TWO-SIDED WINDCATCHER IN LOW WIND SPEED ENVIRONMENT

PAYAM NEJAT

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Universiti Teknologi Malaysia

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Dedicated to my beloved parents, particularly my wife who suffered too much. Thank you very much for being supportive, helpful and understanding.

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

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ABSTRACT

Global warming is a major threat and is mainly caused by emission of greenhouse gases. The building construction sector or buildings are accountable for about 40% of total greenhouse gases due to energy consumption. The application of air conditioning systems is reported to reach 70% of this energy consumption. In contrast, natural ventilation systems such as windcatcher are a promising passive cooling alternative that not only improve indoor air quality (IAQ) and thermal comfort but also reduce energy consumption. However, the efficiency of windcatcher is hindered by two factors: air short-circuit phenomenon and low ambient wind speed. The aim of this research is to develop a new windcatcher design that addresses both problems by integration of wing wall and installation of a new device called anti-short circuit device (ASCD). Based on review of literature, wing wall and ASCD can enhance the performance of windcatcher in low wind speed. To achieve this aim, two methods namely wind tunnel testing and simulation using computational fluid dynamics (CFD) were explored. The results showed that the difference between the CFD and experimental results was within the acceptable range. Integration of wing wall and ASCD to the windcatcher improved the IAQ factors such as air flow rate, air change rate and air velocity. It was observed that the ventilation performance of the new design in 45^{o} wind incident angle was better than the 0^{o} wind incident angle. In conclusion, this study has proven that the new design can effectively be implemented to improve the ventilation and IAQ.

ABSTRAK

Pemanasan global merupakan ancaman utama dan biasanya disebabkan oleh pelepasan gas rumah hijau. Sektor pembinaan atau bangunan menyumbang kira-kira 40% daripada jumlah gas rumah hijau melalui penggunaan tenaga. Bahagian sistem penyaman udara dilaporkan menyumbang 70% daripada penggunaan tenaga tersebut. Namun begitu, sistem pengudaraan semula jadi seperti perangkap angin menjanjikan alternatif penyejukan pasif yang bukan hanya mampu meningkatkan kualiti udara dalaman (IAQ) dan keselesaan haba tetapi juga mampu mengurangkan penggunaan tenaga. Walau bagaimanapun, kecekapan perangkap angin dihalang oleh dua faktor: fenomena litar pintas udara dan kelajuan angin persekitaran yang rendah. Tujuan kajian ini adalah untuk membangunkan reka bentuk perangkap angin baharu yang dapat menangani kedua-dua masalah dengan penyepaduan dinding sayap dan pemasangan peranti baharu yang dikenali sebagai peranti litar pintas (ASCD). Berdasarkan sorotan kajian, dinding sayap dan ASCD dapat meningkatkan keupayaan perangkap angin dalam kecepatan angin rendah. Untuk mencapai matlamat ini, dua kaedah diterokai, iaitu ujian terowong angin dan simulasi menggunakan dinamik bendalir pengkomputeran (CFD). Hasil kajian menunjukkan bahawa perbezaan antara CFD dengan hasil eksperimen adalah dalam jangkauan yang boleh diterima. Integrasi dinding sayap dan ASCD terhadap perangkap angin telah meningkatkan faktor IAQ seperti kadar aliran udara, kadar perubahan udara dan halaju udara. Hasil dapatan diperhatikan bahawa prestasi pengudaraan reka bentuk baharu dengan 45^{o} sudut kejadian angin adalah lebih baik daripada sudut kejadian angin 0^{o}. Kesimpulannya, kajian ini dapat membuktikan bahawa reka bentuk baharu boleh dilaksanakan dengan berkesan untuk meningkatkan pengudaraan dan IAQ.

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LIST OF ABBREVIATIONS

AIAA	American Institute of Aeronautics and Astronautics
ACR	Air change rate
ASCD	Anti short circuit device
ASCE	American Society of Civil Engineers
CFD	Computational fluid dynamics
GHG	Greenhouse gas
IAQ	Indoor air quality
NASA	National Aeronautics and Space Administration
Re	Reynolds number
TWIW	Two sided windcatcher integrated with wing all
SBS	Sick building syndrome
VOC	Volatile organic components

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Current research evaluates the potential of a new design of windcatcher for natural ventilation in residential building. Thn6e first chapter of this research introduces the background of study, aim and objective, research questions, scope, brief research methodology and thesis outline.

1.2 Background of The Study

The most important challenges of the world are related to the environmental threats with global warming which is the most serious. Buildings with 30% CO_2 emissions and 40% global energy consumption (Jazizadeh, Ghahramani, Becerik-Gerber, Kichkaylo, & Orosz, 2014; L. Yang, Yan, & Lam, 2014), play significant role in climate changes which is predicted to rise in the future on account of urbanization and population growth (Iannaccone, Imperadori, & Masera, 2014). Energy is used for different purposes in buildings. Among different services, the ventilating and air conditioning (HVAC) systems have the most share with more than 50% than of energy consumption (Castilla, Álvarez, Ortega, & Arahal, 2013).

In addition, it can be claimed that nearly 80% of total life span building energy consumption in hot climate is allocated to operation of air conditioning systems and rest 20% to 30% is used for material production, construction and demolition etc. (Koch-Nielsen, 2013) that consequently, has made the energy used for cooling as the major contributor of Greenhouse Gas (GHG) emissions in this climate (Bruelisauer, Meggers, & Leibundgut, 2013).

Iran is considered a developing country with reported GDP per capita amounting to 17251 $ in 2015; and buildings account for approximately 41% of energy demand. Energy consumption by sectors both in the world and Iran is shown in Figure 1.1a, from which the significance of energy saving in building in comparison with other sectors can be obviously concluded. In Figure 1.1b, it is indicated that most energy (61% of total energy consumption) in Iran is consumed in heating and cooling sectors (Mohammadi, Saghafi, Tahbaz, & Nasrollahi, 2017; Soflaei, Shokouhian, Abraveshdar, & Alipour, 2017).

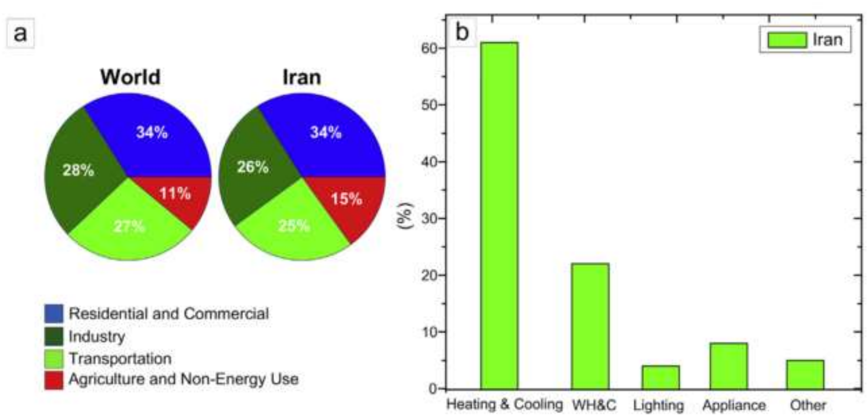

Figure 1.1 Energy demand by sectors (a) Energy demand by sectors in the world and Iran, (b) Share of energy consumers in building sector in Iran (Soflaei et al., 2017).

From the environmental point of view, Iran is one of the 20 countries contributing to 75% share in the greenhouse gas emissions. Furthermore, the ratio of CO_2 (kilograms) to GDP (US dollars) in Iran reached 3.15 in 2008, while the global average was 0.73. A major factor in the pollutants production is the consumption of fossil fuels in Iran (Bagheri Moghaddam, Mousavi, Nasiri, Moallemi, & Yousefdehi, 2011).

The crude oil and natural gas are the two resources on which Iran's energy consumption is dependent (Shad, Khorrami, & Ghaemi, 2017) and the final energy consumption per capita in agricultural, building sector, transportation and industry is 3.3, 1.9, 1.7 and 1.5 times the global average (Deputy of Electricity and Energy Affairs, 2017).

Thus, according to ESI (Environmental Sustainable Index), Iran is one of the top countries contributing to high CO_2 gas emissions. In Iran, both greenhouse gas emissions and the total energy consumption percentage in building sectors are above average compared to the world average (Shad et al., 2017).

CO_2 emission in Iran between 2005 and 2011 depicted in Figure 1.2 represents the ascending trend in the Middle East. Iran's contribution to CO_2 emission is 20% in the Middle East (Shaddel & Shokouhian, 2014). Furthermore, Iran's growing population and economy together with life style changes are causing the energy consumption to increase (Shad et al., 2017).

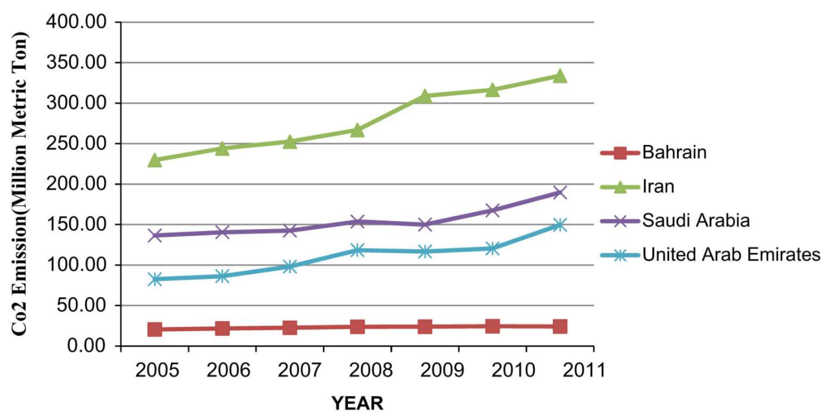

Figure 2.2 CO_2 emissions of Iran and some countries in middle east (Shaddel & Shokouhian, 2014).

The building sector is the first major energy consumer in Iran with 41% share from total consumption (Hushmand & Mahdavian, 2016). Iran is required to build 1.5 million new dwelling units each year. As a result of housing development, there is a serious need to develop solutions and strategies for energy efficient buildings (Roshan, Ghanghermeh, & Attia, 2017).

Thus, the attempts of Iranian authorities is concentrated on optimizing energy consumption mainly in both the official and residential buildings and how to enhance sustainable solutions (Shad et al., 2017).

In 1991, the first energy code was introduced by the Government in Iran which was a major step taken to save energy in buildings, and its implementation for state-owned buildings was mandatory from 2005 (Bradran, 2011).

In Iran, a considerable portion of the total electricity consumption during summer in residential sector is concerned with cooling energy. Although The overall average annually consumed electricity per household in Iran equals 2615 kWh, high demand for cooling systems in hot provinces increases this amount to 9675 kWh (Baneshi & Maruyama, 2016).

Therefore, the above reasons demonstrate the importance of application passive cooling systems such as windcatcher to direct the Iran building sector toward the sustainability concept through application of renewable energy (wind) instead of fossil fuels and reduction in greenhouse gas emissions.

In addition to high share of energy expenditure, a considerable source of indoor air quality (IAQ) problems may be related to air conditioning systems. Fungal and mold may be produced in fans by organic dusts which contaminate the cooling coils and condensate trays. Likewise, dirty filters may lead to significant pollution problems (Chenari, Dias Carrilho, & Gameiro da Silva, 2016; Santamouris & Kolokotsa, 2013). Consequently, they can potentially cause “Sick Building Syndrome” (Elmualim, 2003; Hughes & Abdul Ghani, 2009) and also metabolic diseases. Sick building syndrome symptoms are 30% to 200% more frequent in air-conditioned buildings (Environmental Protection Agency, 1991). Failure to maintain good IAQ can result in poor performance and illness for occupants under prolonged exposure (Calautit, O’Connor, & Hughes, 2014). According to the U.S. Environmental Protection Agency

(Environmental Protection Agency, 1991), indoor air pollution is among the top five environmental health risks. Since people spend 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 (Calautit, Hughes, O'Connor, & Shahzad, 2016; Zomorodian, Tahsildoost, & Hafezi, 2016).

To harness the current trend on energy consumption due to reliance on conventional air conditioning systems, it is necessary to explore alternative methods. However, the alternatives should not dwindle the occupants' comfort and health (Salvalai, Pfafferott, & Sesana, 2013).

Passive cooling, as a promising alternative for air conditioning systems, is a building design approach that focuses on heat gain control and heat dissipation in a building in order to improve the indoor thermal comfort with low energy consumption. Unlike air conditioning systems, passive cooling can be considered as a viable and attractive strategy for sustainable building concept, encompassing mitigation of energy consumption and GHG simultaneously (Geetha & Velraj, 2012). Existing experience has shown that passive cooling provides excellent thermal comfort and indoor air quality, together with very low energy consumption (Santamouris & Kolokotsa, 2013).

Natural ventilation, as a type of passive cooling, is recognised as an energy efficient alternative for reducing the building energy consumption and has become an alternative cooling strategy to mitigate the problems which originated from air conditioning systems (Daghigh, 2015). The two main functions of natural ventilation concepts are (1) the provision of good IAQ without any electricity demand for moving the air and (2) the improvement of thermal comfort by ventilating the users (Al-Hemiddi & Megren Al-Saud, 2001; Chenari et al., 2016; Dimitroulopoulou, 2012; Faggianelli, Brun, Wurtz, & Muselli, 2014; Schulze & Eicker, 2013).

One of the traditional natural ventilation systems applied in buildings, which exploits wind renewable energy for its operation, is the windcatcher (M. Ghadiri, Mohamed, & Ibrahim, 2012; Hosseinnia, Saffari, & Abdous, 2013; Reyes, Moya, Morales, & Sierra-espinosa, 2013). It is an environmental friendly and sustainable system which targets to combat energy crisis, while improving IAQ and thermal comfort inside the buildings (Afshin, Sohankar, Manshadi, & Esfeh, 2016; Hedayat, Belmans, Hossein Ayatollahi, Wouters, & Descamps, 2015; Saadatian, Haw, Sopian, & Sulaiman, 2012). Additionally, other benefits of windcatcher is low maintenance cost due to having no moving parts, utilization of clean and fresh air at roof level compared to low level windows (Elmualim & Awbi, 2003; Monodraught, 2017) and decreasing greenhouse gases (GHGs) and air pollution (Soni, Pandey, & Bartaria, 2016).

Windcatcher has been utilized in buildings in the Middle East for more than three thousand years (Calautit & Hughes, 2014a; Hughes, Chaudhry, Ghani, et al., 2011). Currently, the utilization of commercial windcatcher is now widespread, especially for indoor spaces with high occupant numbers such as schools and office buildings (Benjamin Jones & Kirby, 2011). For instance, in recent years over 7000 windcatchers have been installed for public buildings in the UK (Monodraught, 2017).

1.3 Problem Statement

The performance of windcatchers in climate with low wind speed can be limited which lead to low induced fresh air to building. Moreover, regardless of climate, there is another problem namely air short circuit which reduces the efficiency of ventilation. These two problems are discussed in the following subsections.

1.3.1 Low External Wind Speed

Previous investigations studied the windcatcher performance mostly in hot-arid regions such Middle East and moderate climate such as the UK (Bouchahm *et al.* 2011). Most of the pervious researches, evaluated the windcatcher in high ambient wind speed such as (Afshin et al., 2016), (M. H. Ghadiri, Lukman, Ibrahim, & Mohamad, 2013), (Maneshi M, Rezaei-Bazkiaei, A Weber & Dargush, 2012), (Afshin, Dehghan Mohandesi, Daneshagr, & Dehghan Kamaragi, 2014), (Hossein Ghadiri, Maryam, Mohamed & N. Ibrahim, 2012), (Mirzaei, Eghbali, Mahdavinejad, & Rohani, 2014) and (Montazeri, 2011). However, in some regions where the average wind speed does not exceed 3.5 m/s, the success of windcatcher to provide natural ventilation faces with serious hesitation. Therefore, the pervious researches mostly focused on regions with high ambient wind speed and did not study the windcatcher in low wind speed areas due to inefficiency of common windcatcher design (Albani & Ibrahim, 2013; Bahadori & Dehghani-sanij, 2014; Jazayeri & Gorginpour, 2011; Karakatsanis, Bahadori, & Vickery, 1986; Khan, Su, & Riffat, 2008; Masseran, Razali, Ibrahim, & Wan Zin, 2012). Thus, it is necessary to design a new windcatcher which can work efficiently in low wind speed areas.

1.3.2 Short Circuit Problem

Another significant problem of common windcatchers is the air short-circuit reported by different previous studies which has a negative impact on the ventilation efficiency of windcatcher (Calautit & Hughes, 2014a; Calautit et al., 2014; Elmualim, 2006a; Elmualim & Awbi, 2002; Hughes & Abdul Ghani, 2009; Montazeri, Montazeri, Azizian, & Mostafavi, 2010). Air short-circuiting occurs when the air entering through the inlet channel and immediately leaving through the outlet without circulating inside the enclosed space (Figure 1.) (Chaudhry, Calautit, & Hughes, 2015; Montazeri, 2011). Montazeri (2011) claimed that short-circuiting is one of the most influential factor in decreasing the ventilation efficiency of windcatcher system.

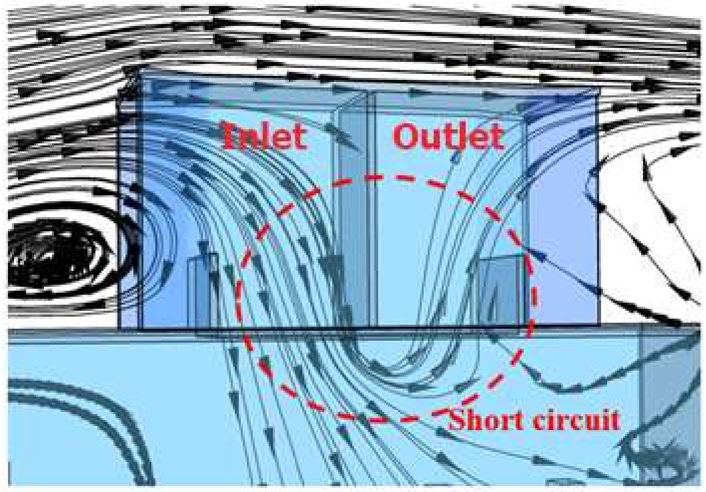

Figure 1.3 Short-circuit problem in windcatcher diffuser.

1.4 Aim and Objective of the Study

The aim of current research is development of a windcatcher design which can provide enough ventilation in low wind speed areas and also reduce the short circuit phenomena to be appropriate for natural ventilation in buildings. To achieve this aim, the objectives are:

Objective 1: To evaluate the effect of anti-short circuit device (ASCD) on short circuit reduction

Objective 2: To evaluate the ventilation performance of windcatcher integrated with wing wall for low wind speed climate

Objective 3: To investigate the improvement of the new design of windcatcher against the commercial windcatcher

Objective 4: To validate the new design in consideration to different wind speeds and directions.

1.5 Research Question

This study attempts to answer the following question:

1. Does the integration of windcatcher with wing wall improve the ventilation performance?
2. Does new design of windcatcher reduce the short circuit problem?
3. Does new design surpass the commercial design in view of ventilation?
4. Is the new design effective in different wind conditions in low wind speed climate?

1.6 Scope of the Study

This section states the scopes of this research. The followings sections explain and justify the "**Scope of study on Human comfort, Climate and Method, Driving Forces of Natural Ventilation, Building type and Climatic factor".**

- **Human comfort:** from different aspects of human comfort only Indoor Air Quality factors are studied in this research.

- **Climate:** In this study the semi-arid climate was selected as the climate of study.

- **Method:** This study is based on two main methods for data analysis including experimental test conducted in wind tunnel lab and theoretical tool done by Computational Fluid Dynamics (CFD). In experimental method, small scale models were tested in wind tunnel to collect data (air velocity). These data in the next stage will be compared with results of simulation to verify the simulation. The mentioned methods were selected based on the literature review.

- **Natural ventilation strategy:** From different strategies for natural ventilation inside the building, this study only focuses on single-sided ventilation.

- **Building type**: This study only focuses on single-story residential building.

- **Climatic factor:** This study considers climatic factors of wind speed, the wind speed and direction.

1.7 Research framework

In this section, a brief explanation of research methodology and phases is presented (Figure 1.). To achieve the aim and objectives of the study, the research methodology consists of six main phases. Phase I is the literature review, Phase II is the data collection by wind tunnel experiment, Phase III is the verification study of simulation, Phase IV is development of new windcatcher design, Phase V is comparison of new design with commercial design and Phase VI is validation of new design in different climate conditions.

Phase I: Literature review

The purpose of this phase is Systematic Literature review on windcatcher types, natural ventilation, climate conditions, short circuit, features that can improve the ventilation performance of windcatcher and different methods used to study natural ventilation.

Phase II: Data collection by wind tunnel experiment

The aim of this phase is to conduct the small scale test in wind tunnel lab to collect experimental data. This data will be used in the next phase for verification of CFD simulation.

Phase III: Verification study

Due to nature of numerical simulation which always associated with some level of errors and uncertainty, it is critical to conduct verification study before any detailed CFD development and optimization. The general target is to show the accuracy of CFD software so that it can be utilized with confidence for simulation and the findings be considered credible for decision making in design stage. Thus, in this step, the simulation results are compared against the experimental data to ensure that the results of CFD code are reliable and trustable.

Phase IV: Developing the new windcatcher design

The objective of this phase is to develop the new windcatcher design to address the first and second objective. It is expected after complement of this phase, the new achieved design can work efficiently in low ambient wind speed to provide enough ventilation rate for occupants.

Phase V: Comparison between the new design and commercial design

In this phase the new design of windcatcher, which developed in pervious section will be compared with commercial design to observe that to some extent the new design can surpass the commercial one in terms of ventilation performance. The criteria for this comparison will be the indoor air quality factors including air velocity, air flow rate and air change rate.

Phase VI: Validation of new design in different climatic condition

The final phase, which is the most important one, is to validate the new design of windcatcher which developed in pervious section in different conditions. These conditions include simulation of new windcatcher design in different wind speed from 0.5 m/s to 3.5 m/s with increment of 0.5 m/s in wind incident angle of 0° and 45°. The criteria for validation will be the indoor air quality factors such as air velocity, air flow rate, air change rate. This phase determines that how much the new design will be successful to provide adequate ventilation for occupants in different wind speed and directions.

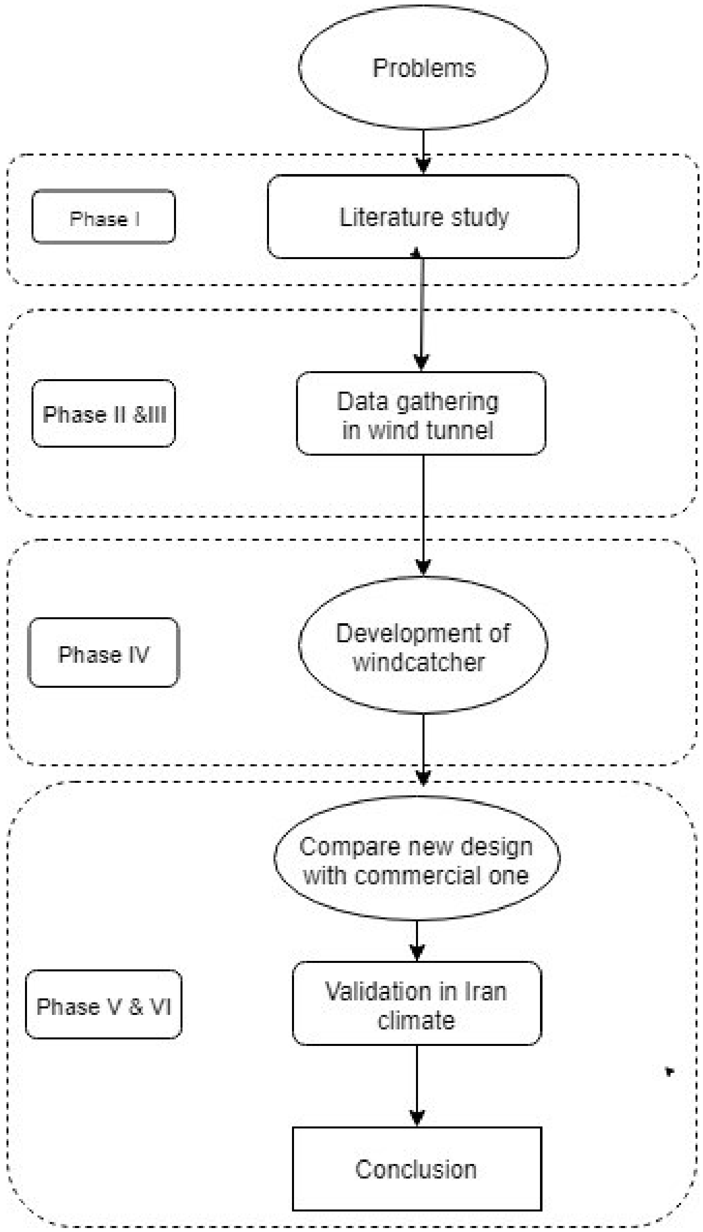

Figure 1.4 Research diagram of the research.

1.8 Significance of Study

This section describes the significance of this study. In fact, this part is based on problem statement. The followings are the significance of this study.

- The proposed new windcatcher design can provide healthier environment for occupants by inducing fresh air.

- The integration of wing wall with windcatcher could enhance the ventilation performance of windcatcher in low wind speed condition.

- This new design can mitigate the short circuit problem which leads to increase efficiency of windcatcher.

1.9 Thesis Outlines

To address the aim, this research consists of five objectives. To do so, this research covers six chapters which are: Chapter 1: Introduction, Chapter 2: Literature Review, Chapter 3: Methods to Study Natural Ventilation, Chapter 4: Research Methodology, Chapter 5: Results and Discussion and Chapter 6: Conclusion.

- Chapter 1: Introduction, this chapter includes background of research, problem statement, aim and objectives, brief research methodology, significance of the study.

- Chapter 2: Literature Review covers a comprehensive review on the previous studies on natural ventilation, windcatcher, indoor air quality and climate.

- Chapter 3: Review on the predicting methods of natural ventilation performance.

- Chapter 4: Research Methodology presents the research methodology of this research in details which includes the theoretical and experimental methods utilized in current research.

- Chapter 5: Results and discussion, in this chapter the results of theoretical and experimental methods are presented and related discussion explains about the findings with respect to previous related studies.

- Chapter 6: Conclusion and recommendations which address the conclusion regarding each objective. In addition, the limitations of this study is presented and further studies is recommended.

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