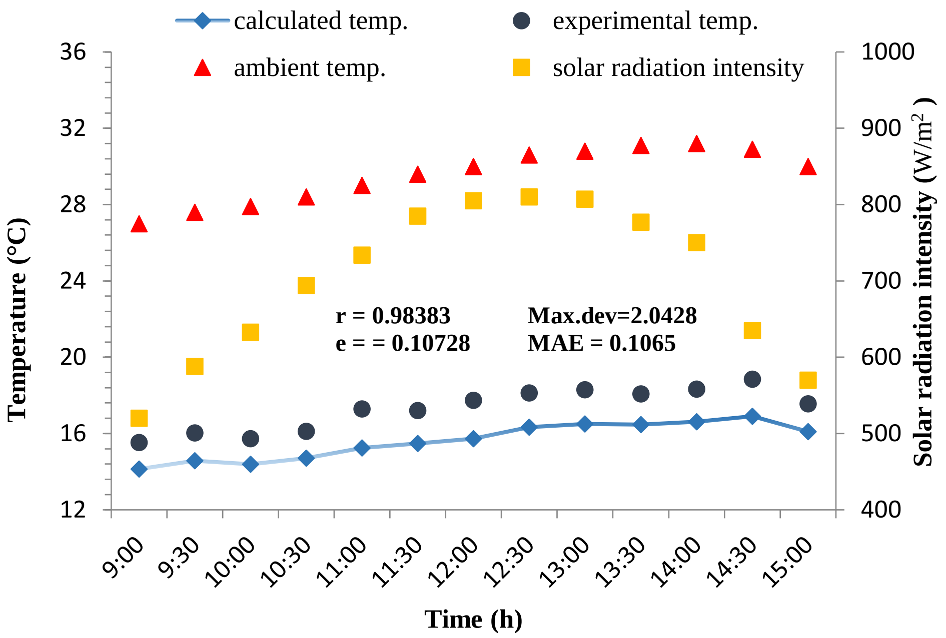
The proposed system is designed to provide thermal comfort for the residents of the building in a Hot-Dry region. The four environmental variables, temperature, humidity, solar radiation, and air movement, directly determine the thermal comfort condition. The presented wind catcher can directly improve the thermal comfort of the inhabitants, since it impresses the three variables of temperature, humidity and air movement velocity. The results of this impact are presented in two sections.

The Result of the Evaluation the Wind Catcher Integrated with Evaporative Cooling System (WCIECS)

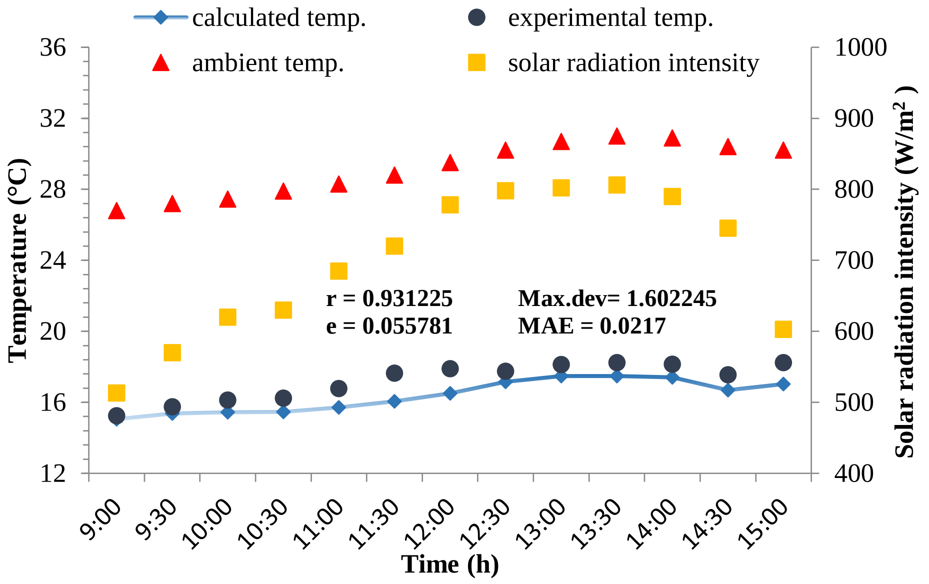
Model Verification

The predicted data of outlet temperature and relative humidity were compared to experimental observe to verify the obtained models. Subsequently, the validated models investigated the effect of some design parameters and operating conditions imposed on the performance of the designed wind catcher.

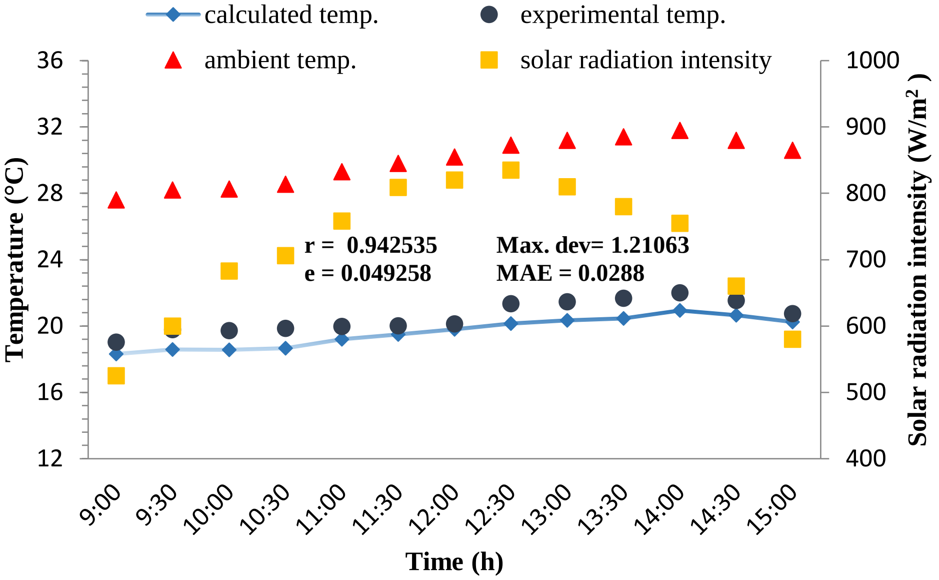
Figure 27 shows variations of solar radiation intensity, ambient temperature, and comparison between experimental and calculated outlet temperature of the wind catcher at the three inside air velocities of (a) 1, (b) 1.5, and (c) 2.5 m/s. The measurements taken during the test indicated that the temperature drop inside the designed wind catcher has been between 9.29 and 14.63 °C. The temperature decrease in a modular wind catcher with wetted surfaces founded to be in a range of 9.2–13.6 °C [75]. The root means square deviation (e) ranges from 0.04925 to 0.10728 while the observed correlation coefficient was between 0.9312 and 0.9438. The maximum deviations between the analytical and the experimental temperatures were 1.21, 1.60, and 2.04 °C at the air velocities of 1, 1.5, and 2.5 m/s, respectively. The result also indicated that minimum absolute error associated with the analytical expressions is less than 10%. A study that had been conducted to simulate indoor temperature of a greenhouse in Iraq based on thermo-physical properties of the greenhouse components showed that the predicted data had an absolute error of lower than 10% [96]. The results of similar research achieved a mean absolute deviation of lower than 20% between the predicted and the experimental temperatures of a greenhouse equipped with a heat-pump heating system [97]. According to the research observation, it can be said that the experimental data adequately reflects analytical data.



(a)



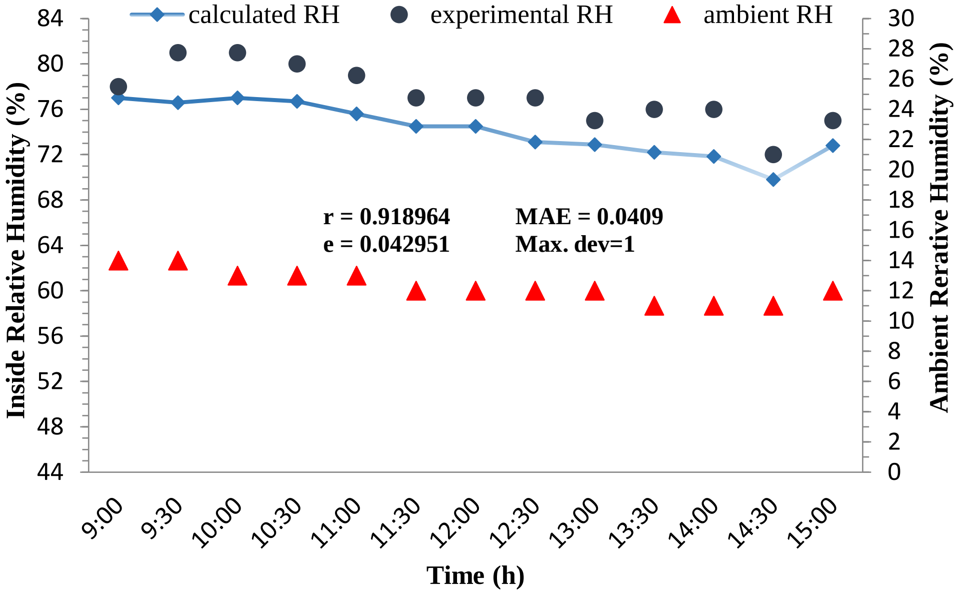
(b)



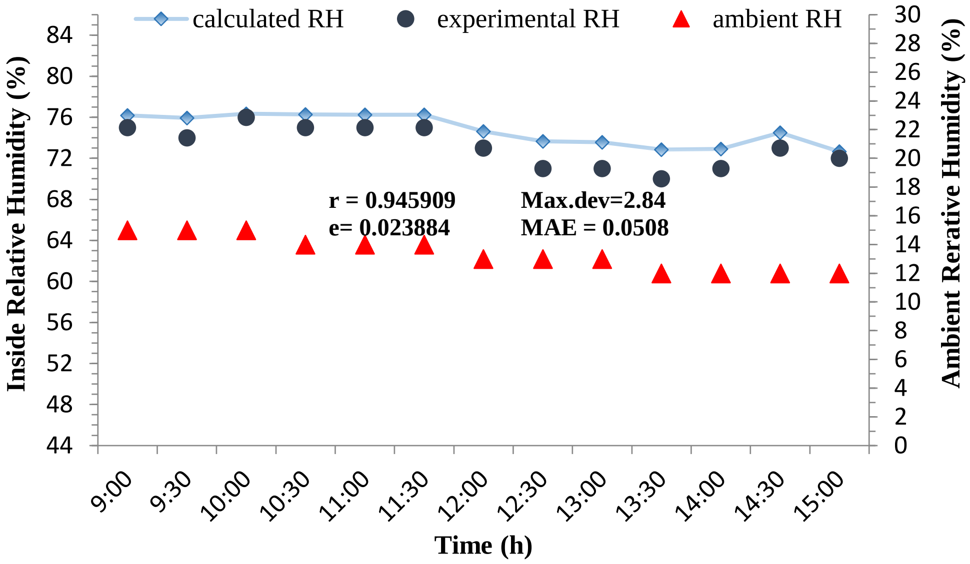
(c)

Figure 27. Hourly variations of experimental and calculated outlet air temperature under the conditions of Qaen city during 3–5 May 2017, at the air velocities of (a) 1, (b) 1.5, and (c) 2.5 m/s.

Figure 28 depicts the experimental and calculated RH variations of the airflow during the three days of the test. The figure indicates the RH enhancing of the moving air by 39.55 to 64% at the designed device. The range of RH increase in the wind catcher designed by Khani et al. [75] was from 23–53%. The root mean square deviations were less than 0.04586, the values of the Pearson correlation coefficient were more than 0.9188, and the difference between the experimental and analytical RH was less than 5%. Consequently, the resulting expressions can accurately predict the output air RH.


calculated RH
experimental RH
ambient RH
Inside Relative Humidity (%)
Ambient Rerative Humidity (%)
84
80
76
72
68
64
60
56
52
48
44
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
r = 0.918964
e = 0.042951
MAE = 0.0409
Max. dev=1
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
13:30
14:00
14:30
15:00
Time (h)

(a)


calculated RH
experimental RH
ambient RH
Inside Relative Humidity (%)
Ambient Rerative Humidity (%)
84
80
76
72
68
64
60
56
52
48
44
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
r = 0.945909
e= 0.023884
Max.dev=2.84
MAE = 0.0508
9:00
9:30
10:00
10:30
11:00
11:30
12:00
12:30
13:00
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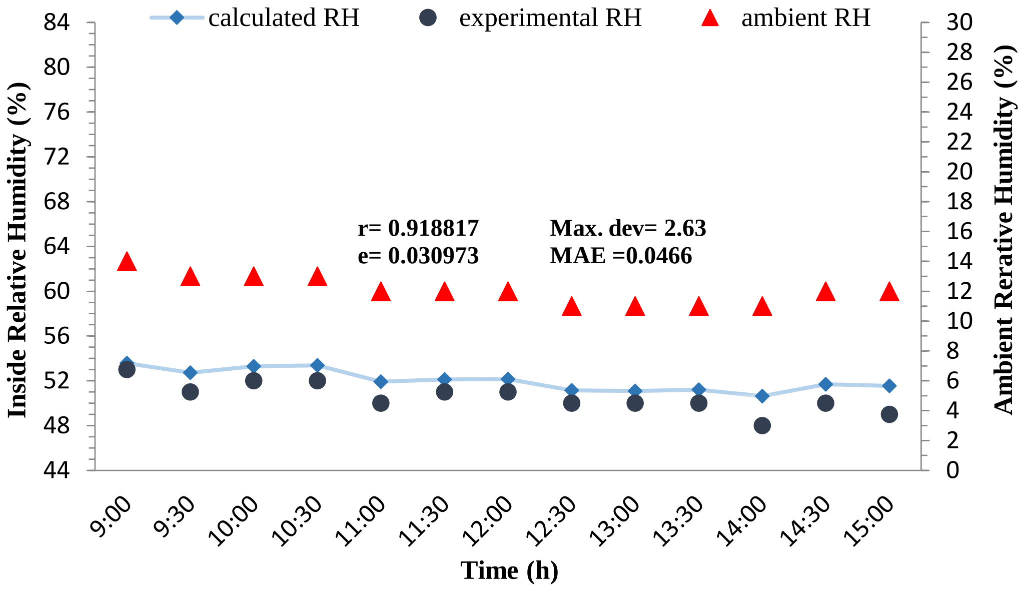
15:00
Time (h)

(b)



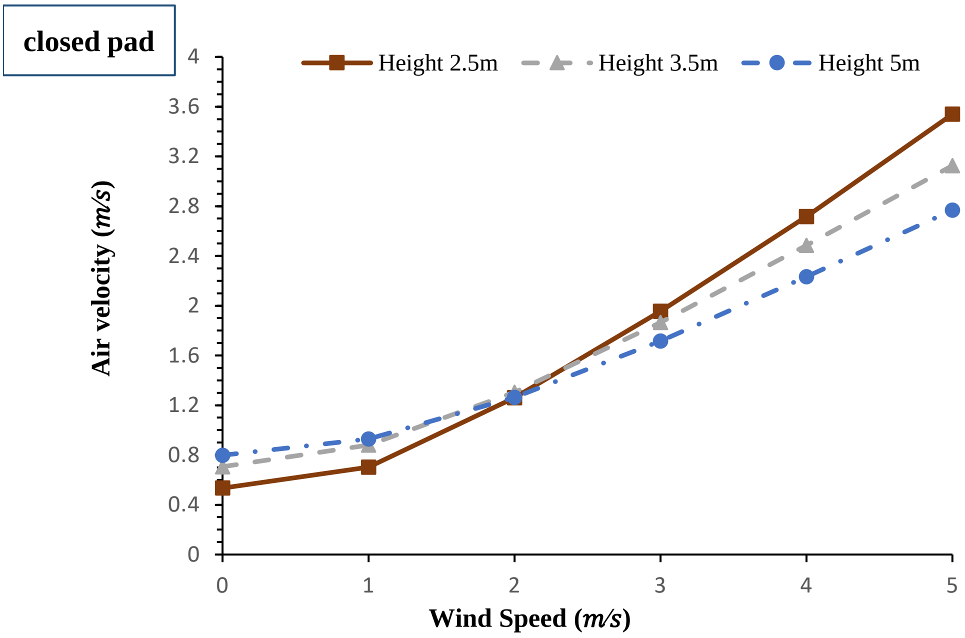
(c)

Figure 28. Hourly variations of experimental and calculated outlet air relative humidity under the conditions of Qaen city during 3–5 May 2017, at the air velocities of (a) 1, (b) 1.5, and 2.5 m/s.

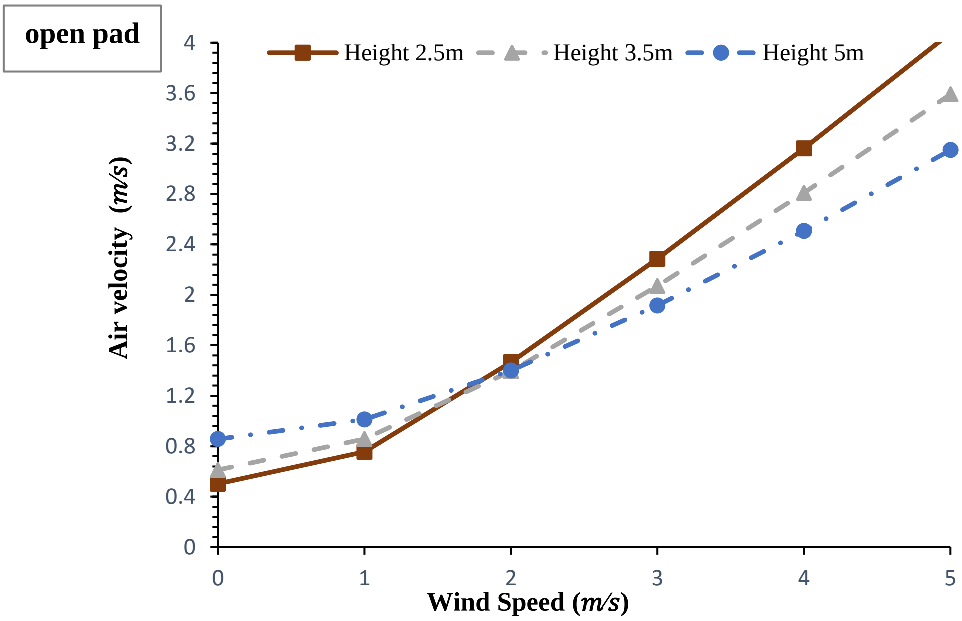
Effect of Wind Speed and Wind Catcher Height

The effect of wind speed and wind catcher height were analytically investigated on the air velocity inside the conduit, temperature, and cooling load. Since the position of the inlet pad could influence the operating parameters of the wind catcher, the tests were carried out with both open and closed pads.

Figure 29 illustrates the effect of wind velocity and height of the wind catcher on air velocity inside the conduit at the two modes of the pad (open and closed). It is apparent that the increase of the wind speed enhanced the air velocity in the column. Moreover, the rate of changes was higher at the lower heights of the wind catcher. The heightening of the wind catcher increases the pressure drop which would result in the slower growth of air velocity in the column. Likewise, figure 29 indicated that in a windy climatic condition, the air velocity was slightly higher inside the column when the pad was open. This is more due to the air pressure drop when it is passing through the pad. Vice versa, when the wind speed was low, the closed pad contributed to a relatively higher air velocity inside the wind catcher. The airflow inside the wind catcher at the condition of no external wind is under the influence of the buoyancy effect (depends on the air temperature) and the pressure drop (because of the length of the duct). Therefore, as the temperature drops at the closed-pad mode are more, the air velocities were higher compared to the open-pad mode. However, the effect of pressure drop is considerable at the taller wind catchers, which ultimately would lead to a decrease in air velocity at the height of 5 m.



(a)

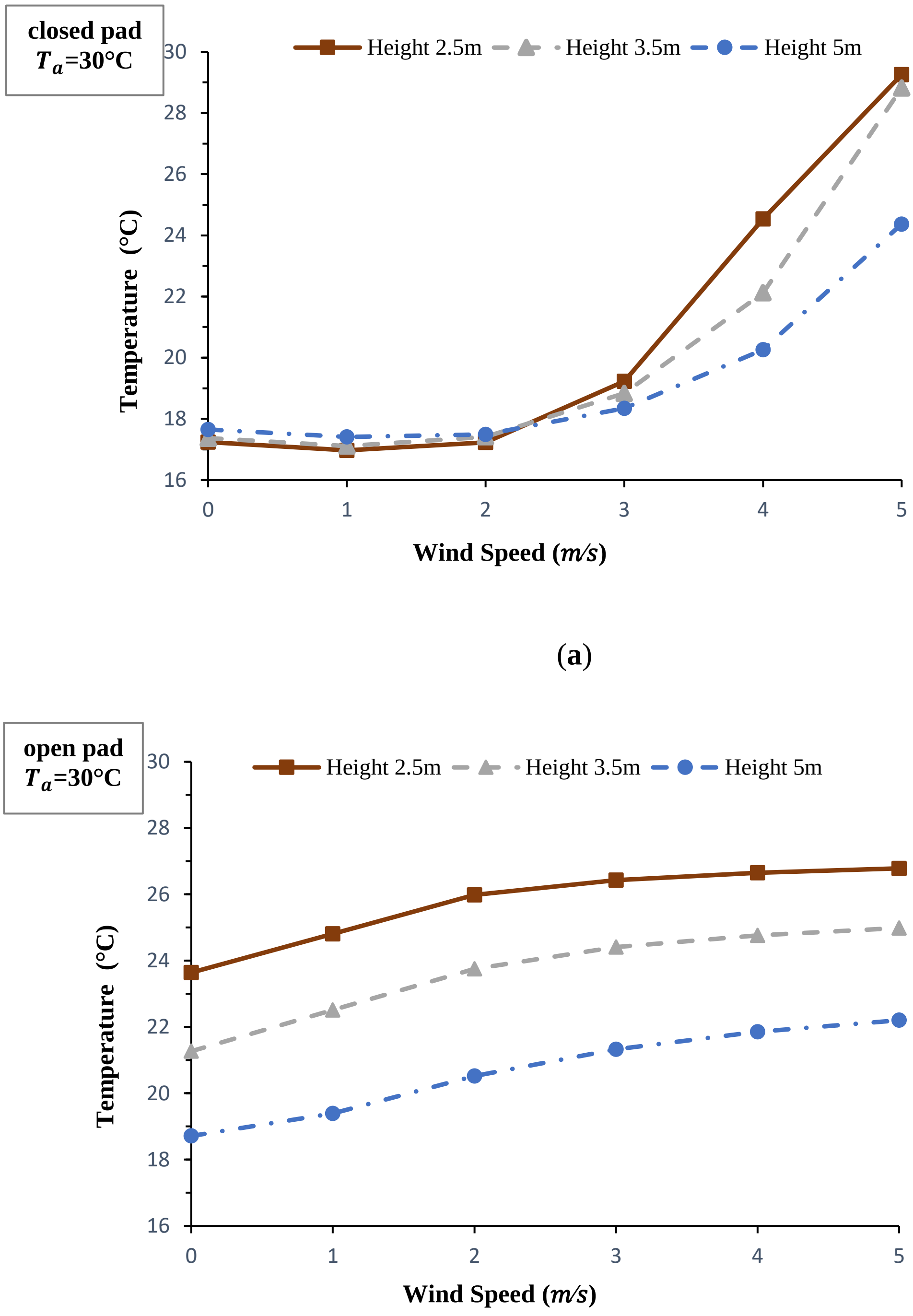


(b)

Figure 29. Effect of wind speed and wind catcher height on air velocity under the conditions of Qaen city at 12:00 p.m. on 3 May 2017 and the modes of: (a) closed pad, (b) open pad.

Figure 30 depicts the effect of wind velocity and height of the wind catcher on the outlet temperature at the two modes of the open and closed pad. When the closed pad was imposed as pad mode, the changes in wind speed and the height have a negligible impact on the outlet temperature at low wind speeds (smaller than 2 m/s). The slow passing of the air through the wetted pad makes it almost saturated, accordingly brings to the lowest possible temperature. This result demonstrates the columns after the pad is neutral on the temperature and RH of the moving air. However, at higher wind speeds, when the air velocity inside the wind catcher was significantly high, the pad unit accomplished only a fraction of evaporative cooling while the wetted columns supplied the process. Therefore, the height of the columns was a dominant factor in the amount of cooling load and the temperature drop of the moving air. When the pad was open, the outlet temperature raised with wind velocity, as the velocity of the air in the conduits of the wetted blades increased. Furthermore, increasing the height of the wind catcher has reduced the air velocity. Accordingly, the outlet temperature at the longer wind catchers was lower. Moreover, it made the wetted screens (evaporation area) more effective. On the open pad mode, the air temperature drop in the wind catchers with higher height was further, which was in accordance with the results of the wetted columns wind catcher proposed by Bahadori et al. [40].

Cooling load is directly related to the air velocity and the temperature drop in the column. Figure 31a shows cooling load variations at the different dominant wind speed as well as wind catcher height applying the closed-pad mode. It is intelligible that the increasing of the wind speed up to 3 m/s improved the amount of sensible cooling load. However, the increase in wind speed result in a decreasing trend in the cooling load. This result is mainly due to the outlet temperature increasing at the higher wind speeds suddenly and without any significant increase in the air velocity. On the other hand, when the pad was open the amount of cooling load has been continuously increased with the wind speed (see figure 31b). The comparing of the two modes of wind catcher (figure 31a,b) indicated that at the wind catcher heights of 2.5 and 3.5 m and the wind speeds of lower than 3 m/s, the cooling loads approximately doubled by employing closed-pad mode. While, at the height of 5 m, there was not a significant difference between the two modes. However, at the condition of no wind flow, a maximum sensible cooling load of 0.48 kW was achievable if the wind catcher height was 5 m.



(a)

(b)

Figure 30. Effect of wind speed and wind catcher height on outlet temperature under the conditions of Qaen city at 12:00 p.m. on 3 May 2017 and the modes of: (a) closed pad, (b) open pad.

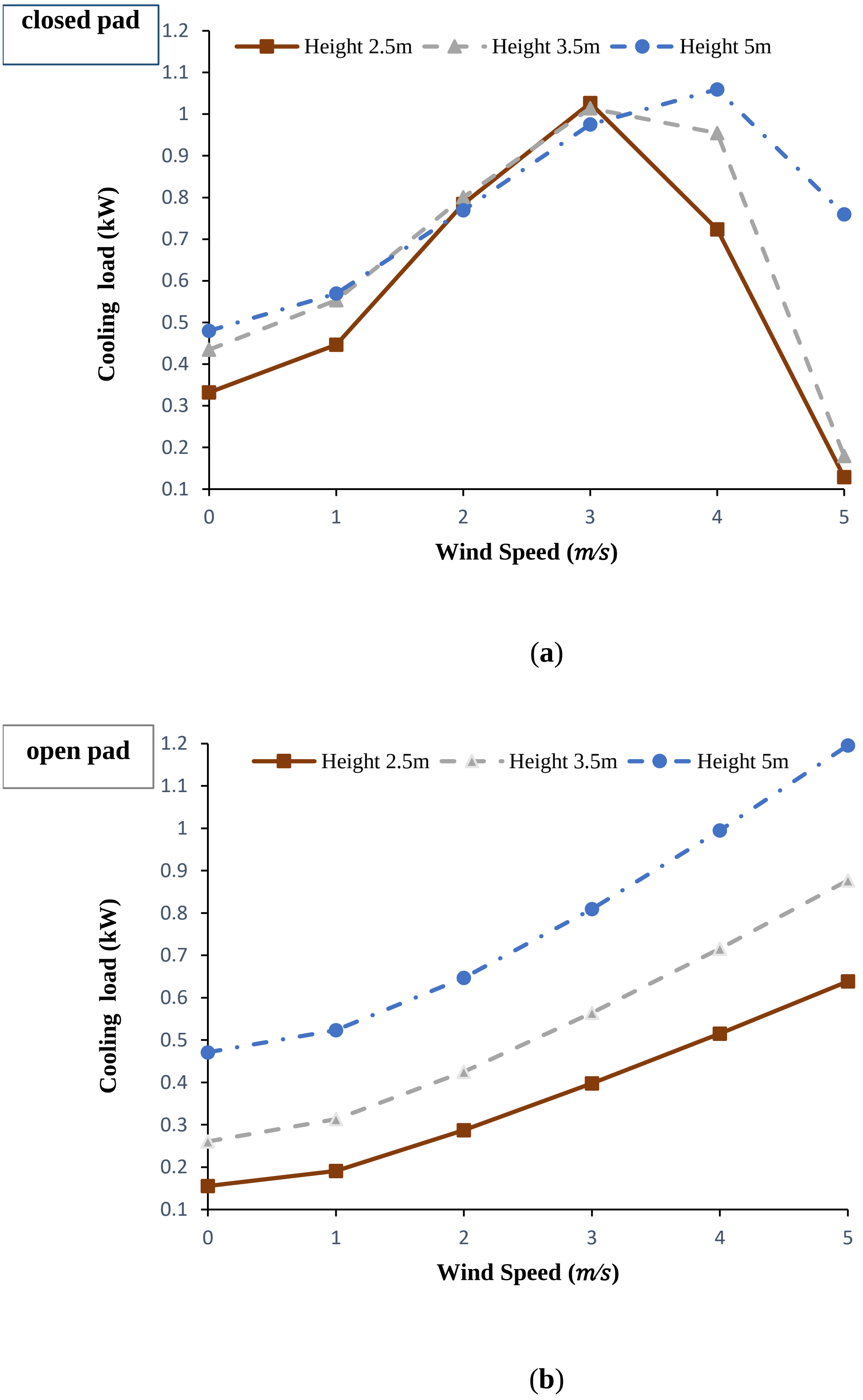


Figure 31. Effect of wind speed and wind catcher height on provided cooling load under the conditions of Qaen city at 12:00 p.m. on 3 May 2017 and the modes of: (a) closed pad, (b) open pad.

Calculating the volumetric dimensions of the room, connected to the wind catcher

The dimension of the room which is connected to the system has been calculated by the manual calculated method. The cooling load of a building depends on a number factors such as local climate, building type and thermal properties of material. . The method is now called CLTD (cooling load temperature difference), SCL (solar cooling load factor), and CLF (cooling load factor) method using simple multiplication factors.

The overall dimension of the room is assumed to be a cube by length and width equal "x". The height is set at 3 meters. The walls on three sides and the floor are insulated. The heat gain through walls have not been investigated in this work so that the energy exchange between inner and outer are solely through the south wall and roof. The wall is constructed from cement blocks and 20 cm in width. Moreover, a double-glazed window, in dimensions 1/3 of the wall surface, is installed on the wall. The room has a concrete roof of 30 cm.

Based on the meteorological data for the six-year period of 2012 to 2017, the highest mean monthly maximum temperature in Qaen (33°43′36″ N and 59°11′04″ E) was equal to (38 (°C)=100.4 (°F)) in June and July. This temperature is considered as ambient temperature with the mean daily temperature of 81.6°F and the daily range of 28.5°F. Likewise, the solar radiation intensity on the south wall is 900 (W/m2), and the average wind speed is 3 (m/s).

The values of (23 (°C) =73.4 (°F)) dry bulb temperature and 50% relative humidity are imposed as thermal comfort conditions which are a result of some researches.

The cooling load of the prototype wind catcher is produced in mentioned condition (Q_{total}) equal 1(KW)=3412.13($^{Btu}/_{hr}$) and the equation is as follow:

$$Q_{total}=Q_{Win-Sol}+Q_{Win-Con}+Q_{Wall-Con}+Q_{Roof-Con}$$

Where

$Q_{Win-Sol}$ is Solar transmission load through the window in ($^{Btu}/_{hr}$) and calculated with the following equation:

$$Q\_(Win-Sol) = SHG * A * shade\ factor * storage\ factor$$

SHG , Solar Heat Gain takes ($^{Btu}/_{hr}$) into account the latitude, month and hour. A is area of the glass in(ft^2). The values are tabulated in ASHRAE fundamentals handbook.

The modified equation for cooling load of the basic conduction equation for heat gain is as follows:

$$Q = UA(CLTD)$$

Where

U is Coefficient of heat transfer roof or wall or glass, ($^{Btu}/_{hr.ft^2.°F}$). A is area of the roof or wall or glass in (ft^2). Moreover, $CLTD$ defined as cooling load temperature difference(°F). The values are determined from available tables on ASHRAE fundamentals handbook [98].

The above calculation is carried out for cooling load in each component.

$Q_{Win-Con}$ is Conductive load through the window in ($^{Btu}/_{hr}$).

$Q_{Wall-Con}$ is Conductive load through the walls in ($^{Btu}/_{hr}$).

$Q_{Roof-Con}$ is Conductive load through the roof in ($^{Btu}/_{hr}$).

The results of calculation are given in the table 13.

Table 13. Calculation process of cooling load in the room

Q	calculated	
$Q_{Win-Sol}$	$\boldsymbol{SHG = 67.38}$ ($^{\boldsymbol{Btu}}/_{\boldsymbol{hr}}$) $\boldsymbol{A = 3.28x\ (ft^2)}$ $\boldsymbol{shade\ factor}$= **0.9** $\boldsymbol{storage\ factor}$=**0.65**	129.289x ($^{Btu}/_{hr}$)
$Q_{Win-Con}$	$\boldsymbol{U = 0.51}$ ($^{\boldsymbol{Btu}}/_{\boldsymbol{hr.ft^2}.°F}$) $\boldsymbol{A = 3.28x\ (ft^2)}$ $\boldsymbol{CLTD = 15}$(°F)	25.092x ($^{Btu}/_{hr}$)
$Q_{Wall-Con}$	$\boldsymbol{U = 0.11}$ ($^{\boldsymbol{Btu}}/_{\boldsymbol{hr.ft^2}.°F}$)	

	$\boldsymbol{A = 6.56x}$ $(\boldsymbol{ft^2})$ $\boldsymbol{CLTD = 31.55}$(°F)	22.77x $(^{Btu}/_{hr})$
$Q_{Roof-Con}$	$\boldsymbol{U = 0.077}$ $(^{\boldsymbol{Btu}}/_{\boldsymbol{hr.ft^2}.°\mathrm{F}})$ $\boldsymbol{A = x^2}$ $(\boldsymbol{ft^2})$ $\boldsymbol{CLTD = 37.12}$(°F)	$2.86x^2$ $(^{Btu}/_{hr})$
Q_{total}		3412.13$(^{Btu}/_{hr})$

According to the above calculations, the room dimension is 4.7 m* 4.7 m * 3 m. Consequently, the prototype wind catcher can provide thermal comfort in a room by about 66.2m^3.

Comparing the Performance of the Proposed System with Traditional Wind catcher

The results of Bahadori et al., who have conducted extensive studies on traditional and conventional wind catchers, are used to evaluate the performance of the proposed system. The normalized cooling load compared as the primary criterion in the determined climatic conditions. The normalized cooling load is calculated at various wind speed as imposed conditions as the following equation:

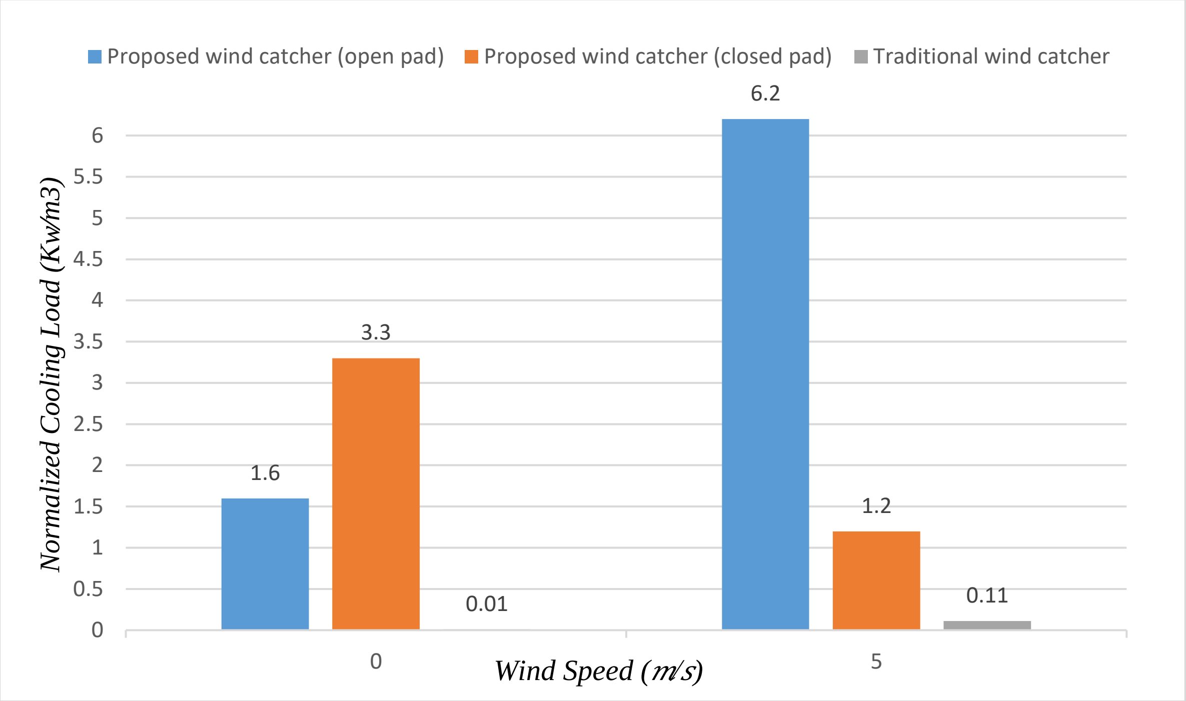
$$Q_{cN} = \frac{\dot{m}_a C_p (\Delta T)}{V}$$

Where

Q_{cN} is normalized cooling load $(^{kW}/_{m^3})$, C_p is the specific heat of the air $\left(^{J}/_{(kg°\mathrm{C})}\right)$, $\dot{m}$ is defined mass flow rate($^{kg}/_{s}$) and V is the volumetric dimensions of the system (m^3).

The mass flow rate of the air entering the building by the traditional wind catcher at two wind speed (0 and 5$^{m}/_{s}$) were 0.25 and 2.3 $^{kg}/_{s}$ respectively. The volumetric dimensions of the device are set at 4.2m^3 [40], which resulted in the temperature variations of indoor air in 0.1 and 0.2 °C. Table 14 shows the result of the comparison of the systems operatives.

Table 14. Comparison of the normalized cooling load with different wind speed at prototype wind catcher and traditional wind catcher



It is observed that at the closed pad mode when the wind speed is low, the cooling load is maximum. The traditional wind catcher is not applicable at this wind speed. When wind speed is 5 $^{m}/_{s}$, the efficiency of the proposed system is much better than the traditional one, especially at the open pad mode.

The Result of the Evaluation the Wind Catcher Integrated with Solar Chimney System (WCISCS)

Effect of Wind Speed and Solar Irradiance on Airflow Pattern

The predicted air-flow pattern around and inside the designed wind catcher at the different wind speeds (0, 3 and 5 m/s), solar irradiance on the absorber plate of 0 and 1000 W/m2 and two modes of with and without evaporative cooling was illustrated in figure 32, 33, 34. The figures indicate the fresh air, which enters the room through an inlet vent located the bottom of the wind catcher. The heated air inside the room throws out through the window. Therefore, it leaves the solar chimney due to the buoyancy force. Increasing solar radiation increases the air velocity in the entrance to the room which enhances the zone of air circulation inside the room, mostly due to intensify of the buoyancy force. Moreover, the same results were achieved when evaporative cooling was used in the wind catcher.

Comparing the airflow pattern of the different wind speeds at the constant solar radiations indicated that increasing the wind speed from 0 to 5 m/s significantly increased the air velocity inside the wind catcher. Furthermore, the effect of solar radiation and evaporative cooling on the air velocity inside the wind catcher was less at the higher wind speeds. In other words, buoyancy force is more effective in characterization of the airflow inside the systemin comparison with the external wind.

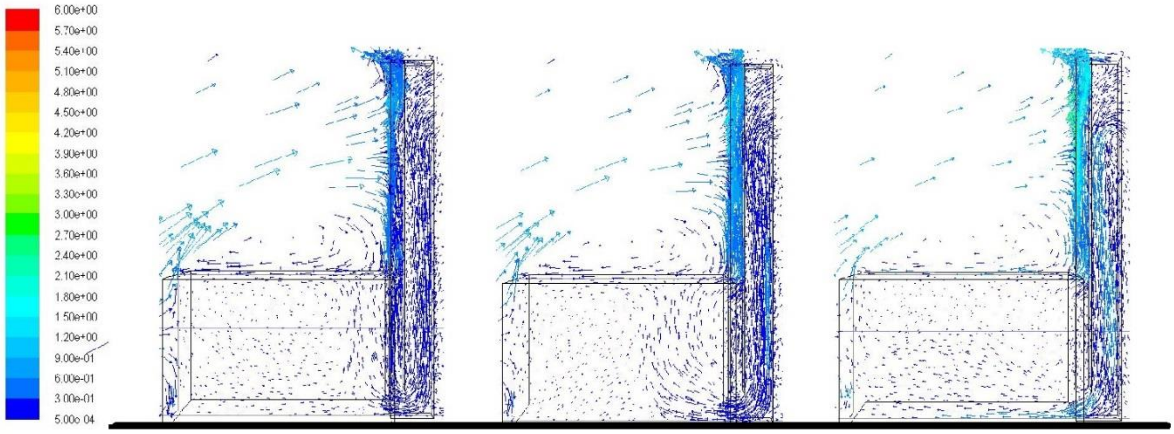


Figure 32. The airflow pattern inside the prototype wind catcher and room at the wind speeds 0 m⁄s, 1) Solar irradiances on the absorber plate of 0W⁄m^2 , 2) Solar irradiances on the absorber plate of 1000 W⁄m^2 , 3) Solar irradiances on the absorber plate of 1000 W⁄m^2 with evaporative cooling

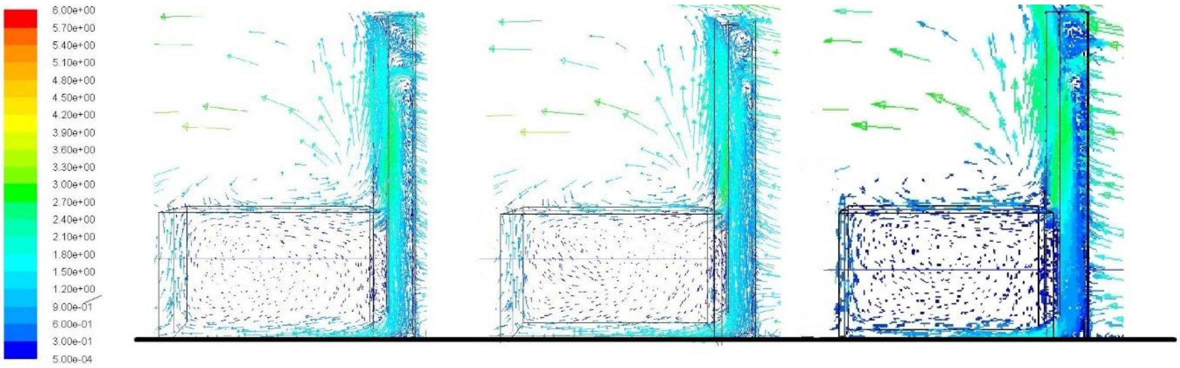


Figure 33. The airflow pattern inside the prototype wind catcher and room at the wind speeds 3 m⁄s, 1) Solar irradiances on the absorber plate of 0W⁄m^2 , 2) Solar irradiances on the absorber plate of 1000 W⁄m^2 , 3) Solar irradiances on the absorber plate of 1000 W⁄m^2 with evaporative cooling

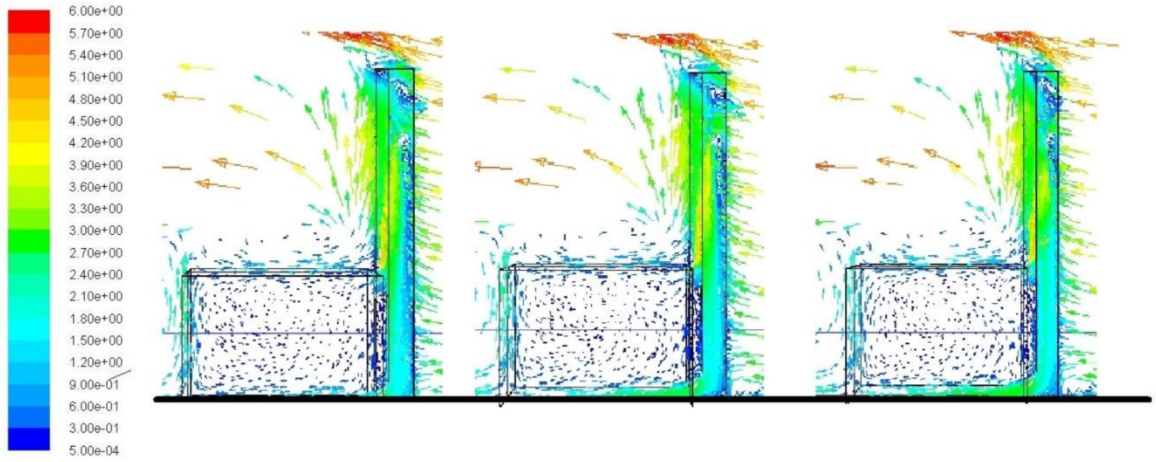
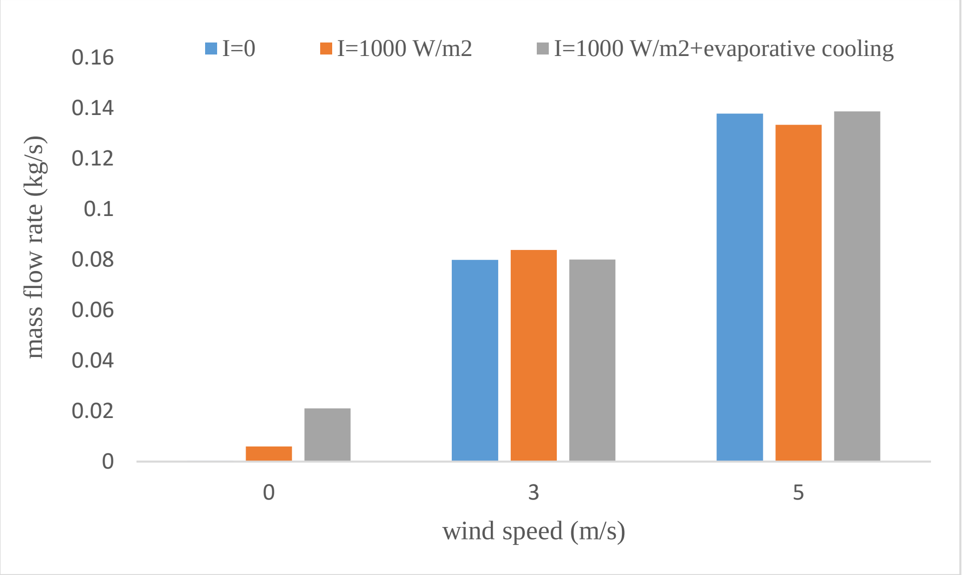


Figure 34. The airflow pattern inside the prototype wind catcher and room at the wind speeds 5 m⁄s, 1) Solar irradiances on the absorber plate of 0W⁄m^2 , 2) Solar irradiances on the absorber plate of 1000 W⁄m^2 , 3) Solar irradiances on the absorber plate of 1000 W⁄m^2 with evaporative cooling

Effect of Wind Speed and Solar Irradiance on Airflow Rate

The airflow rate is one of the essential parameters in the ventilation systems. Ventilation rate, which depends on airflow rate, influenced the concentration of contaminants, heat generation and air change rates. Table 13. shows the air mass flow inside the wind catcher at the different imposing conditions. The airflow rate at the non-existent wind flow and set solar radiation by 1000 W/m^2 was eventuated around 0.006 kg/s. Additionally, it improved by 0.021 kg/s supplementing the evaporative cooling system. The result agrees with the results were achieved in Elmualim et al. [41] and Bansal et al. [78] works. For instance, Bansal et al. demonstrated that in ambient wind speed of 1.0 m/s the wind tower only creates a mass flow rate of 0.75 kg/s, while the system assisted by solar chimney causes an airflow up to 1.4 kg/s at 700 W/m2 incident solar radiation. Table 13. depicts a maximum airflow rate of 0.1387 kg/s at the wind speed of 5 m/s and the solar irradiance of 1000 W/m^2 , if applying the evaporative cooling system. Consequently, the effect of the solar chimney is essential in the low speed of the wind, as well as the combined system increases the mass flow rate of air by several times, which improves the residence ventilation.

Table 15. Comparison of the airflow rate with different wind speed at inlet air window



Comparing the Performance of the Proposed System with an Evaporative Cooler

An evaporative cooler is a cooling system which has an impact on the humidity and air temperature of the room. In this cooler, the spending thermal energy of the moving air for vaporization of the moisture reduces the temperature while increases the RH of the air. Therefore, increasing air humidity is one of the advantages of the cooler compared to other air conditioners in a hot and dry area. The total volume of the room, attached to the prototype wind catcher, is about 70 m^3 to provide the thermal comfort.

The suitable capacity of evaporative cooler for a place of $70m^3$ should be around 2500 Cubic Feet per Minute (CFM), based on the manufacturer instruction. The CFM is the amount of fresh air circulated through building each minute. The minimum power consumption of such cooler is 200 watts. As a result, the proposed wind catcher has shown better energy efficiency and is more environmentally-friendly compared with the evaporative cooler. In dry climates, the designed system can reduce energy consumption and the need for conditioning equipment as a substitute for mechanical based cooling.

Chapter 7

Conclusion

This thesis tries to introduce a novel wind catcher system. In this research the efficiency of a prototype system as a simplified model of the primary proposed wind catcher was evaluated. This simplified model was evaluated in two stages, including the performance evaluation of the evaporative cooling system as well as the analyzing the effect of the presence of a solar chimney presence along with a wind catcher. The results of the assessment were demonstrated extensively for each section. The main outcomes are briefly summarized here.

Effect of Evaporative Cooling Parts

Thermal performance of prototype wind catcher equipped with a combinatorial evaporative cooling system (moist blades section and wetted pad unit) was studied. Theoretical assessment of the wind catcher was carried out. A set of experiments also were organized to validate the results of the obtained models. Moreover, the effect of wind speed and wind catcher height on two pad position were considered. The results of which can be described as follows:

- Increasing the wind speed could considerably raise the air velocity within column, while the growth rate of air velocity was higher at the lower heights of wind catcher. Moreover, in a higher wind speed of 3 $({}^{m}/_{s})$, speed increasing results in the faster drop of outlet air temperature while the pad was put on the closed mode, which subsequently led to a significant decrease in sensible cooling load.
- When the wind speed was almost zero, the close-pad mode resulted in a relatively higher air velocity within the wind catcher compared with the open-pad mode. On the other hand, at the conditions of wind existence, inside air velocity was slightly higher when the pad was open.
- Cooling load continuously was increased with respect to the wind speed when the pad was open. If the pad was closed, the maximum value of cooling load was achieved at the wind speed of $3({}^{m}/_{s})$. In addition, at the wind catcher heights of 2.5 and 3.5 m and the wind speeds of lower than $3({}^{m}/_{s})$, the cooling loads approximately doubled by employing closed-pad mode.

Compared with the open-pad mode, the closed-pad mode has shown better results, when the wind speed was low.

- In comparing the performance of the proposed system with traditional wind catcher, when wind speed was 5($m/_s$), the normalized cooling load of the proposed system was 6.2($kW/_{m^3}$) at the open-pad mode versus 0.11 ($kW/_{m^3}$). The maximum value of cooling load was achieved by closed-pad mode of the proposed wind catcher, at the low wind speed.

Effect of Solar Chimney Part

The CFD software calculated the air velocity fluctuations into the prototype wind catcher has been integrated with a solar chimney system, as well mass flow rate. The modelling was conducted to investigate the ventilation performance of the model. The impressions of the system in this way are:

- Air velocity in the entrance of the room was increased with respect to solar radiation and wind speed which enhances the zone of air circulation inside the room. An evaporative cooling system was incorporated into the prototype wind catcher, which lead to raise the air velocity.
- The airflow rate at the non-existent wind flow and set solar radiation of 1000 W/m^2 was eventuated around 0.021 kg/s, if applying the evaporative cooling system. Consequently, the combined system increases the mass flow rate of air by several times in the low speed of the wind.

The total volume of the room, attached to the prototype wind catcher, is about 70 $m3$ to provide the thermal comfort. The suitable capacity of evaporative cooler for a place of 70$m3$ should be around 2500 Cubic Feet per Minute (CFM), which minimum power consumption of such cooler is 200 watts compared with proposed system as a passive system for saving energy.

The Characteristic Items of the Final Presented Structure as well as the Application Area

The primary concern in Hot-Dry regions is thermal comfort in the hot seasons. As, the significant problems are the lack of water resources and green spaces, hot days, low humidity, the intensity of solar radiation and stagnant air (lack of airflow), specially at the lower altitudes. Forasmuch as the wind catcher is a ventilation system as well a cooling system. Therefore, it plays an essential role in the building performance in Hot-Dry areas.

The designed device is a four-directional wind system that is equipped with two evaporative cooling parts (wetted blades and adjustable opening pads), also supplemented with a solar chimney structure. The system dimensions could be determined based on the required amount of the cooling load and mass flow rate of the building. Moreover, it is calculated according to the calculations in “Calculating the volumetric dimensions of the room, connected to the wind catcher” (chapter 6).

The mud, mud-brick, and dense construction materials were applied to increase the time-lag and to retain some heat from nighttime warming in the wall and blades of traditional wind catchers. The materials that are characterized by the low heat transfer and the high-water absorption can be used in the construction of the wall of the proposed structure. Cement blocks and clay bricks are common building materials in Iran, which are extensively applied in buildings because of their high porosity and lightweight properties.

The column, the middle part of the wind catcher, consists of some ceramic parapets. Wetted-blade section with vertical cloth curtains is positioned inside of the main conduits. The pad unit, made from the straw layers, is designed to rotate around the vertical axis.

Similar materials can also being used in renovation or new construction. The moisture inside the shaft make it a great base for different fungi and mildews to grow in live. It is recommended to use glass-ceramic coating to facilitated regular maintenance including washing. Moreover, the curtains and their assembly should be easily accessible for the repair or possible exchanges.

The mass production of the unit in different sizes could be considered as the system has the capability of being prefabricated with smaller units that can be assembled in the target location. Prefabricated system reduces transportation cost and can make construction process faster and cost effective. Furthermore, the structure can be incorporated to the design of a new construction or be integrated to the renovation process of the existing buildings. Hereon, washable wall sandwich panels, and concrete slab systems are proposed for the walls which have good thermal insulation and waterproofing characteristics.

The water nozzles, installed on the top of the pad unit and the blades section, spray water and keep them wet. The excess water is collected in a container located at the bottom of shaft to be recirculated in the system. An electric pump is recommended to pump the water from the container to nozzles. To prevent blockage of pipe springs the hardness of the water should be reduced.

There are different kinds of wind catcher in Iran constructed in Hot-Dry regions. The proposed system can be utilized in the urban and the rural areas as the same way are used traditional wind catchers.

As mentioned in the analytical model, the air velocity inside the wind catcher depends on various factors such as the wind pressure coefficient. At the inlets of the building the coefficient is intensely fluctuated depends on the present and density of walls, trees, and other physical structures. Some studies demonstrated that the impact on the inlet air velocity may be ignored when the physical barriers to wind catcher is farther than 8 times the height of it [99]. Moreover, the proposed system attempts to augment the efficiency using solar radiation absorption on the south side. Therefore, the shadow of the physical structure on the absorber plate (collector) can diminish the efficiency. In this condition, a solution would be the usage of a forced-air system by applying a small blower.

The highest efficiency of the system is achievable during the sunshine hours in the day. Moreover, the system performance is significantly dependent on duration of sunlight in a typical day. Consequently, the proposed structure is more suitable as an air condition system for with buildings that are active during the day and are less used at night, such as office buildings, as well the buildings with the hybrid air conditioner system.

Future works

Future research could be considered to develop the proposed wind catcher:

- Since this system is evaluated in a hot and dry climate in a geographically defined area, further study is needed to extend it to other areas and other climates.

- The sizes and proportions observed in the system are based on previous studies and existing cases, which can be corrected by conducting further tests to enhance the performance of the device.
- The productivity of the device can be increased by using intelligent control systems as well as using fuzzy systems.

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1. Azam Noroozi, Yannis S. Veneris, “Thermal Assessment of a Novel Combine Evaporative Cooling Wind Catcher”, Energies, 2018, 11(2), 442; https://doi.org/10.3390/en11020442

2. Azam Noroozi, Yannis S. Veneris. “Compatible Elements of House in Hot-Dry Climate on Weather Conditions”, the International Conference on Applied research in Science and Engineering, France, Paris, 2 May 2018.