

Achieving wind comfort through window design in residential buildings in cold climates, a case study in Tabriz city

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Abstract

Air movement affects thermal comfort both by increasing evaporative loss through the skin and heat transfer between the body and surrounding environment through convection. Generally, in cold climates, it is best to avoid wind to better control the thermal environment. However, crafted passive airflow is essential for providing fresh air and natural ventilation at certain times of year. The use of a window of the right size and location in a cold climate is also indispensable. In this study, the wind speed was calculated for the height of a residential building in the city of Tabriz. A computational fluid dynamics simulation was used to calculate the inflow air speed for each window and the comfort conditions were compared. The findings determined the months where window openings can be used to enhance thermal comfort. The analysis shows how the direction and shape of the window play a major role in directing outdoor air flow indoors at the right time in the right quantity. East- and west-facing windows are most favorable and north- and south-facing windows can only be used in some months. This shows how building designers can quantify the effect of window design in each climate for the occupant's comfort.

Keywords: local wind; thermal comfort; window design; computational fluid dynamics; cold climate

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1. INTRODUCTION

Saving energy is a significant variable in building design [1, 2]. Nearly 40% of the world's energy is consumed in buildings [3–7]. The share of energy usage in buildings is increasing as the standard of living and the population increases [8]. Indoor air quality has become a significant concern for researchers [9]. Because of the increasing concern about climate change and energy conservation, researchers have sought to study building occupants, behavioral adaptation and thermal conditions [10]. The study of thermal comfort has become a growing concern [11, 12]. Thermal comfort is the level of satisfaction with the thermal environment that can be assessed by subjective evaluation [13]. It can be attuned to air movement and temperature [14]. Indoor environ-

mental quality can be defined using parameters such as indoor air quality, thermal comfort, visual comfort and acoustics [15, 16]. Bioclimatic passive and active design considerations have been used by climate conscious designers to preserve indoor comfort [16]. Air flow is of special importance [17] because it influences indoor air quality and thermal comfort. Wind is a main parameter of outdoor and indoor spaces. Even a gentle breeze outdoors feels different from indoor air movement [18]. Controlled natural ventilation can provide comfort and health for residents [19]. Ventilation is an effective passive cooling strategy for cold climates [19, 20]. An important component of building ventilation is the window opening, which also lets in the daylight and provides a view [1, 21]. In a residential building, the use of windows by residents depends on the difference between interior and exterior

environmental parameters and the residents [22]. The increase in the constructions of glazed sealed buildings means that window openings are less attractive in modern cities. It is necessary to design a window opening, which can provide the right amount of ventilation every month of the year.

Studies have been carried out to verify thermal comfort conditions by applying natural ventilation. Ning–Wang examined the differences in behavioral regulations among home residents and office workers that could lead to a difference human thermal response in a cold climate. It was found that residents of offices were more willing to open windows to reduce the temperature of buildings than the occupants of other buildings [23]. Roulet [24] studied healthy and comfortable buildings and suggested effective methods of saving energy measures for comfort and indoor environment quality. There are few studies on the behavior of wind inside and outside of a building. Almeida investigated the effects of wind and its behaviors and types. As a result, a new structure was introduced and enabled people to engage in daily activities, sports and work on the same floor [25]. Huifen *et al.* analyzed the influence of wind direction for indoor natural ventilation and energy consumption in residential buildings. They noted that when the wind direction angle is from 0° to 45° , the effect of indoor natural ventilation is greater. When the wind direction angle is 15° , comprehensive energy consumption of a building is the lowest [26]. Hong Liu *et al.* [27] measured and analyzed the impacts of indoor temperature and velocity on human physiology and thermal comfort for different temperatures and types of ventilation. The effect of air temperature on skin temperature is significant. Thermal comfort in the external environment and micro-climatic factors were examined by the American Society of Civil Engineers. Wind measurement methods were described, wind indicators were introduced and control methods were described. Wind analysis and ways to achieve thermal comfort have been noted for architects and urban designers [28]. Razjouyan investigated aerodynamics in architecture and constructional types in terms of the neighborhood and the effects of wind on them. He also studied ventilation in interior spaces and indoor air velocity in buildings to gain thermal comfort [29]. In order to take advantage of limited natural air flow and provide the conditions for residents, designers and architects have demonstrated a variety of practical experiences. Undoubtedly, in all of these designs, windows are necessary for the natural movement of air.

In many researches, natural ventilation creation methods are being studied in hot and warm climates, either dry or humid. So many times it has been forgotten that the buildings in cool or cold climates need ventilation to supply the fresh air and suitable indoor conditions for residents' comfort, too. Maybe not attending to the requirement ventilation in such climates is due to prepare sufficient heating to gain indoor thermal comfort. Now, the considered question is that how the ventilation factors such as openings of windows can provide both suitable indoor fresh air and thermal comfort. Because of the harsh climate, a comfortable and healthy indoor environment is difficult to achieve. It seems that the best and affordable way for air filtration in the building is through controllable windows opening. Therefore, manual or

Table 1. Tabriz weather station properties.

Latitude	Longitude	Elevation	Heating degree day	Cooling degree day
38 5 N	46 17 E	1361.0 M	2773.2	392.9

mechanized control of these openings in residential buildings in cold climate can provide both fresh air and also at the same time prevent the cold air infiltration, which may cause occupants' discomfort. So, this investigation not only examines the natural ventilation through the building but also provides this opportunity to reduce the heating and cooling energy demand through the efficient design. The purpose of this study was to develop an appropriate model for a window opening in cold climates for residential buildings. This paper also considers the provision of ventilation and prevention of unwanted cooling in order to satisfy thermal comfort.

2. RESEARCH METHODOLOGY

a) Data

Iran has different climatic zones, one of which was selected for the current research. The Köppen climate classification is widely accepted [30]. This research was conducted in the cold climate of Iran in the city of Tabriz, which is geographically located in a mountainous region. According to bioclimatic studies, such regions have very cold winters and hot and dry summers.

The monthly statistical data from synoptic station of Tabriz Meteorology Organization were extracted from 1951 to 2010. The general description of the station in the area under study is shown in Table 1. The monthly and annual datasets from Tabriz meteorological station are listed in Table 2.

Because the research focused on local wind conditions, the seasonal wind in this city and the frequency of each wind speed were separately studied. The winter (22 December–20 March), the windrose is presented in Figure 1 with an average wind speed of 2.81 m/sec. The frequency of winter wind is high from different angles; however, most of the winds are southwest prevailing winds.

In autumn (23 September–21 December), as shown in Figure 2, the average windrose speed is 2.87 m/sec. The autumn prevailing wind blows from the southwest and other directions have sub-winds as well.

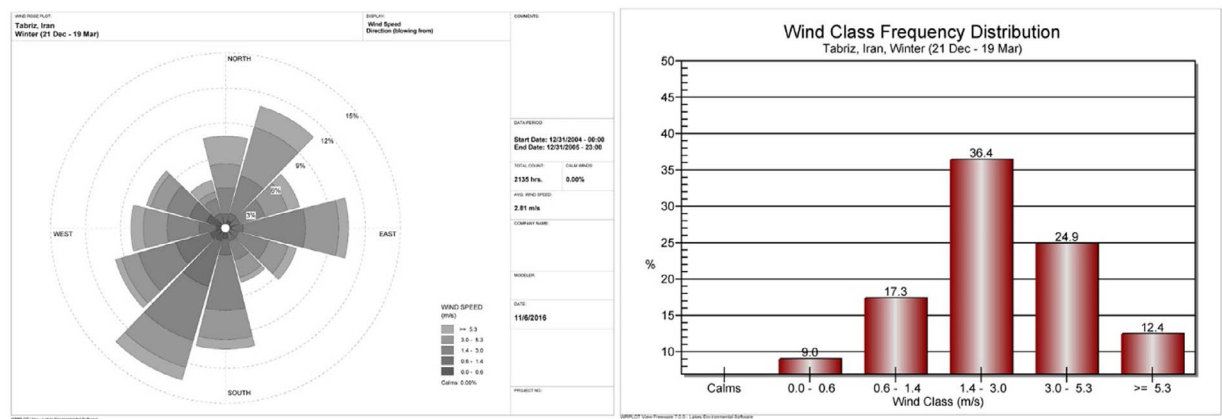
In the spring (21 March–21 June), the windrose shown in Figure 3 has an average wind speed of 3.96 m/s. The prevailing wind flows from the west and southwest, and other sub-winds are low in abundance.

In the summer (22 June–22 September), the windrose in Figure 4 shows an average wind of 4.28 m/s. The prevailing wind is from the south and sub-winds flow from other directions, including from the north.

In order to identify the wind conditions in the outside environment and determine its interior effects, the speed and direction of the local wind were obtained. By investigating the monthly

Table 2. Tabriz monthly climate summary.

Weather data \ Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
1 Average of dry bulb temperature (°C)	−2.3	−0.2	5.0	11.2	16.4	21.8	25.6	25.4	21.0	13.8	6.4	0.5
2 Average of maximum Temperature (°C)	2.3	4.7	10.3	16.9	22.7	28.7	32.7	32.6	28.2	20.5	11.9	5.1
3 Average of minimum temperature (°C)	−5.7	−4.1	0.4	5.9	10.6	15.2	19.3	19/0	14.4	8.2	2.1	−2.8
4 Average of relative humidity (%)	72	69	62	56	51	41	36	36	39	51	65	72
5 Average of maximum relative humidity (%)	84	83	80	77	72	60	53	54	58	69	81	84
6 Average of minimum relative humidity (%)	57	52	43	36	31	23	21	21	22	32	46	55
7 Cooling degree days (°C)	0	0	0	0	3	54	156	150	39	0	0	0
8 Heating degree days (°C)	610	497	391	199	66	6	0	0	7	118	328	523
9 Average of wind speed (m/s)	4.1	4.7	5.8	6.5	6.4	7.6	9.4	8.9	6.6	4.8	3.9	3.8
10 Prevailing wind speed (m/s)	5.9	6	7.2	8.1	8.1	9.7	11.3	11	9.7	7.3	6.2	5.9
11 Monthly total of precipitation (mm)	22.3	24.2	40.1	52.7	42.6	16.9	5.8	3.2	7.6	21.9	27.9	23.2
	Annual											
1 Total cooling degree days (°C)	402.7											
2 Total heating degree days (°C)	2743.5											
3 Total precipitation (mm)	288.9											
4 Annual temperature range (°C)	38.4											
5 Evapotranspiration potential	67.785											
6 Thornthwaite humidity index	−63.23											



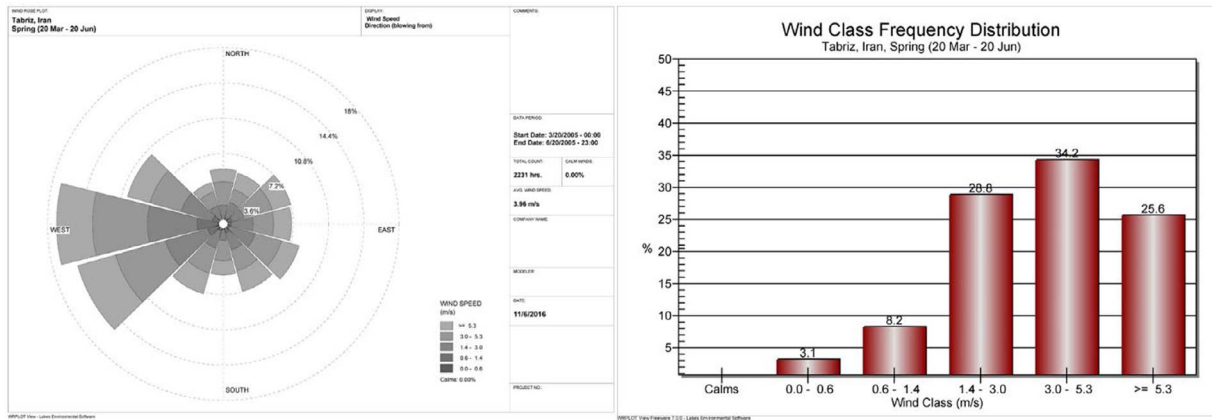


Figure 3. Spring windrose.

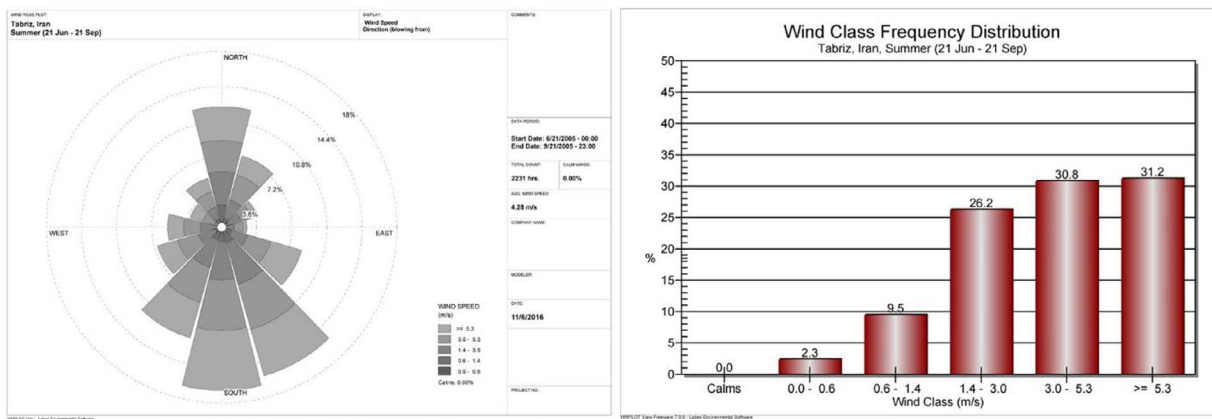


Figure 4. Summer windrose.

windroses of Tabriz, the prevailing winds each month were determined as shown in Table 3.

Monthly prevailing wind speeds and monthly average wind speeds were gathered from Tabriz synoptic meteorological station data and are shown in Table 7.

b) Determination of wind speed

The wind data for Tabriz were extracted and its specifications were quantified each month outside each window. By determining the angle and wind speed outside the window and at specific heights of the building, air flow inside the building could be calculated. An important parameter influencing the internal space is the design of windows for each orientation.

The Davenport formula can be used to calculate the wind speed at the desired height on the outer surface of a building. For this purpose, the wind speed data from the meteorological station data, which is usually measured at 10 m above ground level, and the type of ground texture are required. Using the Davenport formula, wind speed at a desired height can be obtained from the following equation [32–35]:

$$V_x = V_r \left(\frac{x}{r} \right)^\alpha$$

V_x : wind speed at the desired height

V_r : wind speed at windscreen height

X : desired height

r : windscreen height. As noted, it is usually measured by the Meteorological Organization at a height of 10 meters

α : wind speed coefficient calculated based on the terrain conditions for different regions according to Table 4.

This wind study was carried out on the outer surfaces of mid-rise residential buildings (four levels). Because wind speeds are near zero near ground level [29, 38, 39] and, in the urban compact context, wind speed is severely reduced in proximity to the ground [29, 40]. Thus, only the wind speed on the third and fourth stories was considered. The Davenport formula was used to calculate wind speeds at heights of 8.5 and 11.5 m from the ground (third and fourth stories).

c) Impact of wind on comfort

In order to control the environment and effect cooling due to a combination of wind and temperature, indicators such as the wind chill index (WCI) can be used. The WCI is an empirical index developed from cooling measurements obtained in Antarctica on a cylindrical flask partly filled with water [41]. The index describes the rate of heat loss from the cylinder by radiation

Table 3. Monthly prevailing wind speed and direction for Tabriz [31].

Month	Average prevailing wind speed (m/s)	Wind direction							
		North	South	East	West	Northwest	Northeast	Southwest	Southeast
Jan	2.11	*							
Feb	2.42	*						*	
Mar	2.99	*					*		
Apr	3.35			*				*	*
May	3.30				*	*		*	
June	3.91	*	*			*		*	
July	4.84				*	*			
Aug	4.58							*	*
Sep	3.40	*							
Oct	2.47		*				*		
Nov	2.10			*	*				
Dec	1.96							*	*

Table 4. given by davenport [33, 34, 36, 37].

Terrain condition	α
Open country, flat coastal belts, prairie grassland, etc.	0.16
Wooded country side, parkland, small towns, outskirts of large cities, rough coastal belts, etc.	0.28
Center of large cities	0.40
Center of very large cities with building height over 100 m	0.50

and convection at a surface temperature of 33°C as a function of ambient temperature and wind velocity. As originally proposed,

$$WCI = (10.45 + 10\sqrt{V - V_0}) (33 - t_a) \text{ in } \text{kCal}/(\text{h} \cdot \text{m}^2),$$

where V and t_a are in m/s and °C, respectively.

Rather than using the WCI to express the severity of a cold environment, meteorologists use an index derived from the WCI called the equivalent wind chill temperature ($t_{eq,wc}$). This is the ambient temperature that would be produced in a calm wind (defined for this application as 6.4 km/h or 1.8 m/sec), the same WCI as the actual combination of air temperature and wind velocity:

$$t_{eq,wc} = -0.0528(WCI) + 33,$$

where $t_{eq,wc}$ in °C (wind chill factor) is distinguished from the WCI, which is given either as a cooling rate or as a plain number with no units. For velocities of less than 6.4 km/h (1.8 m/sec), the equation does not apply and the wind chill temperature is equal to the air temperature [42].

When wind speeds are only considered for environmental comfort, wind speed limits express the definition of individual comfort. Table 5 shows how occupants react to various conditions of air velocity.

In this table, scholars agree that an air flow speed of 1 to 1.5 m/sec is sometimes uncomfortable, while a wind speed of more than 1.5 m/sec is usually disturbing and even harmful [44]. Szokolay postulates that, in a warm environment, the flow of air at a speed of 1 m/sec is pleasant and may be acceptable up to 1.5 m/sec, but not at more than 2 m/sec. In cold weather, the air

Table 5. Human natural reaction to air velocity (m/s) [43].

Air velocity at head level of occupant (m/s)	Typical subjective occupant evaluation
0–0.05	Complain about stagnant air
0.05–0.25	Generally favorable (manufacturers of air outlet devices, e.g. base performance on 50 fpm air velocity in occupied zone)
0.25–0.5	Awareness of air motion but can be comfortable (e.g. some retail shops and stores) when temperature of moving air is above room air temperature.
0.5–1.02	Constance awareness of air motion but can be acceptable (e.g. some factories) if air supply is intermittent and above air room temperature
1.02 and above	Increasingly drafty conditions with complaints about ‘wind’ in disrupting a task, activity, etc.

flow should not exceed 0.25 m/sec and a flow of less than 0.1 m/sec is not pleasant [45].

d) Research modeling

In this study, computational fluid dynamics (CFD) calculations were carried out in DesignBuilder software for indoor and outdoor spaces. DesignBuilder can predict indoor temperature and air velocity with relatively good accuracy and it can be applied by researchers to measure natural ventilation and thermal comfort to improve living quality [46]. The CFD study can be performed using occupancy density and indoor air quality [47]. The application of CFD in wind engineering has significantly increased in last two decades [48–55]. There exist many types of turbulence mode: the k-ε turbulent model is one of the many, which have been demonstrated accurate findings and less time consuming with compare to other models [56]. In this study, DesignBuilder version 5.4 was used based on EnergyPlus standard k-ε turbulent model.

CFD presented for industrial goals has become a common method of evaluating the ventilation and environment of buildings [57]. Many parameters affect the accuracy of CFD results

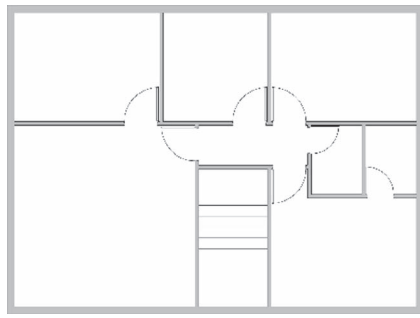


Figure 5. The plan layout of the residential apartment.

for natural ventilation study such as users' knowledge of fluid dynamics and experience and skill using numerical techniques. However, the main parameter which has a critical effect on CFD results is appropriate selection of CFD approach and turbulence model. CFD has been used to determine the airflow and heat transfer in the analysis of indoor environmental conditions as well as a range of HVAC&R applications [58]. The use of CFD models is not limited to ventilation in buildings but is used to predict different parameters of thermal comfort, indoor air quality and HVAC system efficiency in several types of buildings [59]. CFD analysis is used to better understand air movement in outdoor and indoor environments.

The residential apartments under study in Tabriz have four stories. They have windows to the north, east, west and south. The prevailing wind data for each geographical direction in the cold months of the year were determined and the wind speed at the desired height outside the windows on the third and fourth stories was calculated. With this information, it was possible to model the flow of air into spaces. It was necessary to determine the conditions of the research and its variables. These variables were related to the physical condition of the room and its window openings.

e) Model parameters

In this study, the plan of residential building based on typical standard of Tabriz construction policy has been considered [60]. Figure 5 shows the residential plan of the study area. Due to the variety of windows and opening variables, this plan has been drawn without the location of exact windows.

Studies show that the most important space is the living room with an east–west orientation of 8×6 m. So a model of such room was prepared to simulate the air movement. Nasrollahi has shown that the suitable width of a south-facing window in the living room in Tabriz city is 5 m. Models applied in cold climates indicate that a width of 0.5 m is suitable for a window opening [61]. The size of the window sill with respect to the conventional dimensions of construction was considered to be 0.9 m from the floor of each story. The window is placed precisely in the middle of the wall and opens either vertically or horizontally. Vertical openings can be placed either to the right or left of the window. The foreseen window to obtain all kind of openings is shown in

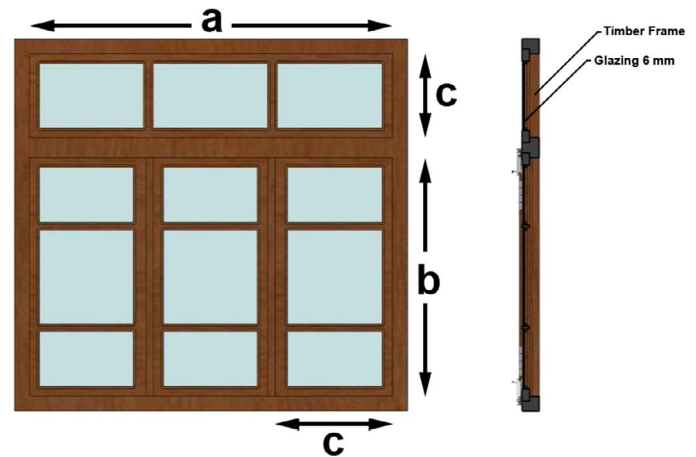


Figure 6. Window detail and its openings.

Table 6. Dimensions of the windows.

Geographic direction of window	a (m)	b (m)	c (m)
North	1.5	2	0.5
South	5	2	0.5
East	3	2	0.5
West	2.5	2	0.5

Figure 6. It shows a sample window suggestion of this research. The divisions of opening in this window design are such that the desired horizontal and vertical openings can be implemented in it and it is also possible to place the vertical opening on the left or right of the window.

In cold climate conditions, it is necessary to limit the size of the openings. Geographic directions can also affect their size. Table 6 shows foreseen dimensions of the openings. The size of a south-facing opening was considered to be 5×0.5 m in horizontal mode. In north-facing windows, horizontal openings were 5×0.5 m, in east-facing windows were 3×0.5 m and in west-facing windows were 2.5×0.5 m. In order to prevent disturbance to residents, however, the dimension of vertical openings for all facades was 2×0.5 m. The distance between the vertical openings from the floor was 0.9 m.

This research focuses on popular residential buildings of Tabriz, which are often 4-stories apartments and obey urban construction rules. It should note that four-story apartments are the majority kind of residential house in this city. The studies show that local wind speed strongly decreases near the ground in urban environments [37, 62, 63]. So the present research was restricted to the third and fourth stories of residential houses in order to limiting the simulation of various positions of different openings. It was assumed that the very low wind speed at a low height meant that the first and second stories of the buildings were little affected by wind and could be ignored.

Table 7. Monthly wind data for simulation.

Month	Monthly prevailing wind speed (m/s)	Monthly prevailing wind direction	Monthly average wind speed (m/s)	Exterior wind speed height			
				H = 8.5 m		H = 11.5 m	
				Seasonal maximum prevailing wind speed (m/s)	Exterior average wind speed (m/s)	Seasonal maximum prevailing wind speed (m/s)	Exterior average wind speed (m/s)
Jan	3.04	N	2.11		1.98		2.23
Feb	3.09	SW	2.42		2.27		2.55
Mar	3.70	NE	2.99	2.47	2.80	3.91	3.16
Apr	4.17	SE	3.35		3.14		3.54
May	4.17	NW	3.30		3.10		3.48
June	5	SW	3.91	4.69	3.67	5.28	4.13
July	5.82	SW	3.84	5.46	4.53	6.15	4.06
Aug	5.66	SW	4.58		4.29		4.84
Sep	5	N	3.40		3.19		3.59
Oct	3.80	S	2.47	3.56	2.31	4.01	2.61
Nov	3.19	E	2.10		1.97		2.22
Dec	3.04	SE	1.96		1.84		2.07

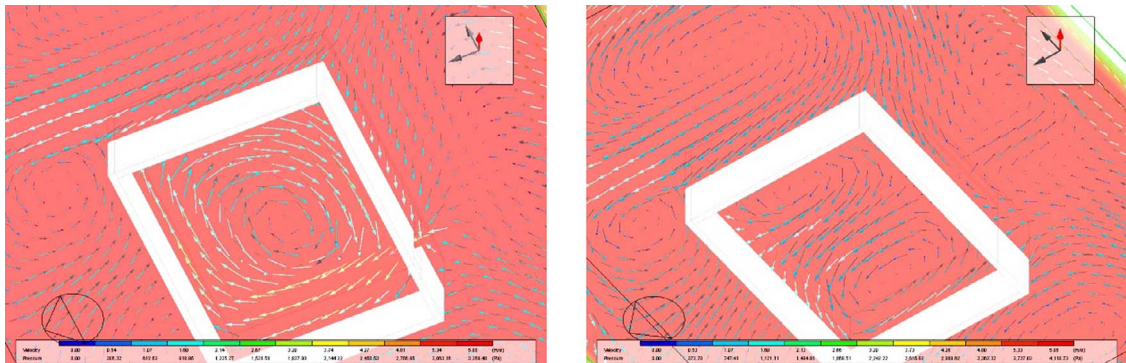


Figure 7. CFD simulation sample of air movement in each room; left: vertical opening, right: horizontal opening.

f) Simulation condition

CFD simulation of air movement inside residential homes required calculation of the inflow of the wind coming from openings at each level. The calculations and simulations are carried out for wind year round. Figure 7 displays CFD simulations results for vertical and horizontal openings and the air flow pattern. At baseline wind speed calculations, the monthly average wind speed and monthly prevailing wind speed and direction were used according to meteorological data on Tabriz station. The seasonal maximum prevailing wind speed and monthly exterior average wind speed at a height of $H = 8.5$ m (third story) and $H = 11.5$ m (fourth story) was calculated using the Davenport formula and the results are given in Table 7. These numbers would use for input data of CFD simulations.

The room under study, along with the openings, was modeled in DesignBuilder software. Table 8 shows the model image of the room and the characteristics of the openings of each room.

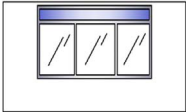
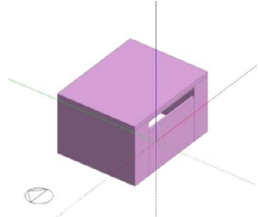
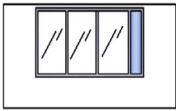
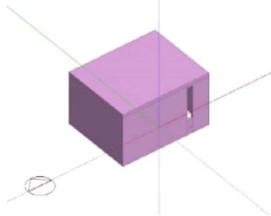
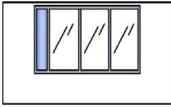
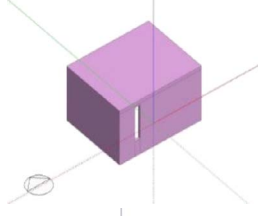
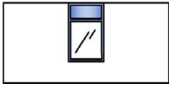
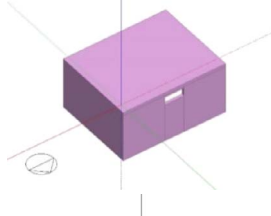
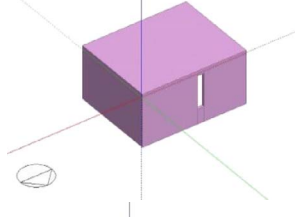
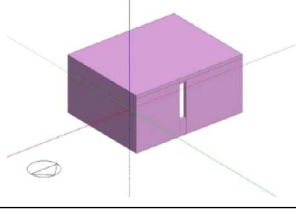
Figure 7 illustrates two examples of CFD simulations performed on rooms with horizontal and vertical openings.

3. RESULTS

The air velocity inside the room was measured by CFD simulation of the models with the default openings. The air velocity was calculated in the center of the room at the living height of the residents. In the months when there are maximum seasonal prevailing winds, simulation was performed for both the monthly average speed and for the prevailing wind speed. The results are given in Table 9.

The maximum air velocity simulated for horizontal and vertical openings on the third and fourth stories (8.5 and 11.5 m) is shown in Figure 8. These results indicate that the air velocity from the vertical openings was greater than that of the horizontal openings. There was also no significant air flow from the east- and west-facing openings in cold months. Most air passes through the north-facing openings in winter and the south-facing openings in spring, summer and autumn. In warm months (June and July), the inflow air velocity through the south- and west-facing openings was greater than in other months, especially for vertical openings.

Table 8. *The modeled room and its façade and opening properties.*

Opening direction	Model	Opening dimension	Façade	Perspective
South	1	5*0.5 m Vertical distance from floor: 2.4 m Horizontal location: middle		
	2	0.5*2 (willing to right) Vertical distance from floor: 0.9 m Horizontal distance from each corner: 6 m–1.5 m		
	3	0.5*2 m (willing to left) Vertical distance from floor: 0.9 m Horizontal distance from each corner: 1.5 m–6 m		
North	1	1.5*0.5 m Vertical distance from floor: 2.4 m Horizontal location: middle		
	2	0.5*2 m (willing to right) Vertical distance from floor: 0.9 m Horizontal distance from each corner: 3.25–4.25 m		
	3	0.5*2 m (willing to left) Vertical distance from floor: 0.9 m Horizontal distance from each corner: 3.25–4.25 m		

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Table 8. *Continued*

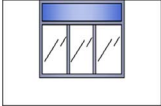
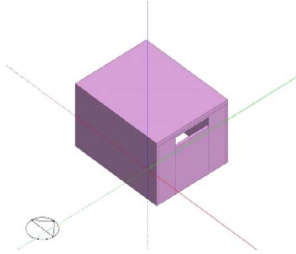
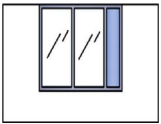
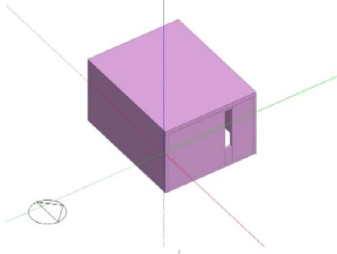
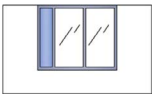
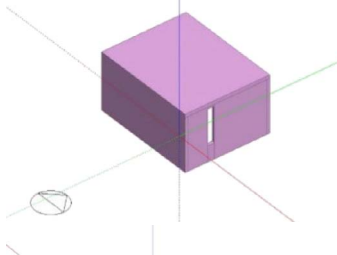
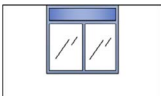
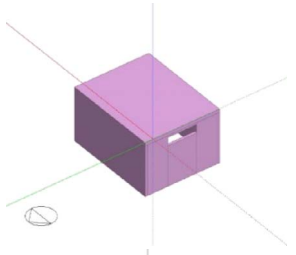
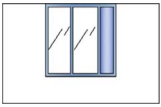
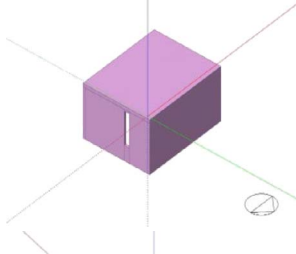
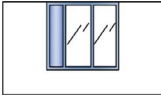
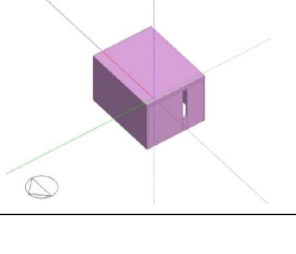
Opening direction	Model	Opening dimension	Façade	Perspective
East	1	3*0.5 m Vertical distance from floor: 2.4 m Horizontal location: middle		
	2	0.5*2 m (willing to right) Vertical distance from floor: 0.9 m Horizontal distance from each corner: 1.5–4 m		
	3	0.5*2 m (willing to left) Vertical distance from floor: 0.9 m Horizontal distance from each corner: 1.5–4 m		
West	1	2.5*0.5 m Vertical distance from floor: 2.4 m Horizontal location: middle		
	2	0.5*2 m (willing to right) Vertical distance from floor: 0.9 m Horizontal distance from each corner: 1.75–3.75 m		
	3	0.5*2 m (willing to left) Vertical distance from floor: 0.9 m Horizontal distance from each corner: 1.75–3.75 m		

Table 9. Monthly calculated indoor air velocity through openings.

Month	Window orientation	Wind direction	Opening type	Indoor air velocity (m/s)	
				Building height level 8.5 m	Building height level 11.5 m
Jan	North	360	H	1.48	1.45
			V (L)	1.61	1.74
Feb	North	360	H	1.47	1.63
			V (R)	1.73	1.96
	South	225	H	0.69	0.73
			V (L)	2.06	2.34
	West	225	H	0	0
			V (R)	0	0
Mar	North	22.5	H	0.75	0.94
			V (R)	1.59	1.84
			H	0.85	1.57
			V (R)	1.5	2.08
	East	45	H	0	0.23
			V (L)	0	0
			H	0	0.23
			V (L)	0	0
Apr	East	90	H	0	0
			V (R)	0	0
	West	225	H	0.22	0.23
			V (L)	0.23	0.23
	South	135	H	0	1.07
			V (R)	1.51	1.70
		202.5	H	0.5	0.53
			V (L)	2.67	2.95
May	South	225	H	0.5	1.59
			V (L)	2.23	2.53
	West	270	H	0	0
			V (L)	0	0
		225	H	0	0
			V (R)	0	0
	North	315	H	0.45	0.45
			V (R)	0.44	0.44
Jun	South	225	H	1.86	2.19
			V (L)	1.16	3.92
			H	1.43	1.73
			V (L)	3.13	3.44
	West	225	H	0	1.46
			V (R)	1.83	2.57
			H	1.22	1.15
			V (R)	1.43	1.61
Jul	South	225	H	1.86	2.15
			V (L)	1.66	1.90
			H	0.91	1.42
			V (L)	3.61	3.50
		180	H	1.11	1.28
			V (L)	1.10	1.57
			H	0.92	0.84
			V (L)	1.36	1.25
	West	225	H	0.74	1.34
			V (R)	0.74	0.89
			H	0.60	0.62
			V (R)	0.59	0.30
Aug	North	360	H	0.88	0.96
			V (L)	1.32	1.44
	South	180	H	0.88	0.96
			V (L)	1.30	1.42
Sep	North	360	H	0.33	0.72
			V (L)	0.98	1.07

(Continued)

Table 9. *Continued.*

Month	Window orientation	Wind direction	Opening type	Indoor air velocity (m/s)	
				Building height level 8.5 m	Building height level 11.5 m
Oct	South	180	H	0.7	1.13
			V (R)	1.69	2.16
			H	1.07	2.06
			V (R)	1.30	1.95
	North	45	H	0	0
			V (R)	0.15	0.15
Nov	East	315	H	0.15	0.46
			V (L)	0.15	0.15
			H	0	0
			V (R)	0	0
	West	270	H	0.08	0.15
			V (R)	0.07	0.15
Dec	East	135	H	0	0
			V (L)	0	0
			H	0.46	0.65
			V (R)	1.47	1.62
	South	225	H	0.08	0.15
			V (L)	1.34	1.46
			H	0.08	0.15
			V (R)	0.08	0.15
	West	225	H	0.08	0.15
			V (R)	0.08	0.15

H = horizontal openings, V (R) = vertical openings in right side of window, V (L) = vertical openings in left side of window.

Table 10. *Comfort index for wind speed [43].*

Wind speed limit(m/s)	Human sensation	Color
0–0.05	Stagnant air	
0.05–0.254	Favorable	
0.254–0.51	Comfortable	
0.51–1.02	Acceptable	
1.02–1.5	Disrupting activities	
1.5 and above	Discomfort	

Naturally, according to height, the average air velocity in different months of the year through the fourth story openings was higher than those of the third stories.

After determining the air velocity inside the rooms, the WCI and its resulting temperature were calculated and are shown in Figure 9 for the openings in four directions. The results show that for the low air velocity from the east- and west-facing openings, no change in the temperature was detected in the environment except for the west-facing openings in June. For the north-facing openings, only the room located on the fourth story ($H = 11.5$ m), which has a vertical opening had equivalent wind chill temperatures in February and March of 7°C and 5°C colder, respectively. For south-facing rooms with horizontal openings, there was no change in the temperature sensed, while for rooms with vertical openings to the south, there was a significant decrease in temperature in February, April, May, June, July and October.

The adaptive comfort model [64] has been used to determine the lower temperature limits of comfort for the months of the year

under the thermal conditions in the city of Tabriz. This range is shown in Figure 9. Under all conditions, except for the summer months (July and August), if heating systems are not active, there is no possibility of reaching a comfortable temperature, given the low temperatures.

4. DISCUSSION

As seen, in the cold months of the year, provision of ventilation with passive systems is not possible in indoor spaces. In fact, when air enters a room, because the outside air temperature is lower than the comfort range, there is further cooling when using north- and south-facing openings. When using east- and west-facing openings, even with low wind flow, the low ambient temperature can cause discomfort. Therefore, opening the window should be avoided during cold months and other means of providing fresh air, such as small scale heat recovery systems, should be considered.

Controlling the air velocity inside the room is also necessary to maintain comfortable conditions. The increase in air velocity alone may cause discomfort; therefore, it should be determined in which months the flow of air through the windows leads to the optimum air velocity inside the room and whether or not the speed sometimes increases to above the comfort range. Measurement of internal air flow velocity each month resulting from the passage of wind through horizontal or vertical openings can be used to identify patterns in the types of openings and how residents use them. An index for comfort conditions is given in Table 10.

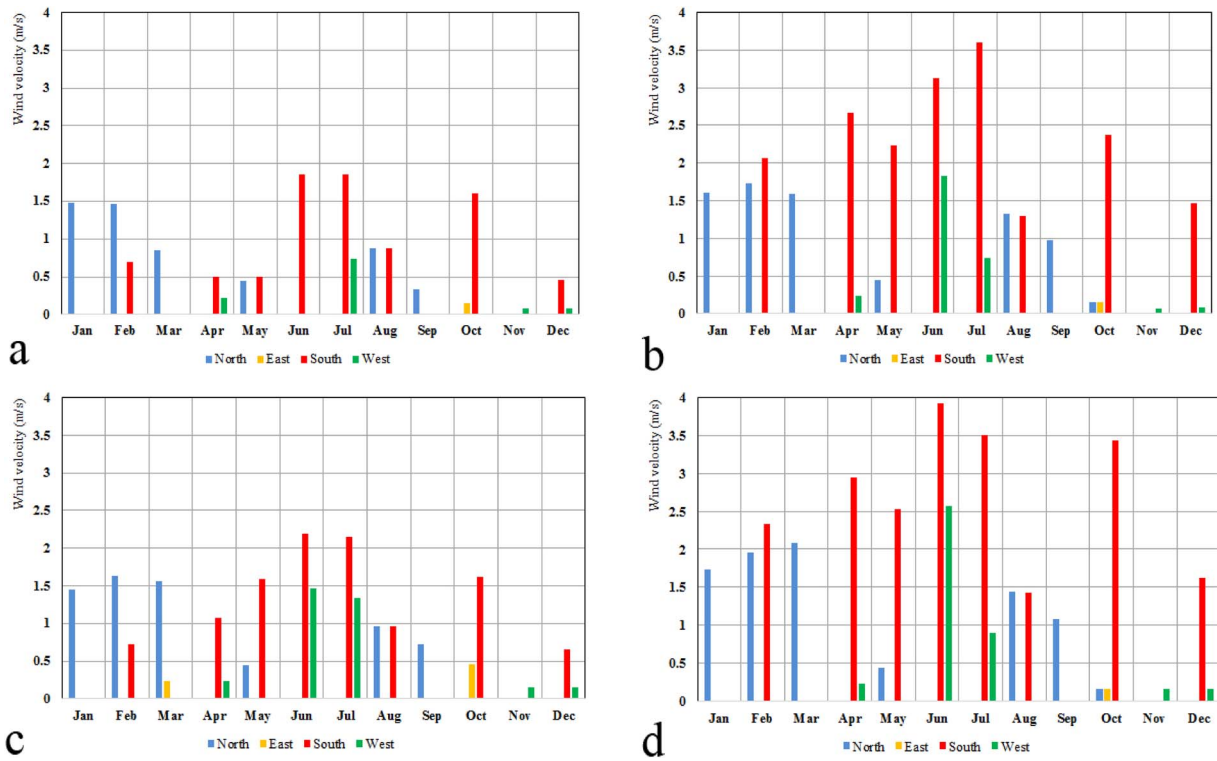


Figure 8. Monthly indoor air velocity blowing from four sides of building through openings; (a) height = 8.5 m and horizontal opening, (b) height = 8.5 m and vertical opening, (c) height = 11.5 m and horizontal opening, (d) height = 11.5 m and vertical opening

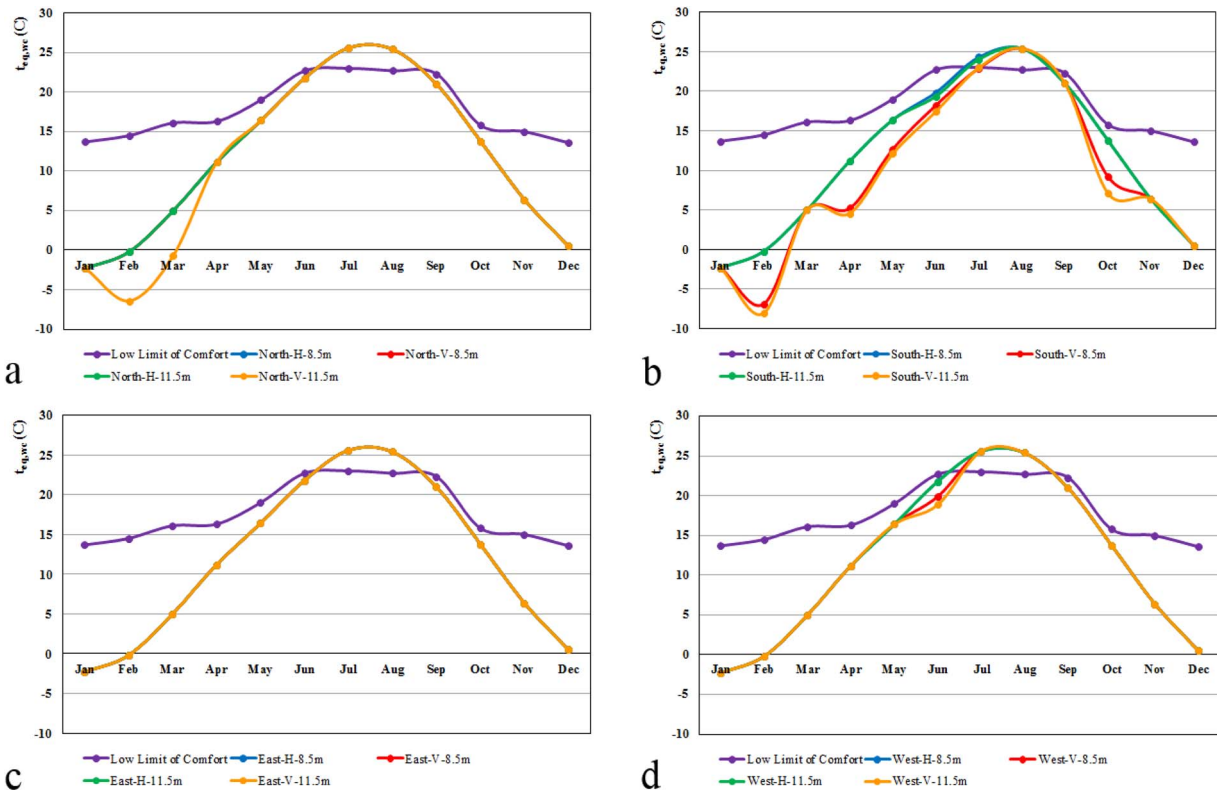


Figure 9. Monthly equivalent wind chill temperature for four sides of building openings; a) north openings, b) south openings, c) east openings, d) west openings.

Table 11. Indoor air velocity on third level.

$H = 8.5$	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V
North	1.48	1.61	1.47	1.73	0.75	1.59	-	-	0.45	0.44	-	-	-	-	0.88	1.32	0.33	0.98	0	0.15	-	-	-	-
East	-	-	-	-	0	0	0	0	-	-	-	-	-	-	-	-	-	-	0.15	0.15	0	0	0	0
South	-	-	0.69	2.06	-	-	0.50	1.51	0.50	2.23	1.86	1.16	1.86	1.66	0.88	1.30	-	-	0.70	1.69	-	-	0.46	1.47
West	-	-	0	0	-	-	0.22	0.23	0	0	0	1.83	0.74	0.74	-	-	-	-	1.60	2.37	-	-	0.08	1.34
									0	0	1.22	1.43	0.60	0.59							0.08	0.07	0.08	0.08

Table 12. Indoor air velocity on fourth level.

$H = 11.5$	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V
North	1.45	1.74	1.63	1.96	0.94	1.84	-	-	0.45	0.44	-	-	-	-	0.96	1.44	0.72	1.07	0	0.15	-	-	-	-
East	-	-	-	-	0	0	0	0	-	-	-	-	-	-	-	-	-	-	0.46	0.15	0	0	0	0
South	-	-	0.69	2.06	-	-	0.53	1.70	1.59	2.53	2.19	3.92	2.15	1.90	0.96	1.42	-	-	1.13	2.06	-	-	0.65	1.62
West	-	-	0.74	2.34	-	-	0.22	0.23	0	0	1.46	2.57	1.34	0.89	-	-	-	-	1.62	3.43	-	-	0.15	1.46
									0	0	1.15	1.61	0.62	0.30							0.15	0.15	0.15	0.15

In order to control the air velocity caused by opening in each month of the year, the air velocity was simulated in the residential spaces by taking into account the comfort of the residents. The results are given in Tables 11 and 12. Table 11 shows the results of air velocity data for a residential home on the third story ($H = 8.5$ m).

As seen, installation of the horizontal and vertical openings in the east- and west-facing walls is desirable; however, the air velocity of the west-facing openings is high in June. There are no restrictions for the north-facing wall openings in the spring summer and autumn, but in winter months, horizontal openings can only be used at limited times as the residents desire. Vertical openings bring in high speed wind in August. In the south-facing windows, the use of any type of opening in June, July and October is not recommended. In February, April, May, August and December, only horizontal south-facing openings are recommended.

Table 12 shows the results of air velocity data for a dwelling on the fourth story ($H = 11.5$ m).

The installation of horizontal and vertical openings in the east- and west-facing walls is desirable; however, wind speed through all the west-facing openings in June and for horizontal windows in July is high. There are no restrictions for north-facing wall openings in the spring and autumn. However, in winter, the use of openings is not recommended and horizontal openings can only be used for a limited time in January. It is recommended that only horizontal south-facing openings be used. In south-facing walls in

May, June, July and October, it is best not to open any windows. In February, April, August and December, only horizontal openings are desirable and are limited to April.

In cold climates like Tabriz, to benefit from fresh air and natural ventilation, one should take limitations into account when opening windows. Tables 13 and 14 show three comfort conditions for each opening on the third and fourth stories of a building.

Once thermal comfort is achieved, there is a need for wind speed control. In fact, in spite of the provision of thermal comfort, opening windows are recommended only when the indoor air movement inflow speed is less than 1 m/sec. Simulations show the indoor airflow speed determination for every month for each window Table 15.

5. CONCLUSION

Due to the lack of modern air-conditioning in typical urban residential buildings, this study focused on passive methods of providing fresh air with an emphasis on thermal comfort. For this purpose, windows were designed and after simulating the air movement, the air speed through the open windows was analyzed. Windows that allow wind indoors can affect living conditions in three ways:

1. By changing the WCI and reducing the equivalent temperature.

Table 13. Achieving three comfort conditions by openings in third level.

	$H = 8.5 \text{ m}$	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
Months	Comfort conditions	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V
North	Equivalent WCI temp.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
	Air velocity	✗	✗	✗	✗	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✓	✓	✓	✓	✓	✓	✓	✓
	Achieving fresh air	✓	✓	✓	✓	✓	✓	-	-	✓	✓	-	-	-	-	✓	✓	✓	✓	✓	✓	-	-	-	-
East	Equivalent WCI temp.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
	Air velocity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Achieving fresh air	-	-	-	-	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓	✓
South	Equivalent WCI temp.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
	Air velocity	✓	✓	✓	✗	✓	✓	✓	✗	✓	✗	✗	✗	✗	✗	✓	✗	✓	✓	✗	✗	✓	✓	✓	✗
	Achieving fresh air	-	-	✓	✓	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	✓	✓	-	-	✓	✓
West	Equivalent WCI temp.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
	Air velocity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Achieving fresh air	-	-	✓	✓	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	✓	✓	✓	✓

✓: Comfort ✗: discomfort -: likely comfort.

Table 14. Achieving three comfort conditions by openings in fourth level.

	$H = 11.5 \text{ m}$	Jan		Feb		Mar		Apr		May		Jun		Jul		Aug		Sep		Oct		Nov		Dec	
Months	Comfort conditions	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V	H	V
North	Equivalent WCI temp.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
	Air velocity							✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Achieving fresh air	✓	✓	✓	✓	✓	✓	-	-	✓	✓	-	-	-	-	✓	✓	✓	✓	✓	✓	-	-	-	-
East	Equivalent WCI temp.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
	Air velocity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Achieving fresh air	-	-	-	-	✓	✓	✓	✓	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	✓	✓
South	Equivalent WCI temp.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
	Air velocity	✓	✓	✓		✓	✓									✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Achieving fresh air	-	-	✓	✓	-	-	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	-	-	✓	✓	-	-	✓	✓
West	Equivalent WCI temp.	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✗	✗
	Air velocity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Achieving fresh air	-	-	✓	✓	-	-	✓	✓	✓	✓	✓	✓	✓	✓	-	-	-	-	-	-	✓	✓	✓	✓

✓: Comfort ✗: discomfort -: likely comfort.

Table 15. Main suggestions for residents of buildings to use the openings.

Months	Suggestions	Need for heating system
Jan	Using north window openings is not recommended.	✓
Feb	Using north window openings is not recommended, but south horizontal openings are suitable.	✓
Mar	Using north vertical window openings is not recommended. The north horizontal openings can be used just for building third level.	✓
Apr	Using south window openings is not recommended, but south horizontal openings can be used just for building third level.	✓
May	Using north horizontal openings are suitable. South window openings are not recommended, but south horizontal openings can be used just for building third level.	✓
Jun	Using south and west window openings is not recommended.	-
Jul	Using south window openings is not recommended. All west openings can be used for building third level and west vertical openings can be used for building fourth level.	-
Aug	Using north and south horizontal openings is suitable.	-
Sep	All north openings can be used for building third level and north horizontal openings can be used for building fourth level.	-
Oct	Using south window openings is not recommended. All north and east openings are suitable.	✓
Nov	Using west openings is suitable.	✓
Dec	Using west openings is suitable. South horizontal openings can be used.	✓

2. When the inflow of air movement at a comfortable velocity is favorable for the occupant for at least for 5 months in certain orientations.
3. When the fresh air supply and natural ventilation from proper design are effective means for environmental health and comfort in cold climates.

The results of this research have shown that opening windows reduces temperatures to below the comfort zone, except during June to September, which are warm months. Under cold conditions, it is not possible to open windows and provide passive thermal comfort. Therefore, when the occupants must open windows to get fresh air, it is necessary to use mechanical heating systems and small-scale heat recovery units in the wall or windows.

The method of this study can be used by researchers to identify proper window design in similar cities and climate conditions. As each climate comes with its own wind speed and temperature variation, this method can help identify the proper design limitations and help architects in the design of residential and other building types. For further research, it is recommended to expend this kind of study in different climate zones by considering other factors contributing to thermal comfort. Due to wind behavior especially in high-rise one, it is suggested that such kind of research be conducted for more precise investigation on tall buildings in different floors. In addition, this type of study can be expanded based on different methodologies like field measurement and experimental studies.

REFERENCES

- [1] Acosta I, Campano MÁ, Molina JF. Window design in architecture: Analysis of energy savings for lighting and visual comfort in residential spaces. *Appl Energy* 2016;**168**:493–506.
- [2] Leslie RP, Radetsky L, Smith A. Conceptual design metrics for daylighting. *Light Res Technol* 2012;**44**:277–90.
- [3] Santamouris M. Energy in the urban built environment: the role of natural ventilation. *Natural Ventilation in the Urban Environment: Assessment and Design* 2005;1–19 London: Earthscan.
- [4] Bodach S, Lang W, Hamhaber J. Climate responsive building design strategies of vernacular architecture in Nepal. *Energy Build* 2014;**81**:227–42.
- [5] Nejat P, Jomehzadeh F, Taheri MM *et al.* A global review of energy consumption, CO₂ emissions and policy in the residential sector (with an overview of the top ten CO₂ emitting countries). *Renew Sustain Energy Rev* 2015;**43**:843–62.
- [6] Le Guen M, Mosca L, Perera ATD *et al.* Improving the energy sustainability of a Swiss village through building renovation and renewable energy integration. *Energy Build* 2018;**158**:906–23.
- [7] Alonso MJ, Liu P, Mathisen HM *et al.* Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries. *Build Environ* 2015;**84**:228–37.
- [8] Singh MK, Mahapatra S, Atreya S. Bioclimatism and vernacular architecture of north-east India. *Build Environ* 2009;**44**:878–88.
- [9] Rizk M, Guo F, Verrielle M *et al.* Impact of material emissions and sorption of volatile organic compounds on indoor air quality in a low energy building: Field measurements and modeling. *Indoor Air* 2017.
- [10] Manzano-Agugliaro F, Montoya FG, Sabio-Ortega A, García-Cruz A. Review of bioclimatic architecture strategies for achieving thermal comfort. *Renew Sustain Energy Rev* 2015;**49**:736–55.
- [11] Rupp RF, Vásquez NG, Lamberts R. A review of human thermal comfort in the built environment. *Energy Buildings* 2015;**105**:178–205.
- [12] Almeida RM, de Freitas VP, Delgado JM. 2015. *Indoor Environmental Quality, School Buildings Rehabilitation*. Springer. 5–17.
- [13] ASHRAE. 2013. *Standard Committee, ASHRAE Handbook: Fundamentals* 2013. Ashrae.
- [14] Attia S, Carlucci S. Impact of different thermal comfort models on zero energy residential buildings in hot climate. *Energy Build* 2015;**102**:117–28.
- [15] Frontczak M, Wargocki P. Literature survey on how different factors influence human comfort in indoor environments. *Build Environ* 2011;**46**:922–37.
- [16] Marino C, Nucara A, Pietrafesa M. Proposal of comfort classification indexes suitable for both single environments and whole buildings. *Build Environ* 2012;**57**:58–67.
- [17] Tahbaz M. 2011. *The Role of Architectural Design in Reducing Energy Consumption in Buildings* Tehran: Scientific-Applied Training Center of Rahshahr International Group (Quick Build).
- [18] Bell DA. 2004. *Outdoor Human Comfort and Its Assessment*. American Society of Civil Engineers (ASCE).
- [19] Omrani S, Garcia-Hansen V, Capra BR, Drogemuller R. Effect of natural ventilation mode on thermal comfort and ventilation performance: full-scale measurement. *Energy Build* 2017;**156**:1–16.
- [20] Santamouris M, Allard F. 1998. *Natural Ventilation in Buildings: A Design Handbook*. Earthscan.
- [21] Treado S, Gillette G, Kusuda T. Daylighting with windows, skylights, and clerestories. *Energy Build* 1984;**6**:319–30.
- [22] Yao M, Zhao B. Window opening behavior of occupants in residential buildings in Beijing. *Build Environ* 2017;**124**:441–9.
- [23] Ning H, Wang Z, Ren J, Ji Y. Thermal comfort and thermal adaptation between residential and office buildings in severe cold area of China. *Procedia Eng* 2015;**121**:365–73.
- [24] Roulet C-A. Indoor environment quality in buildings and its impact on outdoor environment. *Energy Build* 2001;**33**:183–91.
- [25] Wing YAL. 2001. *Analysis and Control of Wind Effects on Tall Buildings*. Civil and Environmental Engineering, Massachusetts Institute of Technology.
- [26] Huifen Z, Fuhua Y, Qian Z. Research on the impact of wind angles on the residential building energy consumption. *Math Probl Eng* 2014;**7**:1–15.
- [27] Liu H, B-z LI, Chen L *et al.* Impacts of indoor temperature and velocity on human physiology in hot summer and cold winter climate in China. *Proceedings of Clima 2007 Wellbeing Indoors* 2007;501–9.
- [28] ACSE AC. 2003. *Outdoor Human Comfort and Its Assessment*. Boston, VA: American Society of Civil Engineers. Aerodynamics Committee.
- [29] Razjouyan M. 2001. *Wind and Comfort: Design with Climate*. Tehran: Shahid Beheshti University.
- [30] Olgyay V. 1963. *Design with Climate: Bioclimatic Approach to Architectural Regionalism*. Princeton University Press.
- [31] I.M.O. (IRIMO). 2015. *Iran Meteorological Data*. Tehran: C.D. Office.
- [32] Penwarden AD. Wind environment around buildings. *Building Research Establish Report* 1975.
- [33] Givoni B. 1989. *Urban Design in Different Climates* World Meteorological Organization.
- [34] Pourdeihimi S. 2011. *Climate Language in Sustainable Environmental Design*. Tehran: Shahid Beheshti University.
- [35] Davenport A. G. The dependence of wind loads on meteorological parameters, *Proc. Int. Research Seminar on Wind Effects on Buildings and Structures, Ottawa* 1967. University of Toronto Press. 1968: 19–82.
- [36] Poreh M, Paciuk M. 1980. *Criteria for Identifying Wind Problems in Initial Planning Stages*. Haifa Google Scholar: Building Research Station, Technion.
- [37] Davenport AG. 1960. *Wind Loads on Structures* Ottawa.
- [38] Leung WYA. 2001. *Analysis and Control of Wind Effects on Tall Buildings*. Civil and Environmental Engineering, Massachusetts Institute of Technology.

- [39] Lawson T. The wind content of the built environment. *J Wind Eng Ind Aerodyn* 1978;**3**:93–105.
- [40] Tahbaz M. Determine wind speed in an urban context. 1991;58–67.
- [41] Siple PA, Passel CF. Measurements of dry atmospheric cooling in subfreezing temperatures. *Proc Am Philos Soc* 1945;**89**:177–99.
- [42] ASHRAE F. 2017. *Fundamentals Handbook*. SI edn. American Society of Heating, Refrigerating and Air-Conditioning Engineers.
- [43] Egan MD. 1975. *Concepts in Thermal Comfort*. New Jersey: Prentice-Hall Englewood Cliffs.
- [44] Akhtar kavan M, Sedigh H, Akhtar kavan H. 2012. *Setting the Compatible Conditions with Ecology and Climate of Iran*. Tehran: Kalhor Press.
- [45] Szokolay SV. 1987. *Thermal Design of Buildings*. RAI Education Division.
- [46] Baharvand M, Hamdan A, Abdul M. DesignBuilder verification and validation for indoor natural ventilation. *J Basic Appl Sci Res* 2013;**3**:8.
- [47] Alizadeh M, Sadrameli S. Numerical modeling and optimization of thermal comfort in building: central composite design and CFD simulation. *Energy Build* 2018;**164**:187–202.
- [48] Franke J, Hirsch C, Jensen G, Kürs HW, Miles SD, Schatzmann M *et al.* 2004. Recommendations on the use of CFD in wind engineering. In *Proceedings of the International Conference on Urban Wind Engineering and Building Aerodynamics* 2004;C.1.1–C1.11.
- [49] Ai Z, Mak C, Niu J *et al.* The effect of balconies on ventilation performance of low-rise buildings. *Indoor Built Environ* 2011;**20**: 649–60.
- [50] Asfour OS, Gadi MB. Using CFD to investigate ventilation characteristics of vaults as wind-inducing devices in buildings. *Appl Energy* 2008;**85**: 1126–40.
- [51] Jiang Y, Alexander D, Jenkins H *et al.* Natural ventilation in buildings: measurement in a wind tunnel and numerical simulation with large-eddy simulation. *J Wind Eng Ind Aerodyn* 2003;**91**:331–53.
- [52] Elmualim AA. Effect of damper and heat source on wind catcher natural ventilation performance. *Energy Build* 2006;**38**:939–48.
- [53] Da Graça GC, Chen Q, Glicksman L, Norford L. Simulation of wind-driven ventilative cooling systems for an apartment building in Beijing and Shanghai. *Energy Build* 2002;**34**:1–11.
- [54] Assimakopoulos V, Georgakis C, Santamouris M. Experimental validation of a computational fluid dynamics code to predict the wind speed in street canyons for passive cooling purposes. *Solar Energy* 2006;**80**:423–34.
- [55] Nielsen P, Li Y. CFD predictions of non-isothermal ventilation flow-how can. *Air* 2018;**28**:866–880.
- [56] Baharvand M, Ahmad MHB, Safikhani T, Mirmomtaz SMM. Thermal performance of tropical atrium. *Environ Clim Technol* 2013;**12**:34–40.
- [57] Asfour OS, Gadi MB. A comparison between CFD and network models for predicting wind-driven ventilation in buildings. *Build Environ* 2007;**42**:4079–85.
- [58] Chen Q, Srebric J. A procedure for verification, validation, and reporting of indoor environment CFD analyses. *HVAC&R Res* 2002;**8**:201–16.
- [59] Thacker BH. 2001. ASME Standards Committee on Verification and Validation in Computational Solid Mechanics. *Report*. The American Society of Mechanical Engineers (ASME) Council on Codes and Standards.
- [60] Nasrollahi F. 2009. *Climate and Energy Responsive Housing in Continental Climates (The Sustainability of Passive Houses for Iran Dry and Cold Climate)*, *Building Technology and Design*. Berlin University of Technology.
- [61] Dean BN. 2001. *Natural Ventilation Possibilities for Buildings in the United States*. Architecture, Massachusetts Institute of Technology.
- [62] Davenport A. 1967. The treatment of wind loading on tall buildings. *Tall Buildings*. Elsevier. 3–45.
- [63] Davenport AG, Grimmond CSB, Oke TR, Wieringa J. 2000. Estimating the roughness of cities and sheltered country. In *15th Conference on Probability and Statistics in the Atmospheric Sciences/12th Conference on Applied Climatology*, pp. 96–9. Ashville, NC,: American Meteorological Society.
- [64] Heidari S, Ghafari Jabari S. Determining thermal comfort period for Tabriz. *Modares Mech Eng* 2011;**10**:44–37.