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# A review on windcatcher for passive cooling and natural ventilation in buildings, Part 1: Indoor air quality and thermal comfort assessment

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**Abstract**

The most prominent challenge in 21th century is global warming which seriously threats the mankind. Building sector with 40% of global energy consumption and GHG emission play a key role in this threat. In this regard, the impact of cooling systems cannot be ignored where along with ventilation and heating systems totally account for 60% of energy consumed in buildings. Passive cooling systems can be a promising alternative to reduce energy consumption. One of the oldest passive cooling system that is still being used today is windcatcher. By manipulating pressure differences and the buoyancy effect, an adequate level of ventilation in buildings can be provided by windcatchers. Since most of the previous windcatcher studies assessed the design characteristics, the current investigation focused on the indoor air quality (IAQ) and thermal comfort aspects. The review details and compares the different theoretical and experimental methods employed by researchers in different case studies to assess the IAQ and thermal comfort. It was found that most IAQ studies were conducted in the UK using CFD and experimental techniques. Previous studies assessed IAQ based on several parameters such as air flow rate, air change rate, $CO_2$ concentration, air change effectiveness and mean age of air. The findings of the studies revealed that satisfactory IAQ were generally achieved using the windcatcher. On the other hand, thermal comfort studies of windcatchers were mainly conducted in hot climates such as in the Middle East. In addition to night ventilation, the review also looked into the different types of cooling methods incorporated with windcatchers such as evaporative cooling, earth to air heat exchangers (EAHE) and heat transfer devices (HTD). Night ventilation was found to be effective in temperate and cold conditions while additional cooling using evaporative cooling, EAHE and HTD were found to be necessary in hot climates.

**Keywords:** Windcatcher; Natural ventilation; Passive cooling; Wind tower; Thermal comfort; Indoor air quality (IAQ); Badgir

## 1. Introduction

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 [1]. Greenhouse gas (GHG) emissions particularly $CO_2$ emissions originating from fossil fuels consumption in buildings further amplified the global warming trend much intensively [2]. Buildings account for about 40% of the global energy consumption [3] and [4] and contribute over 40% of the total world $CO_2$ emissions [5] and [6]. Moreover, this sector is responsible for 30% of the global electricity consumption [7]. The fact is that among all building services, space heating, ventilating, and air conditioning (HVAC) systems are the largest energy consumers in buildings (more than 60%) [8], [9] and [10] which are mostly supplied by fossil resources [11].

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 [12]. Consequently, they can potentially cause “Sick Building Syndrome” [14] and [15] and also metabolic diseases. Sick building syndrome symptoms are 30–200% more frequent in air-conditioned buildings [15]. Failure to maintain good IAQ can result in poor performance and illness for occupants under pro-longed exposure [16]. According to U.S. Environmental Protection Agency

(USEPA) [17], indoor air pollution is among the top five environmental health risks. 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 [10] and [18]. As shown in Fig. 1, each building is an integrated dynamic system separately and requires considerable amounts of energy to provide thermal comfort and acceptable IAQ for its' occupants [19].

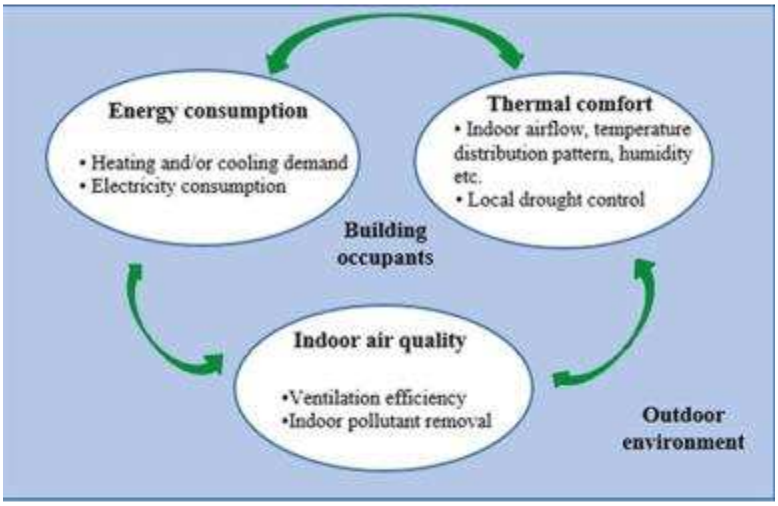


Fig. 1. Relationships between the occupants, building energy and indoor environment [19].

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 [20]. Existing experience has shown that passive cooling provides excellent thermal comfort and indoor air quality, together with very low energy consumption [12]. According to Fig. 2, solar and heat control, heat dissipation and heat modulation techniques are a widely accepted framework for passive cooling in buildings [12] and [20]. Heat modulation techniques relate to the thermal storage capacity of the building structure while solar and heat control techniques deal with reducing building heat gains by several ways such as vegetation, glazing, shading, insulation, etc. Moreover, lower temperature sinks such as the ground, the ambient air and the water are used in heat dissipation techniques in order to remove the excess heat of the buildings. Generally, heat dissipation techniques are classified into three main categories:

• Ground cooling using the ground as a heat sink for building,
• Evaporative cooling based on the use of water,
• Natural ventilation exploiting the ambient air as a heat sink [12].

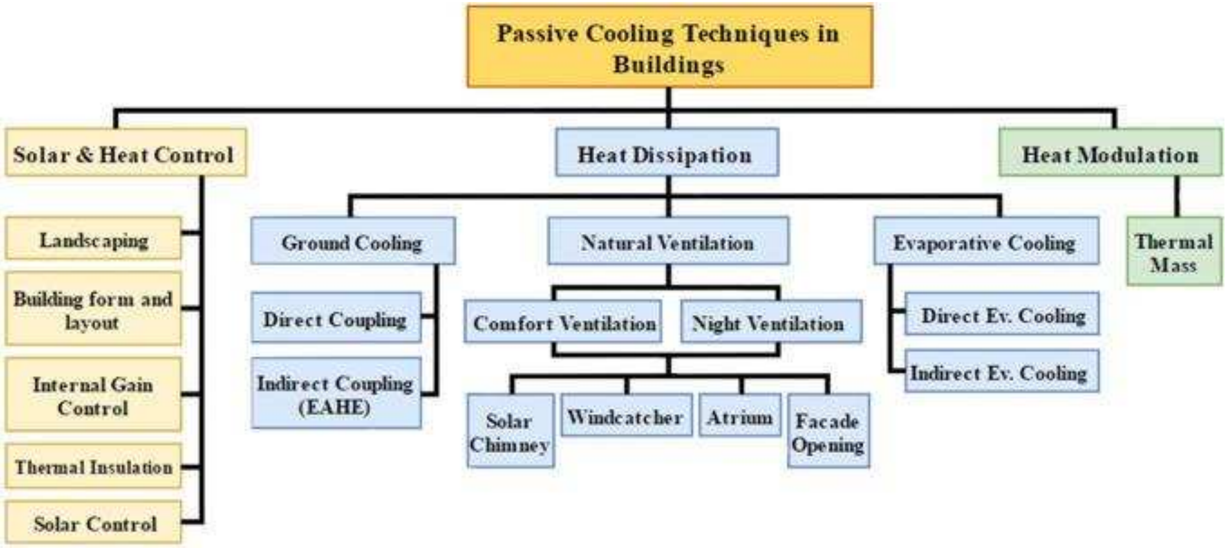


Fig. 2. Different techniques of passive cooling in buildings [12], [20], [26] and [27].

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 air conditioning systems [21]. 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, either directly, when airflow increases the cooling sensation (comfort ventilation), or indirectly, when night ventilation is used to cool the built mass and delay the next day's thermal gains [10], [22], [23], [24] and [25]. It is well-accepted that health, productivity and comfort of occupants are significant issues that should be considered throughout building design [10].

One of the traditional natural ventilation systems applied in buildings, which exploits wind renewable energy for its operation, is a windcatcher [28], [29] and [30]. It is an environmental friendly and sustainable system which targets to combat energy crisis, while improving IAQ and thermal comfort inside the buildings [31], [32] and [33]. Additionally, other benefits of windcatcher are low maintenance cost due to having no moving parts, utilization of clean and fresh air at roof level compared to low level windows [34] and [35], and decreasing greenhouse gases (GHGs) and air pollution [36]. A remarkable numbers of previous researches have focused on the effect of different configurations and components of windcatcher on its performance using CFD modelling, experimental and analytical approaches [14], [30], [37], [38], [39], [40], [41], [42], [43], [44], [45], [46], [47], [48], [49], [50] and [51]. To the best of our knowledge there is no review paper that provides a holistic overview of the windcatcher performance in terms of IAQ and thermal comfort aspects; hence, this paper aims to conduct it. The review will look into the different methods of studying the IAQ and thermal comfort in interior spaces. Furthermore, it will highlight the different types of cooling methods incorporated into the windcatcher to improve its cooling performance. The paper will present several case studies conducted by researchers in different climates.

## 2. Windcatcher concept and history

Before the invention of mechanical cooling systems, human utilized natural resources in innovative manner to provide ventilation and thermal comfort in hot climates, an example of one such technique is the windcatcher [52]. Bahadori et al. [53] and Saadatian et al. [3] defined the windcatcher 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. It is also known as a wind tower. Windcatchers as dramatic architectural features demonstrate the harmony of human created environment with nature [54] and [55]; in other words, they are ingeniously tailored to suit the local climatic conditions [56].

Windcatchers were not only strikingly beautiful and decorative, but were also highly functional and have played a considerable role in cooling and ventilation of the living spaces and the basement of residential buildings, water cisterns, prayer halls of mosques, the pavilions of gardens and the living quarters of caravanserais (an inn with a central courtyard for travellers in the desert regions of Asia or North Africa) in a natural way, without using energy [54], [57], [58], [59], [60], [61], [62] and [63].

In the Middle East especially in Persian Gulf countries, windcatchers have been used for many centuries as a means to cool and ventilate buildings and provide thermal comfort for inhabitants [10], [64], [65] and [66]. It is not straightforward to ascertain the first origin of windcatcher in the world. However, during archaeological investigations conducted by Masouda in 1970s, the first historical evidence of windcatcher was found in the site of Tappeh Chackmaq near city of Shahrood, Iran which dates back to 4000 BC [13], [54], [67], [68], [69] and [70]. According to an ancient discovered painting in Egypt [56], [71] and [72], windcatcher is a well-known conventional architectural feature [13] and the Egyptians have used it since 1300 BC [65]. In Middle Eastern countries, windcatcher is called with different names such as “Badgir” in Iran, “Malqaf” in Egypt [72] and [73], “Barjeel” (originated from Badgir Persian word) in Iraq and the Gulf [13] and [72] “Bating” in Syria, and “Mungh” or “Hawa-dani” in local language of the Sindh province of Pakistan [74] (Fig. 3).


Fig. 3. Different traditional windcatchers in the Middle East: (A) Badgir in hot and humid climate of Iran; (B) decorative Barjeel in Qatar; (C) Barjeel in the Bastakiya Quarter of Dubai; (D) Badgir in hot and dry climate of Iran; (E) Malqaf in Egypt; (F) Barjeel in Bahrain; (G) Mungh in Pakistan [57], [75], [76], [77] and [78].

## 3. Windcatcher function

The operation principals of windcatcher natural ventilation system are mainly based on wind-driven ventilation and stack (buoyancy) effect [55] and [79]. During the daytime, by the movement of external wind at roof level, a positive pressure on the windward side of the structure and at the same time, negative pressure on the leeward side are produced. This pressure difference is highly sufficient to deliver fresh air to indoor space and extract stale and warm air out [62] and [80]. During night-time, in the absence of air movement or in low wind conditions, the windcatcher device operates using the natural buoyancy of thermal forces like a chimney [59], [66] and [81], which is yielded on the account of air temperature gradient between inside and outside of a building (see Fig. 4). When the ambient air temperature is considerably lower than the indoor temperature, the subsequent of pressure difference and air density gradient of the internal and external air masses leads to rising up low dense indoor air and expelling through the windcatcher leeward side; simultaneously, descending denser cool air through the windward side of the system [82].

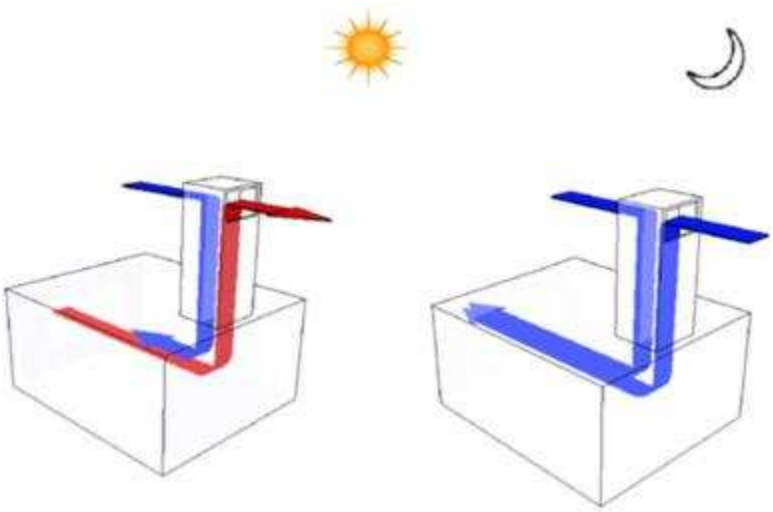

Fig. 4. Windcatcher function during daytime and nighttime [82].

In this regard, Hughes & Cheuk-Ming [83] compared the contribution of two driving forces of wind and buoyancy for a windcatcher. They concluded that the impact of wind pressure driven flow is more effective than buoyancy driven force by 76%. Furthermore, the investigation confirmed that the stack effect is negligible in the windcatcher device when there is not adequate external airflow movement.

**4. Windcatcher types**

In the present paper, windcatchers are classified into two main groups: traditional windcatchers and modern windcatchers. Normally, conventional windcatchers consist of different components including openings, roof, head, channel and internal partitions as depicted in Fig. 5. Generally, the first type is categorized into five groups including one, two, four, six and eight-sided as well as cylindrical windcatchers based on the number of their sides (faces) which contain openings [57], [64] and [84].

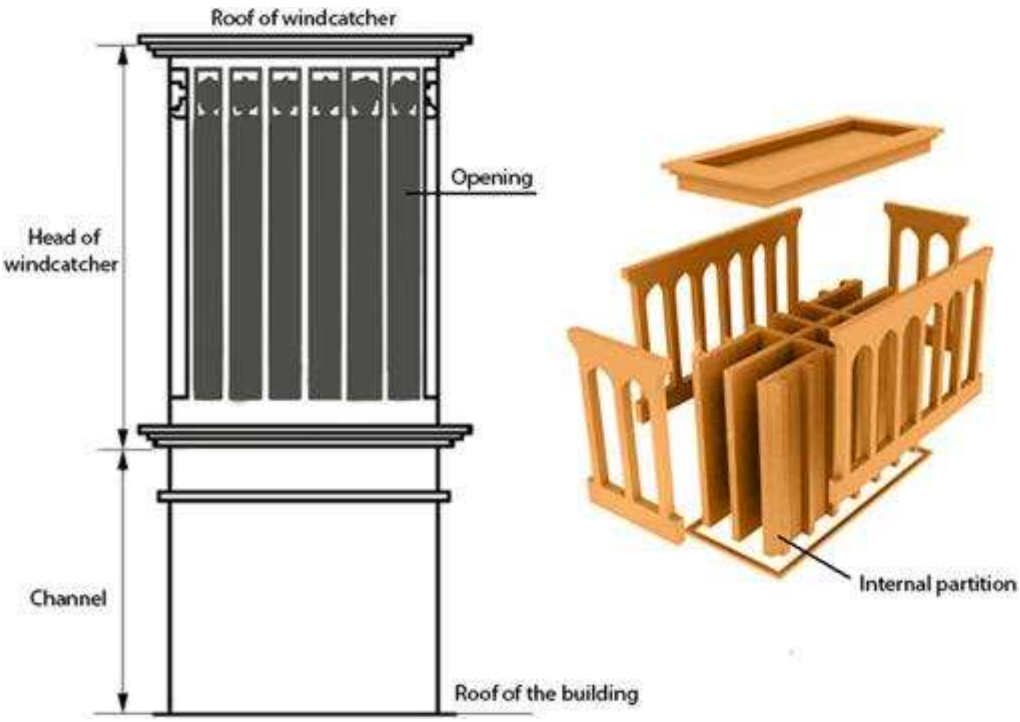

Fig. 5. Different components of traditional windcatcher [85] and [86].

One-sided windcatchers take the wind from the top opening and channel it inside and afterward the air is exits from another opening of a building [3]. They were typically utilized in the areas where air blows in one specific direction [87]. Two-sided windcatcher has two openings on two opposite sides so that one opening is used as an entrance for fresh air and another extracts the warm air [50] and [82]. Moreover, in areas where there is no specific direction for wind, four-sided wind catchers can be frequently seen because their design are mainly dependent upon capturing the prevailing wind from all directions [82]. The six and eight-sided windcatchers (with hexagonal and octagonal cross-sections) have been rarely seen in residential buildings whereas frequently constructed over the water cisterns particularly in hot and arid regions of Iran [84]. A cylindrical windcatcher can be considered as the latest generation of traditional windcatchers [57]. The application of cylindrical windcatchers is limited and a few examples of this type can be found in Iran and Dubai [57] and [84]. Fig. 6 shows all types of traditional windcatchers.

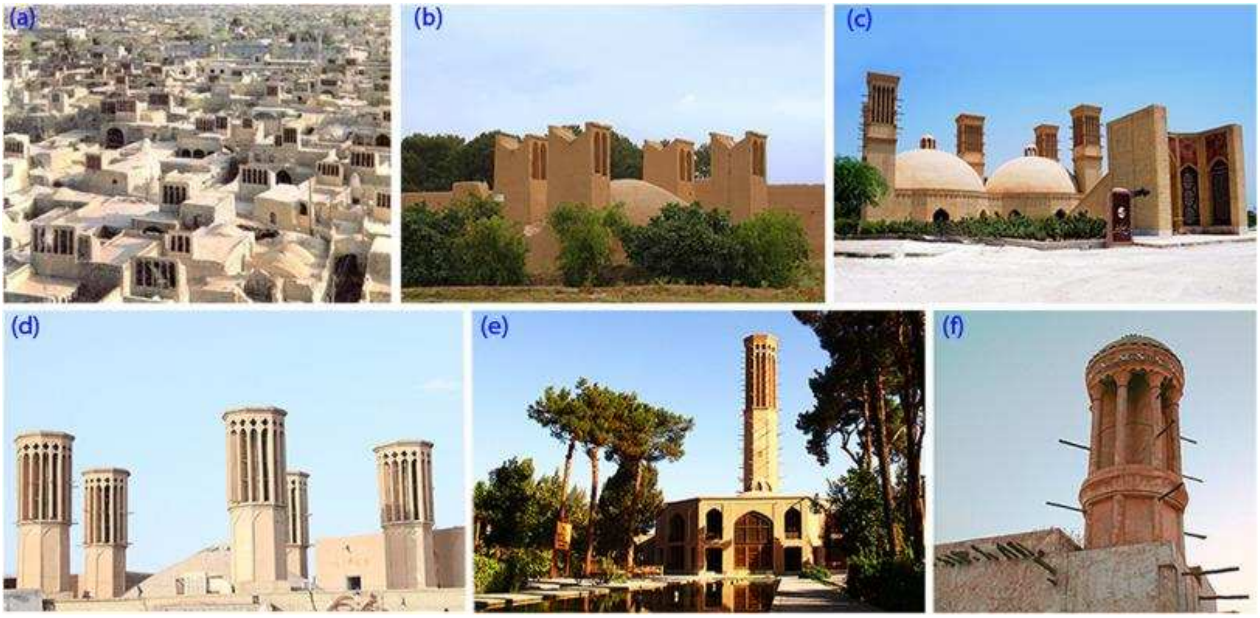


Fig. 6. Various types of traditional windcatchers: (a) one-sided windcatchers in Meybod, Iran [88]; (b) two-sided windcatchers of the water cistern in Dowlat-Abad Garden, Yazd, Iran [89]; (c) four-sided windcatchers of the water cistern in Kish Island, Iran [90]; (d) six-sided windcatchers in Yazd, Iran [57]; (e) eight-sided windcatcher in Dowlat-Abad Garden, Yazd, Iran [91]; (f) cylindrical windcatcher in Dubai [57].

Contemporary architects and engineers have adapted modern windcatchers from the vernacular architecture of the Middle East [92]. Modern windcatchers have been developed to take the advantages of traditional windcatcher and eliminate their limitations to adopt them with advanced building principals and technologies [93]. The utilization of commercial windcatcher is now widespread, especially for indoor spaces with high occupant numbers such as schools and office buildings [94]. For instance, over 7000 windcatchers were installed in the UK public buildings during the last 15 years [35] (see Fig. 7). Fig. 8 displays commercial four-sided windcatcher with solar panel, louvers, solar powered fan and adjustable dampers. Furthermore, other examples of modern windcatchers in different parts of the world are illustrated in Fig. 9.


Fig. 7. Different Monodraught windcatchers in the UK: (A) Royal Chelsea hospital, London; (B) Seaside School, Lancing; (C) Addey and Stanhope school Deptford; (D) Tesco Eco-store Cheetham Hill [35].

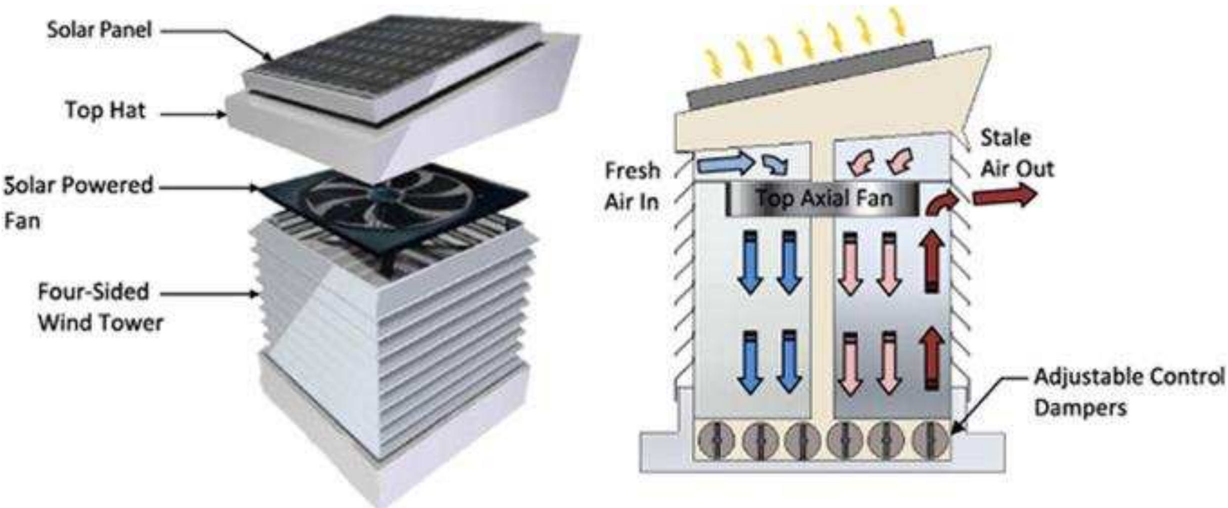


Fig. 8. Schematic of a modern windcatcher integrated with a solar powered fan [82].

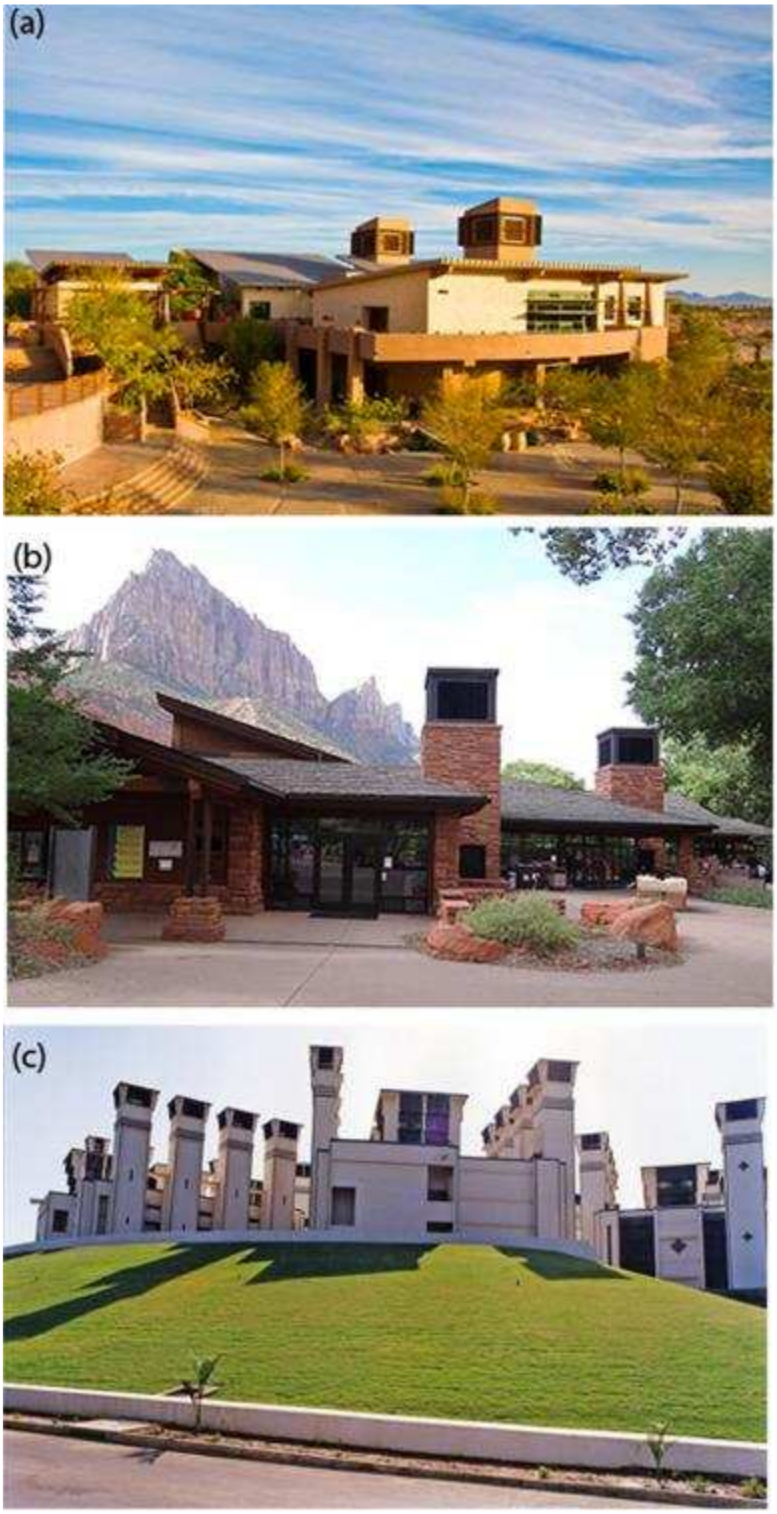


Fig. 9. Windcatchers in contemporary buildings: (a) Springs Preserve building in Las Vegas, USA; (b) Zion National Park Visitors Center in Utah, USA; (c) Torrent Research Center Building in Ahmedabad, India [65], [75] and [95].

**5. Indoor air quality assessment**

According to USEPA [17], indoor air quality (IAQ) refers to "the air quality within and around buildings and structures, especially as it relates to the health and comfort of building occupants". It defined elements of good IAQ as: a) ensuring adequate ventilation (introduction and distribution of clean indoor air), b) controlling contaminants travelling in the air, and c) maintaining acceptable thermal comfort.

In the past, up to the beginning of 20th century, it was thought that the building occupants were the main source of indoor pollution, due to human bio-effluents and/or tobacco smoke. In today's contemporary world, however, the indoor environment is made up of elements such as furniture and office equipment, internal partitions, surface paint and decorative pieces which contain and release chemicals to the indoor air and can present increased health risks to the occupants [10]. Hence, sufficient ventilation is needed to maintain safe concentrations of contaminants for occupants. By removing or diluting indoor pollutants with fresh outdoor air, the build-up of pollutants can be controlled and prevent sick building syndrome (SBS) [25]. In fact, good IAQ is usually a direct product of using natural ventilation [96] which mainly depends on the supply of fresh air. The quantity of ventilation required to ensure an adequate air quality indoors depends on the amount of the pollutant in a space. It is known that the pollution level reduces exponentially with the airflow rate. Therefore, the ideal airflow rate can be calculated by knowing the pollution intensity of the system. Fig. 10 illustrates the exponential rate of pollution with increasing flow rate [97].

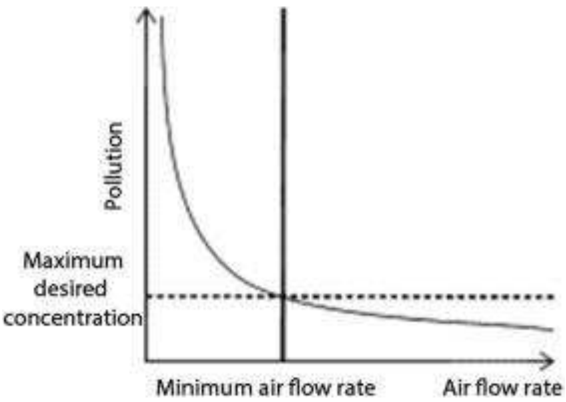


Fig. 10. Natural ventilation for indoor air quality [97].

Normally, the quality of indoor air is evaluated by means of parameters such as air flow rate, air change rate (ACH), $CO_2$ concentration, air change effectiveness (ACE) and mean age of air (MAA). Considering the importance of air quality inside the building, several researchers studied the ventilation performance of windcatcher in terms of IAQ parameters which is reviewed in this section.

Mavrogianni and Mumovic [98] investigated the effect of the commercial windcatchers performance on IAQ and thermal comfort in UK classrooms using a series of field measurements and questionnaire surveys during winter and summer periods. The monitoring results revealed that the classrooms achieved the requirement of not exceeding 1500 ppm of $CO_2$ averaged over the day, but none met the higher supply rate requirement of 8 $ls^{-1}$ per person at full occupancy. The survey study concluded that 40% of the occupants were generally satisfied with the air quality inside the classrooms.

Calautit and Hughes [99] used experimental and CFD techniques to evaluate the IAQ within the classroom ventilated by a commercial windcatcher. The system was subject to computational analysis to study the supply rates, the mean age of air (MAA) and air change effectiveness (ACE). The results showed that the windcatcher surpassed the required ventilation rate (10 L/s per person) at the external velocity of 2 m/s and above. The lowest MAA was observed underneath the windcatcher supply jet displaying a fresher air in that area. The values of MAA were 200 s and 100 s close to walls and in the middle of the room at the height of 1 m above the floor level respectively as shown in Fig. 11A. Fig. 11B illustrates the calculated values of ACE at breathing height (1 m) ranging from 0.86 (recirculation zones) to 2.1 (supply jet) at external wind speed of 3 m/s. According to Fig. 11C, values of the ACE in the occupied space were generally close to 1.0 at different external air velocities, which was consistent with good mixing of the ventilation air within the ventilated space.

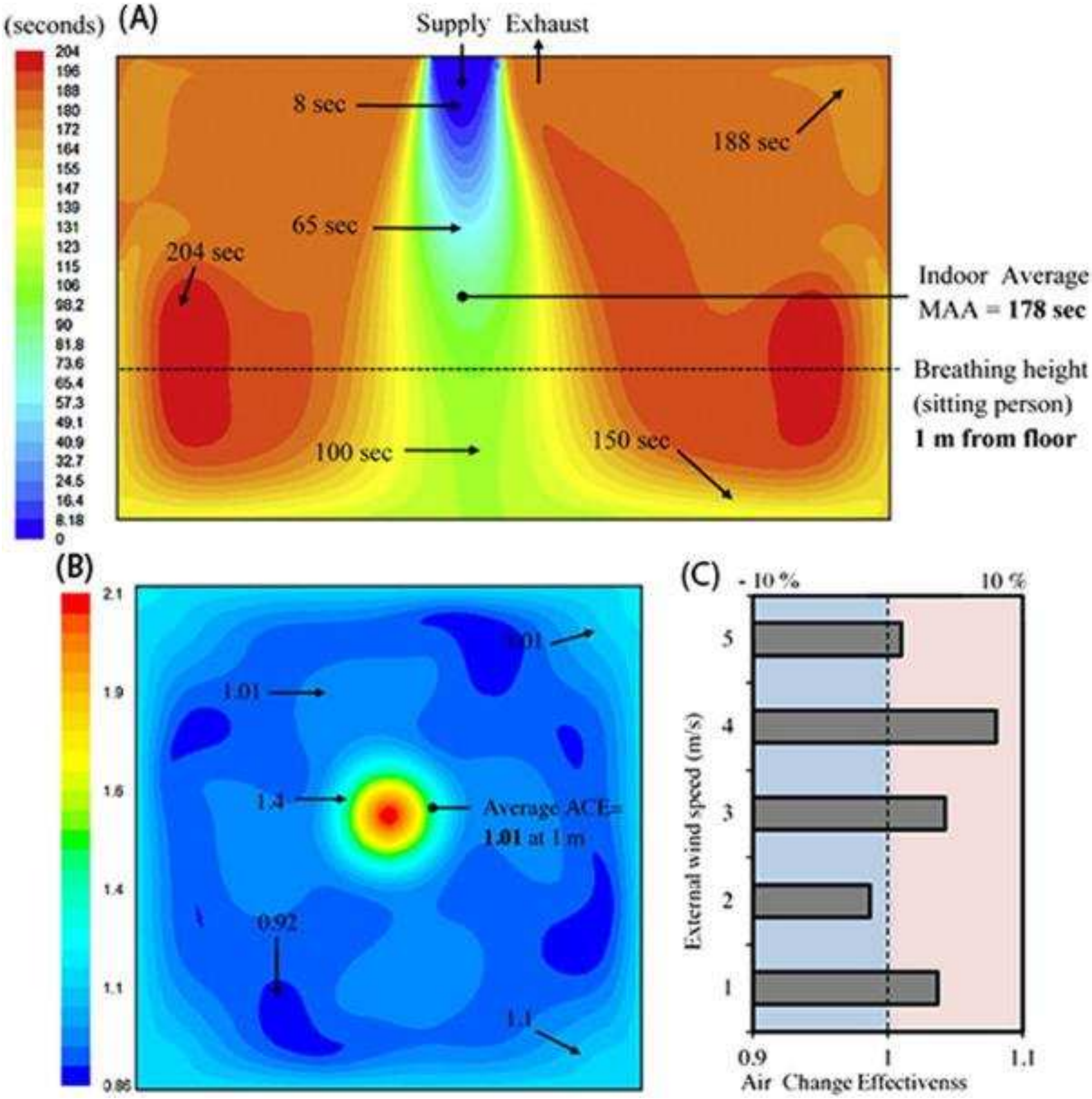


Fig. 11. (A) Mean age of air (MAA) contours within the test room at external wind speed of 3 m/s; (B) Air change effectiveness (ACE) contours at 1 m height (breathing height); (C) effect of different external wind speed on the ACE [99].

Furthermore, an IAQ assessment in an occupied space which was naturally ventilated by a commercial windcatcher during the summer period was conducted in [100]. The work involved in-situ measurements of indoor air temperature, humidity and $CO_2$ concentration. It was observed that levels of $CO_2$ (not exceed 500 ppm) and humidity (between 50% and 60%) were well within acceptable range for good IAQ. In addition, during the monitoring period, the air temperature inside the space was constant around 23 °C while the maximum external temperature reached as high as 29 °C.

Jones et al. [101] compared the performance of two classrooms in a UK school, one equipped with commercial windcatcher (test room) and the latter was ventilated by conventional opening windows (control room). In order to evaluate the windcatcher performance, parameters including indoor air temperature and $CO_2$ concentrations and in classrooms were measured over an eight month period. The air quality measurements showed that the test room was able to meet the carbon dioxide and temperature requirements while control room cannot meet the UK standards for $CO_2$.

Calautit et al. [16] numerically investigated the contribution of the commercial windcatchers layout and spacing on indoor $CO_2$ concentration and ventilation rates for a small classroom of 30 people. For the CFD modelling, 3 staggered and 3 parallel arrangements for windcatchers location were considered as shown in Fig. 12. The results revealed that at zero wind angle the average indoor $CO_2$ concentration within room ventilated by the leeward windcatcher in staggered arrangement was considerably lower than the parallel one because the staggered arrangement effectively minimized the re-entry of pollutants. As depicted in Fig. 13, the average $CO_2$ concentration was 28–50 ppm and 1–3 ppm higher than the external air (382 ppm) for the parallel and staggered arrangements respectively. It was also found that in parallel arrangement at 5 m spacing, the maximum supply rate for the leeward windcatcher is half of the British standard building ventilation rates (10 L/s/occupant). In addition, the supply rate was decreased to 2.4 L/s/occupant when the spacing between the parallel windcatchers was reduced to 3 m. However, an air supply rate enhancement for the parallel layout of windcatchers was observed by increasing the air incidence angle. On the other hand, the leeward windcatcher in staggered arrangement was able to deliver the required fresh air supply at all tested spacing lengths.

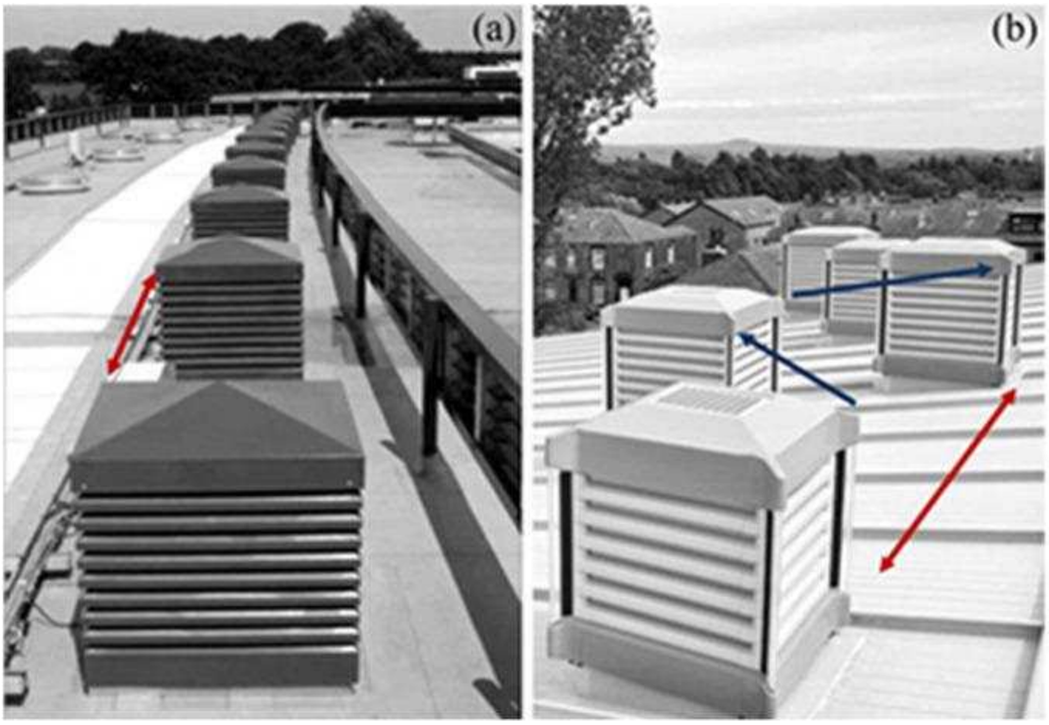


Fig. 12. Roof mounted windcatcher (a) parallel arrangement (b) staggered arrangement [16].

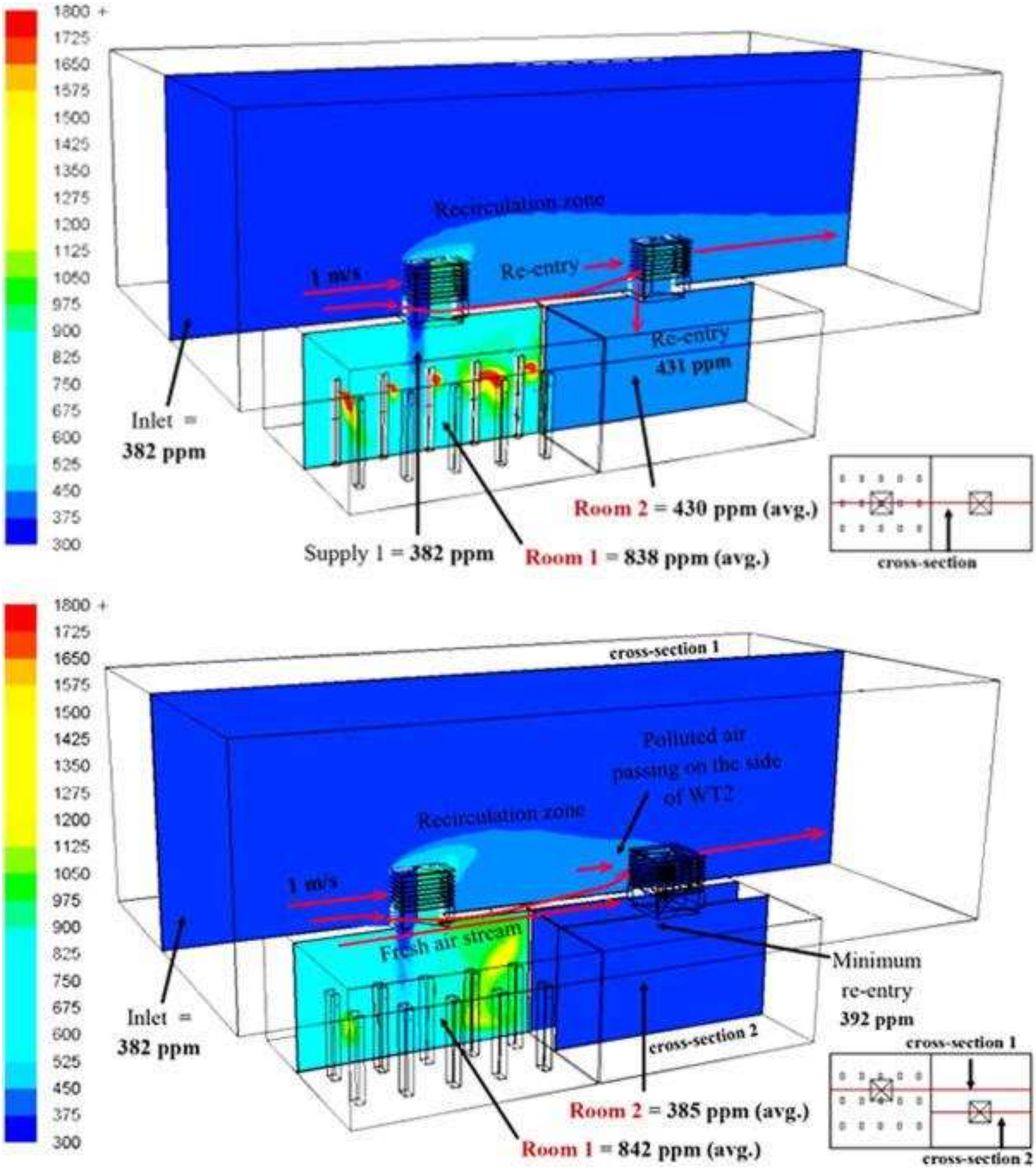


Fig. 13. Contours of $CO_2$ concentration (ppm) inside the occupied and un-occupied room ventilated with parallel (up) and staggered (down) arrangement windcatchers with spacing of 5 m [16].

Moreover, Abdallah et al. [102] carried out a parametric study of the effect of dimension parameters of a combined system (evaporative cooling windcatcher with solar chimney) on IAQ and ventilation rate for hot and arid climate of Egypt. In order to achieve high-performance and compact design with acceptable range of indoor thermal comfort and air quality, significant dimension parameters (inclination angle, air gap, chimney width as well as windcatcher depth and width) were optimized using numerical simulation (see Fig. 14).

The results established that according to adaptive comfort standard and ASHRAE standard, the optimized system is able to achieve acceptable thermal comfort range (80%) and $CO_2$ concentration (not exceed 1000 ppm). A maximum difference of 7.8% with average 3.1% was obtained in $CO_2$ concentration before and after the parametric studies as shown in Fig. 15. It was also found that compact design is achieved with dimensions 1 m by 1 m for windcatcher and 0.75 m by 0.4 m for the solar chimney with an effective ventilation rate of 414 $m^3$/h during the hottest summer days.

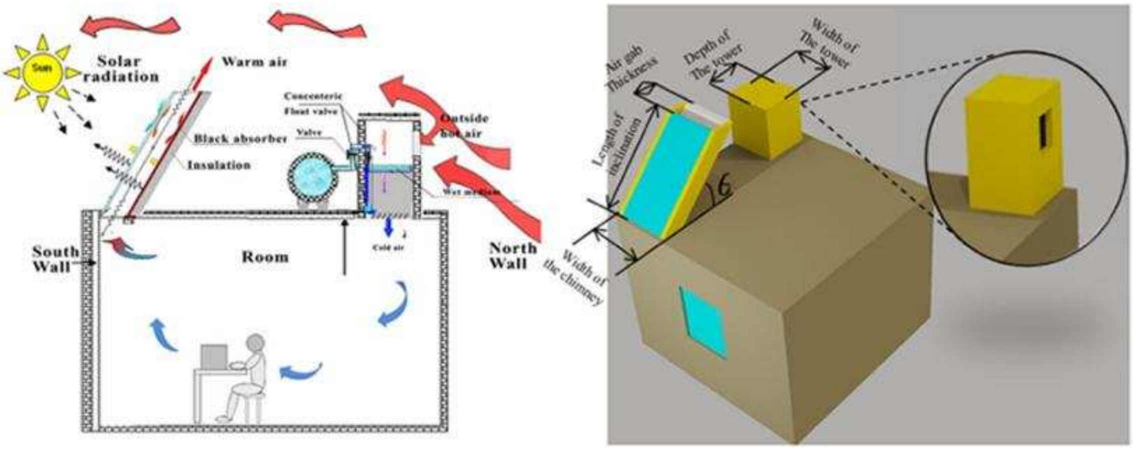


Fig. 14. Schematic diagram of evaporative cooling windcatcher with inclined solar chimney [102].

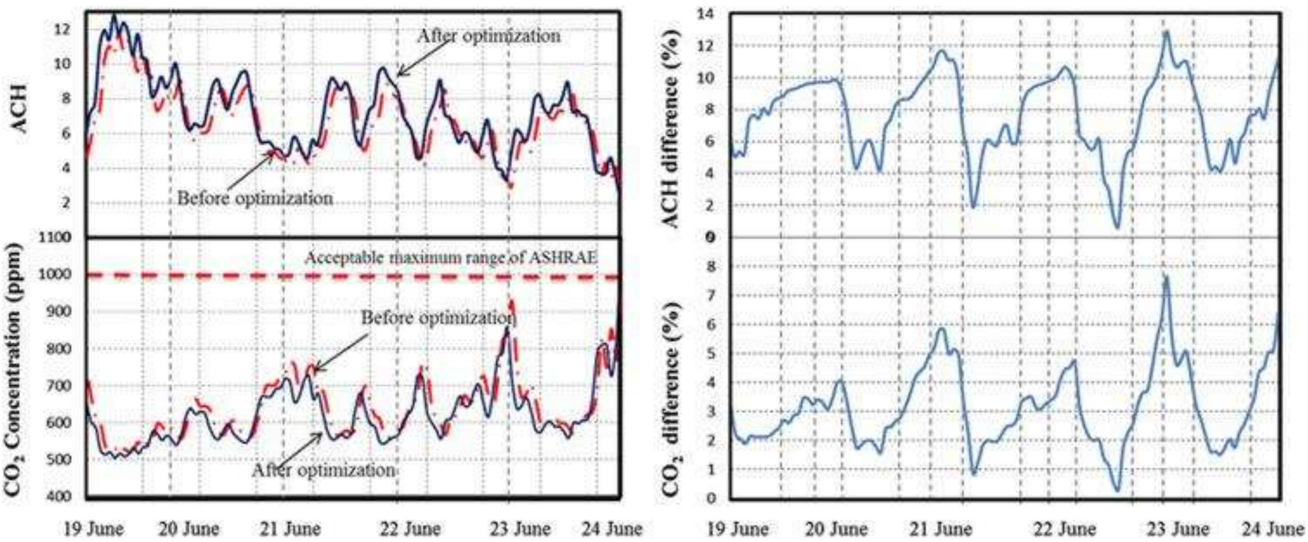


Fig. 15. ACH and CO2 concentration of the combined system before and after parametric studies [102].

Alshitawi et al. [103] conducted in-situ measurements of particle concentrations and air change rate inside a classroom under two ventilation modes, when the windcatcher device is in operation (fully open dampers) and when it is switched off. The work also highlighted the influence of external environmental factors such as outdoor particulate matter (PM) concentration, wind speed, relative humidity and ambient air temperature on indoor particle concentration. The indoor air change rate was 1.75 ACH, when the system was switched off while it reached to 3.2 ACH in the mode of fully open dampers; thus, the IAQ in the classroom is improved by the windcatcher. It was also found that indoor particle concentration has negative relation with ambient temperature, external concentration, wind speed and direction and positive relation with the outdoor relative humidity.
Elmualim and Awbi [104] experimentally and numerically compared the performance of two commercial windcatchers with different cross-sections (square and circular) in terms of ventilation rate. It was found that the windcatcher system achieved a ventilation rate of 5 ACH (15.25 $m^3$ room) with an external wind speed of 3 m/s. The results established that the ventilation efficiency of windcatcher with circular section is significantly lower than the square windcatcher as shown in Fig. 16. The author concluded that this was a consequence of sharp edges of square windcatcher which produce a wide area of flow separation with higher pressure gradient across the device.

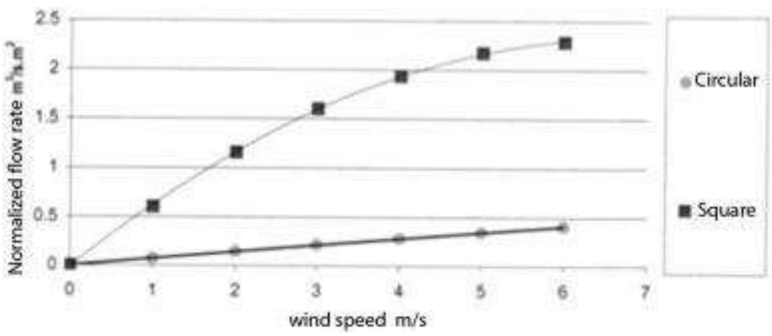


Fig. 16. Performance comparison between circular and square windcatcher [104].

Haw et al. [105] assessed the ventilation performance of a windcatcher with a venturi shaped roof in the hot and humid climate of Malaysia using numerical and experimental analysis. The obtained results showed that at a low outside air velocity of 0.1 m/s, the windcatcher is capable of producing 57 air changes per hour (ACH) inside the building. Moreover, the indoor air velocity fluctuated between 0.05 m/s and 0.45 m/s. The study demonstrated that the windcatcher contributed significantly in achieving adequate IAQ and enhancing interior thermal comfort of the inhabitants under hot and humid climate.

Hughes and Ghani [93] conducted a CFD study of a windcatcher ventilation rates inside a classroom and compared against current British Standards. The numerical results indicated that at external velocity of 4.5 m/s, the windcatcher provides air supply rate of 15.1 L/s/m$^2$, this is 19 times the recommended minimum of 0.8 L/s/m$^2$. Likewise, it was able to provide 27.1 L/s per occupant for a small classroom, which is 5.5 times the minimum standard of 5 L/s per occupant. The study confirmed that the system is a successful ventilation strategy for providing the required fresh air supply even in urbanized or well-shaded applications and during low wind conditions.

Furthermore, Nejat et al. [106] studied a new design of a Two-sided Windcatcher integrated to Wing Wall (named as TWIW) in order to enhance the ventilation performance of windcatcher in low wind speed climatic conditions of Malaysia (Fig. 17). Wind tunnel testing and CFD simulations were conducted to analyse the indoor airflow rate and ACH supplied by windcatcher with different angles of wing wall at varying wind velocities. The best operation was observed in the windcatcher with 15–30° wing wall angles. Likewise, the TWIW achieved 45.5 ACH at wind speed of 2.5 m/s. Hence, the new design showed 50% more ventilation performance comparing with conventional two-sided windcatcher in the same external wind speed. It can be concluded that the implementation of the new design in low wind speed conditions (including tropical climate and urban environment) was successfully approved by satisfying the minimum ventilation requirement of ASHRAE standard.

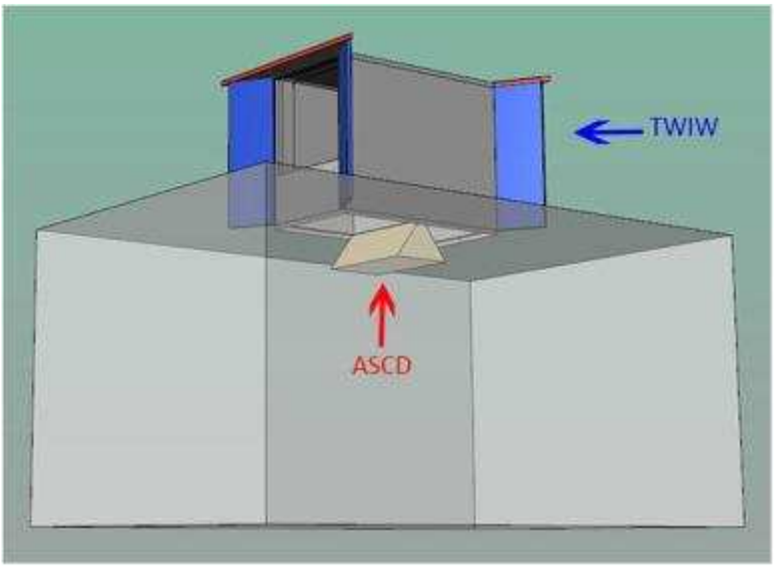

Fig. 17. Two-sided windcatcher integrated to wing wall (TWIW) and anti-short-circuiting device (ASCD) [106] and [107].

Later, Nejat et al. [107] added a new device (ASCD) to TWIW to lessen air short circuit beneath windcatcher channels (Fig. 17). The work used wind tunnel testing and CFD techniques to determine the influence of the anti-short-circuiting device (ASCD) on indoor air quality and $CO_2$ concentration inside the building. The results showed that the ASCD with angles between 20° and 80° prevented air-short-circuiting while supplying up to 40–51 l/s per occupant, which is higher than the minimum recommendations of ASHRAE62.2. In addition, the TWIW without ASCD showed 8% higher $CO_2$ concentration in the room, indicating that the windcatcher with ASCD was more effective in removing stale air out of the room. Hence, the proposed new design was successful to mitigate short circuit phenomena.

## 6. Thermal comfort assessment

According to ASHRAE [108], thermal comfort is defined as “that condition of mind that expresses satisfaction with the thermal environment”. Natural ventilation is used not only for providing an acceptable air quality inside a building, but also for improving thermal comfort [48]. Natural ventilation can be applied for comfort ventilation during day (comfort ventilation) and for cooling the building at night (night ventilation) [22] and [26].

### 6.1. Comfort ventilation

Comfort ventilation provides the physiological cooling effect on the building occupants by introducing fresh cool ambient air inside the building at higher air velocity [26] and [109]. The increased air speed over the occupant's body minimize the feeling of discomfort by convective heat loss and sweat evaporation from the skin, which enhances physiological cooling and thus induces thermal comfort [110] and [111]. Jones et al. [101] stated that windcatcher can substantially contributes to a provision of comfort ventilation without relying upon opening windows. Since the desirability of a higher air speed occurs often during the daytime hours, comfort ventilation is effective in daytime, and is referred to as daytime ventilation, when the indoor air temperature is higher than outdoors in un-ventilated buildings [111].

In this section, several investigations reported the contributions of windcatcher to comfort ventilation (as a result of increased air movement) are reviewed. Then a few available Post Occupancy Evaluation (POE) studies, which are crucial to obtain building occupants’ feedback to know whether the building is comfortable in practice, are also presented.

Reyes et al. [28] conducted a numerical study of a two-sided windcatcher in providing thermal comfort inside the residential buildings in arid and semiarid regions of Mexico. The indoor air temperature and velocity were analysed for the windcatcher at various height levels ranging from 0.1 to 2.20 m along the room. In order to determine comfort conditions, the mean velocity and temperature of fifteen zones inside the room were simulated as shown in Fig. 18. The CFD results established that the top and floor areas of the room are in poor comfort zones while the most important part of human body matched well with comfort conditions. The study demonstrated the potential of windcatcher system for providing acceptable level of thermal comfort in approximately 50% of interior environment.

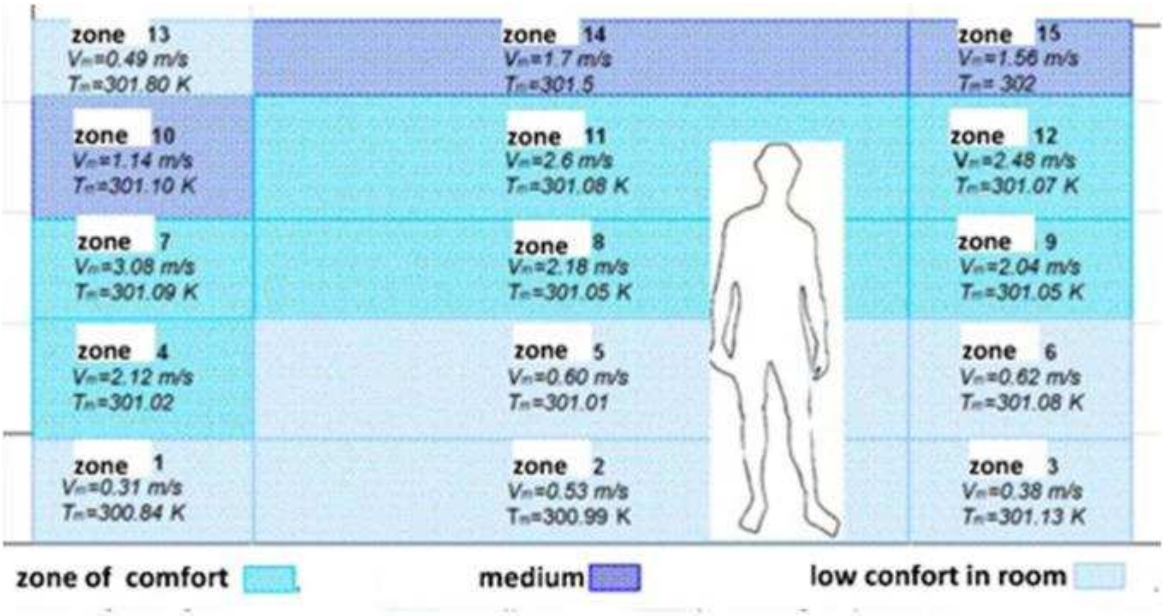


Fig. 18. Comparison of thermal comfort conditions for different zones inside the room based on average values of indoor air temperature and velocity [28].

Moreover, in [71] an experimental study was performed in order to determine the potential of a one-sided windcatcher in providing comfort condition for the occupants in residential building in hot and humid climate of India. The results of in-situ measurement showed that mean indoor wind velocity is 0.8 m/s, which falls within the comfort zone for the tropics. It was also observed that the windcatcher is able to decrease the relative humidity and indoor air temperature by 15% and approximately 5 °C respectively. The investigation proved the capability of windcatcher to attain internal thermal comfort in such climate.

In the study conducted by Maneshi et al. [112] a four-sided windcatcher was subject to CFD analysis at different values of ambient air temperature and velocities to assess the internal thermal comfort based on Percent Dissatisfaction (PD) factor. PD values were calculated at varying heights of room. The overall results indicated that PD values are increased at ceiling and floor levels while the corresponding values for the occupant's activity levels (0.6, 1.2 and 1.8 m) are greatly lower (see Fig. 19). It was also found that higher dissatisfaction levels occurred at higher external air velocities which are mainly due to the direct relationship between the draft dissatisfaction and the wind magnitude.

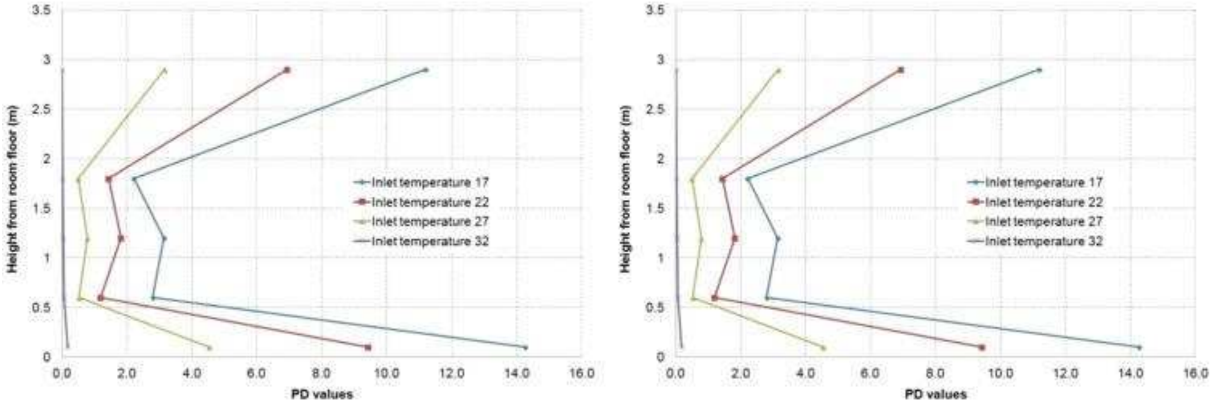


Fig. 19. The PD for the range of inlet temperature (left) and velocity (right) values in selected elevations in the room [112].

Calautit et al. [113] compared numerically the performance of traditional and modern windcatchers based on achieved indoor air temperature and velocity. The computational results indicated that the modern windcatcher is capable of enhancing the indoor airflow distribution, reducing air temperature by 13% and increasing air velocity by 63%. The study also highlighted the potential of an optimized windcatcher configuration as a sustainable alternative to the conventional cooling techniques for providing effective natural ventilation.

McCabe and Roaf [114] used dynamic modelling tools to simulate the indoor operative temperature and air flow rate of traditional windcatcher house in Bastakiya, Dubai. Windcatcher models were developed to ascertain whether indoor comfort condition could be improved by different iterations of the windcatcher design. The results showed that the operative temperature inside the rooms is slightly increased by decreasing the windcatchers height. The study concluded that even on exceedingly hot hours the windcatchers (after some modifications including reducing the cross-section of air channel and increasing the height) are capable to provide internal conditions very close to thermal comfort standard based on an adaptive comfort model. Moreover, Mahmoudi [85] used CFD to simulate the air temperature and relative humidity inside a house ventilated by a traditional windcatcher. The study

pointed out that the windcatcher was capable to decrease the air temperature by 11 °C and increase the relative humidity by 19%.
In [115] a Building Energy Simulation (BES) tool (EnergyPlus) was used to assess the effect of windcatcher performance on comfort condition of an office building in china. The CFD results indicated that windcatcher system plays a significant role in decreasing indoor air temperature (around 2 °C). The work also demonstrated that with the help of windcatcher, natural ventilation contributed in achieving internal thermal comfort for the whole occupied hours in October. Ghadiri et al. [116] also found that a vernacular windcatcher with height of 6 m has potential to decrease the air temperature from 25 °C to 21 °C in hot and dry region of Yazd.

Elmualim and Awbi [117] conducted a subjective occupancy survey to assess the thermal comfort in a UK university seminar room equipped with a commercial windcatcher. The findings of the post occupancy evaluation demonstrated 41.7% of occupants reported feeling neutral to temperature, 16.7% of them felt only slightly warm and the rest felt significantly warm. It was also found that the air velocity inside the room was in an acceptable range and 75% of occupants welcomed the installation of the windcatcher device. Interestingly, although 25% of the inhabitants stated that the air is stagnant inside the room, they still welcomed the installation of the windcatcher. This could be because of the environmental awareness of the occupants and their desire to apply renewable energy techniques in buildings.

Thomas and Baird [118] carried out post occupancy evaluation of the Torrent Research Center in Ahmedabad, India. The building performance and occupants' experience were compared in air-conditioned blocks and naturally ventilated blocks with passive downdraft evaporative cooling (PDEC) windcatcher. User perception of indoor air temperature, air quality and overall comfort was assessed using the Building Use Studies (BUS) workplace survey. The BUS results revealed that the overall satisfaction for comfort, air temperature and quality are observed in both PDEC and air-conditioned buildings (see Fig. 20). Although the BUS results of air-conditioned blocks were relatively better than PDEC blocks, it is significant to note that the results of buildings integrating the passive downdraft evaporative cooling systems were constantly better than international benchmarks. Moreover, due to lower energy consumption in PDEC blocks coupled with vastly positive occupants' satisfaction responses, the study confirmed the feasibility of incorporation of evaporative cooling windcatcher system in current buildings in India.

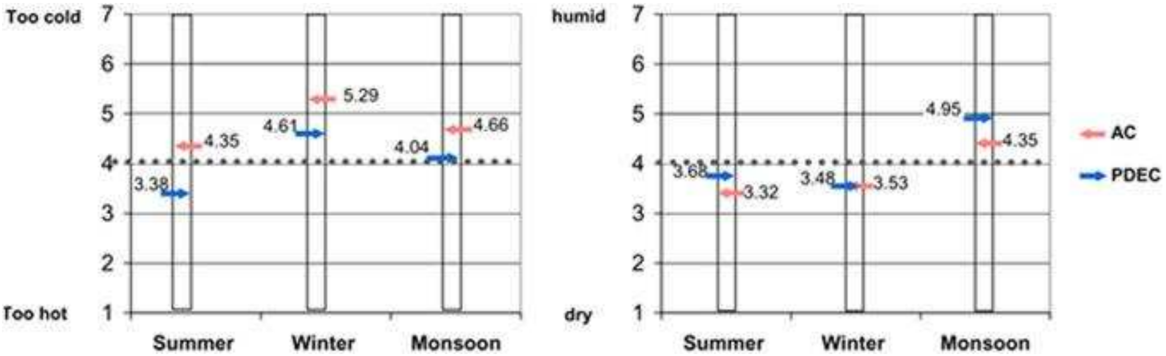


Fig. 20. Left: BUS results for air temperature, Right: BUS results for air humidity [118].

As mentioned earlier, Mavrogianni and Mumovic [98] assessed the occupants' thermal comfort using questionnaire survey in typical classrooms in UK. It was observed that during winter, most of occupants were satisfied with the thermal comfort inside the classrooms; however, only 12% of occupants stated that they feel comfort during summer. This was because the building had suffered from inappropriate user control as the windcatcher system control settings were accidentally set to winter mode during summer. Due to this malfunction, it was not known whether better occupant comfort levels could have been achieved if the summer mode control settings were applied. The authors claimed that naturally ventilated school buildings integrated with windcatchers reveal sufficient thermal performance until the 2050s.

### 6.2. Night ventilation

Night ventilation or night cooling is a passive cooling technique which exploits the cold night air to cool down the windcatcher's absorbed heat gains during daytime and decrease the daytime temperature rise [12], [97] and [119]. As a result, temperature peaks are reduced or even postponed [12]. Normally, an adequate heat-storage capacity and heat-transfer area for this task are provided by the configuration of the upper part of the tower, namely the thickness of the walls and internal partitions [74]. Eventually, the cooling effect of the tower is lost when the temperature of the thermal mass reaches the same temperature as the ambient air [82] and [119]. Khan et al., stated that [79] windcatcher is able to provide the benefit of night ventilation without posing a security risk.

A few studies highlighted the cooling benefit of night ventilation provided by the windcatcher system [96], [98], [99], [113] and [120]. For instance, Kirk [120] evaluated the performance of a commercial windcatcher in a council office in Kings Hill, UK. The work demonstrated that the indoor temperature was cooled by up to 4 °C through night ventilation and exploiting the thermal mass of the building. The findings of study carried out by

Mavrogianni and Mumovic [98] (see Section 5) revealed that the morning temperature was diminished around 1 °C, when the windcatcher dampers remained open during the night. The authors claimed that the night cooling strategy can be beneficial even for a thermally lightweight structure. Furthermore, Jones et al. [101] stated that windcatcher provide the substantial night-time ventilation and decreased indoor temperature by up to 2.8 °C.

Likewise, Ji et al. [115] simulated the effect of openable top-hung windows on the windcatcher operation during night-time. It was found that by providing secure night cooling during unoccupied time, the combination of these two natural ventilation strategies made significant contribution to pre-cool the structure, thus lower interior temperatures can be achieved in the next morning. The internal temperature in the first occupied hour in the next morning is on average decreased by 4.2 °C and the peak temperature is postponed approximately one to two hours.

In fact, the cooling potential of night ventilation technique for a typical windcatcher is limited because they are only dependent on thermal mass of the structure to decrease the air temperature [122]. Hence, in order to enhance the thermal comfort of the occupants, other passive cooling methods such as evaporative cooling, earth to air heat exchanger (EAHE) and heat transfer device (HTD) which have been integrated with windcatcher, are also reviewed in this paper.

### 6.3. Evaporative cooling

Evaporative cooling technique is one of the most efficient and long recognized ways of providing thermal comfort in hot and dry climates particularly in the Middle East [123] and [124]. In this method, large enthalpy of water vaporization makes possible to use it for evaporative cooling. During evaporation, water absorb high amount of heat from surrounding air which results in air temperature reduction. This process, which utilizes much less energy than conventional refrigeration cooling, can be efficient in dry climate where increasing the air moisture content can improve the occupant's comfort [12].

Water utilization as a heat sink in evaporative cooling technique has been applied for centuries in the Middle Eastern countries such as Iran, Egypt and Jordan [3]. One traditional way was use of underground water canal known as Qanat which was integrated with windcatcher design to decrease the air temperature and to humidify the indoor environment [67].

As illustrated in Fig. 21, warm dry air enters the underground water channel and passes distance to reach the building. During this passage, the interaction between warm air and cool water causes the evaporation of water which leads to decreasing in air temperature. On the other side, wind blowing around the windcatcher causes a negative pressure on the leeward side of the opening which exhaust the warm indoor air and replace with fresh cooled air coming from Qanat [82].

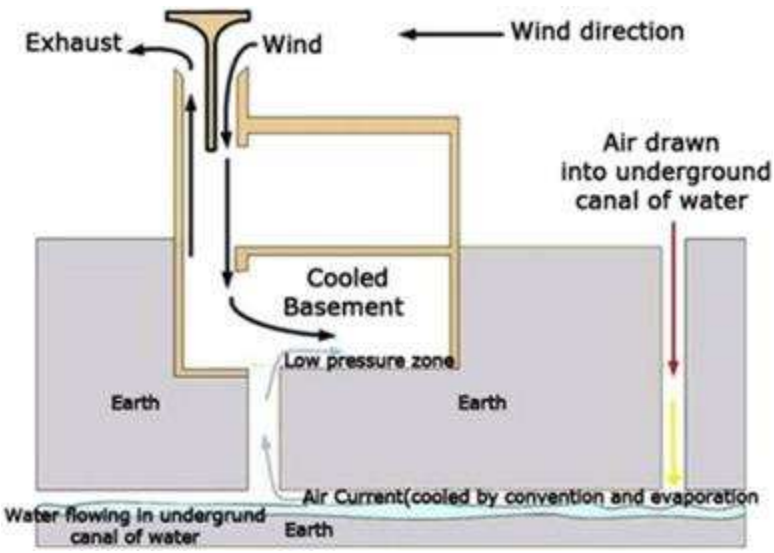


Fig. 21. Cooling performance of windcatcher incorporated with underground water channel (Qanat) [125].

Ahmadikia et al. [126] carried out a numerical study to predict the thermal and ventilation performance of the vernacular Badgir integrated with two water ponds in Yazd, Iran. The computational results revealed that an evaporative cooling system performed better at lower wind velocity than that of higher speed. It was also found that the thermal performance of windcatcher is considerably improved by water spraying by increasing the relative humidity by 5% and declining the average of indoor air temperature by 4 °C, achieved by increasing the mass flow rate of water spray.

Kalantar [127] carried out CFD modelling of an evaporative cooling windcatcher to analyse the airflow pattern inside the windcatcher. The CFD and experimental results indicated that a temperature reduction up to 15 °C is achieved by the evaporative cooling windcatcher at its optimum operation. The study revealed that with a water usage rate of roughly 0.025 kg/s, the system is able to generate cooling load up to 100 kW, which is adequate for air-conditioning floor space of building with 700 $m^2$ areas in such regions.

Although conventional evaporative cooling techniques such as Qanat and water pond have great capability to cool down buildings, they cannot be easily applied in current buildings [3]. To overcome the limitations of the traditional design, modern windcatcher can be equipped with wetted surfaces or wetted columns to improve the thermal and ventilation performance of the system (see Fig. 22) [82] and [128]. The movement of the air over wetted columns or surfaces causes evaporation so that air temperature is reduced and a comfortable environment is provided for the inhabitants [12] and [60]. Several studies have been performed in order to investigate the performance of windcatcher integrated with this type of evaporative cooling [53], [102], [121], [124], [129] and [130].

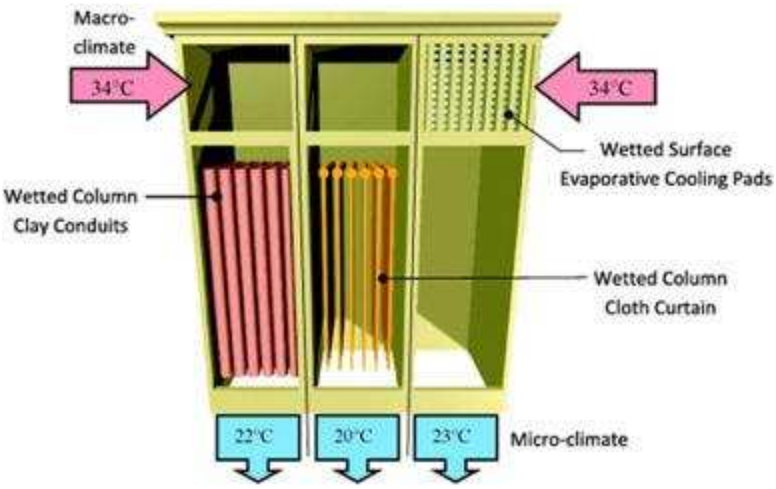


Fig. 22. Thermal operation of windcatcher integrated with wetted columns and surfaces [82].

For instance, Bahadori et al. [53] compared experimentally the thermal performance of conventional windcatcher and two novel evaporative cooling windcatchers. The two designs were one with wetted column, consisting of wetted curtains hung in the tower column, and the other one with wetted surfaces, consisting of wetted evaporative cooling pads mounted at its entrance as shown in Fig. 22. It was observed that the thermal efficiency of the new designs of the windcatcher is considerably higher than the traditional one in terms of increasing relative humidity and indoor air temperature reduction. However, the air flow movement was diminished slightly in evaporative cooling systems. The experimental results highlighted the suitability of the windcatcher with wetted surfaces in low wind conditions and the wetted columns system in high wind speeds.

Saffari and Hosseinnia [124] evaluated numerically the thermal operation of new design of an evaporative cooling windcatcher under varying external conditions and structural parameters. The windcatcher is incorporated with wetted curtains suspended inside the column of the system, which are formed as surfaces that inject droplets of water at extremely low air velocities. The obtained computational results indicated that increasing the water droplet diameter and temperature led to increasing the outlet air temperature of the wetted columns by 3.5 K and 4.5 K respectively. It was also established that the windcatcher with the wetted columns of 10 m height increase the air relative humidity by 22% and decline the internal air temperature by 12 K.

An experimental application of wetted columns integrated with one-sided windcatcher in residential building in hot and arid climate of Algeria was described in [121]. In order to enhance the mass and heat transfer, the channel of the tower was equipped with clay conduits. The results indicated that increasing the number of conduits partitions and height of the wetted column resulted in significantly decreasing the indoor air temperature. The combined system also increased the relative humidity by 62.6% and decreased the temperature by up to 18.6 °C. Furthermore, the findings of parametric studies conducted by Abdallah et al. [102] (see Section 5) revealed that the difference in indoor air temperature between before and after parametric studies was nearly 1.5 °C during the hottest day of Egypt climate condition as illustrated in Fig. 23.

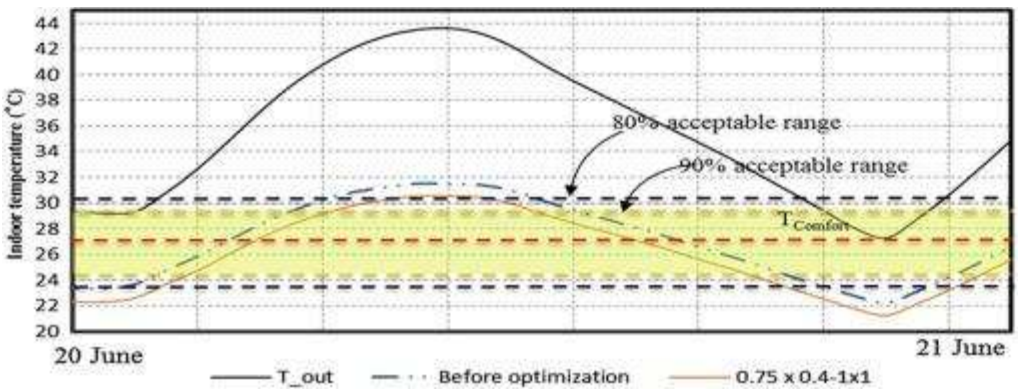

Fig. 23. The predicted temperature during the hottest day achieved by the combined system before and after parametric studies [102].

### 6.4. Earth to air heat exchangers (EAHE)

The most common method to utilize ground as heat sink for building cooling is earth to air heat exchangers (EAHE). In EAHE system, air circulated through pipes, which buried in the soil, to transfer its heat to the surrounding soil; then, the cooled air enters the building space [12]. The concept of EAHE dated back to ancient periods [131]. For example, in Persian architecture EAHE called Naghb which has been applied in buildings for cooling the air by means of temperature gradient between outdoor air and the earth. As illustrated in Fig. 24, the hot ambient air moves in windcatcher and during passing through Naghb the heat transfer occurs on the wall of Naghb and makes the air cooler. Accordingly the air relative humidity increases while its temperature drops off from point A to Point B [52].

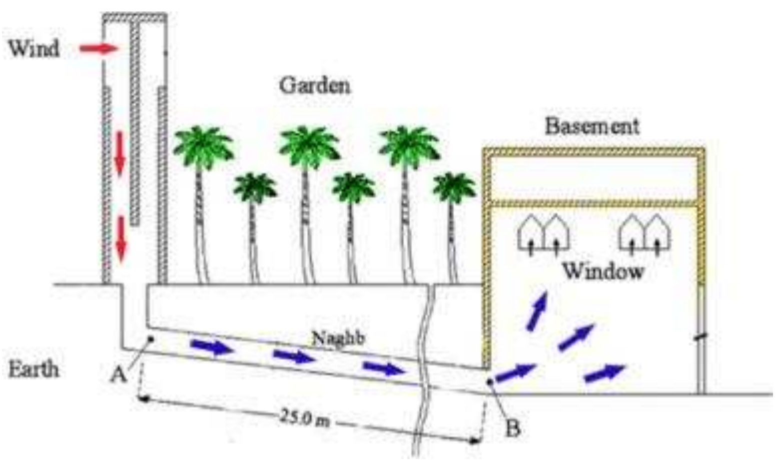

Fig. 24. Schematic view of the air path through the Badgir and Naghb [52].

An analytical model to study the contribution of integrating a windcatcher with the earth-to-air heat exchanger (EAHE) in extremely hot climatic conditions of Algeria was presented in

[132]. The work also highlighted the effect of windcatcher and buried pipe dimensions on the thermal performance of the unit. The predicted results showed that the air flow rate of 592.61m3/h is achieved by the windcatcher with a cross sectional area of 0.57 $m^2$ and overall height of 5.1 m. Moreover, increasing the pipe length led to increasing the mean efficiency and the gradient of temperature while they were reduced by increasing the pipe diameter. The study demonstrated the daily potential of the combined system for cooling the building up to 30.7 kW h corresponding to a pipe length of 70 m. It was also found that the thermal efficiency of the windcatcher integrated to the EAHE is much higher than the evaporative cooling windcatchers with wetted surfaces (see Fig. 25).

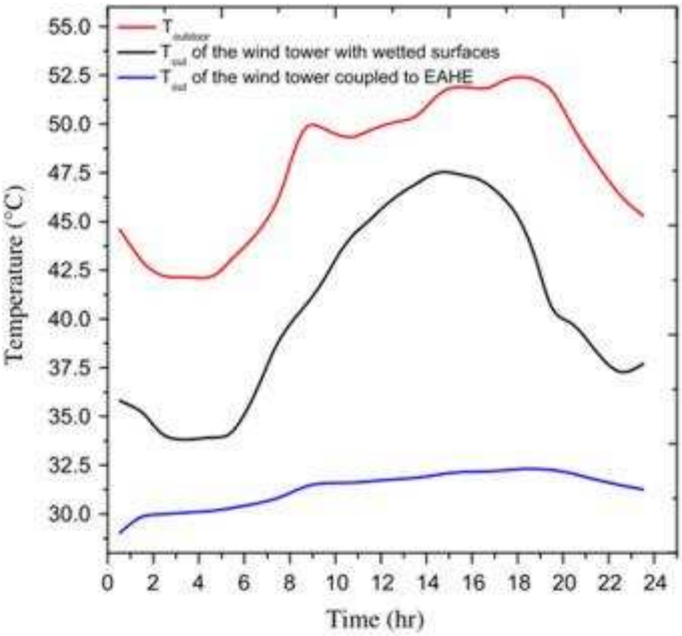


Fig. 25. Comparison of the thermal performance of two passive cooling systems [132].

Furthermore, Jassim [133] evaluated the thermal performance of a similar windcatcher incorporating EAHE system using experimental and CFD techniques. During hot summer months in Baghdad, Iraq, the in-situ measurement of indoor and outdoor air temperature for a house was conducted. The results established that by in air velocity, the windcatcher integrated with EAHE is able to decrease the air temperature up to 18 °C, while the outdoor temperature is 45 °C. The work demonstrated that the proposed design contributed greatly in improving the internal comfort and reducing the energy consumption in hot and dry climate such as Iraq.

### 6.5. Heat transfer device (HTD)

Windcatchers with evaporation system usually have taller channel with bigger size to provide sufficient time for contacting the wetted surfaces and the air flow. Hence, they are more expensive to build. Moreover, the addition of cooling devices such as wetted columns and wetted surfaces may decrease the air flow rate inside the channel and lessen the overall efficiency of the windcatcher [134]. On the other hand, evaporative cooling systems utilize a significant amount of water for operation. In some regions where water is expensive or in short supply, the use of water for evaporative cooling constitutes as an environmental concern [135]. Furthermore, in tropical climate where the air has high contents of moisture this technique cannot be implemented.

To address these shortcomings, a novel passive cooling technique known as heat transfer device (HTD) developed by Calautit et al. [136] for integrating with windcatcher to meet the indoor comfort criteria in extreme hot climate. Unlike evaporative cooling which directly evaporates water to the airstream, HTDs are an indirect cooling system. Due to its compact size, it is a suitable alternative for modern windcatchers [122]. The HTD is a simple device of very high thermal conductivity with no moving parts. It is essentially a conserved slender tube containing a wick structure lined on the inner surface and a small amount of fluid such as water at the saturated state [135]. They are installed inside the windcatcher unit, highlighting the potential to achieve minimal restriction in the external air flow stream while ensuring maximum contact time, thus optimizing the cooling duty of the device. [134]. Fig. 26 presents the operation of commercial one-side windcatcher with heat transfer device.

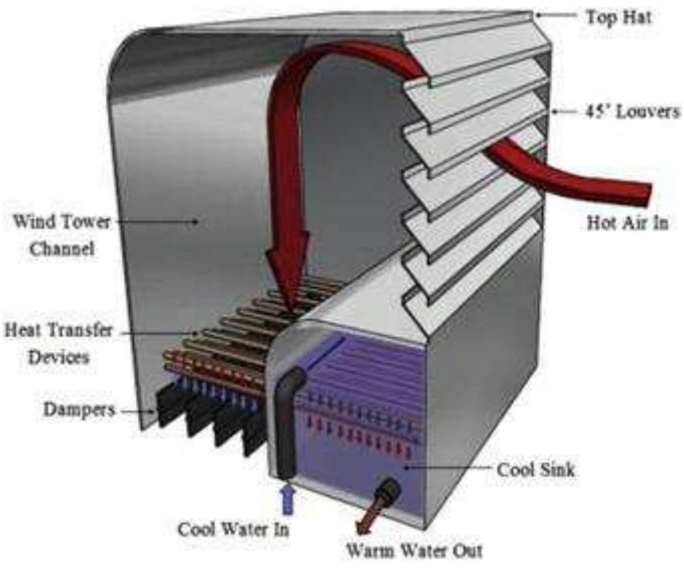


Fig. 26. One-sided windcatcher incorporating heat transfer devices (HTDs) [137].

Calautit et al. [136] carried out a thorough investigation into a thermal comparison between a traditional evaporative cooling windcatcher and a proposed windcatcher system integrated with heat transfer devices (HTDs). Moreover, the contribution of the horizontal and vertical HTDs on the thermal performance of the windcatcher model was evaluated. The one-sided windcatcher equipped with horizontal heat transfer devices and standard four-sided windcatcher model equipped with vertical heat transfer devices. Fig. 27 displays the temperature contours inside the terminal of the tower with evaporative cooling and HTDs. The findings revealed that the exit temperatures using traditional cooling were decreased up to 14 K while the height of windcatcher is not an influencing factor when using a heat transfer device assisted cooling cycle making it feasible for modern architecture. The heat transfer device integrated windcatcher was capable of reducing the air temperatures by 12–15 K, depending on the configuration and operating conditions. The results revealed that the internal airflow rate was slightly reduced following the integration of the heat transfer device configuration, reductions of 2–7% (vertical HTD) and 4.3–10% (horizontal HTD) were obtained from the achieved computational model.

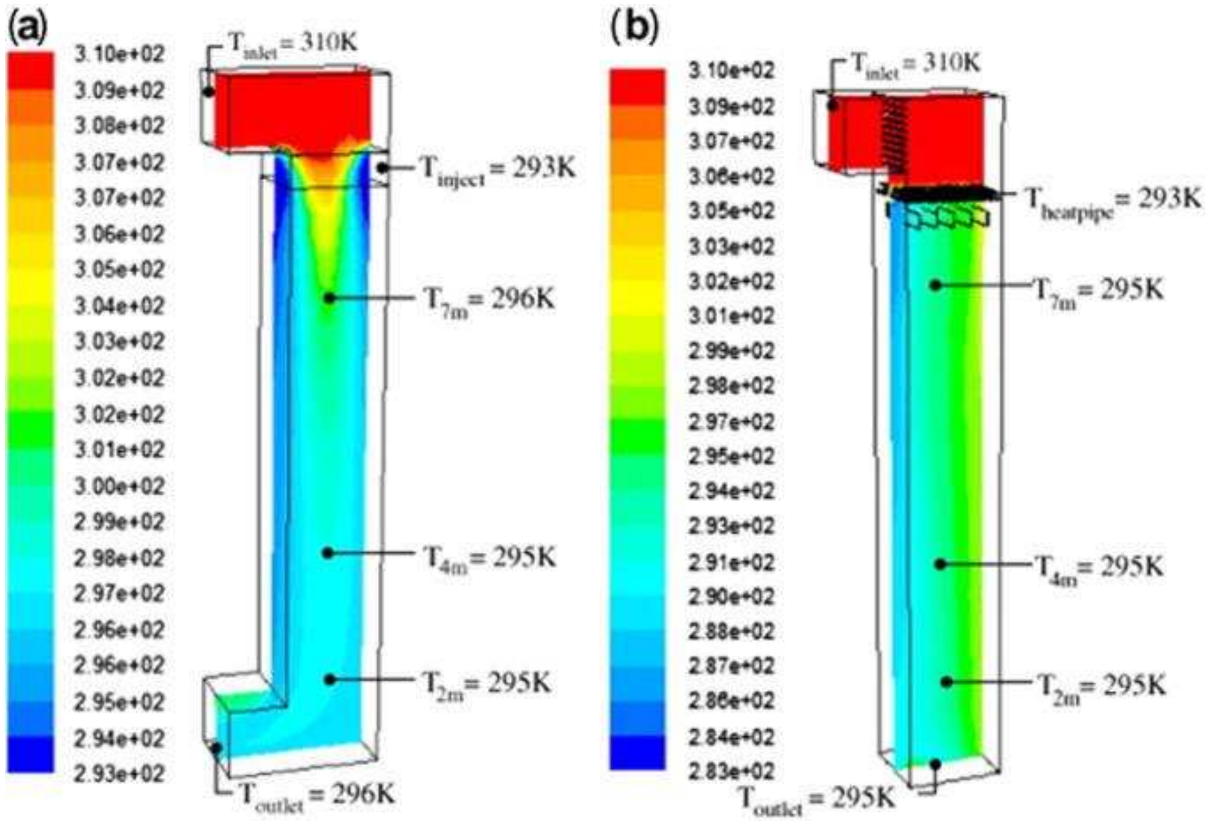


Fig. 27. Temperature contour lines of a cross sectional plane in the test channel; (a) traditional evaporative cooling (b) heat transfer device [137].

Furthermore, Chaudhry et al. [122] investigated the thermal performance of a circular windcatcher as illustrated in Fig. 28. A commercial FLUENT code was used for velocity and pressure field simulations. The results showed that the proposed cooling system was capable of meeting the regulatory fresh air intake requirements per occupant of 10 L/s. In addition, the results indicated that a passive cooling capacity ranging between 6 K and 15 K depending on the operating configuration.

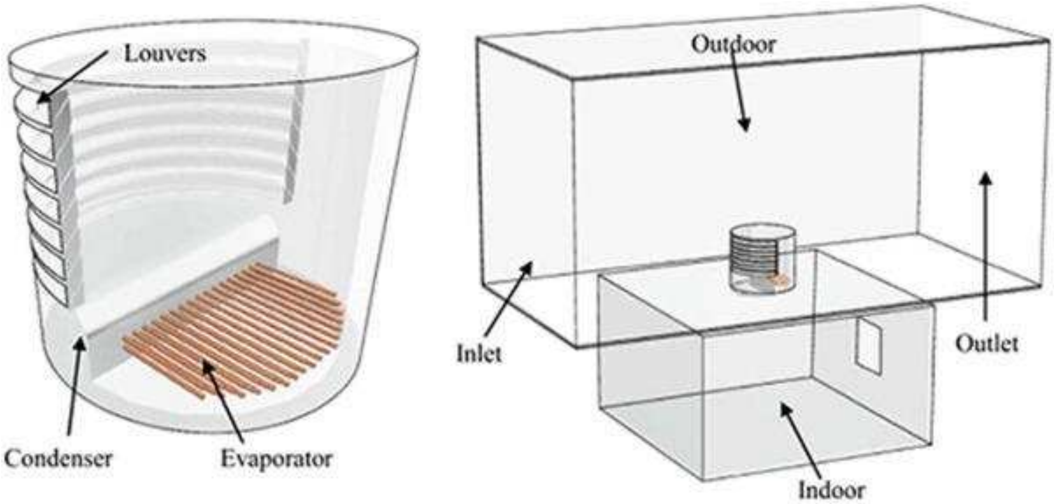


Fig. 28. Schematic of the circular windcatcher model coupled with the horizontal heat transfer device [122].

Recently, Calautit and Hughes [138] examined the effect of the cooling devices (heat pipes) on the performance of the windcatcher, highlighting the capabilities of the system to deliver the required fresh air rates and cool the ventilated space. In addition to CFD and wind tunnel measurements of the airflow through the windcatcher, a full-scale field testing of the device was also carried out in Ras Al Khaimah, UAE to evaluate its thermal performance under real operating conditions. A cooling potential of up to 12 °C of indoor air temperature was identified in the study. It was also established that the air temperature was only decreased by 5–6 °C at 5 m/s external air speed. While, higher temperature reduction was observed at lower wind speed, 9.5 °C reduction at 2 m/s. The field test demonstrated the positive effect of the addition of heat pipes on the cooling performance but also revealed technical issues which remain to be solved such as airflow control strategy and cool sink operation. The authors recommended that further testing of the windcatcher is required to characterise its full year operation.

## 7. Summary and discussion

Windcatcher system plays an important role in enhancing IAQ and thermal comfort inside the buildings. Windcatcher performance analysis can be conducted using two main approaches: experimental and theoretical methods. The first one can be classified into full scale and small scale. In full scale, the case of study can be investigated in real environment (in-situ) or analysed in the lab. In small scale, reduced-scale model of windcatcher is studied in the lab (usually wind tunnel testing). Both types of experimental technique have their own advantages and disadvantages. For example, although the results of full scale measurement are very reliable, this approach is usually too expensive to conduct and the results are restricted to a specific case which cannot be generalized to other cases easily. In addition, it is time consuming method compared to small scale [139] and [140]. On the other hand, small scale is more economical in the long run and efficient as well as independent from outdoor environment which means the conditions (such as wind speed or direction) can be easily controlled [141]. However, the similarity between small scale and real scale model has been a challenging matter for researchers [142]. Another limitation of wind tunnel technique is evaluation of windcatcher thermal performance due to difficulty in the scaling down of cooling system in wind tunnel.

Meanwhile, theoretical approach to analyse the windcatcher performance can be classified into analytical modelling and numerical modelling. Analytical models include basic physics equations for heat transfer and fluid dynamics. Therefore, it cannot be expected that it has the detailed prediction of fluid behaviour for windcatcher but they are useful tools for a general understanding and fast estimation of windcatcher performance [141]. It is found that the contributions of the analytical models to the windcatcher studies are minimal, but rather CFD has occupied this position due to increasing computing power and flexibility of CFD software in recent years. CFD can analyse and optimize complex 3D design with high resolution for temperature, velocity and air flow patterns around or inside the three-dimensional model that analytical models are not able to do [143] and [144]. The most important challenge of CFD modelling is reliability and validity of data [142]. Nowadays, it has been a common practice by CFD researchers to compare their predicted results against any physical measurement data be it at small scale or full scale experiment, prior to a comprehensive parametric study. Furthermore, a small numbers of studies used post occupancy evaluation (POE) approach to determine the capability of windcatcher system to provide an acceptable range of indoor thermal comfort for occupants [98], [117] and [118].

Table 1 summarized various studies which assessed the air quality inside the buildings integrated with windcatchers using different methods of analysis such as experimental, numerical, analytical, etc. Most applications of the windcatchers are found to be educational buildings in UK [16], [93], [98], [99], [100], [101], [103] and [104]. Only two different publications have been identified reporting the windcatcher applications in the houses in hot-arid and tropical climates [102] and [105]. Varying parameters of IAQ such as air flow rate, air change rate (ACH), $CO_2$ concentration, air change effectiveness (ACE) and mean age of air (MAA) were analysed by previous studies. The highest air change rate (57 ACH) inside the building was achieved in the investigation carried out by Haw et al., [105]. It is observed that in many cases, the indoor concentration of $CO_2$ within the space ventilated by windcatcher device was not exceeding the requirements. Moreover, the air supply rate produced by the windcatchers was in the range of 5–27.1 L/s per occupant. The overall findings of the reviewed works indicated that a windcatcher as a sustainable system considerably contributes to the improvement of the indoor environmental quality.

**Table 1**
Summary of the windcatcher contribution in the improvement of indoor air quality (IAQ)

| Ref. | Type of Building | Method of study | | | | Case-study | Results |
|---|---|---|---|---|---|---|---|
| | | Experiment | | Theoretical | | | |
| | | Full scale | Small scale | CFD | Other | | |
| [631] | School classrooms | √ | - | - | POE | UK | 40% of the occupants were generally satisfied with IAQ |
| 68 | Classroom | - | √ | √ | - | UK | Values of MAA were 200 sec and 100 sec close to walls and in the middle of the room, values of ACE at breathing height ranging from 0.86 to 2.1 |
| 11 | University seminar room | √ | - | - | Analytical | UK | Levels of CO2 (not exceed 500ppm) and humidity (between 50% and 60%) were well within acceptable range for good IAQ |
| 19 | School classrooms | √ | - | - | - | UK | The test room can meet the temperature and CO2 requirements while control room cannot meet the UK standards for CO2. |
| 60 | Classroom | - | √ | √ | - | UK | An average CO2 concentration was 28-50 ppm and 1-3 ppm higher than the outdoor air for the parallel and staggered arrangements respectively, the maximum supply rate for the leeward windcatcher in parallel arrangement was 5 L/s/occupant |
| | House | - | - | - | Multizone model | Egypt | The maximum difference of 7.8 % with average 3.1 % was obtained in CO2 concentration before and after parametric studies, the system provided an effective ventilation rate 414 m3/h during the hottest summer days. |
| 28 | University classroom | √ | - | - | - | UK | The indoor air change rate was 1.75 ACH, when the windcatcher did not operate while it reached to 3.2 ACH in the mode of fully open dampers of windcatcher |
| 4 | - | √ | - | √ | - | UK | The ventilation rate of windcatcher with circular section is significantly lower than the square windcatcher (at least half) |
| 39 | House | √ | - | √ | Empirical | Malaysia | The windcatcher was capable of producing 57 ACH inside the building at a low outside air velocity of 0.1 m/s |
| 21 | Classroom | - | - | √ | - | UK | The windcatcher provided air supply rate of 27.1 L/s per occupant, this is 5.5 times the minimum standard of 5 L/s/occupant. |

POE: Post Occupancy Evaluation

Table 2 summarized thermal comfort investigations in naturally ventilated building by means of windcatcher system. Comfort ventilation was mostly studied for residential buildings followed by other types including offices and educational. McCabea and Roaf [114] as well as Ji et al. [115] used building energy simulation (BES) tools to predict the effect of windcatcher performance on indoor comfort environment in two different climates including Dubai, UAE and China respectively. Furthermore, specific post occupancy evaluation (POE) studies in real buildings coupled with the modern windcatchers were reported in [98], [117] and [118]. According to Table 2, thermal comfort studies of building-windcatcher passive cooling systems were greatly carried out in hot and dry regions such as Iran, Mexico, UAE, Qatar and India (Ahmedabad) [28], [85], [113], [114], [116] and [118]. Previous researches have often focused on evaluating the windcatcher performance in terms of key parameters of thermal comfort including air temperature, velocity and relative humidity. The highest reduction in indoor air temperature (11 °C) using a traditional windcatcher was found in [85] while the lowest one (2 °C) was presented in [115]. Calautit et al., [113] concluded that the commercial windcatcher is capable of reducing air temperature by 13% and increasing air velocity by 63%. Additionally, reducing the relative humidity by 11% and increasing indoor air velocity up to 0.8 m/s were observed in [71]. The findings of POE studies revealed that satisfactory occupant comfort levels were generally achieved using windcatcher system.

**Table 2**
Summary of the windcatcher contribution to comfort ventilation

| Ref. | Type of Building | Method of study | | | | Case-study | Results |
|---|---|---|---|---|---|---|---|
| | | Experiment | | Theoretical | | | |
| | | Full scale | Small scale | CFD | Other | | |
| [50] | House | - | - | √ | - | Monterrey, Nuevo Leon, Mexico | Providing appropriate thermal comfort in nearly 50% of interior environment |
| [143] | House | √ | - | - | - | Nagappatinam, India | Reducing the relative humidity and temperature by 15% and 5°C respectively. Also, mean indoor air velocity was 0.8 m/s, which falls within the comfort zone for the tropics |
| 41 | - | - | - | √ | - | - | PD values are increased at floor and ceiling levels while the corresponding values for the occupant's activity levels (0.6, 1.2 and 1.8 m) were considerably lower |
| 42 | House | - | - | √ | - | Qatar | Decreasing air temperature by 13% and increasing air velocity by 63% |
| 51 | House | - | - | - | BES | Dubai, UAE | Providing internal conditions very close to thermal comfort standard based on an adaptive model |
| 25 | House | - | - | √ | - | Yazd, Iran | Declining the indoor air temperature by 11°C and increasing the relative humidity by 19% |
| 40 | Office | - | - | - | BES | China | Reducing air temperature around 2°C, providing internal thermal comfort for the whole occupied hours in October |
| 34 | House | - | - | √ | - | Yazd, Iran | Decreasing the air temperature from 25°C to 21°C |
| 6 | University seminar room | √ | - | - | POE | UK | 41.7% of occupants reported feeling neutral to temperature, 16.7% of them felt only slightly warm and the rest felt significantly warm |
| 21 | Office | - | - | - | POE | Ahmedabad, India | The overall satisfaction for comfort, air temperature and quality were observed in both buildings |
| 31 | School classroom | √ | - | - | POE | UK | During winter, most of occupants were satisfied with the internal thermal comfort; however, only 12% of them stated that they feel comfort during summer |

BES: Building Energy Simulation, POE: Post Occupancy Evaluation

Different types of windcatcher cooling techniques achieved based on previous studies are tabulated in Table 3. A small numbers of research groups reported the contribution of night ventilation to passive cooling using windcatcher device [98], [101], [115] and [120]. On the other hand, the evaporative cooling coupled with the windcatchers was extensively analysed [53], [102], [121], [124], [126], [127], [129] and [130]. Moreover, Benhammou et al. [132] and Jassim [133] studied thermal operation of windcatcher incorporating Earth to Air Heat Exchange (EAHE) system. Recently, new cooling technique known as Heat Transfer Device (HTD) is introduced in windcatcher application field by Calautit et al. [136] and its performance was evaluated in several works [122], [134], [136], [137] and [138]. The cooling benefit of night ventilation provided by the windcatchers is found to be in the range of 1–4.2 °C. Evaporative cooling has high potential for temperature reduction (up to

18.6 °C); however, it only can be efficient in hot and dry regions such as Iran, Jordan, Algeria, Egypt etc. as shown in Table 3. Moreover, the addition of cooling devices such as wetted columns and wetted surfaces may decrease the air flow rate inside the channel and lessen the overall efficiency of the windcatcher. Conversely, EAHE and HTD cooling methods are able to decrease air temperature up to 18 °C and 15 °C respectively and suitable not only for hot and dry climate but also for hot and humid conditions.

**Table 3**
Summary of the windcatcher cooling techniques

| **Cooling Techniques** | | **Method of study** | | | | **Cooling Effect** | **Case-study** | **Refs.** |
|---|---|---|---|---|---|---|---|---|
| | | Experiment | | Theoretical | | | | |
| | | Full scale | Small scale | CFD | Other | | | |
| **Night Ventilation** | | √ | - | - | - | Reduction of indoor air temperature by up to 4°C | UK | [138] |
| | | √ | - | - | - | The morning temperature was diminished around 1°C | UK | [138] |
| | | √ | - | - | - | The internal air temperature was decreased by 2.8 °C | UK | [138] |
| | | - | - | - | BES | The interior temperature in the next morning was on average reduced by 4.2°C | China | [138] |
| **Evaporative Cooling** | Qanat | | - | √ | - | Increasing the relative humidity by 5% and declining the indoor temperature by 4◦C | Yazd, Iran | [136] |
| | | √ | - | √ | - | An indoor air temperature reduction up to 15°C | Yazd, Iran | [113] |
| | wetted surfaces / wetted columns | √ | - | - | Analytical | Diminishing the temperature on average around 7°C and increasing the relative humidity approximately 60% | Yazd, Iran | [19] |
| | | - | - | - | Analytical | Lessening the indoor temperature from 36 °C to 25 °C | Jordan | [138] |
| | | - | - | √ | - | Decreasing the temperature by12 K and increasing the relative humidity by 22% | Yazd, Iran | [134] |
| | | √ | - | - | Analytical | Increasing the relative humidity by 62.6% and declining the temperature by up to 18.6°C | Ouargla, Algeria | [139] |
| | | - | - | - | Multizone model | The proposed system was able to reduce the internal temperature around 1.5 °C | Egypt | [122] |
| | | √ | - | - | - | An average cooling production of 9.7 KJ/sec | Tehran, Iran | [140] |
| **EAHE** | | - | - | - | Analytical | The cooling potential of 30.7 kWh | Adrar, Algeria | [142] |
| | | √ | - | √ | - | Reduction of the air temperature up to 18°C | Baghdad, Iraq | [143] |
| **HTD** | | - | - | √ | - | The temperature reduction of 12–15 K | - | [146] |
| | | - | - | √ | - | The cooling capacity ranging between 6 K and 15 K | - | [131] |
| | | √ | √ | √ | - | A cooling potential of up to 12 °C | UAE | |

BES: Building Energy Simulation, EAHE: Earth to air heat exchangers, HTD: Heat transfer device

## 8. Recommendation for further studies

Numerous previous investigations have evaluated the windcatcher performance in terms of indoor air temperature, $CO_2$ concentration, ventilation rate and relative humidity and also have looked into the simple building geometries particularly in hot-dry and moderate climates, short-term studies including physical measurement and CFD modelling. There are a small number of literatures in windcatcher field about building occupants' feedback (POE) and since it is crucial to obtain building occupants' experience and satisfaction to know whether the building is comfortable and energy efficient in practice, more POE studies are required to be covered in this field. More thermal comfort studies in windcatchers in cold climates such as in UK is required while more IAQ studies in windcatchers in hot climates is necessary. Moreover, important parameters in windcatcher operation including indoor air velocity, air change effectiveness (ACE) and mean age of air (MAA) should be taken into consideration in further studies. Other potential area of studies would be windcatcher application in tropical climates; the impact of surrounding buildings on its performance; cost analysis such as life cycle assessment and energy analysis; aerodynamic designs for windcatcher; integration of different construction materials such as PCM, new cooling methods such as Thermoelectric, Magnetic and dehumidification systems with windcatcher; structural analysis as well as social and aesthetics aspects of windcatcher. In terms of CFD modelling, researchers should investigate the impact of using other turbulence models to further improve the prediction of the models, particularly the complex flows inside the windcatcher. Furthermore, CFD modellers should take into account the effect of the urban environment (atmospheric boundary layer flows) when simulating windcatchers which is typically simulated in an empty domain. This also applies to wind tunnel or small scale laboratory test which is usually carried out using uniform flows which does not replicate the actual scenario. A more accurate IAQ model should be developed by future work to take into consideration human occupants and also several pollutants.

## 9. Conclusion

The aim of this review paper is to summarise previous studies on indoor air quality (IAQ) and thermal comfort achieved through natural ventilation using a windcatcher device. Previous review articles on windcatchers have mainly focused on different configurations and components of windcatchers. Therefore, this current work addressed this by providing a holistic overview of performance of traditional and modern windcatcher in terms of IAQ and comfort aspects. It was found that there are two main methods used by researchers; experimental approaches including full scale testing and laboratory scale testing; as well as theoretical approaches such as Computational Fluid Dynamics (CFD) and analytical modelling. The review compared the advantages and limitations of each method in term of carrying out IAQ and comfort assessment for indoor spaces with windcatcher. In terms of experimental methods, many studies have used full scale analysis for both IAQ and thermal comfort investigations which is because of the limitations of small scale testing such as scaling down the cooling system in wind tunnels. However, several studies also highlighted that full scale testing is expensive and the results are restricted to a specific case which cannot be generalized to other cases easily. In terms of theoretical methods, most studies used CFD modelling and simulation due to its capability to accurately predict the 3D flows in windcatchers as proven by many researchers and also the significant increase in computing power in recent years. However, it is usually coupled with other methods such as full or small scale experiments or analytical models for validation of predicted results. A small number of studies used post occupancy evaluation (POE) approach to determine the capability of windcatcher system to provide an acceptable range of indoor thermal comfort for occupants. Furthermore, limited studies also used Building Energy Simulation (BES) for studying the windcatcher.

It was found that most IAQ studies were conducted in the United Kingdom (UK) using Computational Fluid Dynamics (CFD) and full scale testing. In addition, most applications of the windcatchers are found to be educational buildings in UK. Previous studies assessed IAQ based on several parameters such as air flow rate, air change rate (ACH), CO2 concentration, air change effectiveness (ACE) and mean age of air (MAA). The findings of the studies revealed that satisfactory IAQ were generally achieved using the windcatcher device providing supply rates in the range of 5–27.1 L/s per occupant. Many case studies have observed that the indoor concentration of $CO_2$ within the space ventilated by windcatcher device was not exceeding the requirements particularly when combine with other ventilation methods such as external openings. Thermal comfort studies of windcatchers were mainly conducted in hot climates such as in the Middle East. The findings of POE studies revealed that satisfactory occupant comfort levels were generally achieved using windcatcher system. Moreover, the review also looked into the different types of cooling methods integrated with windcatchers to improve its thermal performance such as evaporative cooling, earth to air heat exchangers (EAHE) and heat transfer devices (HTD). Night ventilation was found to be effective in temperate and cold conditions while additional cooling using evaporative cooling, EAHE and HTD were found to be necessary in hot climates.

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