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RESEARCH PAPER

General Architecture

The Impact of Wind on Ambient Temperature and Thermal Comfort through Wind Catcher by Employing PMV-A Case of Salehi's House in Shiraz, Iran

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Abstract

Wind catchers in arid climates are one of the most prominent masterpieces of Iranian traditional architecture which can improve thermal comfort through natural ventilation. With the aim of recognizing the impact of this masterpiece on thermal comfort, this research examined the effect of wind on summer ambient temperature and Predicted Mean Vote (PMV). To this end, wind catchers of Salehi's House in Shiraz case in arid climate and the ambient temperature, humidity and wind speed were measured by data logger TA120 between 9:00 to 16:00 in summer for calculating PMV and Predicted Percentage of Dissatisfied (PPD) through Fanger Formula. The results through open or close wind catcher and openings showed that the thermal comfort was directly related to the amount of wind coming from the wind catcher. It was also concluded that the average ambient temperature in ground was declined by 0.8 °C and in the first floor it was declined by 0.9°C.

Keywords: *Thermal Comfort, Wind Catcher, Wind, Natural Ventilation, PMV.*

1. INTRODUCTION

Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment [1]. According to ASHRAE, thermal comfort of each person is the mental condition showing his/her satisfaction of thermal environment [2]. The psychological definition relates to the brain's satisfaction of the ambient temperature. The thermal-physiological definition relates to the biological response of the body and the nervous system to externalities imposed upon the thermoreceptors, the other definition relates to the balance between the heat flow inside and outside the body [3]. In general, the thermal comfort depends upon air temperature, humidity, water vapor pressure, air movement, radiation from internal walls (average radiant temperature), human (age, gender), type of human physical activity and his/her clothing [2,4-5]. Many factors are taken into account when designing a building. One of the important factors architects should take into account in building design is the physical comfort of a person, which is the result of a thermal energy balance between that person and the his/her surrounding space [6]. In fact, thermal and environmental comfort factors affect the shape and orientation of buildings, streets, alleys and also the selection of materials [7].

One of the architects' solutions for reaching thermal comfort in the arid climate is to create a natural ventilation by air and wind flow which can modify indoor humidity and temperature [8]. Natural conditioning solutions can be divided into three types: Physical ones on the ceiling, in the facade and the body of the building, and a combination of both [9]. The element used by Iranian architects to ventilate in arid climate is called wind catchers which more than the beauty, it have played a vital role in the ventilation of the interior space naturally [10]. It can be said that wind catchers play a significant role in one’s bringing the temperature to the needed for human's comfort [11].

The Iranian wind catchers due to body are divided into three categories: Ardakani (uni-directional), Kermani (bi-directional) and Yazdi (four-directional) [12-16] and based on its function divided to direct airflow downward or/and direct airflow upwards. Vertical ventilation is effective when the wind speed is over 2.5 m/s [17] The use of wind

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in the past architecture most importantly, improves the quality of men's comfort and health [18], favorite inner air temperature and ultimately thermal comfort [19]

The present study investigated the impact of wind speed on ambient temperature and thermal comfort (PMV) through wind catcher in the traditional Salehi's house in Shiraz as hypothesis. The analysis has been done in two different positions of all openings closed and open. This investigation is done in semi-arid climate of Shiraz in summer and the values of ambient temperature, humidity, wind speed, etc. are taken by data logger AT120 between 9:00 to 16:00 with an interval of one hour. Finally, by calculating PMV and PPD through Fanger Formula, the PMV and ambient temperature was compared with wind speed. The results was shown as some solutions for reaching thermal comfort in residential buildings.

2. LITERATURE REVIEW

The importance of the thermal comfort is to a great extent addressed by many scholars and scientists from various fields, including architecture, urbanism, geography, mechanics, energy, etc. There has been a lot of research on the importance of the climate on architecture. Some studies worked on thermal comfort have examined factors such as energy loss temperature and the amount of humidity. Researchers have divided the thermal comfort investigations into two important subsets of thermal comfort in open spaces and closed spaces. For example, in terms of thermal comfort in closed spaces, the first heat balance model was proposed by Fanger on PMV and *PPD* for ventilation engineers in indoor climate condition. Nicol and Humphreys also have considered the adaptive thermal comfort and sustainable thermal standards for buildings and compared it with rational indicators; they found out using rational indicators to be difficult in real situations. Qiabakloo devoted his paper to examine the methods for estimating thermal comfort zone, and the main factors affecting the man’s physical comfort regarding his/her environment. Results stated that factors such as age, gender, color of space and climatic conditions do not have much effect on the thermal comfort [20].

There have been many studies on the issue of thermal comfort as well as natural ventilation. For example, Mahmoudi investigated the cooling behavior of wind catchers in the city of Yazd through modeling of wind catchers and presented a typology of wind catchers based on this analysis [21]. Bouchahm et al, Employing numerical modeling of the wind catchers in different conditions, and concluded that increasing the tower height and reducing the width of the winders can increase the air flow and ventilation [22]. Others have addressed the function of natural ventilation in wind catchers and using wind as well as calculating and estimating wind power. Studies have shown that attention has grown considerably in the case of "indoor air flow" in recent decades [23]. Natural ventilation is an important factor in improving the tolerability and health of indoor environments that are carried out by wind power or buoyancy force or often by combining these two forces [24]. One of the most popular wind catcher species is the four-directional wind catcher that is famous as Yazdi.

The wind catcher examined in this research is a four-directional one. There is a little research done on thermal comfort provided by wind catchers especially the four-directional ones. In addition, there was little research about thermal comfort and ambient temperature of the space beneath wind control. Although the Shiraz wind controls was destroyed and only few (less than 10) once exist and there isn’t any research about them. This investigation, therefore, aimed at examining the impact of wind on summer ambient temperature to improve thermal comfort through wind catchers by employing PMV in Salehi's House located in Shiraz, Iran.

3. METHODOLOGY

There are two main approaches to assessing thermal comfort. First, the heat balance approach based on the results of Fanger's research in laboratory conditions; and second, an adaptive approach. The theoretical basis of the heat balance approach is the close connection between the thermal sensations with the body temperature control system [25]. In this research PMV and PPD are used [26]. The Fanger model is based on the ISO 7730 standard in thermal comfort [27]. The PMV index is expressed as the following formula:

$$PMV = (0.303^{e-0.036M} + 0.028)[(M-W) - H - E_c - C_{rec} - E_{rec}] \quad (1)$$

$$E = 3.05 \times 10^{-3} (256_{tsk} - 3373 - P_a) + E_{sw} \quad (2)$$

$$E_c = 3.05 \times 10^{-3}[5733 - 6.99 \times (M-W) - P_a] + 0.42(M - W - 58.15) \quad (3)$$

$$C_{rec} = 0.0014M(34 - T_a) \quad (4)$$

$$E_{rec} = 1.72 \times 10^{-5} M(5867 - P_a) \quad (5)$$

H is directly measurable and can be calculated by the following equation:

$$H = K_{cl} = t_{sk} - t_{cl}/I_{cl} \quad (6)$$

The PMV is expressed in a seven point scale varying from -3.5 (cold) to +3.5 (hot) which Zero is neutral (Table 1). In order to calculate this criterion easily some software has been design, one of them is Ray Man [28-29].

Table 1. PMV sensation scale [30]

Degree of physiological stress	Extreme cold stress	Moderate cold stress	Slight cold stress	No thermal stress	Slight heat stress	Moderate heat stress	Very strong heat stress	Extreme heat stress
Sensation	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot
PMV	-3.5	-2.5	-1.5	-0.5	+0.5	+1.5	+2.5	+3.5

The PPD index is also used to predict the percentage of dissatisfied people in a given thermal environment. It is designated based on the PMV index. PPD is calculated through the following formula (7):

$$PPD = 100 - 95e^{-(0.03353PMV4+0.2179PMV2)} \quad (7)$$

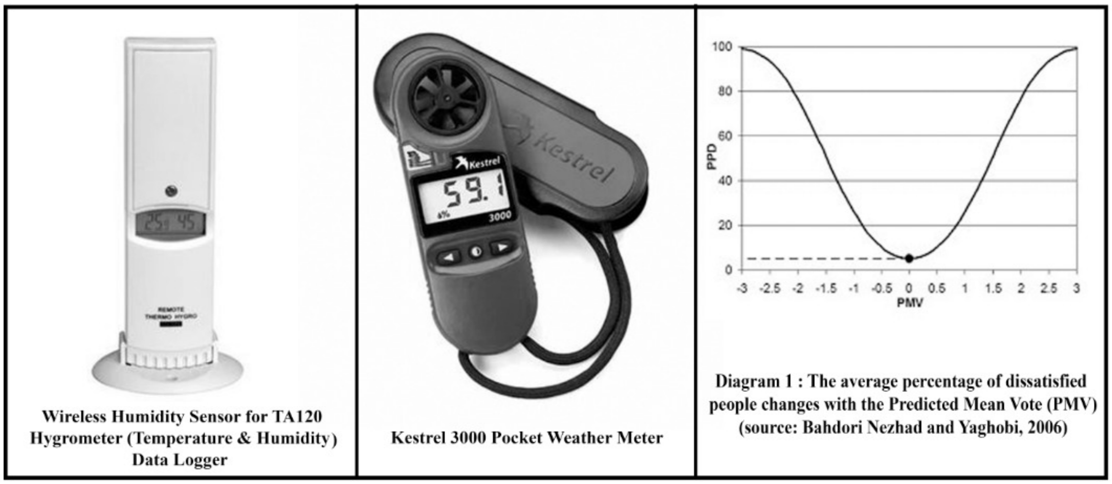


Fig 1. Instruments used in research (source: authors)

As mentioned above, the wind catcher examined is a four-directional one. However the entrance and basin of channel is covered by galvanized sheet. There is also no blade in the inner parts as well as no basin and aqueduct. Using Data Logger TA120, the data were collected in two consecutive days (June 29-30). In the first day, June 29, the data collected while the wind catcher and all closings were closed. In the second day, however, the data collected while the wind catcher and all openings were open. Data gathering occurred once per hour from 9:00 to 16:00. The field variables collected included: air temperature (T), relative humidity (RH) and wind velocity (V). As the building is a two-storey one, therefore, the data collected for each storey separately. To collect data, the data logger, in the ground level, was put on the floor at the height of 1.00 m (since the height of floor to the ceiling is 2.00 m) from the floor once at the beginning of the wind catcher and once in the center of gravity. In the upper floor as the height of floor to the ceiling is 3.00 m, it was done in the height of 1.50 m from the floor, once at the beginning of the wind catcher and once in the center of gravity. In Figure 2, the place of data logger is shown with (×). The size of indoor openings, the geographic orientation, and place of the rooms compared to the yard, the area of the spaces, the dimensions of the wind catcher and its openings, and finally the materials of the walls were simulated by Ecotect Software 2011. The temperature of the special points was calculated in from 9:00 to 16:00 once per hour in June 29-30. In the next step, the values of clothing (Clo) and metabolism (Met) were determined by ASHRAE Standard. According to the calculation, the amount of clothing insulation was 0.5 (Clo). And the value of Met in siting position was 1.0. Finally, the PMV was obtained by CBE Thermal Comfort Tool (which only is a calculating software).

4. CASE STUDY

Iran has different climates; the arid climate is the most important one. Shiraz is built in a green plain nearly 1491 meters (4891.7 feet) above sea level, at 29°32′N 52°35′E [31]. With respect to Köppen climate classification, this city is located in a semi-arid climate (BSH) [32- 33] Table 2 shows the climatic information of Shiraz reported according to GPA Statistics (1951-2010). Iran Meteorological Organization (IMO) (between the years 1999 to 2009), the mean maximum temperature of Shiraz is 38.53°C in June or July and the minimum is nearly 0.43°C in December or January. The wind speed is also 5.21396 Nat in July (IMO 1393).

City core, with an approximate area of 360 hectares, was full of traditional; buildings with central courtyards (2000 Qajar houses) [34]. According to Iranian Cultural Heritage Organization, there are limited numbers of houses with wind catcher in Shiraz. Among the historical houses those enjoying wind catcher only repeated in Tavakoli House, Dokhanchi House, Salehi House, Manteghinezhad House, Forough-ol-Molk House, and Basiri Owji House. Among these houses, the wind catcher of Manteghinezhad House was ruined; Dokhanchi House and Forough-ol-Molk House are inhabitable; Basiri Owji House and Tavakoli House also are not available. Therefore, the research is done in Salehi House.(Fig. 2)

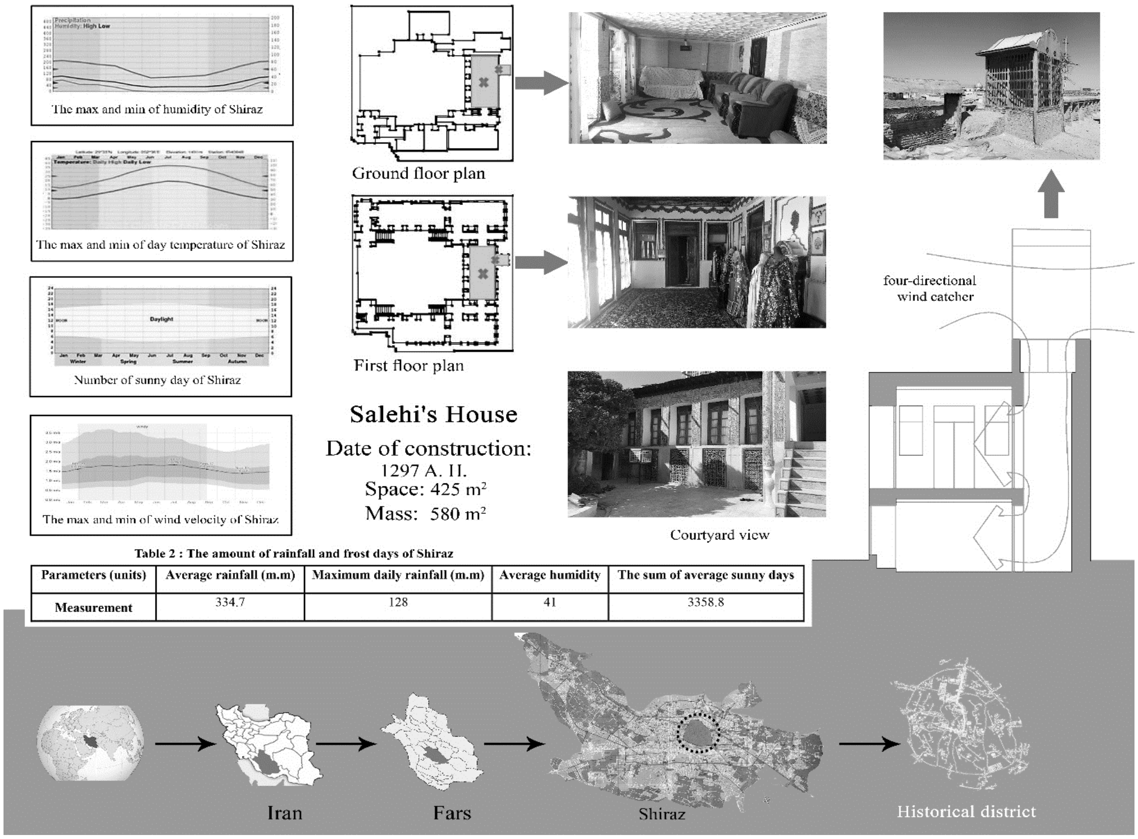


Table 2 : The amount of rainfall and frost days of Shiraz

Parameters (units)	Average rainfall (m.m)	Maximum daily rainfall (m.m)	Average humidity	The sum of average sunny days
Measurement	334.7	128	41	3358.8

Fig 2. Case study introduction (Source: Authors)

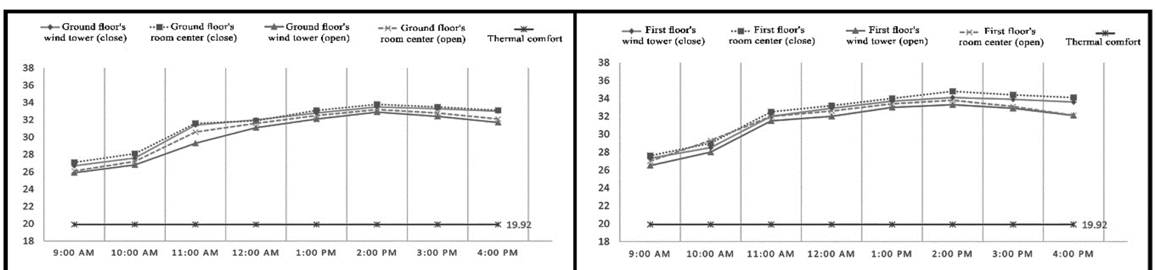
5. RESULTS

As explained before, the indoor temperature of Salehi's house was examined for both ground floor and first floor separately. The result obtained can be interpreted as follow.

5.1. Environmental Factors

a) The Comparison of air temperature changes

Temperature is one of the most effective elements in thermal comfort. In Shiraz, the average temperature to comfort is 19.92 °C.



Temperature difference C^o	The average maximum temperature C^o	The average minimum temperature C^o	Case study	The extent of wind catcher opened
about 0.8	33.65	26.9	Ground floor	Completely close
	33.05	26	Ground floor	Completely open

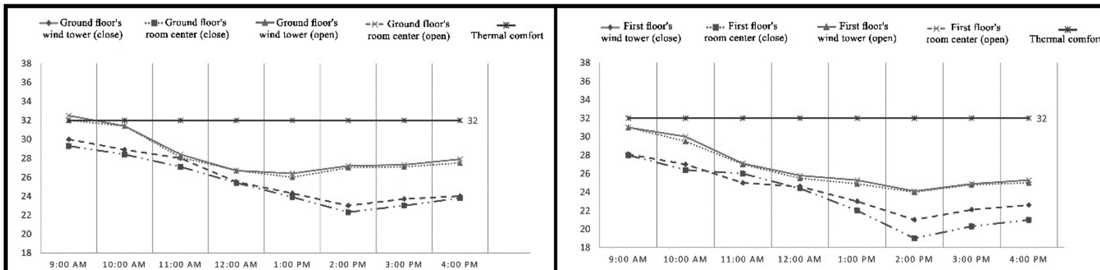
Temperature difference C^o	The average maximum temperature C^o	The average minimum temperature C^o	Case study	The extent of wind catcher opened
about 0.9	34.45	27.45	First floor	Completely close
	33.55	26.75	First floor	Complctely open

Fig 3. The comparison of indoor air temperature collected by data logger based on open and closed wind catcher and openings in Salehi House from 9:00 to 16:00 once per hour (Source: Authors)

According to the data obtained for the ground floor, when the wind catcher and openings are closed, the average maximum temperature is 33.65 °C, and the average minimum temperature is 26.9 °C. When the wind catcher and openings are open, the average maximum temperature is 33.05 °C, and the average minimum temperature is 26 °C. In the first floor, when the wind catcher and openings are closed, the average maximum temperature is 34.45 °C, and the average minimum temperature is 27.45 °C. When the wind catcher and openings are open, the average maximum temperature is 33.55 °C, and the average minimum temperature is 26.75 °C. According to the Figure 3, when the openings are open in the ground floor, the temperature is about 0.8 °C colder than when they are closed. The research also shown that, the difference is about 0.9 °C in the first floor.

b) The Comparison of humidity changes

Humidity is one of the environmental elements that make the air cool. Air humidity does not directly affect human body temperature. However, the evaporation and, consequently, the amount of body drying is determined by the rate of evaporation [35]. In Shiraz, according to meteorological data, average humidity is 32%. It should be noted that, when the data collected, the pond located in the middle of the central courtyard was empty of water; it may be responsible for the low humidity. The traditional architects of Iran understood that the presence of water and plants makes the environment wet and more pleasant. Therefore, they put the ponds in the middle of central courtyards. The ponds make the spaces that are directly facing the yard cooler and more enjoyable.



Humidity difference (%)	The average maximum humidity (%)	The average minimum humidity (%)	Case study	The extent of wind catcher opened
about 3	29.65	22.65	Ground floor	Completely close
	32.25	26.2	Ground floor	Completely open

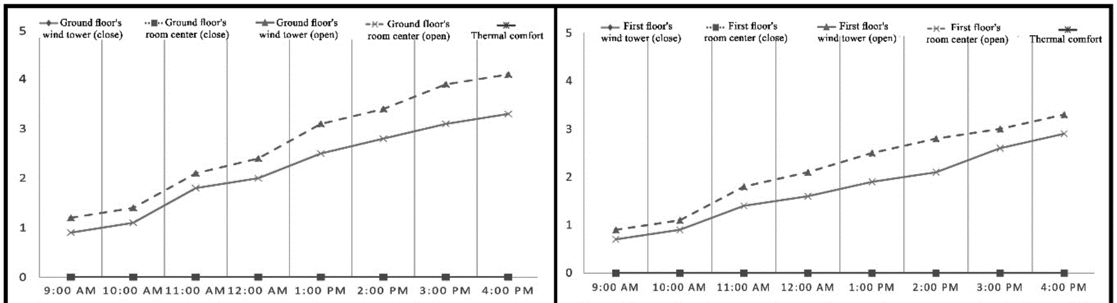
Humidity difference (%)	The average maximum humidity (%)	The average minimum humidity (%)	Case study	The extent of wind catcher opened
about 3.5	28.05	20	First floor	Completely close
	31	24.05	First floor	Completely open

Fig 4. The comparison of indoor air humidity collected by data logger based on open and closed wind catcher and openings in Salehi House from 9:00 to 16:00 once per hour (source: authors)

According to the data obtained for the ground floor, when the wind catcher and openings are closed, the average maximum humidity is 29.65%, and the average minimum humidity is 22.65%. When the wind catcher and openings are open, the average maximum humidity is 28.05%, and the average minimum humidity is 20%. In the first floor, when the wind catcher and openings are closed, the average maximum humidity is 28.05 %, and the average minimum humidity is 20 %. When the wind catcher an d openings are open, the average maximum humidity is 31%, and the average minimum humidity is 24.05%. According to the Figure 4, the difference between open and closed openings is 3% in the ground floor. The research also shown that, the difference is about 3.5% in the first floor.

c) The comparison of wind velocity

Wind is a major element in design for architects. It has a major impact on the thermal comfort by changing the thermal exchange of a building's space either as a condensation phenomenon, or from the influence of air on the building [36]. The flow of air affects body heat regulation, and men's thermal comfort in two ways: 1) It affects the amount of conduction and heat transfer between the skin and the environment; 2) It effects body cooling through moist skin cell. Increasing air velocity increases the amount of heat transferred [37]. Air temperature and velocity, in the heat exchange through convection, depends on each other.



Wind velocity difference (m/s)	The average maximum wind velocity (m/s)	The average minimum wind velocity (m/s)	Case study	The extent of wind catcher opened
about 3.7	0	0	Ground floor	Completely close
	3.7	1.1	Ground floor	Completely open

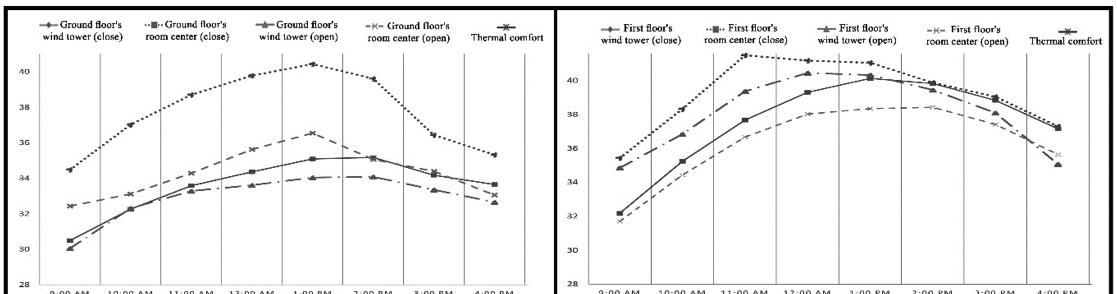
Wind velocity difference (m/s)	The average maximum wind velocity (m/s)	The average minimum wind velocity (m/s)	Case study	The extent of wind catcher opened
about 3.1	0	0	First floor	Completely close
	3.1	0.8	First floor	Completely open

Fig 5. The comparison of indoor air velocity collected by data logger based on open and closed wind catcher and openings in Salehi House from 9:00 to 16:00 once per hour (source: authors)

As seen in Fig. 5, when the wind catcher and openings are closed and in the absence of mechanical instrument, the wind velocity is zero. In the case when the wind catcher and openings are open, in the ground floor the amount of 1.1m/s and 3.7 m/s were observed. However, in the first floor the amount is about 0.8 and 3.1 m/s. Therefore, the difference of wind velocity in the ground floor is 3.7 m/s. In the first floor, it is 3.1 m/s. the environment becomes colder due to air conditioning that happens.

d) The comparison of radiant temperature changes

Heat is exchanged between the body and the environment through thermal radiation. The mean radiant temperature can be defined as the constant temperature of an imaginary black room, in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the environment. In other words, the mean radiant temperature is the average radiation of all surface which is almost constant for most construction materials [38].



Radiant temperature difference C^o	The average maximum radiant temperature C^o	The average minimum radiant temperature C^o	Case study	The extent of wind catcher opened
about 2.84	37.80	32.48	Ground floor	Completely close
	35.32	31.55	Ground floor	Completely open

Radiant temperature difference C^o	The average maximum radiant temperature C^o	The average minimum radiant temperature C^o	Case study	The extent of wind catcher opened
about 1.37	40.81	32.80	First floor	Completely close
	39.44	33.27	First floor	Completely open

Fig 6. The comparison of radiant temperature by Ecotect 2011 (source: authors)

According to Figure 6, in the ground floor, when the wind catcher and openings are closed, the mean radiant temperature is 37.8 and 32.48 °C. When the wind catcher and openings are open, the mean radiant temperature is 35.32 and 31.55 °C. In the first floor, when the wind catcher and openings are closed, the maximum mean radiant temperature is 40.81 °C, and the minimum mean radiant temperature is 33.80 °C. When the wind catcher and openings are open, the maximum mean radiant temperature is 39.44 °C, and the minimum mean radiant temperature is 33.27 °C. According to data obtained, the difference in the ground floor is 2.84 °C. It is, however, about 1.37 °C in the first floor.

6. DISCUSSION

6.1. Thermal Comfort

Fanger presented thermal comfort range based on human body's heat exchange and its interaction with the surrounding [39]. Since this method contains many of the comfort criteria, it is considered as a perfect method. That was offered as PMV in which comfort criteria such as climatic variables, type of clothing and activity are examined together. According to Table 1, PMV boundary is between +3.5 and -3.5. Those between +1 and -1 are in the comfort zones. The other ranges can cause dissatisfaction [40]. The CBE Thermal Comfort Tool is used to calculate PMV. As Figure 7 represents, on the ground floor, the maximum and minimum values of the average comfort temperature is between +3.34 and +1.19, while the wind catcher and openings are closed. When they are open the values are between +0.67 and -0.96.

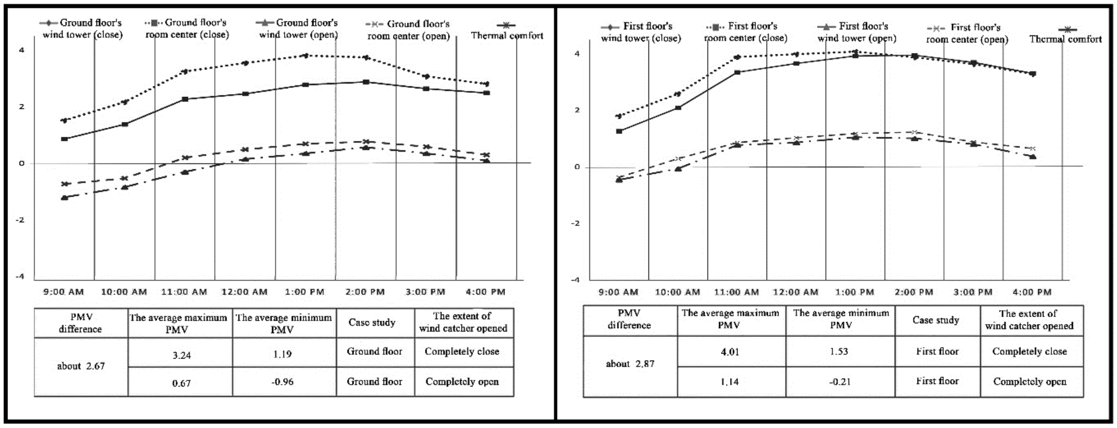


Fig 7. the comparison of PMV through CBE Thermal Comfort Tool (source: author)

In the ground floor, the difference is about +2.67. In the first floor, however, the max and min of thermal comfort is +4.01 and +1.53 respectively, when the wind catcher is closed. When it is open, the difference the max and min are +1.14 and -0.21 respectively. The difference between the open and closed wind catcher is approximately +2.87.

Table 2. PMV in different hours (source: authors)

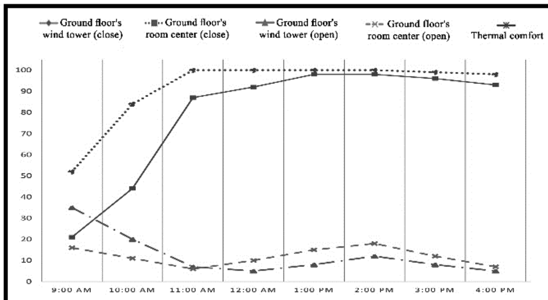
Cases	Time	Closed wind catcher Beginning of wind catcher	Middle of room	Open wind catcher Beginning of wind catcher	Middle of room
Ground floor	9:00 AM	1.52	0.86	-1.2	-0.73
	10:00 AM	2.17	1.38	-0.84	-0.53
	11:00 AM	3.25	2.27	-0.3	0.2
	12:00 AM	3.55	2.46	0.15	0.49
	1:00 PM	3.81	2.78	0.35	0.69
	2:00 PM	3.75	2.88	0.57	0.77
	3:00 PM	3.08	2.64	0.35	0.59
	4:00 PM	2.81	2.49	0.1	0.3
First floor	9:00 AM	1.80	1.26	-0.46	-0.37
	10:00 AM	2.59	2.09	-0.06	0.29
	11:00 AM	3.89	3.35	0.77	0.86
	12:00 AM	3.99	3.66	0.86	1.03
	1:00 PM	4.08	3.93	1.05	1.18
	2:00 PM	3.88	3.95	1.01	1.23
	3:00 PM	3.64	3.70	0.80	0.88
	4:00 PM	3.29	3.31	0.37	0.65

According to Table 2, one can understand when the wind catcher and the openings are closed, the warmest hour of the day is 13:00 and the coolest hour is 9:00. This is different when the wind catcher is open. In fact, in this case, the warmest hour is 14:00 and the coolest hour is 9:00. In the ground floor, the thermal comfort is in the range of very hot between 11:00-15:00. It is hot between 10:00-16:00. It is warm in 9:00. However, when the wind catcher and the openings are open, the values change, and all day long the temperature is within comfort range.

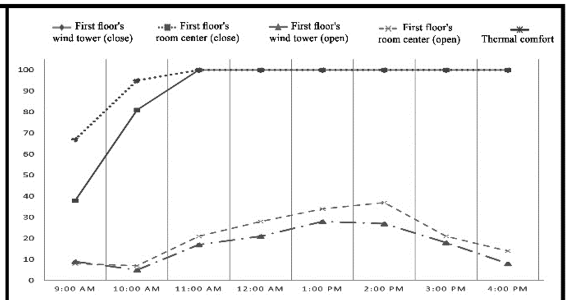
In the ground floor, when the wind catcher and the openings are closed, thermal comfort is in the range of very hot between 11:00-16:00, and in the hot range between 9:00-10:00. When the wind catcher and the openings are open these values have changed. It is in comfort range between 9:00-12:00 and 15:00-16:00. It is, however, warm between 13:00-14:00.

6.2. Thermal Dissatisfaction

ASHRAE Standard 55-2010 of PMV model can be used for determining the prerequisites for indoor conditions. At least 80% of residents' satisfaction is necessary. It means, PPD is better to be in a range of 0-20. As it can be seen in Figure 8, in this research, the PPD was calculated through CBE Thermal Comfort Tool for Met=1 and clo=0.5.



PPD difference (%)	The average maximum PPD (%)	The average minimum PPD (%)	Case study	The extent of wind catcher opened
about 72.5	99	36.5	Ground floor	Completely close
	26.5	5.5	Ground floor	Completely open



PPD difference (%)	The average maximum PPD (%)	The average minimum PPD (%)	Case study	The extent of wind catcher opened
about 77.5	100	52.5	First floor	Completely close
	33.5	6	First floor	Completely open

Fig 8. The comparison of PPD via CBE Thermal Comfort Tool

According to Figure 8, in the ground level, when the wind catcher and the openings are closed, the average maximum of PPD is 99% and the average minimum is 36.5%. When the wind catcher and the openings are open, the average maximum and minimum are 26.5% and 5.5%, respectively. The difference is 72.5% between open and closed wind catcher. In fact, it can be said that the amount of dissatisfaction reaches its minimum when the wind catcher is open; and this amount is acceptable.

In the first floor, similarly, when the wind catcher and openings are closed the average maximum of PPD is 100% and the average minimum is 52.5%. When the wind catcher and the openings are open, the average maximum and minimum are 33.5% and 6%, respectively. The difference is 77.5% between open and closed wind catcher. Based on the results, one can say the amount of dissatisfaction reaches its minimum when the wind catcher is open; and this amount is acceptable except between 13:00 and 14:00.

7. CONCLUSION

Due to its experiences and creativity, the traditional architect of Iran, has made a huge masterpiece, which is still in use in the new era and modern architecture. In this research, aimed at assessing the vernacular architecture, the effect of wind in thermal comfort of the houses enjoy wind catcher was examined. According to the analysis of the effect of wind velocity on the indoor condition of the building in Shiraz, some points were concluded through PMV and PPD figures.

When the wind catcher is open, the movement and wind speed will reduce the air temperature of the environment. Furthermore, it creates air conditioning and brings out moist air out into the building. The change in environmental factors has a direct effect on the thermal comfort and the level of dissatisfaction of individuals. An environment that is in an unfavorable thermal comfort environment can enter into the desirable range to prepare a habitable environment and minimize the percentage of people dissatisfied. This research certifies that this innovative technique is useful in structures. It also suggests that wind catcher to be used in modern buildings, especially in arid and semi-arid climate, to save energy and to prevent air pollution and to make buildings better place to live.

Nomenclature

C_{rec} = Convective heat loss from respiration (w/m^2);
E_{rec} = The evaporation heat exchange in respiration (w/m^2);
E_c = The heat exchange by evaporation on the skin;
I_{cl} = Basic clothing insulation (clo);
M = Metabolic rate of human body (w/m^2);
t_{cl} = Clothing surface temperature (°C);
t_{sk} = Average skin temperature (°C);
W = Rate of effective mechanical work (w/m^2);
e = Respired vapor loos on skin (w/m^2);
H = the sensitive heat losses;
P_a = Water vapor partial pressure (Pa);
T_a = Ambient air temperature (°C).

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