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Applied Research Article

Proposing a New Approach to Optimize the Windcatcher's Performance (Case Study: Bandar_E_Kong)

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ABSTRACT: Hot and humid climate in one of the most robust climates in the world. The vernacular architecture of this area answers to climate conditions with solutions. One of these solutions is windcatchers. These windcatchers are closed because they are not responsive to current thermal comfort conditions. The reduction of wind speed and the lack of control over the opening and closing of the windcatchers can be considered the two main weaknesses of the windcatcher in these areas. This research has suggested installing a Damper and Fan to improve the performance of windcatchers in vernacular houses of Bandar-Kong. Machine learning methods have selected five windcatchers as case studies, and their performance has been simulated and measured in 4 general modes: open windcatcher (past method), closed windcatcher (current state), windcatcher with valve, and windcatcher with fan. Design Builder 7.0.0.116 is used for simulations. Operative temperature is calculated for each space in 24 different modes and compared. The results show that fan and damper use increase thermal comfort hours from about 43 to 52 percent. Besides, using fans and dampers can reduce temperatures by over 35 degrees.

Keywords: *Natural Ventilation, Vernacular houses, Hot and Humid, Simulation, Thermal comfort.*

INTRODUCTION

The hot and humid climate is one of the most critical climates in the world, and it is widespread in the southern region of Iran. Vernacular buildings are known as architecture responsive to climatic conditions. One of the climatic solutions in vernacular houses of hot and humid areas of Iran is windcatchers, which have been used for centuries in the Middle East, especially in the Persian Gulf countries(Chenari et al., 2016; Mostafaeipour et al., 2014; Patel et al., 2015). windcatchers have been used in various climatic conditions, including hot and humid climates. It is not yet known precisely where the first windcatchers were built, but Researchers believe that the first windcatchers belonged to 1200 years ago in Iran.(Dehghani-sanij et al., 2015). Many researches have been conducted in the field of windcatchers on the southern coasts of the Persian Gulf, which show that these windcatchers have significantly created thermal comfort conditions(Nikghadam & Mofidi Shemirani, 2018; Zarandi, 2015).

The stack effect is the primary function of windcatchers(Valipour & Oshrieh, 2013). The main factors that influence the performance of the windcatchers are geometric parameters, local weather, and external conditions (Hughes et al., 2012; Jomehzadeh et al., 2020; Saadatian et al., 2012). The local weather, including wind speed, wind direction, air temperature, and humidity, influences the optimal design and, thus, the ventilation performance(Hughes et al., 2012). When the wind speed is adequate, the airflow creates positive pressure(backward) and negative pressure(Leeward), and as a result, ventilation occurs in the space(Chohan & Awad, 2022). When the wind speed is low, the temperature difference between the outside and inside creates ventilation(Fanood, 2014; Patel et al., 2015). Therefore, the efficiency of windcatchers increases with increasing wind speed(Afshin et al., 2016; Dehghan et al., 2013; Farouk, 2020). In hot and humid areas, the stack effect is reduced due to the little difference between the outside and inside; therefore, the windcatcher's performance is also reduced(Khan et al., 2008).

Windcatchers of Iran have various plans, and depending on climate conditions, they are divided into several parts. Bandar-Kong is one of the coastal cities of the Persian Gulf, and its historical context has been preserved. Vernacular houses in Bandar Kong generally have courtyards and windcatchers. Most houses have two windcatchers on the east and west part of them. Windcatchers of Bandar-Kong are shorter and broader than other windcatchers in Iran. They are more

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comprehensive because they increase the incoming air's flow rate to reduce the living space's air humidity. Due to the air's high humidity, these windcatchers' function is generally cooling by reducing the humidity. The shapes of blades are all X-shaped, and the main reason for the thinness is the poor architecture in the port of Lange. (Zarandi, 2015)

Windcatchers are still being used as passive methods for ventilation in suburban and countryside areas (Chohan & Awad, 2022). In Bandar-Kong, windcatchers are primarily closed and subject to destruction. Despite the mechanical ventilation devices, windcatchers in Bandar-Kong are useless and subject to destruction. The reason for this can be summarized in two cases. People lack control over opening and closing the wind deflector and lack sufficient wind speed on some days of the year and at some hours of the day. Field studies showed that it is more effective for windcatchers to be closed in cold and hot weather so that the temperature can be comfortable. Studies show that during the hot seasons, the combination of windcatchers with damper screens improved the performance of windcatcher and created thermal comfort by minimizing indoor space temperature (Jomehzadeh et al., 2020)

Furthermore, enhancing airflow can improve the performance of windcatchers (Jomehzadeh et al., 2020; Shaeri et al., 2018). therefore, combining a mechanical fan with windcatcher would increase airflow through spaces and increase thermal comfort hours in vernacular houses with low energy consumption. In this paper, two solutions are suggested to improve the performance of the windcatchers. As a first suggestion, a damper is provided and simulated to prevent the cold and hot weather from entering. As a second suggestion, a fan is installed on top of the windcatcher to enhance airflow and natural ventilation through the windcatchers. This study aims to evaluate the performance of a windcatcher equipped with a damper and fan and compare it with the current state (closed) and past state (open) to discover which state is more compatible with climate conditions. Besides these two suggested methods, the effect of cross ventilation through windows and room connections combined with a windcatcher is investigated.

For this purpose, first of all, the research background has been reviewed. Next, the first step selects the windcatchers that are most similar using Machin learning methods with the Cosin similarity function. In the second step, case studies have been investigated for installing fans and dampers due to the air inlet and outlet. In the third step, case studies were simulated in four general modes: open windcatchers, closed windcatchers, windcatchers equipped with a Damper, and windcatchers equipped with a fan. In each mode, the influence of windows and doors has been investigated, too. Therefore, each case study was studied for 24 different modes, and the operative temperature was calculated for each case study in 24 modes over one year. Operative temperature has been measured in simulation. In the fourth step, the data results are analyzed, showing that adding a fan and damper increases thermal comfort hours in windcatchers.

Literature Review

Windcatchers Are a passive cooling method with many positive features, but some limitations decrease their efficiency (Zafarmandi & Mahdavinejad, 2021). The amount of incoming airflow for cooling the indoor environment is directly related to the wind speed of the outdoor environment, so when the wind speed outside decreases, the performance of the windcatchers also decreases. Many studies have been done to improve the performance of windcatchers. These studies have been carried out on the characteristics and location of inlets and outlets of windcatchers, the height of wind catchers, and their orientation to find the most optimal possible state. Another group of researchers has combined modern elements with traditional windcatchers to improve their performance. Some researchers combined traditional windcatchers with Fans, sensors, Dampers, evaporative cooling systems, and funnels to improve the performance of windcatchers.(Zafarmandi & Mahdavinejad, 2021)

Varella has studied the ways to improve the performance of windcatchers. In this study, 33 models of windcatcher outlet configuration have been investigated. The results show that the inlet air window should be four times larger than the outlet not to reduce the flow rate.(Varela-Boydo & Moya, 2020). Later, Varela-Boydo Moya studied a new design of windcatchers with funnels. In this research, the top of the windcatcher is consumed as a funnel in order to enter more airflow in the windcatcher. The results show that in the best case, the airflow has increased by 7.1 percent on average. (Varela-Boydo et al., 2020).

Hughes and colleagues have proposed a method to increase airflow in windcatchers. They have used a low-powered fan inside the windcatcher to have sufficient airflow even if there is no airflow outside. Besides, they suggested a solar fan to reduce energy consumption (Haghighi et al., 2016).

Nejati and colleagues(Nejat et al., 2016) have studied a new method to increase the performance of windcatchers in Malaysia. They integrated wing walls with windcatchers to increase airflow in any wind direction. Results show that adding wings to two-sided windcatchers had 50 percent more ventilation compared to the traditional model and could satisfy thermal comfort conditions, according to AshreA 55.

Bahadorinejad has studied windcatchers in Yazd and investigated new designs of windcatchers. The experiment was carried out that the new windcatchers are more efficient because adding evaporative cooling pads at the entrance region of the tower can significantly reduce temperature and increase relative temperature (Bahadori et al., 2008; Jomehzadeh et al., 2020).

Hosseinnia et al. (2013) studied the effect of different internal divisions of traditional windcatchers on thermal comfort conditions. Besides, they investigated their results for two cases with and without wet partitions as evaporative cooling. The results show that the air temperature decreased by 6.5 degrees in the best design conditions while the outside temperature was 318k, and air velocity could be increased by 1-1.5 m/s. Also, wet partitions could decrease the air temperature from 318 K to 311.3 K and increase relative humidity by 9.2 percent.

Calautit et al. (2014) installed a heat transfer device (H.T.D.) at the entrance of the windcatcher and calculated the results using wind tunnel and numerical calculations. The results have shown that this new method could reduce air temperature by up to 12 degrees, depending on the configuration and operating conditions. Besides, installing this device could increase indoor air speed by 24 percent. Later (Calautit et al., 2015), a Uni-directional windcatcher was studied, focusing on increasing heat transfer. The results show that this new windcatcher model can reduce supply air temperature to 12 degrees cooler depending on outdoor airflow.

O'Connor et al. (2016) introduced a new set of windcatchers. They proposed that wind towers benefit from rotary desiccant wheels to reduce relative humidity by absorbing moisture from the air. The results show that this method can reduce relative humidity by up to 55 percent in indoor spaces.

Haghighi et al. (2016) proposed a new system combining a windcatcher and a solar chiller to improve natural cooling. The results show that with increasing cooling plates, thermal comfort conditions increase, and the system can cool the air between 10 and 20 under different ambient conditions.

Sadeghi and Kalantar (2018) proposed a new method to improve windcatchers' performance. This work studied the combination of underground channels with windcatchers and dry and wet channels in Yazd, Iran. The results show that dry channels reduced the entrance air temperature by reducing 7.6-15.4 depending on the design. Besides, using wet channels increased relative humidity by 52 percent.

According to the research background, in hot and humid regions, a lack of temperature difference is the point(Jomehzadeh et al., 2020; Jomehzadeh et al., 2017; Shaeri et al., 2018). Air circulation is insufficient because there is no significant difference between indoor and outdoor temperatures. Installing a fan inside the windcatchers is thought to improve its performance and increase thermal comfort. This research investigates the influence of installing fans and dampers inside traditional wind catchers. (Table 1).

Theoretical Framework

Wind catchers

Wind catchers have been used for centuries in the Middle East, especially in the Persian Gulf countries. Climatic parameters such as wind speed, wind direction, air temperature, and humidity play an essential role in the efficiency of natural ventilation. The efficiency of windcatchers increases with increasing wind speed. As the wind angle increases, the wind speed decreases. The best angle for windcatchers is perpendicular to the opening surface. The airflow rate decreases as the number of openings increases (Jomehzadeh et al., 2020).

Thermal Comfort Index

In the definition of the Ashrea standard, thermal comfort is a mental condition expressing satisfaction with environmental conditions. Thermal comfort depends on the following factors: 1. Temperature and radiation (dry bulb temperature, average radiation) 2. Radiant temperature. 3. Relative humidity. 4. Airflow speed, 5. Coverage, and 6. Other activity levels include surface temperature, window temperature, Person's age, adaptation, Person with environment, and vertical gradient of air temperature.

The P.M.V. index was invented by Fanger in 1970. This index considers psychological and physiological parameters and human behavior as factors that adjust the temperature of the human body with the external environment. Comfort conditions are well established when the heat of the human body is equal to the environment's temperature (Nicol et al., 2012). According to the mathematical expression in the ISO 7730 standard (ISO, 2005), Asher 55 (Standard, 2017), this difference is acceptable up to +3 and -3.

MATERIALS AND METHODS

Scope of Research

Bandar Kong is one of the coastal cities of the Persian Gulf. Vernacular houses of Bandar Kong (Figure 1) have windcatchers, often in the west and east parts of the house. Windcatchers are the main characteristic

Table 1: research background

Researchers	Proposed Method	Results
Varela-Boydo et al., 2020	windcatchers with funnels	increased 7.1percent on average
Bahadori et al., 2008; Jomehzadeh et al., 2020	adding evaporative cooling pads	can significantly reduce temperature and increase relative temperature
Sadeghi & Kalantar, 2018	Underground channels+windcatchers	Dry channels decrease tempreture7-15 degrees
Haghighi et al., 2016	the low-powered fan inside the windcatcher	Wind speed increased three times
Nejat et al., 2016	They integrated wing walls with a windcatcher	had 50 percent more ventilation in comparison with the traditional model
Haghighi et al., 2016	Windcatcher+sollar chiller	degrees increased 10-20
O'Connor et al., 2016	rotary desiccant wheels	Increase relative humidity up to 55 percent
Calautit & Hughes, 2014	(heat transfer device(HTD	reduce air temperature by up to 12 degrees
Calautit et al., 2015	Uni-directional windcatcher	up to 12 degrees cooler
Hosseinnia et al., 2013	different internal division	decreased 6.5 degree

Fig. 1: (a)The historical context of Bandar-Kong (b)windcatchers in Bandar-Kong

of Bandar Kong architecture, which is used to benefit the sea breeze. Windcatchers of Bandar Kong are square or rectangular, divided into four smaller X-shaped channels. The shape of windcatchers is short and wide because they increase the flow of incoming air to reduce the air humidity of the living space.

Due to the air's humidity, these windcatchers generally cool down by reducing the humidity (Zarandi, 2015). Unfortunately, these windcatchers have often been destroyed or blocked and are generally practically useless.

Case Study Selection

Case studies are selected using machine learning methods. One of the capabilities of machine learning methods used recently in architectural research is the similarity measurement of architectural images. Categorizing and describing the architectural features of each category plays a vital role in recognizing architectural types (Araldi et al., 2021). Cosine similarity measurement has been used for similarity measurement of architectural plans in previous research (Babakhani et al., 2021; Mosavat et al., 2019; Yusif & Yan, 2019; Son & Hyun, 2021; Keifari & Babakhani, 2021). it is a measure of similarity between two vectors of an internal multiplicative space based on the cosine of the angle between them. The cosine of zero theta equals one, and the rest of the angles are smaller than one. Therefore, the measure is the direction of two vectors, not their magnitude (Farhai & Jamzadeh, 2017, 21). The cosine similarity criterion is suitable for evaluation, especially in sparse vectors, and it is used primarily in the positive space with a range of [0.1] (Farhai & Jamzadeh, 2017, 21). For this reason, this method has been used to evaluate the similarity of architectural plan images due to the variety of data.

In this method, the plan of 35 windcatchers is first saved as 400*400 pixel images; these images are converted into a 400*400 matrix in the Anaconda 3.9 based on RGB codes in images. Each matrix has been compared to other matrixes (extracted from images) 34 times. Here is the prompt used in Anaconda for similarity measurement. Hitmap (Figure 2) shows the similarity percentage for 35 houses. The plans that have the most similarity with other plans are Yunesi (Fig. 3 (b)) and Galbat (Fig. 3 (c)) houses.

similarity = -1 *(spatial.distance.cosine(plan_array1, plan_array2) -1)

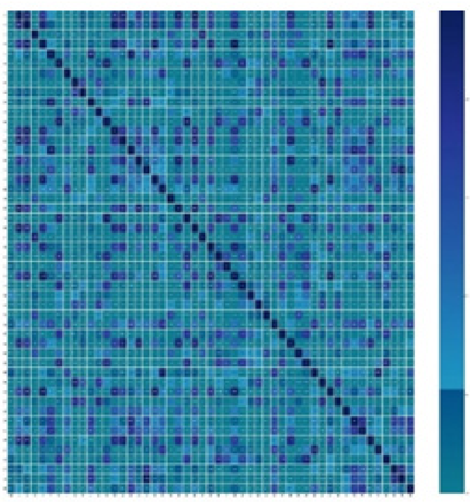

Fig.2: Heatmap of similarity

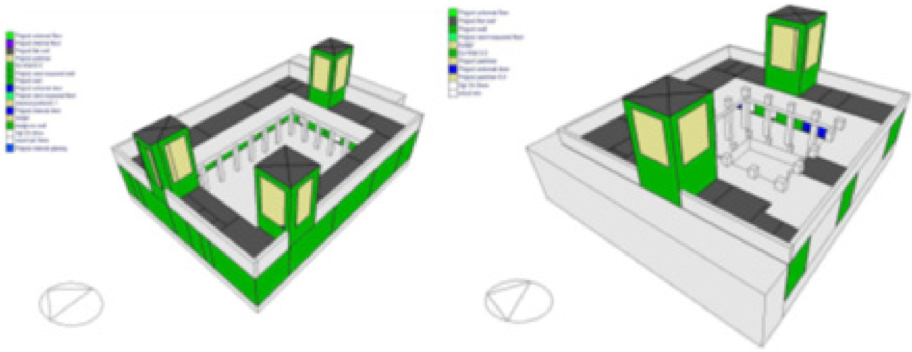

Fig. 3: (a). yunesi house model. (b) Galbat house model

Specifying Comfort Zone

Based on the average temperature of the outside environment, the comfort zone is calculated in different months from Jan to Dec as follows (23.7-24.1-24.9-26.2-27.4-27.9-28.2-28.1-28.0-27.1-25.6-24.2). Therefore, the comfort range will be from 23.71 to 28.2(Figure 4). According to the Ashre A standard 55(Ashrea,2021), a tolerance of 2.5 Celsius will be added to this range, so the comfort temperature range is 21.21 to 30.68 degrees. Figure 4 shows thermal comfort in different months based on adaptive thermal comfort. Operative temperature, mentioned in the diagram, is the outside environment's temperature, and radiant temperature is considered the same as the air temperature. Also, the E.P.W. file for simulation from the nearest weather station (Bander Lange) has been used from the climate. onebuilding.org website.

Simulation modes

This research compares different modes to evaluate suggested approaches (Fig 5). So, the simulation is considered for twenty-four different modes (Table 2), without a windcatcher, open a windcatcher, a windcatcher with a valve, and a windcatcher equipped with a fan.

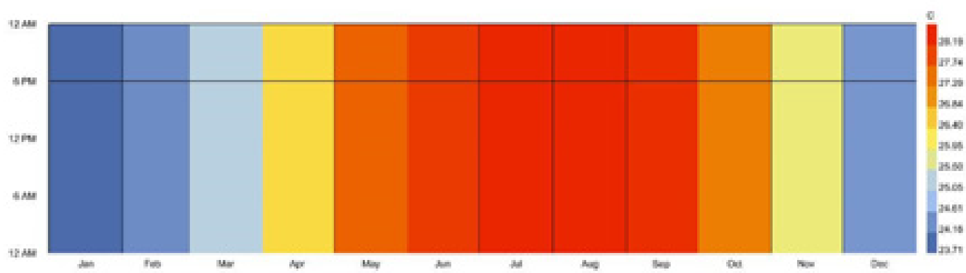

Fig. 4 Thermal comfort temperatures

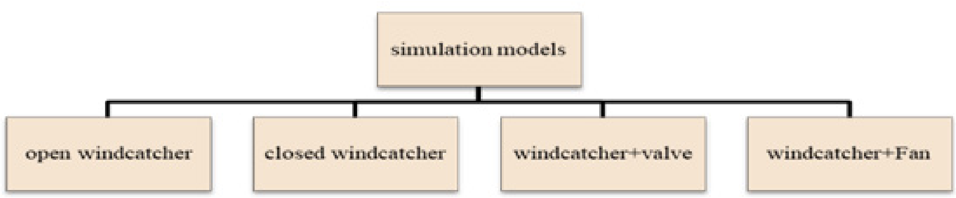

Fig. 5: different modes

Table 2: 24 different simulation modes

State .1	open	Connected with the adjacent room- door and windows are open	D.W.O
State .2		Connected with the adjacent room- doors are closed	D.C
State .3		Connected with adjacent room- windows are closed	W.C
State .4		Not Connected with the adjacent room- door and windows are open	D.W.O
State .5		Not Connected with the adjacent room- doors are closed	D.C
State .6		Not Connected with adjacent room- windows are closed	W.C
State .7	closed	Connected with the adjacent room- door and windows are open	D.W.O
State .8		Connected with the adjacent room- doors are closed	D.C
State .9		Connected with adjacent room- windows are closed	W.C
State .10		Not Connected with the adjacent room- door and windows are open	D.W.O
State .11		Not Connected with the adjacent room- doors are closed	D.C
State .12		Not Connected with adjacent room- windows are closed	W.C
State .13	valve	Connected with the adjacent room- door and windows are open	D.W.O
State .14		Connected with the adjacent room- doors are closed	D.C
State .15		Connected with adjacent room- windows are closed	W.C
State .16		Not Connected with the adjacent room- door and windows are open	D.W.O
State .17		Not Connected with the adjacent room- doors are closed	D.C
State .18		Not Connected with adjacent room- windows are closed	W.C
State .19	Fan	Connected with the adjacent room- door and windows are open	D.W.O
State .20		Connected with the adjacent room- doors are closed	D.C
State .21		Connected with adjacent room- windows are closed	W.C
State .22		Not Connected with the adjacent room- door and windows are open	D.W.O
State .23		Not Connected with the adjacent room- doors are closed	D.C
State .24		Not Connected with adjacent room- windows are closed	W.C

In all simulation modes, the minimum temperature for opening the window and entering the airflow is 24 Celsius. Therefore, in cold seasons, the windows are considered closed when the temperature is lower than 24. In hot seasons, the natural ventilation continues till the outside temperature is higher than inside. Otherwise, the windows are considered closed. Design builder 7.0.0 is used for simulations.

Specifying the air inlet and outlet in the air vents

To determine the air inlet and outlet and install fans, it is necessary to specify the airflow to position the fans properly. Since the fans will be used to strengthen the airflow, the east (Figure 6) windcatchers of the Yunsi house were selected and analyzed. For this purpose, each valve's air inlet and outlet have been measured over one year. The amount of inlet and outlet airflow was calculated separately in square meters per second unit using Design Builder software for over one year for each side of the wind catcher. The blue part of the diagram (shows the outlet air from the room into the draft, and the orange part shows the inlet airflow into the windcatcher. The results show that the west part of the windcatcher has an equal amount of inlet and outlet airflow caused by the chimney effect, even though some air often exited from other valves. In this way, the cool air of the yard and the sabbats (porches) replaced the room's warm air. Therefore, the fans strengthen the chimney effect in windcatchers.

The calculations performed to check the natural ventilation flow have been modeled and calculated based on the Air Flow Network in Design Builder software using natural ventilation in Detail mode. According to the results obtained from the air inlet and outlet investigations, fans with the following specifications (Table 3) have been modeled in the Air Flow Network for each outlet at different sections of the wind catchers.

RESULTS AND DISCUSSION

Diagrams show the results, which are divided into four different temperature zones. The blue part shows a temperature between 16 to 24, the green part shows a comfort temperature from 24 to 31, the pink part shows a tempreture between 31 to 35, and the red one shows a temperature higher than 35. All 24 simulation modes (Table 2) are calculated for five windcatchers (Figure 7), and the results are compared.

Windcatcher.N.1

The diagram below (Figure 8) shows the results of the simulation. The comfort temperature varies from 42 to 52 percent of the year, which indicates 154 and 190 days of thermal comfort in indoor space during a year. In other words, by changing the parameters, thermal comfort increased by 36 days (more than one month) a year. The most suitable

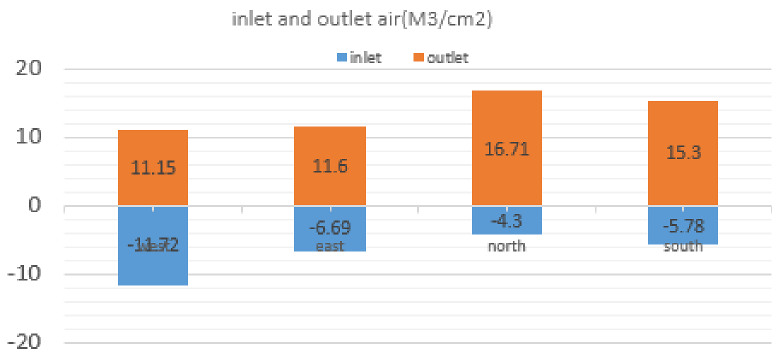

Fig. 6: inlet and outlet air of wind catcher

Table 3: Fan Properties

60	Fan efficiency(percent)	1
125	Pressure increasing (pascals)	2
0.1	Maximum suction (cubic meters per second)	3

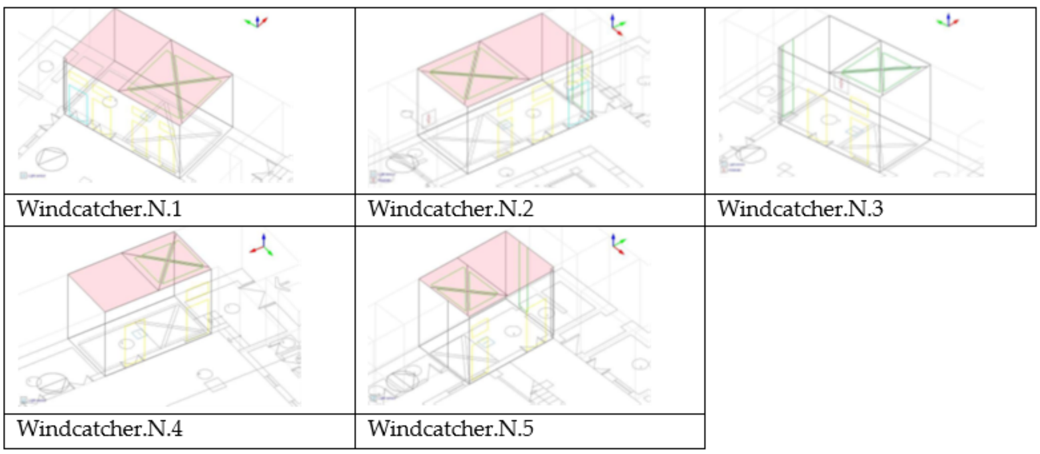

Fig. 7: five windcatchers simulated in the design-builder

thermal comfort conditions occur when there is a connection between the windcatcher room and the adjacent room, and the windcatcher is equipped with a fan. In general, when more widows are open for cross ventilation, there is a better thermal comfort situation in indoor spaces. The worst condition is when the windcatcher is open all year (fully open without vents). In such a situation, comfort temperature decreases to 42 percent a year because the hot air outside easily enters across the windcatcher and increases the temperature. Also, the temperature decreased in cold seasons because the cold weather flew down across the windcatcher.

According to the results, indoor temperatures above 35 degrees can be reduced by installing a fan to increase circulation. In other words, strengthening the airflow prevents the room from overheating and significantly increases the hours of thermal comfort. Also, installing a valve at the opening of the windcatcher produces the same results at temperatures above 35 degrees, but it does not significantly increase the thermal comfort range.

Windcatcher. N.2

This space has more openings than wind catcher number one. As shown in Fig 9, the comfort range in this space varied between 42 and 53 percent. The best mode for creating thermal comfort was related to

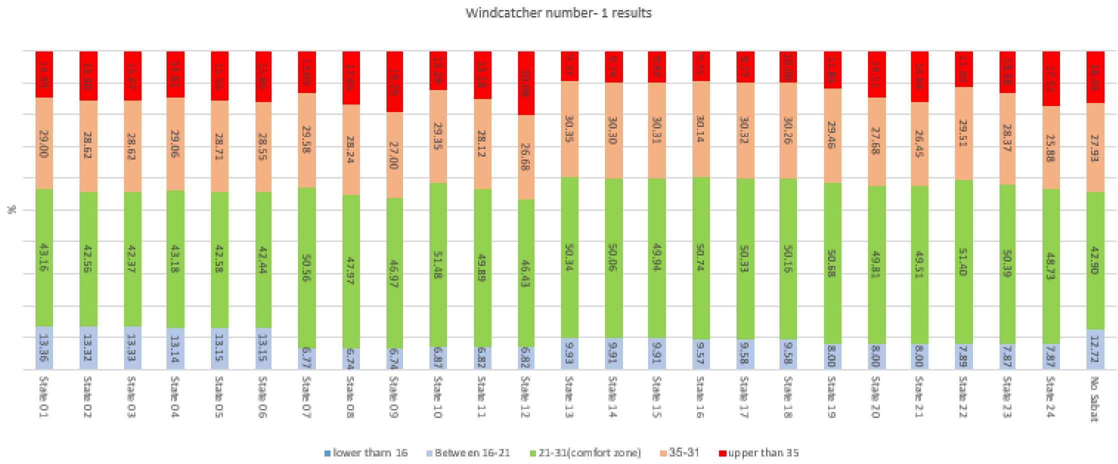

Fig. 8: windcatcher.N.1 results

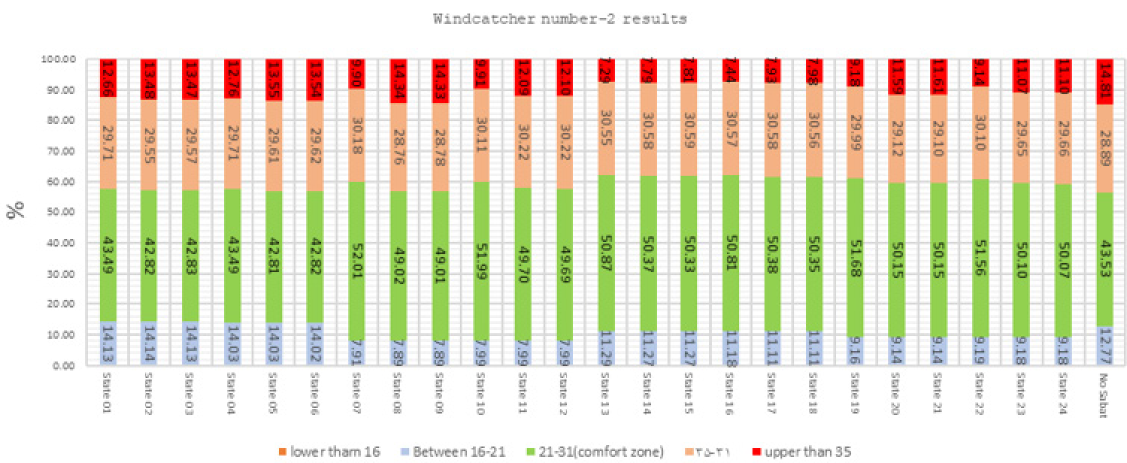

Fig. 9: windcatcher.N.2 results

the mode without a wind catcher and a wind catcher equipped with a fan. Also, the connection of the wind catcher with other rooms led to better thermal comfort conditions. As the air exits through the vent, the negative pressure created inside the room will be balanced through the windows, showing the importance of combining cross-ventilation with the vent.

Installing a fan to create more airflow reduces the range of temperatures above 35 degrees. In other words, by strengthening the airflow, due to the heat of the outside environment, the number of hours that the windproof room is in thermal comfort has not increased, and it has only caused the temperature to decrease by more than 35 degrees. Also, installing a valve at the wind deflector's opening caused the temperature to decrease above 35 degrees Celsius. However, it did not have much effect on increasing significantly the thermal comfort range.

Windcatcher. N.3

The results of windcatcher number 3 are shown in Fig 10. In this room, thermal comfort varies from 43 to 52 percent. The worst situation is when the windcatcher and windows are closed and the windcatcher is not connected to the adjacent room. In all four modes of open, closed, vent, and fan, connecting the windcatcher room and the adjacent room improved the thermal situation and decreased operative temperature. As in previous cases, installing a valve prevented overheating and decreased temperatures above 35 degrees. Also, fan installation increased thermal comfort by 50 percent of the year. So, by installing a fan, thermal comfort can be achieved 30 more days a year than a windcatcher without a fan.

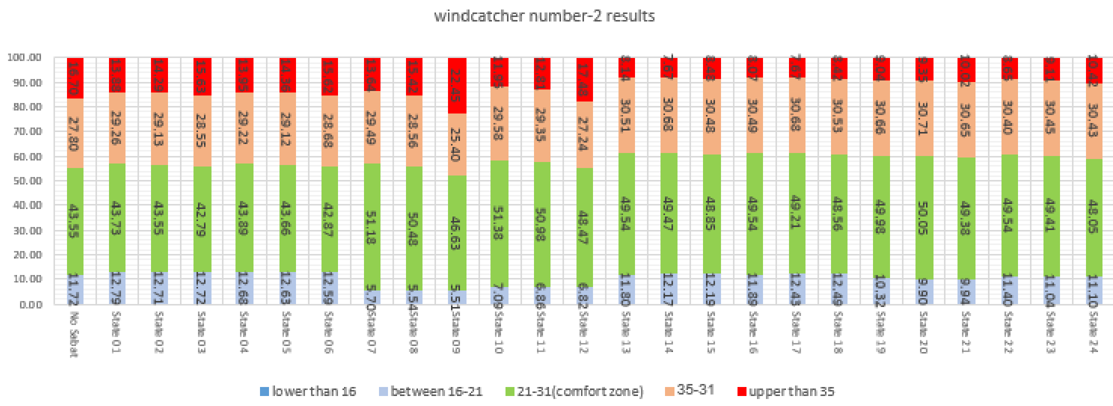

Fig. 10: windcatcher.N.3 results

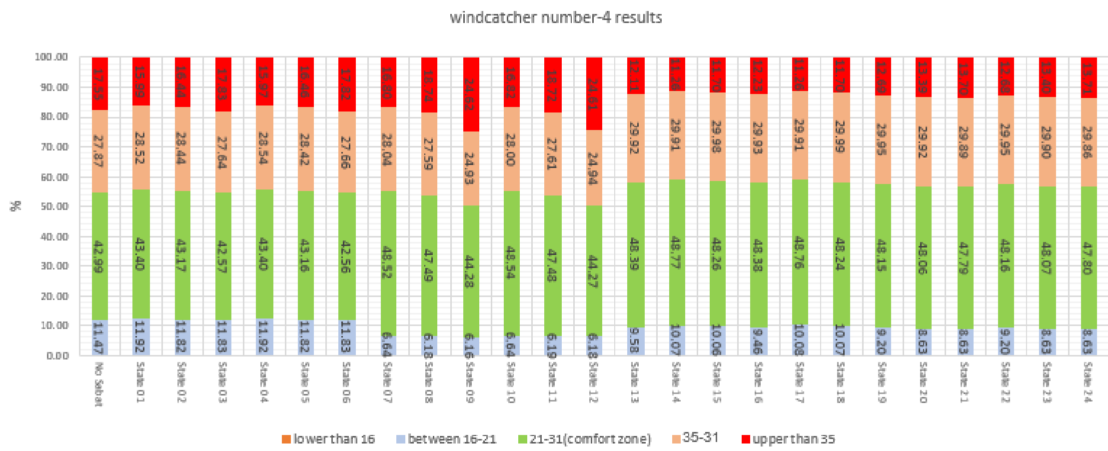

Fig. 11: windcatcher.N.4 results

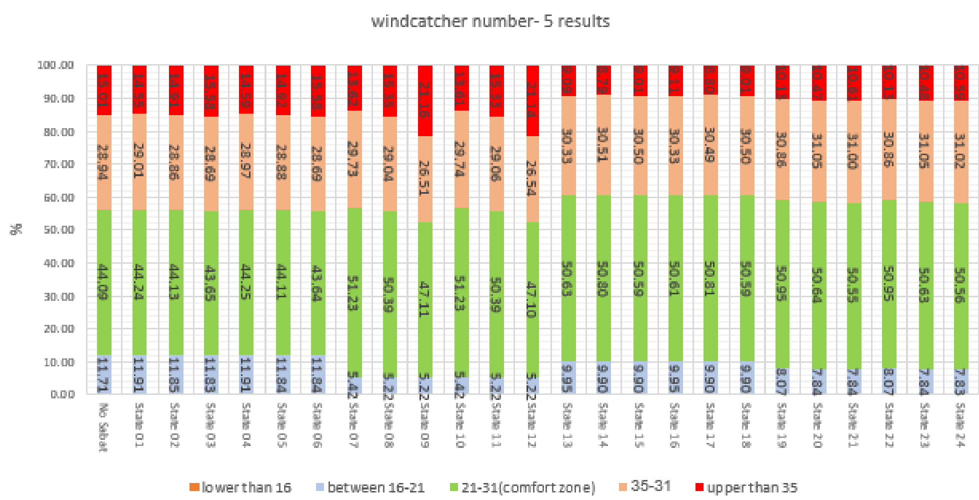

Fig. 12: windcatcher.N.5 results

Table 4: Percentage of temperature ranges in five wind catchers

			Windcatcher.1				Windcatcher.2				Windcatcher.3				Windcatcher.4				Windcatcher.5			
		Tempreture	16-21	21-31	31-35	>35	16-21	21-31	31-35	>35	16-21	21-31	31-35	>35	16-21	21-31	31-35	>35	16-21	21-31	31-35	>35
Open windcatcher	connected	D.W.O	13.4	43.1	29	14.5	14.1	43.5	29.7	12.7	12.8	43.7	29.3	13.9	12	43.4	28.5	16	11.9	44.2	29	14.5
		D.C	13.3	42.6	28.6	15.5	14.1	42.8	29.5	13.5	12.7	43.5	29.1	14.3	11.8	43.2	28.5	16.4	11.8	44.1	28.7	14.9
		W.C	13.3	42.4	28.6	15.7	14.1	42.8	29.6	13.5	12.7	42.8	28.5	15.6	11.8	42.6	27.6	17.8	11.8	43.6	28.7	15.6
	Not.connected	D.W.O	13.1	43.2	29.1	14.6	14	43.5	29.7	12.8	12.7	43.9	29.2	14	11.9	43.4	28.5	16	11.9	44.2	29	14.6
		D.C	13.1	42.6	28.7	15.6	14	42.8	29.6	13.5	12.6	43.7	29.1	14.4	11.8	43.1	28.4	16.5	11.8	44.1	28.9	14.9
		W.C	13.1	42.4	28.5	15.9	14	42.8	29.6	13.5	12.6	42.9	28.7	15.6	11.8	42.6	27.6	17.8	11.8	43.6	28.7	15.6
Closed windcatcher	connected	D.W.O	13.1	50.6	229.6	13.1	7.9	52	30.2	9.9	5.7	51.2	29.5	13.6	6.6	48.5	28	16.8	5.4	51.2	29.7	13.6
		D.C	6.8	48	28.2	17	7.9	49	28.8	14.3	5.5	50.5	28.6	15.4	6.2	47.5	27.6	18.7	5.2	50.4	29	15.3
		W.C	6.7	47	27	19.3	7.9	49	28.8	14.3	5.5	46.6	25.4	22.4	6.2	44.3	25	24.6	5.2	47.1	26.5	21.2
	Not.connected	D.W.O	6.7	51.5	29.3	12.3	8	52	30.1	9.9	7.1	51.4	29.6	12	6.6	48.5	28	16.8	5.4	51.2	29.7	13.6
		D.C	6.9	49.9	28.1	15.2	8	49.7	30.2	12.1	6.9	50.1	29.3	12.8	6.2	47.5	27.6	18.7	5.2	50.4	29.1	15.3
		W.C	6.8	46.4	26.7	20.1	8	49.7	30.2	12.1	6.8	48.5	27.2	17.5	6.2	44.3	25	24.6	5.2	47.1	26.5	21.1
Damper windcatcher	connected	D.W.O	6.8	50.3	30.3	9.4	11.3	50.9	30.5	7.3	11.8	49.5	30.5	8.1	9.6	48.4	29.9	12.1	9.9	50.6	30.3	9.1
		D.C	9.9	50.1	30.3	9.7	11.3	50.4	30.6	7.8	12.2	49.5	30.7	7.7	10.1	48.8	29.9	11.3	9.9	50.8	30.5	8.8
		W.C	9.9	50.7	30.3	9.8	11.3	50.3	30.6	7.8	12.2	48.8	30.5	8.5	10.1	48.3	30	11.7	9.9	50.6	30.5	9
	Not.connected	D.W.O	9.9	50	30.1	9.5	11.2	50.8	30.6	7.4	11.9	49.5	30.5	8.1	9.5	48.8	29.9	12.2	9.9	50.8	30.3	9.1
		D.C	9.6	50.3	30.3	9.8	11.1	50.4	30.6	7.9	12.4	49.2	30.7	7.6	10.1	48.8	29.9	11.3	9.9	50.6	30.5	8.8
		W.C	9.6	50.1	30.3	10	11.1	50.3	30.6	8	12.5	48.5	30.5	8.4	10.1	48.3	30	11.7	9.9	50.9	30.5	9
Fan and wincatcher	connected	D.W.O	8	50.7	29.5	11.8	9.2	51.7	30	9.2	10.3	50	30.7	9	9.2	48.1	29.9	12.7	8.1	50.9	30.9	10.1
		D.C	8	49.8	27.7	14.5	9.1	50.1	29.1	11.6	9.9	50	30.7	9.3	8.6	48	29.9	13.4	7.8	50.6	31	10.5
		W.C	8	49.5	26.4	16	9.1	50.1	29.1	11.6	9.9	49.4	30.6	10	8.6	47.8	29.9	13.7	7.8	50.5	31	10.6
	Not.connected	D.W.O	7.9	51.4	29.5	11.2	9.2	50.6	30.1	9.1	11.4	49.5	30.4	8.7	9.2	48.1	29.9	12.7	8.1	50.9	31	10.1
		D.C	7.9	50.4	28.4	13.4	9.2	50.1	29.6	11	11	49.4	30.4	9.1	8.6	48.1	29.9	13.4	7.8	50.6	31	10.5
		W.C	7.9	48.7	25.9	17.5	9.2	50.1	29.7	11.1	11.1	48	30.4	10.4	8.6	47.8	29.9	13.7	7.8	50.6	31	10.6

Windcatcher. N.4

According to Fig 11, thermal comfort in this space varies between 43 and 49 percent. In this case study, this is because the sabat (porch) is not adjacent to the windcatcher. So, the air entering the room from the window is hot. According to this, installing a fan is less effective than when the window is adjacent to the porch. The best thermal comfort condition occurs when the windcatcher is equipped with a valve and the window adjacent to the courtyard is closed. According to the results, the sabat is essential in thermal comfort conditions.

Windcatcher.N.5

According to Fig 12, the windows face north, and this space has no direct sunlight. Also, there is no sabbat on this side. Therefore, the windows do not have shades. The thermal comfort range in this space varies between 43 and 52 percent. The highest thermal comfort values occur when the windcatcher has a fan. Since the window is not near the shade, closing the windows does not have much effect on thermal comfort conditions.

CONCLUSION

In the past, windcatchers were the only mode of ensuring thermal comfort in the pre-electricity era, and they remained a popular and affordable element of thermal comfort for a long time. However, windcatchers cannot compete with modern air coolers because of their limitations. Therefore, even though windcatchers are proven and practical elements of passive ventilation, their usage is minimized in modern buildings. However, in recent years, designers have reintroduced wind catchers in modern buildings with a modified function and shape. Studies on various types of windcatchers have proven that modified windcatchers can still be used as hybrid ventilation systems in modern buildings. This study's literature review has revealed that the windcatcher design can be revitalized through the suggested guidelines and modifications. These guidelines will drastically improve the working and efficiency of windcatchers and ensure their easy adaptation to the designs of new buildings. This research considers that utilizing windcatchers in the housing sector could be a way forward to save energy resources.

Bandar-Kong is a coastal city in the Persian Gulf with a hot and humid climate. The case studies selected from vernacular houses show that modified windcatchers work effectively, and applying technology to current windcatchers can improve their performance. For this purpose, two methods were proposed to improve windcatchers. According to the literature review, the current windcatchers have two primary weaknesses. The first windcatchers in Bandar-Kong are open over the entire year. So, windcatcher worsens thermal comfort in the hot summers and cold winters, taking interiors out of the thermal Comfort range. The second problem is the low-temperature difference in hot and humid weather, which causes low airflow.

These problems have caused windcatchers to be kept closed. Installing dampers and fans are two methods suggested to improve windcatcher efficiency. Selected windcatchers were simulated in Design Builder and compared in four modes (open, closed, damper, and fan). The results showed an approximate 10 % increase in thermal comfort hours from 42 to 52 % by changing elements. Table 3 shows the percentage of thermal comfort hours in 24 different modes for five windcatchers. Results show a decrease in overheated hours when using fans and dampers of about five percent of the year, which means using fans and dampers can prevent overheating in spaces for 15 more days a year, which saves energy consumption considerably. The following conclusions can reached from the study results.

Open windcatchers let uncontrolled air enter the room and decrease thermal comfort conditions.

Using a fan or damper in the windcatcher can increase thermal comfort conditions for up to one more month a year.

Using a fan and valve significantly reduces room overheating. The results show that temperatures over 35 degrees have been reduced in these models.

Connecting the wind room with the adjacent rooms enables cross-ventilation and increases airflow, providing better thermal comfort conditions.

Window openings and cross-ventilation are essential in improving the windcatcher's performance by replacing the cool air from the courtyard and the yard with the warm air from the windcatcher.

In addition to cross-ventilation, controlling the sun's radiation through the Sa-bat or porch is essential. As shown in cases with windows without a sabat (windcatcher.N.4,5), windows have the opposite effect on thermal comfort conditions and worsen the thermal situation.

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CONFLICT OF INTERESt

The authors declare no conflict of interest. The funders had no role in the study's design, in the collection, analyses, or interpretation of data, in the writing of the manuscript, or in the decision to publish the results.

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