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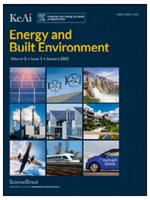

Windcatchers and their applications in contemporary architecture

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ABSTRACT

Natural ventilation and cooling have played an essential role in providing comfort conditions. Windcatchers are passive cooling systems and one of the most familiar elements in Iranian architecture. They can significantly influence on reduce cooling loads and supply the necessary ventilation rate of buildings. This paper aims at providing an in-depth review of the recent developments and applications of windcatchers in modern architecture. The efficiency of windcatcher is also discussed according to the windcatcher's relevant parameters, i.e., height, configuration, and cross-section. This comprehensive review reveals that these factors have significant impacts on the performance of windcatchers. It is also shown that a one-sided windcatcher is a better choice in regions with privileged wind direction. However, other types of it are better in regions with variable wind directions. Finally, windcatchers' potential for applying in the contemporary architecture and urban planning shown in the using windcatcher in contemporary buildings, windcatchers in the urban context, new designs, and new technologies of windcatchers sections.

1. Introduction

The building sector has a significant proportion of total energy consumption in various countries. Therefore, finding solutions for energy saving inthis sector has a considerable impact on total energy consumption [1]. The other main problem is air pollution, especially in big cities. According to researches, the amount of CO2 from 1995 to 2018 became three times. An important factor that affects air pollution is the use of fossil fuels [2]. Natural ventilation reduces the use of fossil fuels [3,4]. Past generations found the solutions to be compatible with nature [5,6]. In the arid and semi-arid regions, elements like windcatchers, courtyards, and domes have been used to attain a more comfortable condition [7–14]. Wind catchers (or wind towers) have been used in the Middle-East countries (for example, more than one thousand years in Iran, which is the origin of this technology [41]) with different names and shapes [10–12]. In Iran, windcatchers were common spacially in hot and arid regions and called Badgir. They were decorative as well as functional elements [15]. The most prominent examples of traditional windcatchers are the windcatcher of Dowlat Abad garden [16], the Amirchakhmaq mosque's windcatchers, and the windcatchers of Alzubair's historical city [11,12,17–19]. Although windcatchers are useful, the architecture and lifestyle changes need modern wind catchers with new designs [20–23]. The new windcatchers should be harmonious with new architecture in any aspect and also be more controllable and flexible. The mechanism of modern and traditional windcatchers is the same. The traditional windcatchers provided comfort conditions in two ways. The traditional houses in the arid areas have two main parts: the southern part where inhabitants dwelled in cold seasons, and the northern part where residents inhabited in warm seasons. The windcatchers have been positioned in the north part facing and catching cold north-flowing winds to fulfill maximum ventilation and cooling [24–28]. In some cases, Qanat increased the evaporating cooling, decreasing temperature, and increasing humidity, velocity, and density of incoming airflow and eventually improving windcatchers' performance [29–31]. Evaporating cooling has been used in some modern windcatchers, but using it depends on climate [32,33]. The second mechanism has been utilized when the wind velocity is low. In this condition, indoor air has been sucked into outdoor space. In this way, the windcatcher has attributes of the solar chimney and used buoyancy forces [24,34]. Between two main forces impacting windcatchers' efficiency, wind-driven power plays a more critical role than the buoyancy force [35,36]. Nowadays, with advanced and accurate software and calculative formulas, achieving a general understanding of windcatchers, their process, and the factors which impact their performance are more feasible than in the past [37,38]. This realization is the first step for designing an efficient and ideal modern windcatcher [39]. In this paper, the first stage tries to obtain comprehensive knowledge about types and configurations of windcatchers. This knowledge helps to understand new ideas about windcatchers and new technologies applied to them, mentioned in the second stage. The last step is about using modern windcatchers in buildings. This use indicates that modern windcatchers have high potential to be a pretty decorative element, an efficient natural ventilation device.

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1.1. Literature review

There are many papers about various aspects of windcatchers. However, there are some issues that the number of researches about them is few. For example, the number of researches about the impact of material, height, and neighborhood on the performance of windcatchers and the economic benefits of using windcatchers is not significant. Table 1 shows the number of investigations carried out on windcatchers.

Fig. 1 shows the proportion of any topics about windcatcher. If "Factors which impact on the performance of windcatcher" are considered as a topic, according to this figure, it has the most portion of the investigations about windcatcher (25 percent), and surveys about the economic aspect of using windcatcher have the lowest proportion (2 percent).

Fig. 1 shows the focuses of researches have been on modern wind catchers instead of traditional windcatchers. Rezaeian et al. [40], in their study, confirm this. Since the year 2000, they have expressed the focusses of studies that have been changed from traditional windcatchers to the development of innovative windcatcher systems. Fig. 2 shows the number of articles in different decades. According to this figure, the number of items about windcatchers increases in the 2010s. This increase indicates that nowadays, windcatchers are essential and have a high potential for modern societies.

Table 1
Number of investigations about various aspects of windcatcher.

Topics		Frequency
Types of windatcher		10
Methods for evaluating the performance of windcatcher		12
Performance of windcatcher		21
The economic aspect of using windatcher		2
Factors which impact on the performance of windatcher	Number of openings	7
	Height of windatcher	4
	Wind approach	10
	velocity	6
	configuration	8
Architectural solutions for improvement Efficiency of windcatchers		3
New designs for windcatcher		38
Using windcatchers in contemporary buildings		10
New technologies of windcatcher		19
windcatchers in urban context		9

Rezaeian et al. [40] explain the procedure of researches about windcatchers. According to their investigation, research about windcatchers started in 1984. A significant increase in the number of articles occurred in 1990. It reached its saturation level in 1997. After the year 2000, by appearing CFD (Computational Fluid Dynamic) number of research increased. This growth has continued until today. Rezaeian et al. forecasted number of researches about windcatchers will arrive at 142 papers.

2. Types of windtchers

Windcatchers have various kinds. Windcatchers have been classified into different groups, including numbers of openings, number of stores, cross-section, and interior dividing [41]. Table 2 shows these classifications.

2.1. Types of windcatchers according to the number of openings

Windcatchers, according to the number of openings classified to [42]:

- One-sided windcatchers
- Two-sided windcatchers
- Four-sided windcatchers
- Six-sided windcatchers
- Eight-sided windcatchers

One-sided windcatcher has an inlet incoming the north direction and has no opening in the east, west, and south, bringing cold northern winds into indoor spaces [41–43]. This type of windcatchers can be found in Ardakan and Maybod [42]. However, just 3 percent of windcatchers in Yazd is one-sided. One-sided windcatchers are more resistant to the storm than other types of windcatchers [44]. Respecting dimensions, two-sided windcatchers are smaller than one-sided windcatchers. Two-sided windcatchers called twin windcatchers too [45]. For dividing them into two separate parts, brick blades are used. Roaf [46] states that 17 percent of windcatchers in Yazd are two-sided, and all of them were used for wealthy people, but Bahadori [40] says most of them were used for storage of water (Ab-Anbar). Four-sided windcatchers are taller and bigger than others. Usually, these windcatchers have been used in

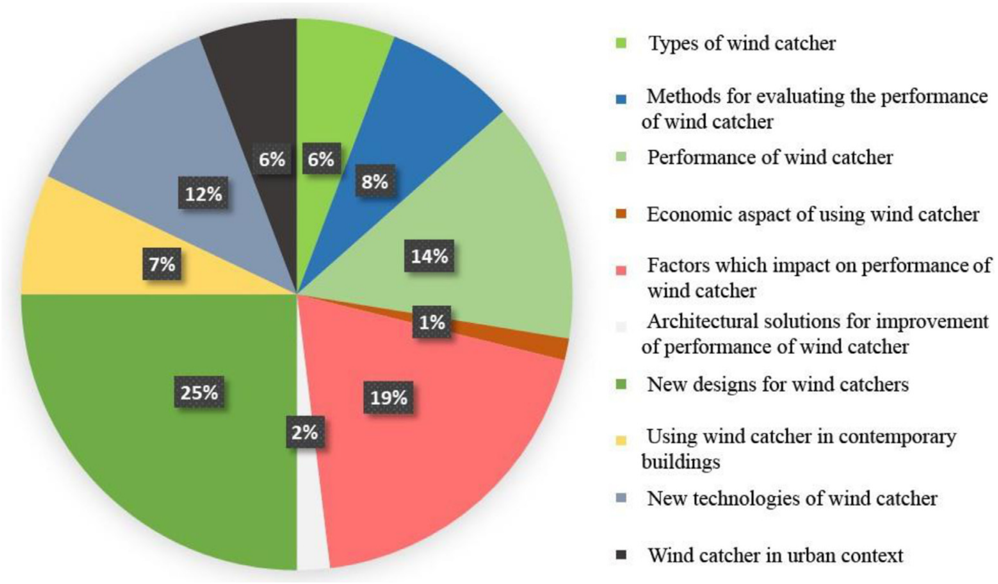


Fig. 1. Proportion of all relevant topics with regard to the windcatcher.

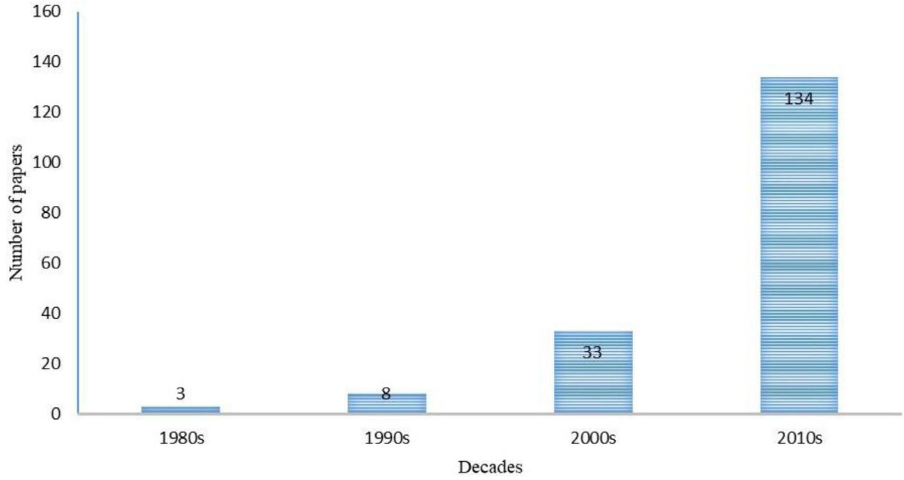
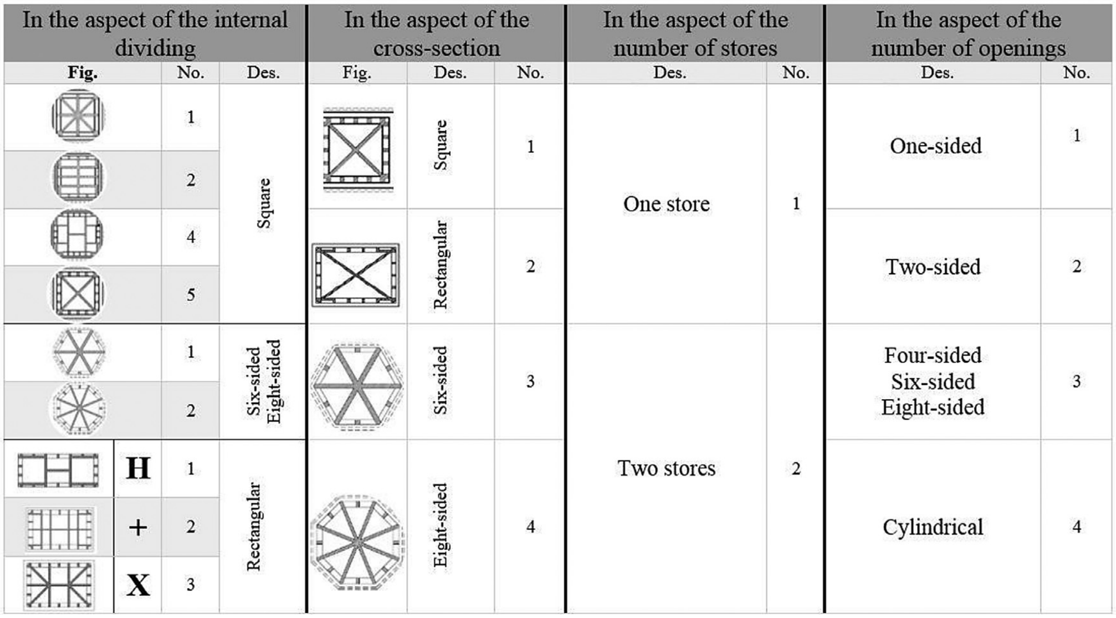


Fig. 2. Number of papers about windcatchers in different decades.

Table 2
Different types of windcatchers in various aspects [45].



In the aspect of the internal dividing				In the aspect of the cross-section			In the aspect of the number of stores		In the aspect of the number of openings	
Fig.		No.	Des.	Fig.	Des.	No.	Des.	No.	Des.	No.
		1	Square		Square	1	One store	1	One-sided	1
		2								
		4			Rectangular	2			Two-sided	2
		5								
		1	Six-sided Eight-sided		Six-sided	3	Two stores	2	Four-sided Six-sided Eight-sided	3
		2								
	H	1	Rectangular		Eight-sided	4			Cylindrical	4
	+	2								
	X	3								

areas with desert-like climate. Their heights are varying according to climate conditions [43]. Four-sided windcatchers are the prevailing type [47]. All of the windcatchers in hot and humid areas are four-sided. Eight-sided windcatchers usually have been used for water storage, and roughly 2 percent of Yazd's windcatchers are from this type [43,46].

2.2. Types of windcatchers according to the cross- section

Windcatchers classified into five main groups based on their cross-section [42]:

- Cylindrical windcatchers
- Square windcatchers
- Rectangular windcatchers
- Hexahedral windcatcher
- Tetrahedral windcatchers

Table 2 illustrates the classification of windcatchers according to the cross-section. Construction of cylindrical windcatchers is more complicated than square, rectangular, and even tetrahedral and hexahedral cross-section windcatchers. Therefore, cylindrical windcatchers were not too common comparing to the others. However, designing cylindrical windcatchers is based on winds' aerodynamic characteristics, so they have high efficiency [42]. Square windcatchers are more common than those with the circle, hexahedral, and tetrahedral cross-section. However, windcatchers with rectangular cross-sections are the most conventional type of windcatchers [42]. Hexahedral and tetrahedral windcatchers are shorter than the other types and usually were used for water storage [43,46].

2.3. Types of windcatchers according to number of stores

Windcatchers are one-story, two-story, and scarcely have more stories. The number of two-story windcatchers is remarkably lower than one story windcatchers and even considered as scarce types. Several outstanding samples of two-story windcatchers are in Amir Garden in Tabas city (eight-sided), in Aghazadeh House in Abarkooh (four-sided), in Chehel Sotoon in Sarhanabad (cylindrical) [42]. In addition to one and two-story types, there are some with more stories. For example,

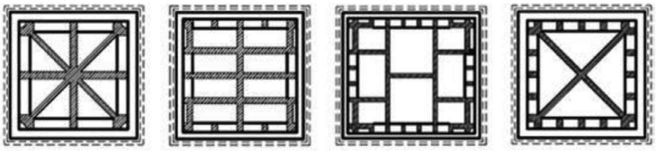


Fig. 3. Different types of square windcatchers in aspect of internal dividing [45].

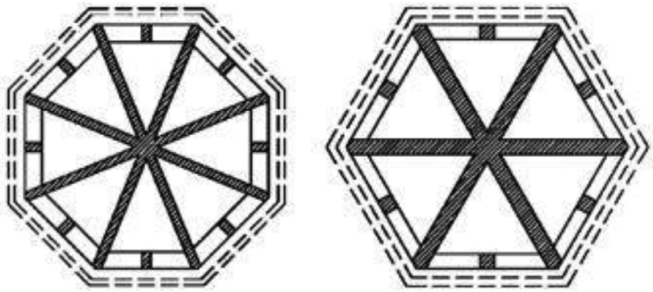


Fig. 4. Internal dividing of six-sided and eight-sided windcatchers [45].

a windcatcher in Sadra Garden in Taft is three-story. However, windcatchers with more stories are scarce, and ignoring them is possible. The one-story windcatchers are the most frequent [42].

2.4. Types of windcatchers according to positions of blades

Interior blades play an essential role in the efficiency of windcatchers. They divide the cross-section of windcatchers into smaller parts and consequently impact the velocity and turbulence of airflow. Therefore, windcatchers with different types of division have various features, affecting windcatcher performance. Windcatchers with square cross-section have four kinds of divisions illustrated in Fig. 3 [48].

Each of the windcatchers with tetrahedral and hexahedral cross-section has one division. In these divisions, blades are connected to the tip of the tetrahedral and hexahedral. Fig. 4 illustrates these types [48].

The different shapes of blades in the rectangular windcatchers are including X shape blades, + shape blades, and H shape blades. Fig. 5 shows a rectangular windcatcher with X shape blades. The ratio of height to width in these windcatchers are 1.5. The number of this type is insignificant. In the study of Amirkhani et al. [43] from 58 investigated windcatchers, just 2 of them have X-shaped blades. Sometimes, K-shaped blades appear for dividing. It's a combination of + and X-shaped partitions [49].

Fig. 6 shows a Rectangular windcatcher with + shape blades. This type is the most frequent type of dividing [50].

The number of windcatchers with H-shaped blades is scanty. Fig. 7 illustrates this type. The principal blade is placed in the center of the channel [43].

Table 2 shows the various classifications of windcatchers with different aspects.

3. Methods for evaluating the performance of windcatchers

Methods for assessing the performance of windcatchers have been classified into two groups. To fulfill this purpose, both experimental and theoretical techniques are useful. However, each of them has its pros and cons. The experimental method has two types. In the first type, a scaled model has been built and investigated in a lab, and the second type (field measurements) has been used to investigate a real model in a real condition, so the results are more reliable. However, scaled models are more money and time saving than the field measurements, and more importantly, a generalization of results to other conditions can be achieved [15,51,52]. Moreover, changes in various parameters are possible easily. Therefore, each parameter's effect on the windcatcher's performance can be revealed, but this process in the field measurements is impossible [15,53–55].

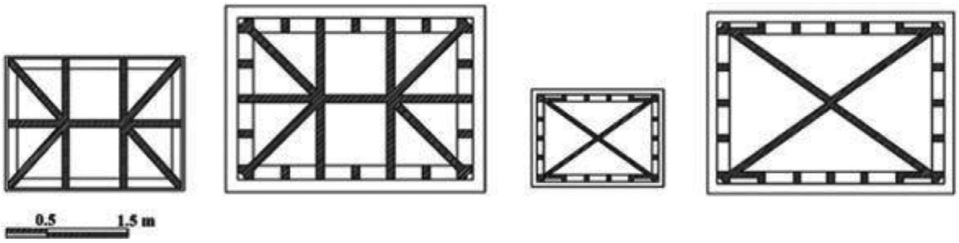


Fig. 5. Rectangular windcatcher with X shape blades [45].

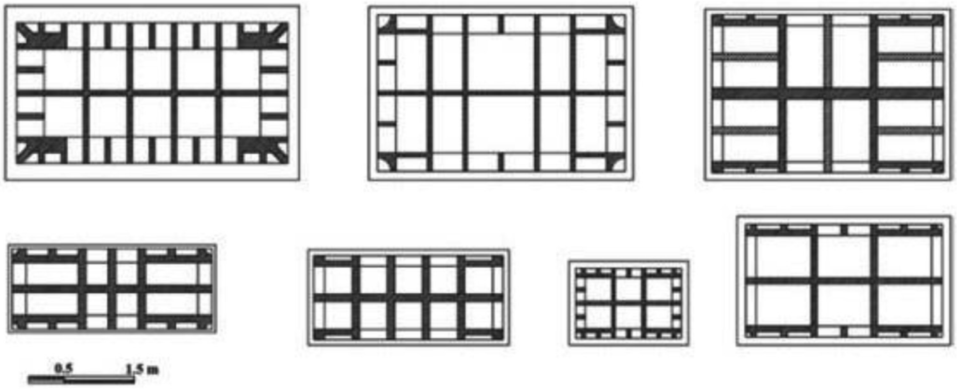


Fig. 6. Rectangular windcatcher with + shape blades [45].

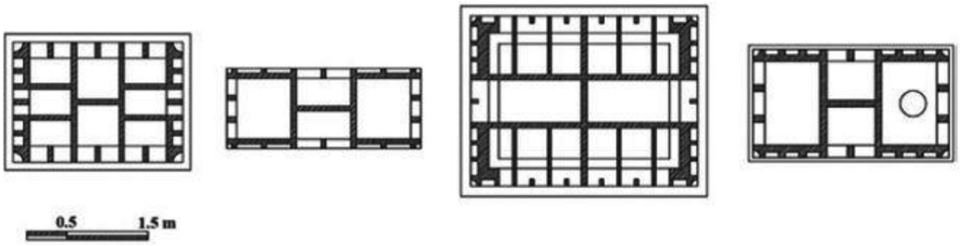


Fig. 7. Rectangular windcatchers with H shape blades [45].

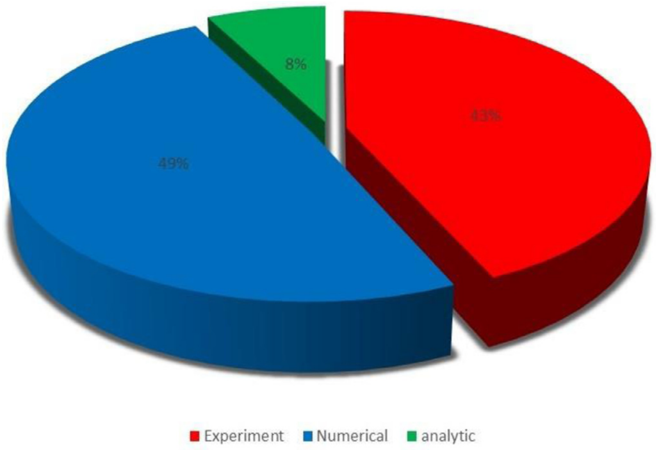


Fig. 8. Proportion of applying different methods in the papers about windcatchers.

3.1. Simulation

The theoretical investigation has been classified into two groups: analytical and numerical modeling. Analytical modeling is a fast way to discover the performance of windcatchers. Still, this method can't solve unforeseen conditions because it only uses heat transfer and fluid dynamics formulas. For instance, a rotary thermal wheel's rotation speed that has a significant impact on windcatcher performance can't be calculated in analytical modeling [15,56,57]. Numerical modeling consists of software simulations of real conditions for models. This kind of software works based on principles of computational fluid dynamics (CFD). CFD can see various factors (temperature, velocity, pressure) in complicated three-dimensional flows [15,58,59]. In the mentioned methods, numerical modeling is more conventional (Fig. 8).

In numerical modeling, simulating different conditions for investigating various parameters is easily possible [60]. Table 3 shows the applied settings in the research.

In a simulation (numerical modeling), there are many parameters, each of which significantly impacts results [70]. Therefore, selecting these parameters needs essential knowledge and accuracy. For example, turbulence is a crucial factor affecting outcomes [71, 72]. Fig. 9 illustrates the impacts of these parameters on the results of the simulations.

4. Performance of windcatcher

Windcatchers have more advantages than other openings [65,73,74]. In a dense urban context, the windows' efficiency is low, and windcatchers can be an efficient superseded solution for supplying the required ventilation rate here. Drach's [75] has researched a three-story house with inadequate natural ventilation. The results of this paper indicate that adding a windcatcher improved natural ventilation in this house. Another advantage of windcatcher rather than other openings is the higher pressure coefficient (CP). The ventilation rate depends on the pressure coefficient at the opening [76]. Table 4 Shows CP for windcatchers and other openings in rural and open areas in various wind approaches. This table's results indicate that CP for windcatcher is higher than other openings [42,77].

Montazeri et al. [69] have measured CP for one-sided and two-sided windcatchers through a wind tunnel experiment. This investigation and the research by Bahadori show a higher performance of windcatchers (Table 5).

Sadeghi et al. [78] studied a windcatcher's performance in the urban context of Australia and compared it with ventilation through windows. Results of this study indicate that:

- The pressure difference between the inlet (windcatcher) and outlet (window) and vice versa was three-time of pressure difference when the window was used for ventilation.
- The average internal airflow velocity in the six warm months of Sydney in the case with an optimized windcatcher was three-time higher than the case of window ventilation.

One of the windows' limitations is that they aren't usable in basements, but windcatchers are useful in these underground spaces. Roaf [27] has investigated Khan Garden in Yazd. In this place, there is a living room in the basement connected to a windcatcher that crosses on a Qanat owning a 50-meter-long tunnel. The investigation indicates that when the exterior temperature was 40°C, the interior temperature was 25°C. Moreover, the effects of windcatchers on increasing velocity and decreasing interior spaces' temperature can reduce the fluctuations of temperature [79–81]. Priya et al. [82] investigated a house with a balcony and windcatcher. While fluctuation of exterior temperature was 11°C, fluctuation of interior temperature was 3°C, and while fluctuations of exterior temperature were 16°C the oscillating of internal temperature was 5°C. In the investigation of Ghadiri et al. [83], windcatchers can decrease the interior temperature 3°C - 5°C compared to the exterior environment during the daytime, but at night, the internal temperature was 3°C - 4°C higher than the outer environment. Sadeghi et al. [84] investigated windcatchers' performance for an apartment in Sydney humid climate. In this case, mean air velocity, incoming by a windcatcher, was as three-fold as mean air velocity, which income by a window to meet thermal comfort needs. Studies of Mohammadi and Barzegar [85] and Kistelegdi et al. [86] confirms the decisive role of windcatchers in providing thermal comfort conditions. Therefore, despite windcatchers' limitations, they can increase velocity and decrease the interior temperature in hot climates for achieving comfort conditions [87]. Therefore, today windcatchers are an efficient cooling passive system that can help reduce the cooling loads in contemporary buildings [84]. Adding evaporative cooling to windcatchers improves their function and indoor conditions [32,33,88–91].

5. Economic aspect of using windcatcher

One of the most critical factors for evaluating a system's usefulness is the economy [92]. For comparing and assessing various systems, the formula below has been used.

Table 3
Different parameters and methods used in papers about windcatcher (E: Expriment, N: Numerical modeling, A: Analytic modeling, DECT: down-draft evaporative cool tower, T: Traditional windcacther, TIW: Traditional windcatcher integrated a wingwall, CW: commercial windcatcher, ABL: atmospheric boundary layer, Uniform: uniform inlet velocity, 3D: three-dimensional, C: coupled outdoor-indoor simulations).

Author (year)	Ref	Method	Number of openings	Type	Turbulence Modeling	Mesh	Inlet profile	Dimension/ coupling	Sensivity analysis	Subject
Erell et al. (2008)	[61]	E	1	DECT	-	-	-	-	-	Thermal performance and flow rate of DECT
Afshin et al. (2016)	[62]	E	2	T	-	-	-	-	-	Performance of windcatcher in various wind angles and wind speed
Nejat et al. (2016)	[63]	E/N	2	TIW	standard k-e	Non-uniform	ABL	3D/C	Grid	Anti-short circuit device performance
Calautit et al. (2015)	[39]	E/N	1	CW	standard k-e	Non-uniform	uniform	3D/C	Grid	Performance of a standard windcatcher and HTD windcatcher
Mak(2010)	[64]	N	4	CW	standard k-e	unstructured grid	uniform	3D/C	-	The function of the windcatcher quadrants in various wind directions and speeds
Montazeri et al. (2008)	[65]	E	1	T	-	-	-	-	-	Effect of placing of urban windcatchers in the boundary layer of atmospheric winds
Dehghan et al. (2013)	[66]	E/A	1	T	-	-	-	-	-	Impact of roof shape on windcatcher performance
Hosseinnia	[67]	N	4	T	Standard k-e	Unstructured tetrahedral cells	ABL	3D/C	-	Impact of Various blades on performance of windcatcher
Kalantar (2009)	[30]	N	4	T	Standard k-e	Unstructured	Uniform	3D/C	Grid	Impact of evaporating cooling
Ghadiri et al. (2014)	[68]	N	4	T	Standard k-e	Structured hexahedral and prism	ABL	3D/C	Grid	The effect of plan size of windcatchers on its ventilation rate
Montazeri et al. (2010)	[69]	A/N/E	2	T	Standard k-e RNG k-e Reynolds Stress model	Unstructured/ structured grid	uniform	3D/C	-	Performance of two-sided windcatcher

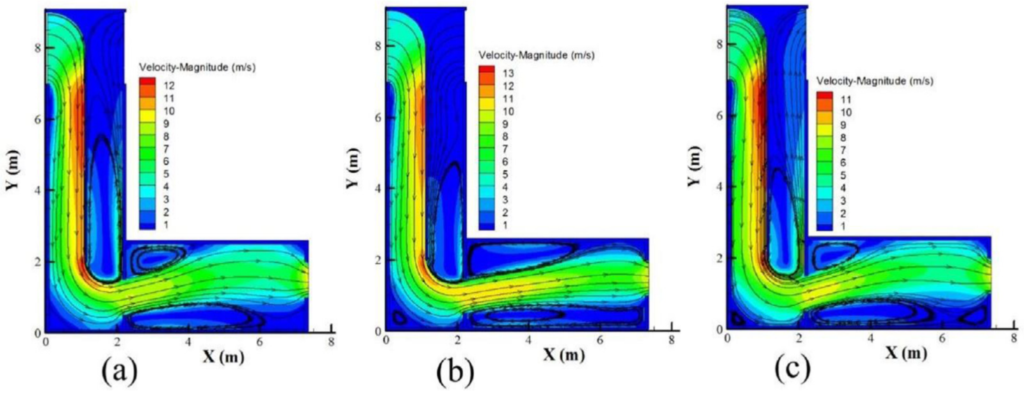


Fig. 9. Assessing velocity inside a windcatcher with different turbulent models. a: k-e Realizable. b: k-e RNG. c: standard k-e. d: sst k-omega. e: sst k-omega. f: streamline built by PIV [72].

Table 4
Pressure coefficient for windcatcher and other openings in different wind angles and areas. WC: windcatcher, O.O: other openings.

Areas	The angle between wind and inlet											
	0°		45°		90°		120°		150°		180°	
	W.C.	O.O	W.C.	O.O	W.C.	O.O	W.C.	O.O	W.C.	O.O		O.O
Rural area	0.53	0.04	0.43	0.12	0.66	0.35	0.50	0.35	0.54	0.25	0.61	0.25
Open area	0.54	0.12	0.43	0.18	0.71	0.33	0.53	0.32	0.55	0.38	0.61	0.32

Economic efficiency = operation/ (producing cost+ using cost+ external cost)

Therefore, enhancing economic efficiency depends on decreasing costs. Solutions like combining architectural techniques with climatic strategies and renewable energy systems significantly reduce these costs [93]. MostafayiPour et al. [93], for evaluating windcatchers' economic efficiency, selected a warehouse with dimensions of 10 m, 14 m, and 50 m. They considered three scenarios for this research:

1- Ground floor level, cooling by an absorption chiller 2- Basement level

Table 5
Comparing Pressure coefficient for one-sided windcatcher, two-sided wind catcher, and other openings in different wind angles.

Wind angles	Two-sided windcatcher		One-sided windcatcher	Other openings
	Windward	Leeward		
0°	0.86	-0.36	0.81	0.12
45°	0.21	-0.37	0.38	0.18
90°	-0.49	-0.46	-0.30	0.33
135°	-0.37	0.21	-0.38	-0.38
180°	0.036	0.86	-0.43	0.32

3- Basement level, cooling by windcatcher

The results of this study indicate that the scenario with wildcatter was most efficient practically and economically.

6. Factors which impact on the performance of windcatchers

There are many factors which have a significant impact on the performance of windcatcher. These factors can be internal like cross-section and height of windcatcher or external like velocity or wind angle [90].

6.1. Number of openings

The number of openings is one of the most critical factors contributing to windcatchers' efficiency [94]. Differences in the number of openings lead to differences in features of various kinds of windcatchers. Therefore, each kind of them is efficient in a particular region with special climatic conditions. For example, two-sided windcatchers act like one-sided windcatchers. One side of them can bring fresh cooled air to indoor space, and another part can act like a chimney and suck indoor air to exterior space at the same time. One-sided windcatchers have not this feature [95]. On the other hand, in several windcatchers with equal dimensions, windcatchers with fewer openings bring air for indoor space with a higher rate. Montazeri [96], in one of his studies, investigated one windcatcher with a cylindrical cross-section and different numbers of openings. He divided the cross-section of windcatchers into 2, 4, 6, and 12 sections and compared the efficiency of them in experimental conditions with each other. The results of this experiment indicate that a two-sided windcatcher had the best performance. On the other hand, the more openings a windcatcher has, the fewer effects wind angles have on the entering flow rate. Therefore, in areas with the one-direction prevailing wind, the one-sided windcatchers are preferred to the others from an economical and technical perspective. This is because, in a one-sided windcatcher, all of the cross-sections act as the entrance of airflow, but in two or more-sided half or less of cross-section, bring airflow to indoor spaces [69,97,98]. In addition to the number of openings of a windcatcher, the building's openings affect this vein in terms of area, location, and distance from the windcatcher [99].

6.2. The height of windcatcher

Height is an effective factor for the performance of windcatcher by two parameters. First, the height of the windcatcher and second, the ratio of windcatcher height to the neighborhood's building height. Determining an optimal height for a windcatcher depends on the climate, type of windcatcher, and cross-section. The effects of these parameters have been shown in differences between Ghadiri [100] and Badran's [101] article results. Ghadiri [95] investigated a windcatcher with H-shaped blades and different height in Yazd city climate. Assumed heights for this windcatcher were 3.5 to 10.5 meters. She assumed 5 meters per second for the velocity of airflow and 37°C for air temperature. At the same time, Badran [101] investigated a windcatcher in Aman (capital of Jordan). The cross-section of this windcatcher was 1m2, and Badran used evaporative cooling in it. Badran investigated windcatchers with heights between 0 to 9 meters. He computed optimum height in mathematical formulas. Consequently, Badran deduced 9 meters is the optimal height for windcatchers. The results indicate that increasing height up to 9 meters improves the performance of windcatchers, and after that, this improvement will be insignificant. Therefore, in his opinion, the optimal height is 9 meters. Whereas, Ghadiri deduced 6 meters for the optimal height for windcatchers. Ismail investigated windcatchers with different heights (3, 6, and 9 meters) integrated with a classroom. Results indicate that with increasing height, the performance will improve. However, the efficiency of windcatchers with 6 and 9-meter height was close to each other. From economic and aesthetic points of view, 6-m height has been considered the optimum height for windcatchers [102].

Sheikhshahrokhdehkordi et al. [103] investigated the windcatchers of different height. According to the results, increasing the height leads to a decrease in the mass flow rate.

The other factors are the distance (density) and the height of neighbor buildings. It has a significant impact on the efficiency of windcatchers [104]. For determining the level of this effect, Afshin et al. [105] performed a study where a windcatcher-integrated building was investigated along with the neighbor buildings with different heights. The results of this study indicate that the existence of a building with low height in the neighborhood (with a height of 0.5 H of windcatcher and distance of 0.75 H of windcatcher) can increase the ventilation rate. However, the existence of higher buildings has a reverse effect. In this condition, both shafts of two-sided windcatcher act as a chimney and suck air of indoor to outdoor space.

6.3. Wind approach

Wind direction is effective on introduced pressure on opening, leeward, and windward sides. Pressure difference on the surfaces plays an important role in supplying the needed airflow rate. For a windcatcher, most pressure coefficient and airflow rate occur at a 0° wind angle. The angles between 0° and transition ventilation rate gradually decline with increasing wind angle [62, 64, 69, 98,106–110]. At the transition angle, the supplied airflow goes to zero. Afshin et al. [62] have introduced it 55°, and Montazeri and Azizian [76] introduce it between 50°- 60°. The minimum ventilation rate occurs in the transition angle. In higher angles, two shafts of two-sided windcatchers act reversely [75]. According to the MAK [64] study, in four-sided windcatchers between 0° and 15° of wind angles, just one side bring airflow to indoor spaces. At 30° and 45° wind angle, two shafts have this function. At 0° to 10° and higher than 40°, as wind angle increases, airflow rate decreases, and at the wind angles between 10° to 40°, increasing in wind angle leads to an increase in the airflow rate.

6.4. Velocity

Increasing velocity will increase the ventilation rate in windcatcher-integrated buildings [110–113]. However, the question is that level of this increase would be the same for all wind angles? MAK [64] carried out a study about the performance of a four-sided windcatcher at 0°, 15°, 30°, and 45° wind angles. The windcatcher at 45° wind angle had the most sensitivity and had less sensitivity toward velocity at 0° wind angles. That means the 45° wind angle increasing in velocity causes to an increase in the airflow rate more than other wind angles. At 0° wind angle, increasing velocity causes an increase in the airflow rate less than other wind angles. Another question is if increasing velocity is beneficial in all kinds of windcatchers? Calautit et al. [114] have studied wind tower integrated with heat transfer devices. While the outdoor flow speed was 5 m/s, the reduction in indoor space temperature was 5°C, but when the outdoor velocity was 1-2 m/s, this reduction reached 9.5 – 12.

6.5. Configuration

Configuration factors like cross-section dimensions, arrangements of interior blades, and roof shape have been investigated in this part.

It's evident that with an increase in cross-section (it means that the opening dimensions will increase too), the amount of airflow will increase. But other factors aren't as simple as dimensions and shape of cross-section. Each of these factors is very effective in the performance of windcatchers. Therefore, designing an optimum windcatcher needs studying these factors for obtaining the best combination for windcatchers [115]. Farouk [109] compared the square, Hexagon, and circular six-sided windcatchers in various velocities and wind angles. The average incoming airflow rate in the hexagon windcatcher was 19 percent more than the square windcatcher. Moreover, the hexagon windcatcher had lower sensitivity to wind angles than the square windcatcher.

However, a 0° wind angle case with the square windcatcher has a higher mean velocity than the hexagon windcatcher in indoor space. The circular six-sided windcatcher had the lowest mean speed. Therefore, at a 0° wind angle, the square windcatcher is more effective for making thermal comfort conditions. Jafari et al. [108] compared two models of four-sided windcatchers. One of them had a square cross-section with X-shaped blades, and another was a circular four-sided windcatcher. They studied these models in various wind angles. In the square model, whirlpool was less than the other models. Therefore, they concluded that sharp edges could be a reason for whirlpool reduction, a broad region of flow separation, more pressure difference, and finally, more flow induction.

Results of an investigation by Sheikhshahrokhdehkordi et al. [103] indicate that cross-section changes lead to changes in windcatchers' efficiency. There are various arrangements for blades of four-sided windcatchers include X, K, +, and H. Different articles have compared these shapes with each other through different indicators: the potential of decreasing indoor temperature. Ghadiri et al. [115] made a comparison between two windcatchers with K and X-shaped of blades with the same dimensions and conditions (Fig. 10). This research indicated that windcatcher with X-shaped blades could bring airflow with a lower temperature to indoor space.

Dehnavi et al. [116] compared windcatchers with +, X, H, and K-shaped blades of windcatchers (Fig. 11 shows these blades). The reference case was a windcatcher with a crosssection of 1.5 m * 1.5 m and height 8 m. Results indicate that a windcatcher with a +shaped blade has less potential for decreasing indoor temperature. After that, windcatchers with K, H, and X-shaped blades have superior potential, respectively.

Zarandi [49] compared dimensions of windcatchers owning three types of blades (shown in Fig. 12) through CFD with dimensions of windcatcher of Rasolian house. Indicators in this research were relative humidity, temperature, and velocity of airflow. According to the results, a windcatcher with +shaped blades was more efficient than other cases.

The roof's impact has been investigated in the research of Dehghan et al. [66]. They considered three roofs (sloped, flat, and curve roof) with various wind angles. In 0° wind angles, the windcatcher's efficiency with the curved roof was 10 and 4.5 percent higher than a flat roof and sloped-roof windcatcher, respectively. However, the windcatcher with a sloped roof had the lowest sensitivity to changing the wind angles. Another parameter that impacts the performance of windcatchers in the shape of the inlet. Abdo et al. [117] considered three forms for inlet of windcatchers (uniform inlet, bulging-converging inlet, and divergent inlet) and compared them in a study. Results indicated that this parameter has a significant effect on efficiency. Between these three cases, a windcatcher with a divergent inlet has the best performance. In wind velocity of 6m/s, the average velocity of cached airflow for windcatcher with divergent inlet was 8.44 percent higher than windcatcher with the bulging-converging inlet.

Varela-Boydo et al. [118] investigated 33 models of the outlet opening of windcatchers. They tried to guide designers in designing windcatchers with higher efficiency. This investigation shows that shape, size, and position of outlet opening have a significant impact on the performance of windcatchers.

Table 6 expresses briefly various parameters impacting the performance of windcatchers and their conclusion.

7. Architectural solutions for improvement of windcatchers performance

Architectural solutions to improve windcatcher's performance, including windcatchers' position toward each other and partition's positions in the most efficient conditions. Calautit et al. [119] investigated the impact of position and distance of windcatchers on the velocity of

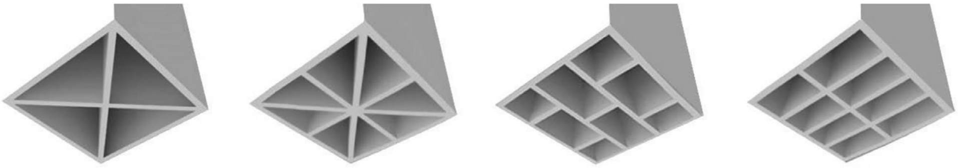


Fig. 10. Investigated models by Ghadiri et al. [115].

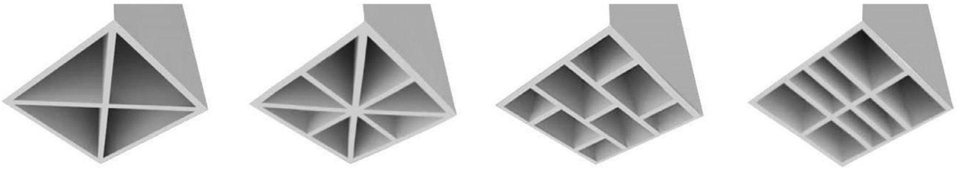


Fig. 11. Investigated cases by Dehnavi et al. [116].

Fig. 12. Investigated models by Zarandi [49].

Table 6
Topics of research about architectural solution and conclusion of them.

Topic	Conclusion
Difference between the performance of windcatchers and other openings	In areas with privilege wind, one-sided windcatcher has higher efficiency,but in areas, that direction of the wind is variable other types are better
Impact of height on the performance of windcatcher	Increasing the height of the windcatcher causes improvement of the performance of it, but at heights more than a particular height, rising in the performance will not significantly increase the height parameter.
Impact of distance and height of surrender buildings on the performance of windcatcher	Short buildings could enhance the performance of windcatcher, but tall buildings cause all channels of windcatchers to act as a chimney.
Impact of wind approach on the performance of windcatcher	Most ventilation rates occur at 0°. amount of it decreases between o° and transition angle. At the transition angle, ventilation arrives at zero.
Impact of velocity on the efficiency of windcatchers	In traditional windcatchers increasing in velocity causes increasing in performance of windcatcher.
Impact of the shape of inlets on the efficiency of windcatcher	Divergent inlet has higher, and the bulging-divergent inlet shape has the lowest efficiency
Performance of windcatchers with various shapes of blades	+shape of internal blades is optimum for a four-sided windcatcher.
Performance of windcatchers with different roofs.	Windcatcher with the curved roof has the highest efficiency in 0 wind angle, but windcatcher with the sloped roof has the lowest sensitivity against changes in wind angle

entering airflow and the performance of windcatchers. Results indicate that oblique positions of windcatchers are more optimal than linear position. The linear position could not supply minimum needed ventilation, whereas incoming airflow was more than required airflow in an oblique arrangement. Other research about the position of windcatchers done by Attia and De Herde [95]. They studied different positions for Malqafs. A 1:20-scaled model was used in this research, and the assumed distance between windcatchers was 60 centimeters. The only factor investigated was the direction of the inlet. Results indicate that the best condition was when one of them was windward, and the other was leeward. Another factor for enhancing the efficiency of windcatchers is increasing the number of interior blades. Hoseinnia et al. [67] changed the number of blades, and other factors were fixed for all cases. Then they investigated the impact of blades on the velocity of incoming airflow. For this purpose, five cases (with different blades) were considered (shown in Fig. 13). Results indicated that the mean velocity of incoming airflow would increase with increasing the number of partitions (both wet and dry partitions). Moreover, moist partitions can add evaporative cooling to windcatcher. Windcatcher with the evaporative cooling feature can decrease indoor space temperature by 7.6° C and increase the relative humidity of indoor space by 9.2 percent.

Table 7
Topics of research about architectural solution and conclusion of them.

Author (year)	Topic	Solution
Calautit et al. (2014)	Impact of various arrangements of windcatchers on the performance of windcatchers	Non-linear arrangement of windcatcher causes improvement in the performance of each of them.
Attia et al. (2009)	Different arrangements of two malqafs	Being in opposite directions causes one of them to bring fresh air into indoor space and another malqaf acts as a chimney
Hosseinnia et al. (2013)	Impact of the number of blades on the efficiency of windcatcher	Increasing the number of openings causes improvement in the efficiency.
Hosseinnia et al. (2013)	Impact of wet partitions on the performance of windcatchers	Wet partitions cause more decreasing in the temperature of incoming air flow.

To put it briefly, Table 7 contains architectural solutions for enhancing the function of windcatcher.

8. New designs for windcatcher

However, traditional windcatchers were beneficial but had some disadvantages that are as follows [120]:

1- Dust and insects can enter in indoor spaces through windcatcher's shafts.

Sometimes, some part of airflow which enters in interior spaces, exits from another channel, and has no circulation in indoor areas.

The efficiency of windcatchers in circumstances with a low velocity of winds is low.

The modern windcatchers have to try to eliminate one or more of these disadvantages. They are more likely to pay off when integrated with new technologies and new designs [120].

8.1. Windcatcher with rotating head

This kind of windcatcher has a rotating head that can be against the wind's direction at every angle it has. The material of it can cross light to buildings profited by more daylights. Some of the main features of this windcatcher is as follow:

- Using relative transparent material for crossing daylight.
- The upper part of it is circular and rotating.
- Number of it depends on temperature and needed ventilation rate [121].

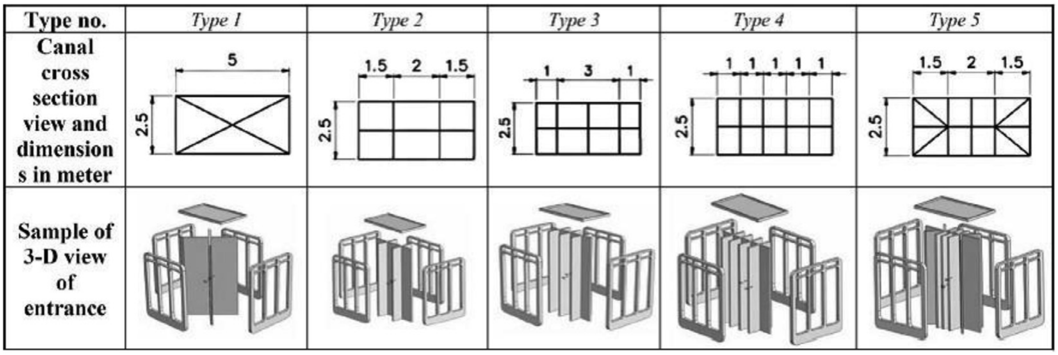


Fig. 13. Investigated types of partitions by Hosein Nia et al. [67].

8.2. Windcatchers with a wetted column, wetted sur- face

Bahadori et al. [122] compared two new types of windcatchers with traditional windcatchers: windcatchers with wet columns and wet surfaces. The results of this comparison show these two new types have higher performance than traditional models [42]. In low velocities, windcatchers with a wet surface and windcatchers with a wet column function more properly in other conditions. Noroozi and Veneris [123] introduced a windcatcher, a combination of these two types. This one-sided windcatcher has wet blades and wet pads on the inlet. The pad can be closed or opened. This windcatcher was simulated in various parameters (velocities, opened, and closed pads). Results showed that this windcatcher could decrease the cooling load significantly. Soltani et al. [124] investigated a windcatcher with a wetted surface. The proposed windcatcher has a fixed column and a rotating head. The inlet has a grid pad wetted by a pump. Results showed that the wetted pad and rotating head could improve the efficiency of the windcatcher significantly.

8.3. Down-draft evaporative cool tower

Passive down-draft evaporative cooling (PDEC) can be an active or passive system [125,126]. PDEC windcatcher is a new kind of windcatcher acting in three stages. In the first stage, the air enters into a windcatcher because of pressure difference. In the second stage, water is sprayed. This process makes entered air denser. Therefore, the denser air moves downward, and in the final stage, the kinetic energy of sprayed drops is conveyed to the air.

Although this windcatcher can be in different types usually has an inlet in the upper part and an outlet in the bottom part for humid air with lower temperature [60,127]. The efficiency of this windcatcher depends on climate [128]. Water spraying is more suitable in dry environments than humid climates [129]. One example that uses this type of windcatcher is the Torrent Research center in India, with a high level of residents [130].

8.4. Air tree

The Air tree is a complex of windcatchers (16 windcatchers), each with metallic construction and a two-layer plastic cover. It has been built in a boulevard in Madrid. Air tree has three processes for increasing ambient air temperature: shadowing, ventilation, and evaporative cooling. Ventilation and evaporative cooling have been performed by an electrical fan, and several water pipes in the bottom part [131]. Soutullo et al. [132] investigated this windcatcher and proposed solutions for optimizing it. According to their research, air trees decrease the surrounding environment's temperature, meant to 8°C. The proposed solution was consisting of:

- Using plastic cover with light color causes more decrease in temperature.
- Decreasing holes from 3 to 1 increases efficiency from 7 to 10 percent.
- Developing an interior wall to make downward it more efficient.

8.5. Rotating windcatcher at blue water

This kind of windcatcher is inspired by old windcatchers of Oast hoses of Keat. These windcatchers have a conical overlay and an aluminum damper with transparent blades located at the end of this overlay for entering daylight to indoor spaces. Another feature of these windcatchers is rotating ability. An intelligent building management system (IBMS) controls the performance of windcatchers. This system at 14°C to 18°C of outdoor dry temperature and velocity of outdoor airflow 1 to 7 m/s deactivates windcatchers, and mechanical ventilation is needed [133]. Overall, three scenarios have been defined for the ventilation of this building. When the velocity of outdoor airflow is lower than 1 m/s for 20 min continuously, mechanical ventilation is used to supply the building's needed ventilation rate. When outdoor airflow speed is between 1m/s and 3 m/s, all of 39 windcatchers of buildings are used [133]. When outdoor velocity is between 3m/s and 7m/s, 19 windcatchers are used. When air velocity is intense, mechanical equipment is used [133,134].

8.6. Commercial windcatcher

Commercial windcatchers have square and circle cross-section, but square cross-section is more common. This type of windcatcher has louvers that prevent penetration of rain and snow to the inside. It has blades for dividing channels to separate parts. Therefore, the channels which have windward opening bring fresh air to the indoor spaces and the channels which have leeward opening suck indoor air outdoor. Mono-draught windcatchers have dampers that automatically open and close according to the amount of CO2 produced [135]. Ji et al. [135] investigated this type of windcatcher for official buildings in various aspects. This investigation was done with Energy plus and different climate conditions in different cities. They considered 11 windcatchers for ventilation of buildings. The simulation results indicate that applying windcatchers and windows can decrease the indoor temperature by 2°C. Moreover, 50 percent of times when could supply needed ventilation.

Windcatchers without other openings 17 percent and with other openings 37 percent reduced cooling load of the building. The fan is one of the new technologies used in the windcatchers. The reason for it is enhancing the efficiency of the windcatchers and reducing its dimension. It works with the electricity of PV located on the windcatcher [136, 137]. Another technology applied in the windcatchers is a heat transfer device (Fig. 14). This technology causes an efficient cooling effect of windcatcher and makes more extensive thermal comfort conditions [138–141]. Results of studies of Calautit et al. [141, 142] estimated the potential of this windcatcher for reducing indoor temperature. According to these studies, it can decrease the temperature of indoor spaces by about 12°C. However, the amount of this decline also depends on the wind velocity.

Calautit et al. [39] investigated the performance of this windcatcher in a small class. Results indicate that commercial windcatchers can supply the needed ventilation rates, even in velocities lower than 2m/s. Moreover, the mean age of air for outdoor airflow was only 23 to 30 percent higher than the mean age of air for indoor airflow.

8.7. Sun catcher

It can bring fresh air and daylight to indoor spaces simultaneously-without any adverse effect on the windcatcher's performance. It can reduce the unwanted sun's radiation, especially in hot climates, because it needs the light supplied by the windcatcher [143].

8.8. Windcatcher assisted adsorption cooling channel

In this system, a windcatcher is combined with an absorbing chiller for cooling and natural ventilation. This system can reduce the indoor temperature by 10°C to 20°C. In dry climates, the efficiency of this system is higher than humid climates [144].Two-sided windcatcher integrated with wing wall

Low velocity leads to a significant reduction in the efficiency of windcatcher. The wing wall (Fig. 15) is useful in this condition for enhancing their effectiveness [145]. The highest performance of this windcatcher occurs between 15° and 30° wind angles. The velocity of entered air flow is 36 percent of outdoor airflow in this type, while it is 24 percent in traditional windcatchers. This windcatcher can supply fresh air 50 percent more than a conventional windcatcher [145]. The length of the wing wall has no significant effect on the windcatcher's performance, but the optimum range for it is between 10cm and 20 cm [146].

Fig. 14. Commercial windcatcher with the proposed horizontal and vertical heatpipe configuration [138].

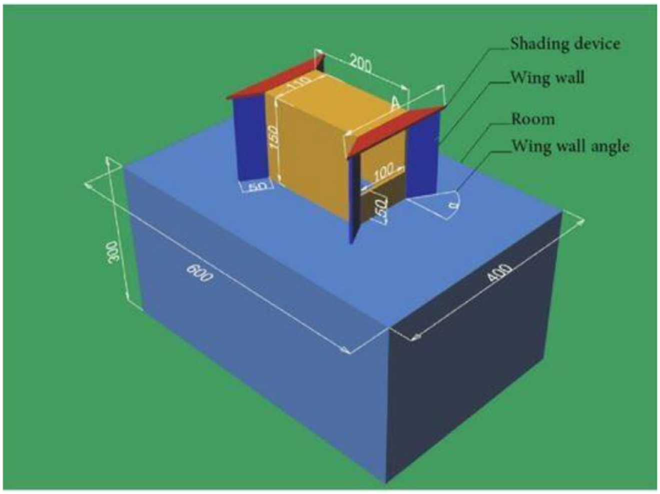


Fig. 15. Two-sided windcatcher integrated with wing wall [145].

8.9. Earth-to-air heat exchanger assisted by a wind tower

The temperature of the depth of soil is near to annual average temperature of the environment. In cold months, the soil depth has a higher temperature and has a lower temperature in hot months than the outdoor. Therefore, using this advantage can be beneficial for providing thermal comfort conditions [147]. The earth-to-air heat exchanger uses the temperature of the depth of ground for cooling and heating. This system is consists of one or more pipes arranged in the depth of soil. Air is pumped in these pipes, and heat is exchanged between it and the soil. This air is pumped over the surface, and that how well it can heat or cool the surrounding environment depends on length, depth, type of soil, and diameter of pipe [148–151]. Banhammou et al. [151] investigated a windcatcher combined with an Earth- to-air heat exchanger. In this study, the effect of the system on decreasing spaces temperature was found. The results of studies by Dwivedi and Sharma [152–154], which done in Baghdad climate, indicate that this system is efficient. The study of Sadeghi et al. [78] showed that the combination of windcatcher and underground channels could reduce fossil fuels' economic costs and consumption.

8.10. Four-sided windcatcher with new design in south Arabia

Al Zaed, in one article [155], introduced a windcatcher with a unique design (Fig. 16). Plate L1 and the windcatcher slope leads to the higher performance (of windcatcher), velocity, and pressure of incoming airflow to indoor spaces than ordinary windcatchers. This system's design is done based on computer simulation.

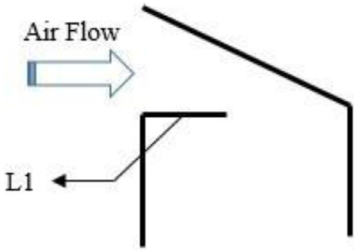


Fig. 16. Four-sided windcatcher with new design in Saudi Arabia.

8.11. Integration of PCM with windcatcher Skin Material

Seidabadi et al. [156] introduced a hybrid system of windcatcher and PCM to increase the heat transfer rate. The results of studying analytical models of this system indicate that it can decrease the temperature of interior spaces to about 25°C for 7 hours. Therefore, the efficiency of this system is acceptable.

8.12. Windcatchers with attached ingress and egress funnels

Valera-Boyda et al. [157] propose a new design for windcatchers. In this design, funnels are integrated with the inlet or outlet of the windcatcher. They performed over 120 simulations for assessing the proposed design and effects of different parameters. The results of these simulations show that adding funnels can enhance the efficiency of windcatchers. In several cases, the volumetric airflow rate increases by 10.7 percent. However, changes in dimensions of funnels can reduce or increase the amount of incoming air.

In another study Valera-Boyda et al. [158] investigated windcatchers with inlet extensions (Fig. 17). The results of performed simulations indicate that adding extensions to inlet has a positive impact on windcatcher performance. According to these results, the extensions can reduce and displace regions with low pressure, and as a result, enhancing the ventilation can be achieved.

8.13. A windcatcher integrated with a solar chimney

Moosavi et al. [159] propose a new design of windcatcher (Fig. 18). In this kind, a one-sided windcatcher is integrated with a solar chimney on the north facade. The investigated building is a two-story building. The windcatcher is connected to the lower floor, and the solar chimney is connected to the top floor through two separate channels. Also, a small void connects two floors. South facing concrete wall separates the windcatcher and the solar chimney. Additionally, this wall acts as a thermal mass for solar chimney. Solar radiations pass through the glass wall of the solar chimney. Therefore, the stack effect emerged—fresh air incomes to interior space through the windcatcher [159].

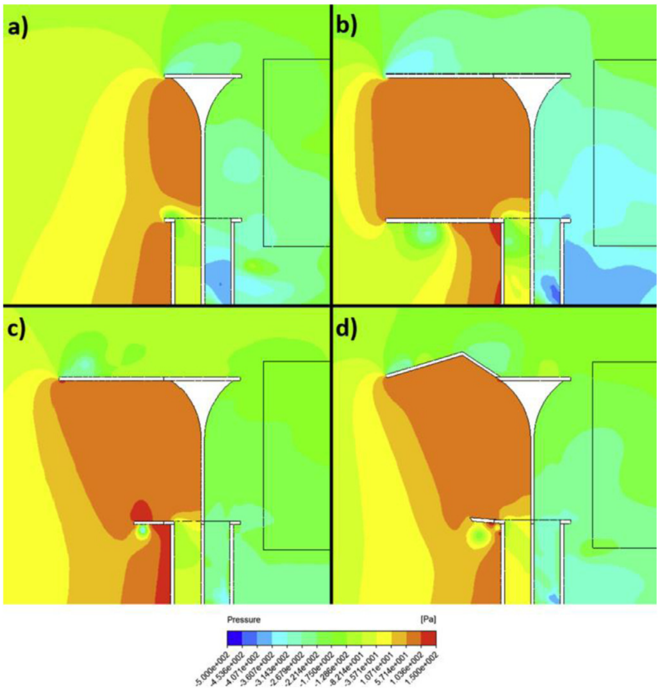


Fig. 17. Some of investigated extensions for inlet of windcatchers by Valera-Boyda et al. [153].

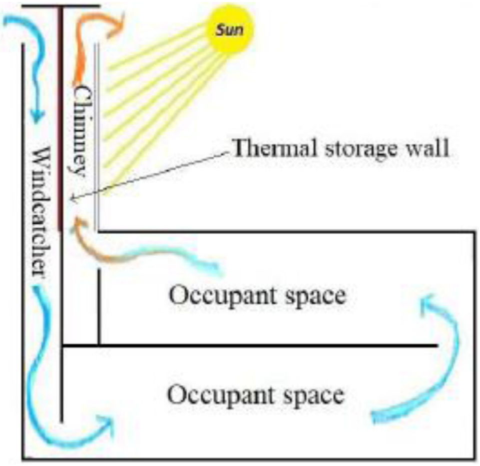


Fig. 18. A windcatcher integrated with a solar chimney [159].

This research indicates that this model with water spraying can reduce the temperature by 5.2 °C. This model can also save 75 percent of consuming energy for cooling and 90 percent of consuming energy for ventilation [159].

8.14. *Using windcatchers in contemporary buildings*

Natural ventilation has some advantages compared to mechanical ventilation. These advantages consist of [155]:

- Lower noise than mechanical equipment.
- Cheaper and providing more comfort condition in the same situations.
- Has no pollution in the environment.

These advantages are the reason that natural ventilation is preferred for mechanical ventilation. This part shows how windcatchers can be used in buildings with different purposes [160].

8.15. *Using windcatcher in a warehouse*

Mostafaeipour et al. [93], as expressed in part 6, showed that windcatchers in a warehouse are useful and have a lower cost than other similar solutions.

8.16. *Using windcatcher in the classrooms*

Morshed [161] investigated windcatchers in a classroom in the UK. Most schools are located in a noisy area in the UK, and noises pass through windows to internal spaces. Therefore, he concluded windcatchers equipped with a fan could meet the healthier and better comfort standards. Jones and Kirby [162] researched about ventilation rate in 16 classrooms in England. In the summer season, a windcatcher from top to the bottom of the building could supply the needed volume of fresh air. Moreover, the concentration of CO2 decreased significantly. They investigated the performance of windcatcher in a classroom in the other paper [163]. Results indicated that a long duct could decrease the efficiency of windcatcher, and applying another opening could increase the efficiency of windcatcher by 47 percent. Research by AlShitawi et al. [164] confirmed the impact of the ventilation rate of windcatcher on the concentration of particles in the indoor space. Results of research by Mavrogianni and Mumovic [165] on two classrooms of a school equipped with Monodraought windcatcher, studies by Ismail and Miran [102] on a school with windcatchers with various heights, and Dorizas et al. [166] on two classrooms integrated with a windcatcher with heat recovery, indicated that it could improve the concentration of CO2 and thermal comfort conditions in winter and summer. However, for supplying the needed ventilation rate (8lit/s), another opening is necessary. Benkariet al. [167] showed in an investigation on two windcatchers in Sultan Qabus university that windcatchers can supply fresh air two-fold than the needed amount.

8.17. *Using windcatcher in a stadium*

Sofotasiou et al. [168] have an article about challenges in world cup 2022 of Qatar. They propose a windcatcher for natural ventilation and evaporating cooling integrated with modern technologies. This system can help the stadium maintain the temperature between 20°C and 25.5°C.

8.18. *Using windcatcher in a greenhouse*

Greenhouses need a determined range of ventilation rate and velocity inside. Windcatchers can be useful in meeting these needs [110]. Pakari and Ghani [110] investigated windcatchers' performance (two windcatchers) integrated with a greenhouse. They measured the performance of them in various wind angles and speeds. The results showed that windcatchers could supply the needed ventilation rate and air velocity inside the greenhouse.

9. New technologies of windcatchers

9.1. *Louver*

The louver is a part of modern windcatchers that prevent the channel of windcatchers from penetrating rain and snow. Opening and closing it can improve the effect of windcatcher or prevent adverse effects [169]. Two parameters affect the performance of louver: number of layers and angle of layers. Maneshi et al. [170] studied two kinds of windcatchers (square cross-section and circle cross-section). They investigated these windcatchers with five-layer and ten layers of louvers. Results indicated that:

- Wake region at the back o0f the windcatcher with five layers of louvers was broader and more visible.

- The ventilation rate for windcatchers with ten layers of louvers was more than windcatchers with five layers.

The investigation of Liu et al. [171] confirmed that increasing layers of louvers improve the amount of supplied airflow. However, the amount of improvement decreases with an increase in the number of layers. The angle of louvers is an essential factor in the performance of windcatchers. Hughes and Ghani [172] studied the effect of this parameter. The results showed that 35° is the optimum angle for louvers.

9.2. Water spraying technologies

Water spraying has a significant impact on decreasing temperature and increasing the humidity of indoor spaces and windcatchers' efficiency [173]. A study by Ahmadikia et al. [174] on windcatcher of Dowlat Abad Garden in Yazd with the help of CFD confirmed it.

9.3. Fan

Most of the modern windcatchers use fans. Elmualim [133] proposed a new windcatcher and showed using fans can increase the velocity of entered airflow, reduce the concentration of CO2, and keep it in standard amount (1000 PPM). Erell et al. [61] proposed a windcatcher for semi-open areas. In this windcatcher (Cool tower), fans play an important role in ventilation. They compared the ventilation rate with fans and without them, and results indicate fans positively affect.

9.4. Damper

Using Dampers is an effective strategy for controlling ventilation. A damper should reduce ventilation to zero and increase it at the predetermined intervals [175]. When the damper is completely open, the ventilation rate is meager. The optimum angle for dampers is between 45° and 55° [176].

9.5. Heat pipe heat recovery

This system is more suitable for cold climates, helps incoming air be in the desired temperature range, and indoor space is in the thermal comfort condition. This system does not cause pressure drops. These pipes have a liquid heat exchanger [177]. This liquid receives heat from the air, which goes out and has evaporated. In this process, the exchanger substance conveys heat to entering airflow and then condensed [178]. However, this system decreases the velocity in a small proportion (8 to 17 percent) but has a significant positive effect on the temperature of entering air (if the temperature of the air is 283° K and the temperature of pipes is 293°K, it can increase the temperature of entering airflow by 4°K) [179]. This system is useful in hot climates too. It can decrease the temperature of incoming airflow [180]. If the outdoor temperature is 38° C, entering airflow temperature can be between 26°C and 28°C [181].

9.6. Horizontally-arranged heat transfer devices (HHTD)

The HHTD is useful for reducing the temperature of entering airflow. Air passes through louvers and transfers its heat to HHTD [182]. The Research by Calautit et al. [182] shows that this system has a significant positive effect and is more efficient in lower velocities (it can reduce the temperature of entering airflow by 9.5°C to 12°C at low speeds).

9.7. Rotary heat recovery device

This system mixes incoming airflow with existing indoor air, and in this process, the temperature of incoming flow will increase. This technology has higher efficiency compared to the other heat recovery devices [183]. Using this system can save 20 percent of the heating cost and rise 1 to 4, depending on the mild-cold climates' outdoor wind characteristics [184].

9.8. Anti-short-circuit device

Short-circuit has a negative effect on the efficiency of windcatchers. Nejat et al. [63] proposed a solution to this phenomenon. This solution is a piece called an anti-short circuit device. This device was integrated into a windcatcher and could reduce the concentration of CO2 by 8 percent and increase mean velocity by 19–28 percent. Besides, this device leads to a better performance of windcatcher in low velocities [185].

10. Windcatchers in the urban context

There are several challenges in microclimates of the urban contexts, such as thermal comfort, air quality, and heat island [186]. Architectural solutions are practical and efficient in facing climate challenges [186] in the design of a single building and urban planning [187,188]. The air velocity at the pedestrian level has a significant impact on thermal comfort in the urban context [189]. Today, various types of windcatchers have been used, especially in a hot climate. The only use of windcatchers is not obtaining thermal comfort. Reducing the concentration of the pollutant in streets and tunnels is another purpose of windcatchers like Air Tree (described in previous parts) [190,131]. It is beneficial in urban areas because they can reduce the ambient temperature of the environment by shadowing, ventilation, and evaporative cooling with electrical fans and nozzles [132,191]. Research showed that it could reduce air temperature to about 6.5°C and increase relative humidity by about 27 percent [192]. Down-draft evaporative cooling is another type of windcatchers that is useful in the urban context [61].

11. Discussion

Windcatcher is a traditional technique for ventilation has the potential of being useful in modern buildings. The new technologies and new designs can be effective in this way.

Windcatchers can be classified into various types according to different factors, including the number of openings, cross-section, number of stores, and position of blades.

There are two main ways of assessing the performance of windcatchers: experimental and theoretical techniques. Each of them has pros and cons. Theoretical classified to analytic and numerical modeling. Among all ways of evaluating the performance of windcatchers, numerical modeling is more common.

Many factors impact on the efficiency of windcatchers. These factors are the number of openings, height, wind angle, velocity, configuration (dimensions, cross-section, and blades). In the 0° wind angle, windcatchers with fewer openings have higher efficiency; however, they have more sensitivity against the wind approach's changes.

Increasing the height of the windcatcher raises the ventilation rate significantly. However, after a specified height (optimum height) rising of the ventilation rate is not tangible. The optimum height changed in different situations.

The wind angle can determine the amount of pressure difference. Therefore, it is an important factor for the ventilation rate. The most pressure differences (most airflow rate) occur at a 0° wind angle. The efficiency of the windcatcher decreased until the transition angle with increasing wind angles. The transition angle is an angle in which the amount of ventilation rate arrived at zero.

In recent years, many new designs for windcatchers have emerged. These designs are based on new technologies and the creativity of designers. Each of them tries to eliminate the weakness of windcatchers and contrive beneficial features for them.

These new design windcatchers have been used in different modern buildings and even urban contexts. This point proved that windcatchers have a high potential for meeting needed natural ventilation in modern architecture and modern lifestyle.

12. Conclusion

The purpose of this paper is to obtain a more comprehensive understanding of traditional windcatchers in the first stage and modern windcatcher and technologies applied to them in the next step. Windcatchers work based on two mechanisms (buoyancy and wind-driven force). These mechanisms are used in both modern and traditional windcatchers. Most of the reviews conducted out about windcatchers concentrate on modern windcatchers or traditional windcatchers. Attention to configurative parameters has been neglected in these articles. This article has tried to achieve a realization about conventional and modern windcatchers. Also, the impact of various factors on the performance of windcatchers were investigated separately. The classification of windcatchers can be done on multiple aspects, like the number of openings or several stories. Different types of windcatchers share common features. All of them have been formed by constant parts like towers, vents, and partitions. Three methods exist for estimating windcatcher's efficiency: experiment, analytical model, and numerical model. Each process has advantages and disadvantages. Most of the articles about windcatchers have used Numerical models, and experimental models also are conventional too. The reason for using windcatchers was showed in the performance of the windcatchers part. Windcatchers have several superiorities in comparison with other openings. Also, from an economic perspective, using windcatchers are better than mechanical ventilation facilities

Therefore, using a windcatcher is an effective way to save energy and money. Parameters like the number of openings, velocity, wind angles, and configuration parameters have a significant impact on windcatchers' performance. Understanding these parameters helps to select and use the correct type. For instance, in regions with one-direction prevail wind, one-sided windcatchers are the most efficient kind, but in areas with variable wind approaches, the conditions are different. Nowadays, new kinds of windcatchers arise with technologies like dampers, louvers, fans, and the other creativity of engineers. Rotating head windcatchers can turn the upper part toward the flowing wind direction. Air tree can decrease the air temperature of the surrounding environment according to three stages: ventilation, evaporating cooling, shadowing. In the new building of the bluewater, an intelligent building management system (IBM) has been used for controlling windcatchers. Commercial windcatchers can decrease temperature down to 14°C. with the help of these technologies and modern designs of windcatchers, they can be compatible with a new form of life and play an essential role in sustainable architecture and decreasing cooling load, especially in hot and dry climates. The number of investigations about windcatchers in other climates like the cold weather is meager. Several issues about windcatchers like materials or positions in highrise buildings need more research.

Declaration of Competing Interest

None

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