SIMULATION OF CLASSROOM MODELING ON FOURFACED WINDCATCHER FOR OPTIMUM INDOOR NATURAL VENTILATION RATE

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DEDICATION

Dedicated to whom teach me since I was born, my beloved family especially my parents, and my supportive supervisor – Dr. Mohd Badruddin Bin Mohd Yusof Thank you very much for being positive, helpful and understanding.

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This research project would not have been possible without the support of my parents and my husband who provided me with love and understanding. Their constant encouragement and emotional support kept my vigor and lifeline alive in research.

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ABSTRACT

Natural ventilation, a sustainable alternative to conventional air conditioning systems, has become an attractive solution for providing a good indoor air environment. The importance of maintaining sufficient Ventilation Rate (VR) and Temperature Performance (TP) particularly in schools is recognized as the main contributing factor to health and learning performance of students. One of the oldest natural ventilation systems that is still being used today is the windcatcher. Although many advancements were made in windcatcher design, there are still unexplored areas especially in terms of design parameters including cross-section, height and its placement on the building roof as well as combination with window. Thus, the present study aims to develop a windcatcher configuration that is appropriate for school building in the hot and dry climate of Iran. The research method involved experimental wind tunnel test and computational fluid dynamics (CFD) simulation. Firstly, a small-scale test in a wind tunnel was conducted to compare the CFD simulation with the experimental results. Secondly, to determine the optimum configuration, a four-faced square windcatcher with varied configurations at different locations on the classroom roof was simulated. The results showed that the average difference between CFD and experimental results was 13% which was in the acceptable range. The findings also proved the potential of the windcatcher centrally positioned on the roof in delivering fresh air inside the classroom. Finally, the windcatcher performance in terms of VR and TP was evaluated at different wind speeds and directions along with a closed/open window of a classroom in Yazd climate. It was found that in both window conditions, the windcatcher can meet ASHRAE recommendation of 8 L/s per person ventilation rate at outdoor wind speed of 3 m/s which is the average of wind speed in Yazd. Moreover, the windcatcher was able to provide maximum temperature performance up to 95% at an air incident angle of 15° in open window condition. The study also demonstrated the positive effect of the combination with an openable window on the windcatcher performance. Overall, it can be concluded that the developed windcatcher contributes significantly to improving VR and TP inside the school classroom in the hot and dry climate of Iran.

ABSTRAK

Pengudaraan semula jadi, sebagai alternatif yang mampan kepada sistem penyaman udara konvensional, telah menjadi penyelesaian yang menarik untuk menyediakan persekitaran udara dalaman yang baik. Kepentingan menjaga Kadar Pengudaraan (VR) dan Prestasi Suhu (TP) khususnya di bangunan sekolah diakui sebagai faktor penyumbang kepada prestasi kesihatan dan pembelajaran pelajar. Salah satu sistem pengudaraan semula jadi tertua yang masih digunakan hingga kini adalah penangkap angin atau *windcatcher*. Walaupun banyak kemajuan dilakukan dalam teknologi penangkap angin, namun ada bidang yang belum diterokai dalam penerapan sistem lestari ini. Oleh itu, kajian ini bertujuan untuk mengembangkan konfigurasi penangkap angin yang sesuai untuk bangunan sekolah di Iran yang beriklim panas dan kering. Kaedah penyelidikan melibatkan ujikaji ujian terowong angin dan simulasi (CFD). Pertama, ujian berskala kecil dalam terowong angin telah dijalankan untuk membandingkan CFD dan keputusan eksperimen. Kedua, untuk menentukan konfigurasi optimum, penangkap angin persegi empat muka dengan konfigurasi yang berbeza di tempat yang berbeza di atas bumbung bilik darjah telah disimulasikan. Keputusan menunjukkan bahawa purata perbezaan antara CFD dan keputusan eksperimen adalah 13% yang berada dalam julat yang boleh diterima. Penemuan juga membuktikan potensi penangkap angin yang diletakkan secara berpusat di atas bumbung dalam menyampaikan udara segar di dalam bilik darjah. Akhir sekali, prestasi windcatcher dari segi VR dan TP dinilai pada kelajuan dan arah angin yang berbeza bersama-sama dengan tingkap tertutup/terbuka bagi bilik darjah dalam iklim Yazd. Didapati bahawa dalam kedua-dua keadaan tingkap, penangkap angin boleh memenuhi pengesyoran ASHRAE sebanyak 8 L/s kadar pengudaraan setiap orang pada kelajuan angin luar 3 m/s iaitu purata kelajuan angin di Yazd. Selain itu, penangkap angin mampu memberikan prestasi suhu maksimum sehingga 95% pada sudut keadaan udara 15° dalam keadaan tingkap terbuka. Penilaian menunjukkan kesan positif terhasil dari kombinasi dengan tingkap yang boleh dibuka Secara keseluruhan, dapat disimpulkan bahawa penangkap angin memberikan sumbangan yang signifikan untuk meningkatkan VR dan TP di dalam bilik darjah sekolah di Iran yang beriklim panas dan kering.

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LIST OF SYMBOLS

ACR	Air change rate (1/h)
T_{air}	Air temperature (°C)
V	Air velocity (m/s)
A	Area of a windcatcher inlet (m^2)
L	Characteristic linear dimension (m)
ΔT	Cooling Effect (°C)
v	Kinematic viscosity (m^2/s)
T_{sen}	Sensed temperature (°C)
Q	Ventilation rate (L/s)

LIST OF ABBREVIATIONS

ABL	Atmospheric Boundary Layer
ACR	Air Change Rate
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	Computational Fluid Dynamics
COVID-19	Coronavirus Disease
CTA	Constant Temperature Anemometry
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
HVAC	Heating, Ventilating, And Air Conditioning
IAQ	Indoor Air Quality
ISO	International Organization for Standardization
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
Re	Reynolds Number
SBS	Sick Building Syndrome
TC	Thermal Comfort
UTM	Universiti Teknologi Malaysia
WHO	World Health Organization

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CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter is an introductory explanation of the study accomplished in this research. The chapter includes the following sections; background of study, problem statement, aim and objectives, scope of study, research framework, significance of study and thesis outlines.

1.2 Background of Study

Global warming is considered as one of society's greatest and most important challenges today because of the potential range and severity of impacts to communities, the nature and environment. Greenhouse gas (GHG) emissions particularly CO_2 emissions originating from fossil fuels consumption in buildings further amplified the global warming trend much intensively. Buildings are accounted for about 40% of the global energy consumption and contribute to over 30% of the total world CO_2 emissions. Moreover, this sector is responsible for almost 60% of the global electricity consumption (Jomehzadeh et al., 2017). The fact is that among all building services, space heating, ventilating, and air conditioning (HVAC) systems are the largest energy consumers in buildings (40% - 60%) which are mostly supplied by fossil resources (Zhang et al., 2021). Energy sector like other aspects of life has significantly affected by COVID-19 pandemic. In this situation, the energy and electricity consumptions are exacerbated in buildings (Klemeš, Fan and Jiang, 2020).

In the last few decades, there has been an accelerating trend with 8% yearly rate in Iran energy consumption, originating from rapid industrialization and urbanization. In Iran, cooling and heating systems in the building sector are accounted for around 60% of the total energy consumption. The average energy consumption in school buildings in Iran, as a major category of public buildings, is over 160 kWh/m^2, which is 2.5 times more than the energy consumed in high-performance schools in developed countries (Tahsildoost and Zomorodian, 2015). Moreover, the total energy consumption of schools in hot and dry climate of Iran is 41.91% of the total energy consumed by school buildings across the country. Hence, it is broadly accepted that a drastic decrease in energy consumption is needed in Iran educational buildings (Mohammadnejad et al., 2011).

In addition to high share of energy expenditure, the HVAC systems may result in the spread of infectious diseases including COVID-19 through the buildings (ASHRAE, 2020a). Moreover, a considerable source of indoor air quality problems may be related to these systems. Fungal and mold are produced by organic dusts which contaminate the cooling coils and condensate trays (Jomehzadeh et al., 2017).

Indoor air pollution is placed as five major environmental health threats. According to World Health Organization (WHO) report, indoor air contaminations are responsible of 2.7% of the world burden of sickness such as asthma allergies, acute illness and Sick Building Syndrome (SBS) (WHO, 2009). Skin allergy; throat, nose, eye irritation; tiredness; headache; and low concentrations are the observed SBS symptoms. In air-conditioned buildings, SBS symptoms are 30% to 200% more frequent (Sarkhosh et al., 2021). Since people spend on an average 80% - 90% of their time on working and living indoors, therefore it is vital to maintain the indoor environment in a good quality (Chenari et al., 2016). Environmental Protection Agency (EPA, 2020) stated that ventilation (removing or diluting indoor pollutants with outdoor fresh air) is the main element of good indoor air quality. In this regard, WHO (2020) and other pertinent guidelines (ASHRAE, 2020a; ECDC, 2020; EPA, 2020; ISHRAE, 2020; REHVA, 2020) emphasize on significance of ventilation to controlling the aerosol transmission of COVID-19. Decrease in the concentration of airborne pollutants can be achieved by adequate ventilation of interior environment with outdoor air (EMG, 2020).

Indoor air quality is mostly significant in schools where students tend to stay together for learning and there is the potential for children to sustain long lasting damage because their tissue and organs are still growing, they breath more air than adults (Harrouz, Ghali and Ghaddar, 2021; Stabile et al., 2016). Low ventilation rate enhances the risk of an outbreak of infectious diseases including COVID-19. Furthermore, low ventilation rate may lead to SBS in the classroom which is associated with lowered attention, ability to concentrate and increase in absenteeism from class (Morawska et al., 2020). In spite of the great importance of the indoor environment quality in the school buildings, not many studies have been done in the field of indoor comfort in educational buildings especially in primary school in comparison to office buildings over the world (Zomorodian, Aminian and Tahbaz, 2017).

In Iran, most of the existing schools have been constructed without any concern for the student's comfort and the adaptation to the local climate (Zahiri, 2014). The results of the field studies conducted in different cities of the hot and dry climate of Iran indicated that low air quality and uncomfortable indoor environment were the main problems experienced by the students in the primary schools (Tahsildoost & Zomorodian, 2015; Zahiri, 2014; Zomorodian et al., 2017). In this regard, Zahiri (2014) concluded that it is necessary to utilize the appropriate passive design strategies to create a high quality indoor environment and to increase the learning performance of the students. Therefore, to harness the current trend on buildings energy consumption and indoor air quality problems, as a result of reliance on conventional air conditioning systems, it is essential to explore alternative ventilation methods.

Generally, there are three types of building ventilation systems including mechanical ventilation which use electricity for the operation, natural ventilation which relies on wind, and hybrid ventilation which is a combination of the two mentioned systems (Sha and Qi, 2020). Natural ventilation, as an energy efficient alternative for reducing the building energy consumption, has become a promising passive cooling strategy to mitigate the problems which originated from conventional air conditioning systems (Daghigh, 2015). Natural ventilation is the process by which airflow through ventilation openings is driven by the natural driving forces of wind and thermal buoyancy (Hirose et al., 2021). It is stated that the energy cost of an air-conditioned building is typically 40% more than that of a naturally ventilated building (Stavrakakis et al., 2010; Tahsildoost and Zomorodian, 2015). The two main functions of natural ventilation concepts are (1) improving thermal comfort by ventilating the users and (2) providing good indoor air quality without any electricity demand by supplying fresh and clean air (Faggianelli et al., 2014; Wang and Malkawi, 2019). In WHO guideline, natural ventilation was considered among the effective environmental approaches to diminish the risk of infections spread in buildings (WHO, 2009). Natural ventilation has attracted more and more attention of research community and scholars in the 21st century, especially under the negative circumstance of COVID-19 due to providing fresh air and saving building energy consumption (Liu et al., 2021).

One of the traditional natural ventilation systems applied in buildings in the Middle East for many centuries is the windcatcher. It is an environmental friendly and sustainable system which aims to reduce buildings energy consumption, while improving indoor air quality and thermal comfort inside the buildings (Varela-Boydo et al., 2021). Windcatcher is defined as a tower designed and mounted on the roof of a building to ‘‘catch’’ the wind at higher elevations and direct it into the inner environment of a building (Jomehzadeh et al., 2017). A windcatcher is divided into shafts by internal partitions, which allow fresh air to enter the room because of positive air pressure on the windward side and the warm and stale air to expel with the assistance of the suction (negative) pressure on the leeward side of windcatcher (Calautit et al., 2020) as shown in Figure 1.1.

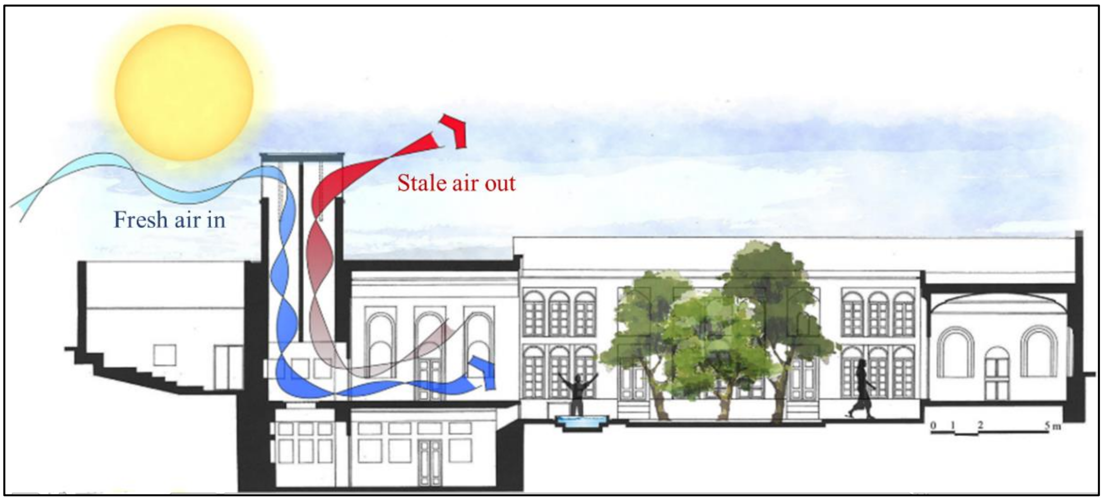

Figure 1.1 Flow diagram representing ventilation through a traditional windcatcher system (Ghodsi, 2013)

Bahadori *et al.* (Bahadori, Mazidi and Dehghani, 2008) stated that the main benefit of windcatchers, like other passive technologies, is that they exploit wind renewable energy for their operation; hence, they are considerably cost effective and more healthier. In addition to improving human comfort, windcatchers have low maintenance cost due to having no moving parts. Besides, it exploits clean and fresh air at roof level compared to low level windows (Fanood, 2014; Valipour and Oshrieh, 2012). Despite all benefits of traditional windcatcher, this sustainable technology has some limitations including huge structure, making it possible for the rain and small birds to enter through openings into the space (as shown in Figure 1.2), efficiency reduction in low wind speed conditions and little control of the volumetric flow rate in windy conditions (Bahadori and Dehghani-sanij, 2014; Farouk, 2020).

Figure 1.2 Traditional windcatcher with massive structure (Bahadori and Dehghani-sanij, 2014)

In order to minimize the limitations of traditional windcatchers and improve their efficiency, current architects and engineers have developed contemporary windcatchers to adopt them with advanced building principles and technologies (Hughes and Ghani, 2008; Kwon, 2013). Main characteristic of contemporary windcatchers which make them applicable for modern buildings in urban environment relates to their compact and smaller size as compared to traditional windcatchers. Moreover, some limitations of traditional windcatchers are eliminated by adding some new components such as dampers for control of flow rate in high external wind speed conditions, and horizontal louvers for increasing air flow rate inside the windcatcher channel as well as preventing rain and small birds from entering (Monodraught, 2011). It should be noted that in this study the term of contemporary windcatcher refers to the natural system of windcatcher without combination with mechanical ventilation such as fan. Figure 1.3 illustrates a schematic diagram of a contemporary windcatcher.

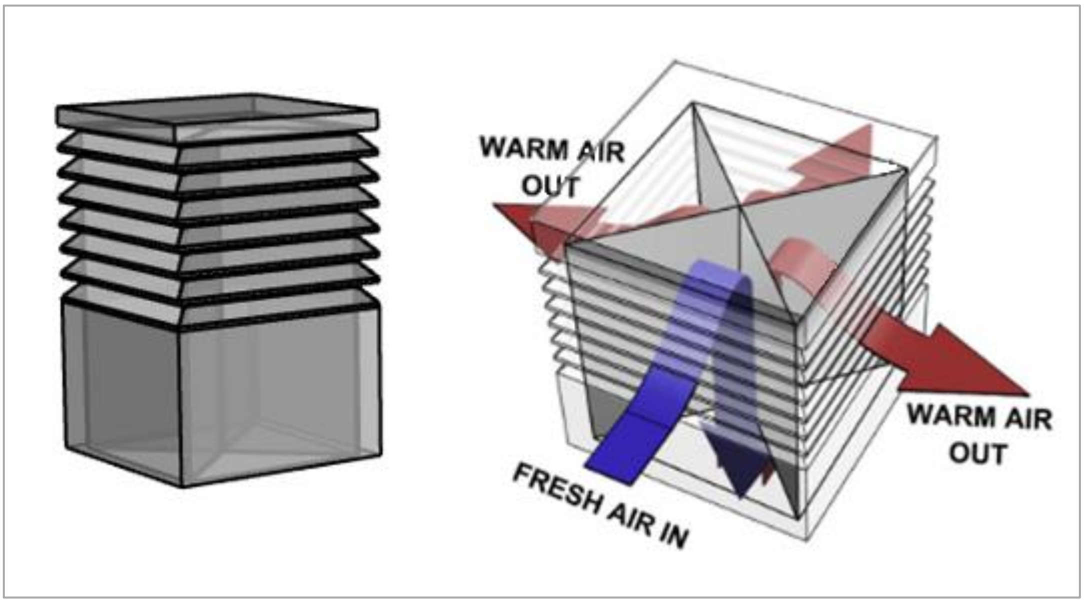

Figure 1.3 Schematic diagram of a contemporary windcatcher (Monodraught, 2011)

1.3 Problem Statement

Generally, the ventilation performance of the windcatcher is mainly dependent on windcatcher design and climate parameters affected by the outdoor environment such as sun path, shading factors, heat island reflections and also building materials (Bahadori and Dehghani-sanij, 2014). The windcatcher operates according to the condition of the wind and sun radiation in the region (Shahamat, 2014). Sun path is the apparent significant seasonal and hourly positional changes of the sun as the earth rotates and orbits around the sun. Consideration of the sun path is essential in saving energy through passive building design. Early and late in the day when the sun shines inclined, the solar gains through a building (and also the windcatcher) is low. Therefore, the windcatcher's efficiency is desired. On the other hand, in the middle of the day when the sun is at its strongest and also highest point, the sun hits a building at a steep angle so the air temperature in and around the windcatcher is high (Sari, Rauzi and Mahmud, 2021).

In addition, the sun path affects the buildings through the daylight access and the shadings (Sari et al., 2021). In urban environments, buildings are often located close to each other, and will be strongly influenced by the surrounding structures. In fact, the tall structures cast shadows on the surrounding buildings. This phenomenon can lead to the air temperature reduction in and around the windcatcher; consequently, the windcatcher is able to provide the air flow with lower temperature for ventilation (Bahadori & Dehghani-sanij, 2014).

Another climatic factor is Urban heat island (UHI). Urban areas typically have high building density, reduced green cover and various anthropogenic sources of excess heat generation (Kandya and Mohan, 2018). These factors significantly alter the heat exchange between the ground and buildings which affect the air temperature in urban microclimate. Subsequently, the air temperature in the densely built-up areas is higher than the air temperature of the surrounding areas which is commonly referred to as the 'heat island effect' (Han, Taylor and Pisello, 2015). Therefore, it is obvious that the cooling effect of natural ventilation systems such as windcatcher decreases in urban heat islands.

Moreover, using the material to reduce/increase moisture on the internal surface of a windcatcher can reduce/increase the rate of relative humidity of inlet airflow. Transparent materials can also be used in the manufacturing of the windcatcher to maximize use of natural light inside the building (Dehghani-sanij, Soltani and Raahemifar, 2015). In Yazd city, the windcatcher surface colour is plastered with cob colour, which has covered windcatchers and thus, its brightness greatly helps the reflection of sun radiation from windcatcher surface and its non-absorption by that surface (Azami, 2005). According to literature (Ameer, Chaudhry and Agha, 2016; Calautit and Hughes, 2014b; Elmualim, 2006a; Farouk, 2020; Hughes and Cheuk-Ming, 2011; Jones and Kirby, 2009a; Li and Mak, 2007; Sangdeh and Nasrollahi, 2022; Varela-Boydo et al., 2021), the most important climatic factors which directly affect the windcatcher performance are wind speed and direction. Thus, the windcatcher performance was analysed based on these two climatic parameters.

Furthermore, key design parameters are cross-section size and form of air channel, tower height, opening, the placement of the tower on the building roof, internal partition, the shape of tower roof, as well as angle and number of louvers and dampers (Afshin et al., 2016; Jomehzadeh et al., 2017). This research identified two main gaps including design aspect and application aspect. As shown in Table 1.1, there are many works available in the literature on the windcatcher (both traditional and contemporary) design parameters including form of cross-section, internal partition, opening, roof, damper, louvre. However, there is no study on cross-section size and height of windcatcher as well as the placement of the tower on the building roof. Therefore, different sizes for cross-section and height of a contemporary windcatcher as well as different places of windcatcher on the building roof are unexplored areas requiring further investigation.

Table 1.1 Previous studies on windcatcher design parameters to identify the research gap

No	Author(s)/Year	Windcatcher Design Parameters	Windcatcher Type
1	Mahmoudi, 2009	Internal partition & opening	Traditional
2	Dehghan *et al.,* 2013	Roof	Traditional
3	Hosseinnia *et al.,* 2013	Internal partition	Traditional
4	Zendehboudi *et al.,* 2014	Opening	Traditional
5	Cruz-Salas *et al.,* 2014	Internal partition & opening	Traditional
6	Benkari *et al.,* 2017	Cross-section form & roof	Traditional
7	Montazeri, 2018	Opening	Traditional
8	Varela and Moya, 2020	Opening	Traditional
9	Sheikhdehkordi *et al.,* 2020	Internal partition	Traditional
10	Gage and Graham, 2000	Cross-section form & opening	Contemporary
11	Elmualim and Awbi, 2002	Cross-section form	Contemporary
12	Elmualim, 2006	Damper	Contemporary
13	Hughes and Ghani, 2009	Damper	Contemporary
14	Hughes and Ghani, 2010	Louver	Contemporary
15	Liu *et al.,* 2011	Louver	Contemporary
16	Haw *et al.,* 2012	Roof	Contemporary
17	Maneshi *et al.,* 2012	Cross-section form	Contemporary
18	Calautit *et al.,* 2013	Internal partition & opening	Contemporary
19	Farouk, 2020	Cross-section form	Contemporary
Present study		• **Windcatcher height & cross-section size** • **Placement of the tower on the building roof**	**Contemporary**

Buildings all over the world are naturally ventilated by relying on the porosity of the envelope and windows or other openings. One of the parameters that evaluate the thermal performance of a building envelope is Overall thermal transfer value (OTTV). It is the value that represents the average rate of heat transfer to a building via building facades. It is generally utilized to compare different building designs in terms of thermal performance (Chan and Chow, 2014). In 1975, the concept and application of OTTV were firstly proposed by the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) (ASHRAE, 1975).

OTTV has been proposed and applied in many countries as a guideline for enhancing energy-efficient building envelopes to restrict excessive external heat gains due to solar heat gain and outdoor–indoor temperature difference then to achieve energy savings in buildings (Hagentoft and Pallin, 2021; Hwang, Huang and Chen, 2021). Smaller the OTTV, less will be the energy used for cooling. There is no doubt that regulating the OTTV of a building can enhance energy-efficient design of building envelope and mitigate the emission of greenhouse gas (Chan and Chow, 2013).

Another similar term used for this assessment is roof thermal transfer value (RTTV) which reflects the average heat gain into the building through the roof. It is a quick tool to quantitatively estimate heat gain or loss through roofs (Hagentoft and Pallin, 2021). Same as OTTV concept, building with a lower RTTV uses less energy for space cooling and the higher RTTV means more energy consumption by air-conditioning system (Yang He et al., 2021).

The building envelopes are the main factors influencing building energy efficiency and consequently human thermal comfort, as they represent a skin of the building's body. Solar radiation has a significant influence on mean radiant temperature. The radiant temperature can be calculated from measured values of the temperature of the surrounding walls and surfaces and their positions with respect to the person (Atmaca, Kaynakli and Yigit, 2007). Thus, there is a direct relationship between mean radiant temperature in building’s envelopes and OTTV (as well as RTTV). So that warm surfaces may cause a person to feel warmer than the surrounding air temperature (Sohrabiasl, 2015). Therefore, it can be stated that both OTTV and RTTV can affect thermal comfort conditions inside the buildings.

Since windows as conventional natural ventilation strategies are widely used in naturally ventilated buildings, its effect should be taken into account in natural ventilation studies such as windcatcher. However, based on literature review findings (Elmualim and Awbi, 2003; Ji, Su and Khan, 2012; Jones and Kirby, 2011), there are few works in windcatcher studies which investigated the effect of open windows on the windcatcher performance. Jones & Kirby (2011), Ji *et al.,* (2012) as well as Elmualim and Awbi (2003) studied the performance of contemporary windcatchers along with open windows only at specific air speed and/or angle, whereas it is comprehensively evaluated at different wind speeds (0.5 m/s - 4 m/s) and directions (0° - 180°) in present study.

Moreover, utilization of contemporary windcatcher is now widespread, particularly for indoor spaces with high occupant numbers such as schools and office buildings (Jones and Kirby, 2011). For instance, in recent years over 7000 contemporary windcatchers installed for public buildings in the UK (Monodraught, 2011). According to Table 1.2, all previous studies focused on the traditional windcatchers in residential buildings in Iran. It reveals the existence of a gap related to the contemporary windcatcher application for buildings particularly educational ones in climatic condition of Iran. Thus, the present study evaluates the ventilation performance of a contemporary windcatcher in school building in Yazd, Iran. Table 1.2 also shows the potential of Yazd city for application of windcatcher. On the other hand, Jones et al. (Jones, 2010) stated that most investigations of ventilation rates in school classrooms in the literature are for mechanically ventilated classrooms. Consequently, it is essential to conduct such studies in classrooms which are naturally ventilated.

Table 1.2 Previous studies on windcatcher in Iran to identify the research gap

No	Author(s)	Windcatcher Type	Building Functionality	Case-Study
1	Mazidi *et al.*, 2007	Traditional	Palace	Yazd, Iran
2	Kalantar, 2009	Traditional	Palace	Yazd, Iran
3	Mahmoudi, 2009	Traditional	House	Yazd, Iran
4	Ghadiri *et al.,* 2011	Traditional	-	Yazd, Iran
5	Ahmadikia *et al.,* 2012	Traditional	Palace	Yazd, Iran
6	Ghadiri *et al.,* 2012	Traditional	House	Yazd, Iran
7	Hosseinnia *et al.,* 2013	Traditional	House	Iran
8	Dehghan *et al.,* 2013	Traditional	House	Yazd, Iran
9	Mahdavinejad *et al.,* 2013	Traditional	House	Yazd, Iran
10	Zendehboudi *et al.,* 2014	Traditional	House	Shiraz, Iran
11	Aini & Ahmadnia, 2014	Traditional	Water cisterns	Yazd, Iran
12	Abouseba & Khodakarami, 2014	Traditional	-	Yazd, Iran
13	Mostafaeipour *et al.,* 2014	Traditional	Warehouse	Yazd, Iran
14	Hedayat *et al.,* 2015	Traditional	House	Yazd, Iran
15	Hosseini *et al.,* 2016	Traditional	House	Yazd, Iran
16	Afshin *et al.,* 2016	Traditional	House	Yazd, Iran
17	Mohamadabadi *et al.,* 2018	Traditional	House	Yazd, Iran
18	Sheikhdehkordi *et al.,* 2020	Traditional	-	Yazd, Iran
19	Miri & Babakhani, 2021	Traditional	Mosque	Kermanshah, Iran
Present study		**Contemporary**	**School**	**Yazd, Iran**

1.4 Aim and Objectives of Study

The aim of current research is to develop a windcatcher configuration appropriate for the school building in hot and dry climate of Iran. To achieve this aim, the objectives are:

(a) To develop the control model for comparison between the simulation and experimental results of natural ventilation on a classroom

(b) To determine optimum configuration (cross-section and height) and placement on the classroom roof for a four-faced square contemporary windcatcher.

(c) To evaluate indoor natural ventilation on air velocity and indoor temperature performance achieved by the windcatcher along with both closed/open window of a classroom at different wind speeds and directions in Yazd climate.

1.5 Scope of Study

This section indicates scope of this study on indoor air movement, natural ventilation performance, climate and building type as following:

i. **Indoor Air Movement:** Due to the important effect of indoor air movement on students learning, performance and productivity; key factors including ventilation rate (Q) and air change rate per hour (ACR) were assessed in present study.

ii. **Natural Ventilation Performance:** Natural ventilation is used not only for providing an acceptable air quality inside a building, but also for improving comfort conditions. Hence, this study investigated the windcatcher performance in terms of important factors including indoor air velocity (V) and air temperature (T).

iii. **Climate:** Hot and dry climate of Iran was selected for conducting this study. In fact, the experimental test was carried out in month of June in UTM wind tunnel. Based on weather station data (JB Weather Station, 2022), the mean temperature in June month was 32 °C in Skudai, Johor Bahru. As presented in Chapter 2 (Section 2.7), the mean temperature is 33 °C in Yazd, Iran during summer season. Since there is a slight difference between these two temperatures, it can be assumed that an outdoor temperature in wind tunnel can represent the outdoor temperature in Yazd, Iran.

iv. **Building Type**: This study focused on one floor school in urban area of Yazd city, Iran which is recommended by Iran's Ministry of Education (2020) for primary schools in Iran. It should be noted that due to the earthquake threat as well as safety issues of low aged students in primary schools, most school buildings are low rise in Iran.

v. **Ventilation type**: Among three types of building ventilation which are mechanical ventilation, natural ventilation, and hybrid ventilation; this study only focused on the natural ventilation system of a contemporary windcatcher (without aid of mechanical systems such as fans).

1.6 Research Framework

This section presents the research design and the methods used in this study. Detailed explanation of the research framework will be presented in Chapter 3. To achieve the aim and objectives of the study, the research framework consists of five main phases as shown in Figure 1.4. Phase I is 'literature study', Phase II is 'experimental test', Phase III is 'pilot study', Phase IV is 'development of windcatcher configuration' and Phase V is 'evaluation of windcatcher efficiency'.

1.6.1 Phase I: Literature Study

This phase conducted a comprehensive review on natural ventilation, comfort condition requirements, windcatcher technology, Iran climatic conditions and common predicting methods for natural ventilation performance.

1.6.2 Phase II: Experimental Test

For collecting experimental data, a small-scale test in a wind tunnel lab was conducted. The obtained data will be used in the next phase for validation of computational fluid dynamics (CFD) simulation.

1.6.3 Phase III: Pilot Study

Before any detailed CFD simulations, it is essential to conduct pilot study because some levels of error and uncertainty are typically observed in numerical (CFD) simulations. This phase was designed to fulfil objective 1. Control (comparison) of CFD results against experimental data meant that CFD simulation procedure was reliable and accurate; consequently, it can be applied for the next objectives.

1.6.4 Phase IV: Development of Windcatcher Configuration

After comparison of CFD results with experimental data, CFD analysis to achieve objective 2 is carried out. To determine optimum configuration for a four-faced square contemporary windcatcher, different sizes of cross-section and height are simulated for the windcatcher. Moreover, different places of the windcatcher on the classroom roof is analyzed to find an optimum placement. The findings of these two parts lead to the development of the windcatcher configuration.

1.6.5 Phase V: Evaluation of Windcatcher Efficiency

This phase was designed to fulfil the final objective. In this phase, performance of the developed windcatcher was numerically evaluated at different wind speeds and directions along with both closed and open window conditions of a classroom. It was also assessed in terms of natural ventilation and temperature performance in hot and dry climate of Yazd, Iran. It should be noted that this study only focused on the natural system of a contemporary windcatcher.

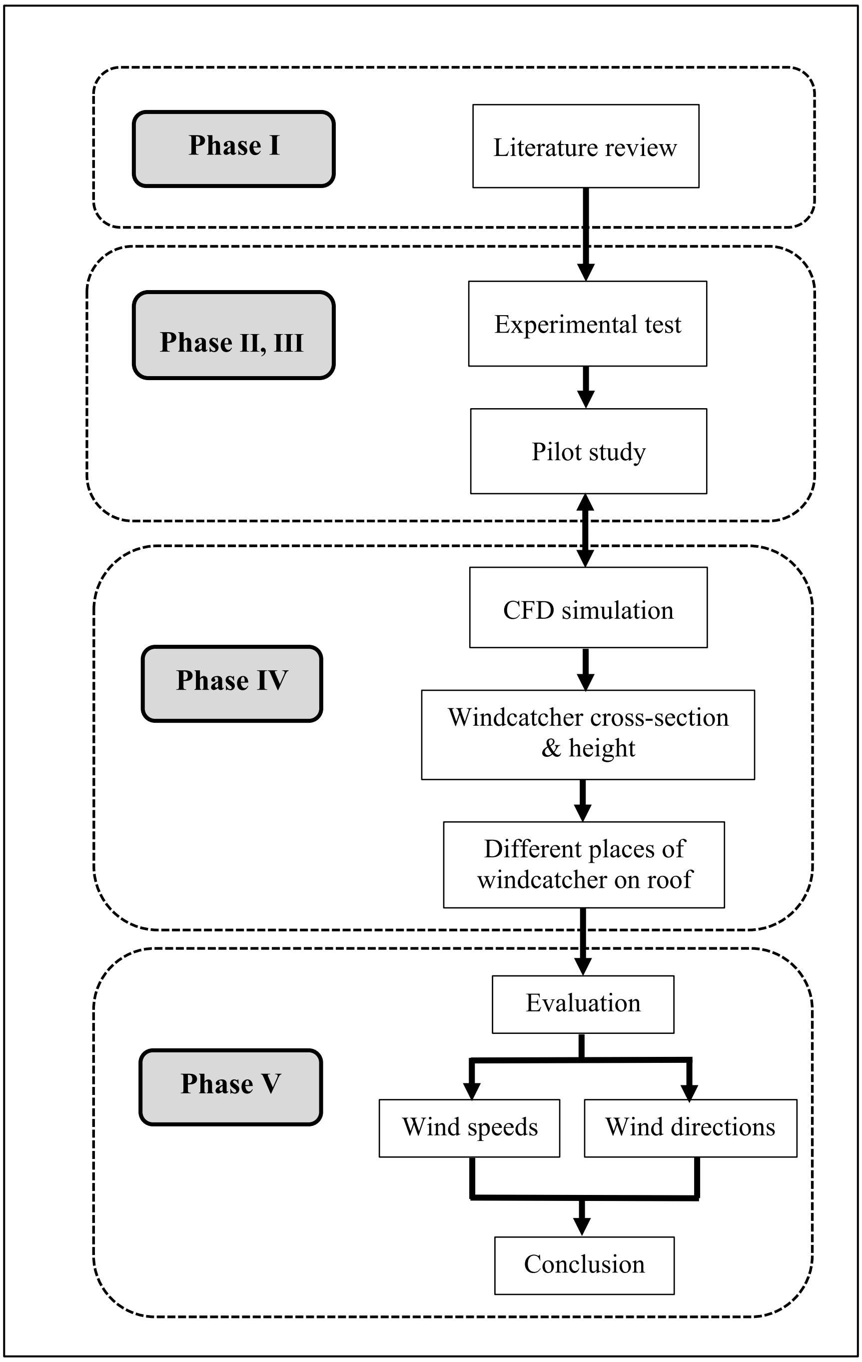

Figure 1.4 Research Flow

1.7 Significance of Study

The research addresses the following significance of studies, ‘ventilation role’, ‘natural ventilation and temperature performance assessments’, ‘windcatcher field’ and ‘building energy sector’.

Ventilation Role: Natural ventilation has attracted more and more attention of research community and scholars in the 21st century, particularly under the negative condition of COVID-19 due to providing fresh air and saving building energy consumption. It is well accepted that ventilating the indoor environments with outdoor air (as much as possible) is the best measure to decrease the concentrations of interior air pollutants including any viruses. During the pandemic of infectious diseases including COVID-19, conducting studies such as present research is of great importance.

Natural ventilation and temperature performance Assessments: The natural ventilation and temperature performance are principally significant in schools where there is the potential for children to sustain long lasting damage. Poor ventilation rate in the classroom could have negative impacts on children’s health, learning, attention, and performance. Previous researchers have mostly focused on ventilation rates in mechanically ventilated school classrooms. Moreover, there is lack of natural ventilation and temperature performance assessments in Iran school classrooms ventilated by a contemporary windcatcher. Therefore, it will be considered in present study.

Windcatcher Field: There is lack of study on the effect of different sizes of cross-section and height of a contemporary windcatcher and different places of windcatcher on a building roof on its performance in Iran. Thus, this study planned to conduct them. Furthermore, no work has been done regarding the contemporary windcatcher application for a school building in the climatic condition of Iran. Hence, this study planned to investigate it. In addition, there are few works in windcatcher studies which investigated the windcatcher performance along with open windows, especially at different wind speeds and directions. Consequently, it will be evaluated in present research.

Building Energy Sector: Currently, a key challenge in the building sector is increasing the buildings energy efficiency, while providing a healthy and comfortable indoor environment. The energy consumption and cost of a naturally ventilated building is much less than that of an air-conditioned building. Numerous scholars and academicians proved the significance of windcatcher natural ventilation system on energy consumption reduction in buildings. For example, Ji *et al.,* (2012) claimed that 17% of cooling load inside the building could be reduced after applying windcatchers, and this can be increased up to 31% in case of utilizing openable windows along with the windcatcher. In another windcatcher study conducted by Mostafaeipour *et al.,* (2014) in Yazd city, 35% energy saving was observed in the building with windcatcher system compared to that of with absorption chiller system. Moreover, Goudarzi and Mostafaeipour (2017) stated that a windcatcher is the most efficient passive system for saving the cooling energy (up to 43%) for the buildings in hot and dry climate of Iran.

1.8 Thesis Outlines

The thesis outlines are as follows:

Chapter 1, Introduction: This chapter includes background of research, problem statement, aim and objectives, scope of study, concise research methodology and significance of study.

Chapter 2, Literature Review: This chapter conducts a comprehensive review on natural ventilation, comfort condition requirements, windcatcher, Iran climate and predicting methods of natural ventilation performance.

Chapter 3, Research Methodology: This chapter addresses the research methodology in detail which includes experimental and numerical (CFD) methods.

Chapter 4, Results and Discussion: This chapter presents the results of CFD simulations and wind tunnel test and related discussion about the findings.

Chapter 5, Conclusion and Further Work: This chapter reviews objective findings of the research. Moreover, it suggests further works in the windcatcher field.

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