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Research Note

Assessment of energy consumption in a building considering combined ventilation method across four different climate zones in Iran

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Abstract

Natural ventilation is considered as a passive energy-efficient strategy that could provide desired thermal comfort conditions for residents and improve the indoor space conditions. However, the aim of the present study is to analyze the potential of natural ventilation in reducing energy consumption for cooling of the building in summer. Therefore, the amount of energy consumption for ventilation and cooling of a single-story building in the four different climate zones in Iran has been evaluated by Energy Plus. Afterwards, to evaluate the amount of the energy saving using natural ventilation, energy analysis has been performed for the reference building using a combined mode including natural ventilation and a mechanical cooling system. The considered climate zones include Tehran, Tabriz, Isfahan and Bandar-Abbas which are the most popular climate zones in Iran. The results show that the reduction percentage in energy consumption applying natural ventilation for Tabriz, Isfahan, Tehran and Bandar-Abbas are 18, 12, 10 and 3%, respectively. The highest percentage of energy saving is for Tabriz with a cold and dry climate and the lowest one is for Bandar-Abbas with hot and humid climate.

1. Introduction

Since thermal comfort has direct effects on occupants' health and productivity, it is essential to maintain thermal comfort conditions for residents in buildings. However, to achieve acceptable indoor environmental conditions, it is necessary to control several indoor parameters such as air temperature, indoor air quality, relative humidity and CO_2 concentration [1]. A significant portion of energy consumption is related to operate the Heating, Ventilation, and Air Conditioning (HVAC) systems to maintain optimal indoor thermal conditions in residential buildings. In recent years, because of the global energy crisis and global warming, several improved energy-efficient techniques and developed sustainable buildings have been proposed to reduce the energy costs associated with the ventilation of the buildings [2]. Natural ventilation is one of these energy-efficient alternatives which can supply fresh air and maintains thermal comfort conditions in the building [3]. Based on the reports, applying natural ventilation in buildings could reduce energy consumption by about 30-40% compared to mechanically ventilated buildings [4]. Therefore, replacing mechanical ventilation with natural ventilation can reduce energy consumption in the building with an acceptable level. So, building designers could play an important role in reducing greenhouse gas emissions by applying energy-efficient ventilation methods [5].

However, natural ventilation uses wind and thermal buoyancy effects to refresh air and ventilate the space. In this system, the pressure difference between the outdoor environment and the inside of the space causes air to move between the interior and the exterior of the building through the openings [6].

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Based on the shape of the building and the location of the openings, natural ventilation may be categorized into four different strategies [7-10]:

- Single-sided ventilation;
- Cross ventilation;
- Stack effect ventilation;
- Combination of three above mentioned ventilations.

So far, many models have been proposed to design and study the natural ventilation. These models can be divided into four general categories [3,11]: Computational Fluid Dynamics (CFD), full scale measurements, scaled wind tunnel measurements, and simple analytic methods.

Zhang et al. [12] numerically investigated the effect of the wind direction on cross ventilation and single-sided ventilation efficiency. Variation of wind incident angle from 0° to 90° decreased the ventilation rate meaningfully. Perén et al. [13] studied the effect of roof inclination and windows locations on natural ventilation efficiency by the CFD approach. Arinami et al. [14] performed a numerical simulation to analyze the impact of adjacent obstacles and guide vanes on ventilation efficiency for a generic building applying single-sided ventilation. The method of the Large-Eddy Simulation (LES) was used to evaluate the turbulent flow in the computational domain. The numerical results showed that guide vane and adjacent obstacle significantly affects the air change rate and ventilation efficiency. Ghadiri et al. [15] numerically assessed the ventilation performance of the two-sided rectangular wind catcher in Yazd city. The numerical results were validated against measurements of the wind tunnel scale model. Elshafei et al. [16] utilized the CFD tool to analyze the effect of the window parameters e.g., window size, window position and shades on natural ventilation performance. Izadyar et al. [17] applied CFD tools to investigate the effect of the balcony geometry on single-sided natural ventilation. Also, the internal obstacle effects on cross ventilation are studied numerically by Chu and Chiang [18]. CFD simulation gives accurate results compared to simple analytical methods, but this method requires sufficient knowledge about the modeling of 3D geometry, meshing, initial and boundary conditions, turbulence models and etc. Also, these models are not applicable in the building simulation software such as Energy Plus.

Researchers also experimentally studied the natural ventilation characteristics and measured the ventilation rates in full-scale models or in scaled wind tunnel models. These models are mainly used to validate numerical simulations and simple empirical correlations. Larriva et al. [19] experimentally analyzed the influence of climatic conditions on thermal perception of residents in naturally ventilated nursing homes. Their results showed that the residents had a different thermal sensation from the naturally ventilated environment, as well as the outdoor temperature and humidity have a significant effect on the thermal perceptions of occupants. Nomura and Hiyama [20] summarized the natural ventilation rate measurements for thirty office buildings in Japan that were reported in academic papers. They observed that the natural ventilation performance depends significantly on the design, building shape, ventilation strategy and ventilation driving force. Wang et al. [21] a field study to evaluate students' thermal sensation in a naturally-ventilated classroom in Xi'an, China applying a year-long field test. Their results show that regarding the cold climate of Xi'an, in the summer for air temperatures above 30℃, the using of mechanical ventilation is mandatory.

Kubota et al. [22] empirically evaluated the impacts of the courtyard on indoor temperature, air velocity and relative humidity in Chinese shophouses based on the results of field experiments conducted in 16 Chinese shophouses in the city of Malacca of Malaysia with the hot-humid climate. Aflaki et al. [23] assessed the performance of cross single-sided natural ventilation through a transom ventilation panel in a tall residential building using full-scale in-situ measurements.

Small-scale models are employed to study the ventilation performance of the real larger objects or structures in wind tunnels. In these models, the effect of outdoor conditions e.g., wind velocity and direction, outdoor temperature and relative humidity on ventilation performance, could be examined. However, this method is time-consuming and expensive [24]. Chu et al. [25] studied single-sided natural ventilation with two openings in one wall using wind tunnel experiments. They analyzed the effects of wind direction and speed on ventilation rate. Dehghani et al. [26] numerically and experimentally investigated wind direction impact on ventilation rate of a scaled four-sided wind tower with courtyard and parlor. Lo et al. [27] presented a method for predicting the flowrate of the wind-driven ventilation using a scaled wind tunnel model coupled with CFD simulation.

Simple analytic methods are extensively used to estimate the natural ventilation rate due to simplicity. These models are implemented in building simulation software e.g., Design Builder [28] and Energy Plus [29]. Martins and da Graça [24] employed a combined mode of CFD and Air Flow Network (AFN) simulations to investigate the wind-driven cross ventilation in an office building. The effect of the window geometry on the average effective flow rate was investigated. Yang et al. [30] investigated the capability of the natural driving force for ventilation of buildings using a simple analytical model. They considered the effect of both thermal buoyancy and wind driving forces in ventilation rate. A combination of three methods including simulation work, field survey and objective measurements has been implemented by Abd Rahman et al. [31] to assess thermal comfort in a public hospital ward considering natural ventilation. Their results show that the use of this combined model could be very effective in achieving accurate results, especially in tropical climates.

The review of the reporting literature shows that most of the previous investigations have been conducted in case studies and climate zones with hot weathers as well as considering natural ventilation as the only cooling system in the building. However, thermal comfort could not be met just by applying natural ventilation especially for hot climates.

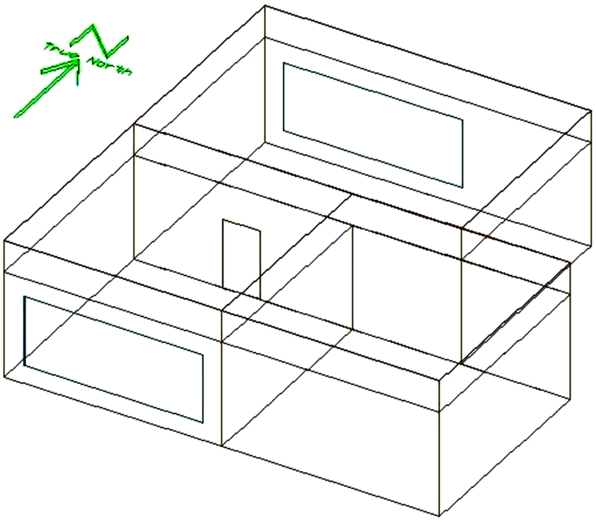

Figure 1. Schematic of the reference building.

Therefore, it is better to implement a combined cooling mechanism including natural ventilation and mechanical ventilation.

The aim of the present study is to investigate the potential of a mixed ventilation (combination of cross natural ventilation and mechanical ventilation) in reducing the energy consumption for cooling and conditioning of a multi-zone building in summer. So, a combined cooling method consist of natural and mechanical ventilation is employed for a three-zone building taking into account four different climate zones in Iran. Since, 3D numerical CFD methods in natural ventilation are commonly used to predict the indoor air flow pattern and temperature distribution, in this work the energy analysis is performed by Energy Plus [29] software and a simple analytic method is applied to calculate the natural ventilation rate.

2. Reference building and geometry details

To estimate the energy consumption for cooling, a single-story office building is considered. This building consists of three conditioned zones and one unconditioned zone (an attic). Figure 1 shows a schematic of the building.

The total height of the building and the height of the attic is 3.048 m and 0.91 m, respectively. The geometry details of the reference building are as follow:

- West zone: 6.096m × 6.096m;
- East zone: 6.096m × 6.96m;
- North zone: 9.144m × 6.096m;
- Windows on both sides of the building: 5m × 2m.

The total area of the building: 130.1 m^2.

Due to the presence of two windows on both sides of the building and a door on the shared wall of the west and north zones, the considered natural ventilation would be cross ventilation.

2.1. Internal thermal gains

Internal thermal loads in the three zones of the reference building are given in Table 1.

Table 1. Internal thermal gains in the reference building.

Zone	Electronic devices (W)	Lights (W)	Number of occupants
West	1464.375	2928.751	3
East	1464.375	1464.375	3
North	878.6252	2928.751	4

To simulate the heat production by occupants, an average person with a bodyweight of 74.4 kg and body surface area of 1.87 m^2 is considered. Also, the metabolic rate of 1.15 met (1met=58.1 W/m^2) and a clothing insulation of 0.7 clo (1clo=0.155 (m^{2}k)/W) are considered for all occupants in the reference building.

3. Methodology

In the present study, the Energy Plus [29] software has been employed to evaluate the amount of energy consumption for cooling in the reference building. However, considering the "AFN" module, it is assumed that when the air supply system is on, the mechanical ventilation is available and when the air supply system is off, there will be natural ventilation in the building. Natural ventilation in the building is done through the windows of the north and south wall and the shared door of the north and west zone. The evaluation of energy consumption for ventilation of the building has been applied for the hot season (three months of the summer) across four different climate zones in Iran.

3.1. HVAC system

In this research, all three zones in the reference building apply a single air loop for cooling. However, a direct expansion cooling and a gas heating coil have been applied for cooling and heating, respectively. For thermostatic control of the cooling system, it is considered 24°C from 7 AM until 5 PM as well as 30°C for the rest of the hours.

When the cooling system is turned off according to the thermostatic control, the natural ventilation is employed in the reference building. To simulate the natural ventilation, the Airflow Network model is applied. This model consists of a set of nodes connected by airflow components through linkages (windows and doors). Energy Plus airflow network model has been validated against measured data from both the Oak Ridge National Laboratory (ORNL) and the Florida Solar Energy Center (FSEC) [32].

In airflow network model, pressure is determined at each node as well as the airflow is computed through each linkage. Also, temperatures and humidity ratios at each node are calculated considering given zone air temperatures and humidity ratios. Finally, using each node temperatures and humidity ratios, the sensible and latent loads are obtained.

A schematic of airflow pattern in vertical openings (door or window) is shown in Figure 2.

The relation between pressure and elevation at each point is determined by the hydrostatic equation [33]:

$$P_n(y) = P_{0n} - \rho_n g y, \tag{1}$$

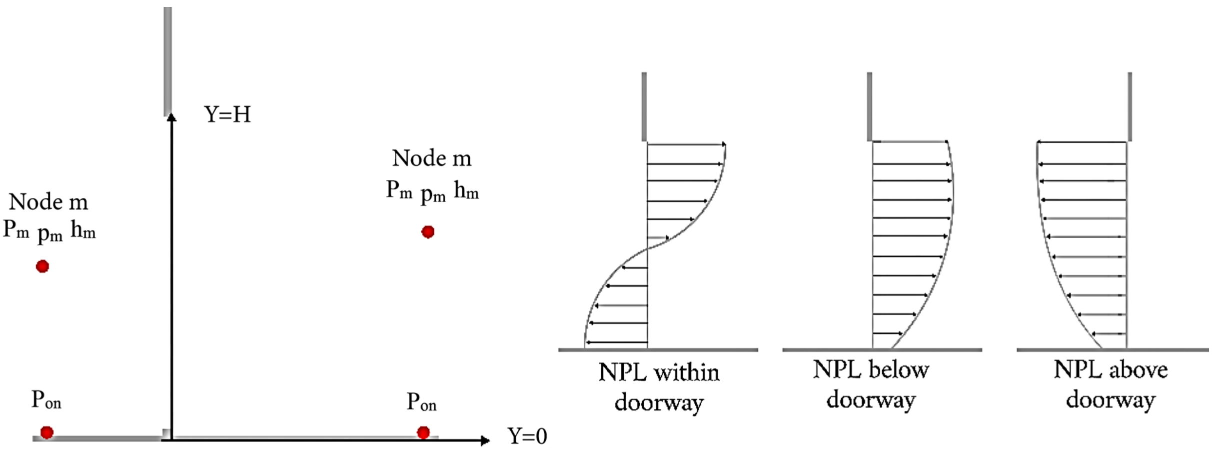

Figure 2. Schematic of large opening and associated three flow patterns [33].

$$P_m(y) = P_{0m} - \rho_m g y, \tag{2}$$

where indices n, m and 0 refer to entry node, exit node and reference elevation ($y = 0$), respectively. Also, P, ρ, y and g are Pressure, air density, elevation, and gravity acceleration, respectively.

It is assumed that the velocity of the airflow (V) is obtained by the orifice equation [33]:

$$V(y) = C_d \sqrt{2\frac{P_n(y) - P_m(y)}{\rho}}, \tag{3}$$

where C_d is the discharge coefficient that is generally considered as 0.6 for large vertical openings.

According to Figure 2, the airflow magnitude and direction depends on pressure difference between node m and n in certain elevation. In certain height which is called Neutral Pressure Plane (NPL), the pressure difference between two nodes is zero, so the airflow is zero. The NPL may be located within the opening, above or below it. The neutral height, Y, may be calculated by the following equations:

$$Y = \frac{P_{0n} - P_{0m}}{g(\rho_n - \rho_m)} \quad \text{or} \quad Y = \frac{P_{0m} - P_{0n}}{g(\rho_m - \rho_n)}. \tag{4}$$

When the NPL is within the opening, two-way (bidirectional) flows occur. So, the total airflow ($\dot{m}$) through a large opening is the sum of both flows [33]:

$$\dot{m}_{0,Y} = \int_{y=0}^{Y} \rho V(y) W dy, \tag{5}$$

$$\dot{m}_{Y,H} = \int_{y=Y}^{H} \rho V(y) W dy, \tag{6}$$

where H and W are the height and width of openings, respectively.

In external nodes the pressure is calculated using wind velocity and pressure coefficient [33]:

$$P_w = \rho C_P \frac{U_{ref}^2}{2}. \tag{7}$$

The local wind speed value is estimated from the reported wind speed by meteorological station using a power law model [33]:

$$U_{ref} = U_{wind} k z^a, \tag{8}$$

where U_{wind} is the measured wind speed by the meteorological station in a standard height of the 10 m in an open field, z is the height of the reference point. The k and a values (depending on the terrain type) for towns and cities are considered 0.21 and 0.33, respectively.

The pressure coefficient (C_P) in Energy Plus is calculated form empirical equation developed by Swami and Chandra [34]:

$$C_P = C_{p0} \cdot ln \begin{pmatrix} 1.248 - 0.703 \sin\left(\frac{\theta}{2}\right) \\ -1.175 \sin^2(\theta) + 0.131 \sin^3(2\theta G) \\ +0.769 \cos\left(\frac{\theta}{2}\right) + 0.07 G^2 \sin^2\left(\frac{\theta}{2}\right) \\ +0.717 \cos^2\left(\frac{\theta}{2}\right) \end{pmatrix} \tag{9}$$

3.2. *Weather data*

As mentioned earlier, the energy analysis has been done for four different cities of Iran, including Tehran, Tabriz, Isfahan and Bandar-Abbas that are the most populous climate zones in Iran. The weather data for these cities has been obtained from the Energy Plus database [35] which consists of hourly temperature, wind direction and wind velocity. Since wind plays a vital role in natural ventilation, the average wind velocity of the four cities is illustrated in Figure 3. As shown in Figure 2, the mean wind velocity in Tabriz with clod and dry climate is higher than other cities.

4. Results and discussions

In this study, the potential of a combine ventilation method

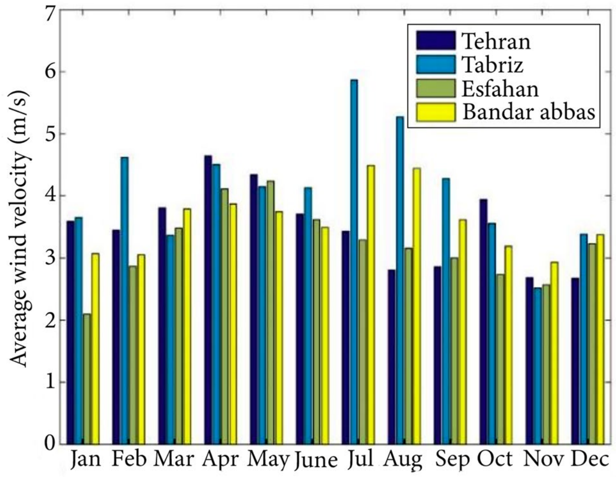

Figure 3. Diagram of monthly mean wind velocity in four Iranian cities.

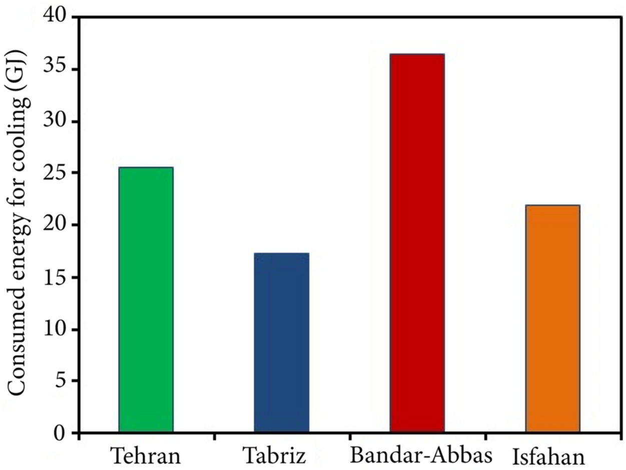

Figure 4. The energy consumption for cooling of the reference building across four different climate zones of Iran.

in reducing energy consumption in the summer for a three-zone building has been investigated. The Energy Plus software has been employed to assess the energy analysis through four different climate zone in Iran which consist of Tehran, Tabriz, Isfahan and Bandar-Abbas. For this purpose, initially, the amount of energy consumption of cooling in summer (without considering natural ventilation) for four mentioned cities is estimated. The obtained results for energy consumption estimations are shown in Figure 4.

According to Figure 4, the amount of consumed energy for cooling in Bandar-Abbas with hot and humid climate is more than other cities. Also, the consumed energy for cooling in Tabriz with cold and dry climate is the lowest one.

4.1. Evaluating the amount of energy saving using natural ventilation in the building

In order to assess the energy savings using natural ventilation, at first, the energy analysis was performed for the building without considering natural ventilation; see Figure 4. As mentioned earlier, without considering natural ventilation the thermostatic control of the mechanical cooling system (see Subsection 3.1) was considered 24°C from 7 AM to 5 PM, as well as 30°C for the remaining times. These control temperatures were chosen based on the American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) comfort zones [1].

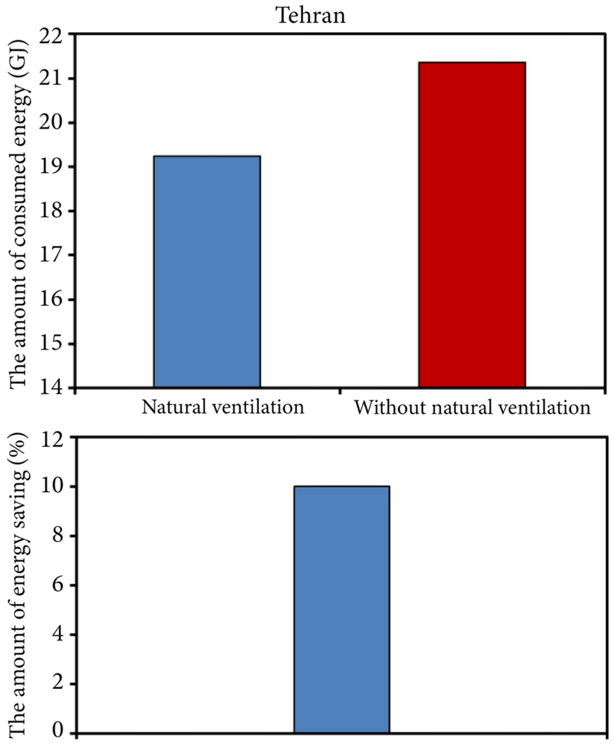

Figure 5. The amount of energy savings using natural ventilation in Tehran.

However, in this part, a combination of natural ventilation and a mechanical cooling system is considered. When natural ventilation is employed as the cooling system, the thermostatic control temperatures would be increase because of the presence of the wind factor. Since ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) comfort zones are for air speeds not to exceed 0.2 m/s, the elevated air speeds can improve comfort beyond the maximum temperature limit of the ASHRAE comfort zones [1]. So, in this study, considering the average wind speed in the four Iranian cities (Figure 3) and referring to the ASHRAE curves (which define the temperature border increase based on the elevated air speeds), it is assumed that the temperature borders in thermal comfort diagrams are increased by 2°C. Therefore, assuming an increase of 2°C, the thermostatic control temperatures of 26°C and 32°C are applied for energy analysis.

So, for temperatures below 26°C in summer, the mechanical cooling system is off and natural ventilation is applied and for higher temperatures, the cooling system (HVAC system, see Subsection. 3.1) is turned on. The results of the energy analysis considering natural ventilation across four different climate zones in Iran are given in Figures 5 to 8.

According to the obtained results, it is clear that the amount of energy savings for cooling using natural ventilation in Tehran, Tabriz, Isfahan and Bandar-Abbas is 10, 18, 12 and 3%, respectively.

The maximum amount of energy savings is for Tabriz city. To maintain thermal comfort inside the building using natural ventilation, the outside temperature should be lower than the room temperature. According to cold and dry climate of Tabriz, the outside temperature of Tabriz in hot

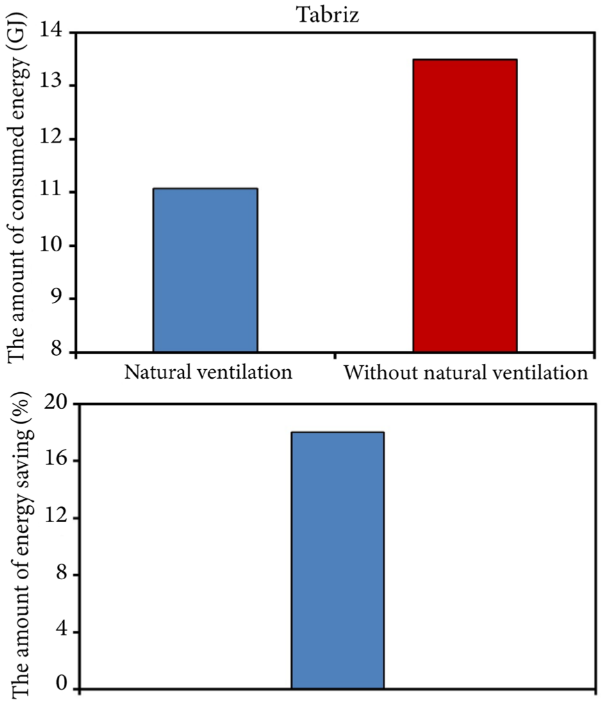

Figure 6. The amount of energy savings using natural ventilation in Tabriz.

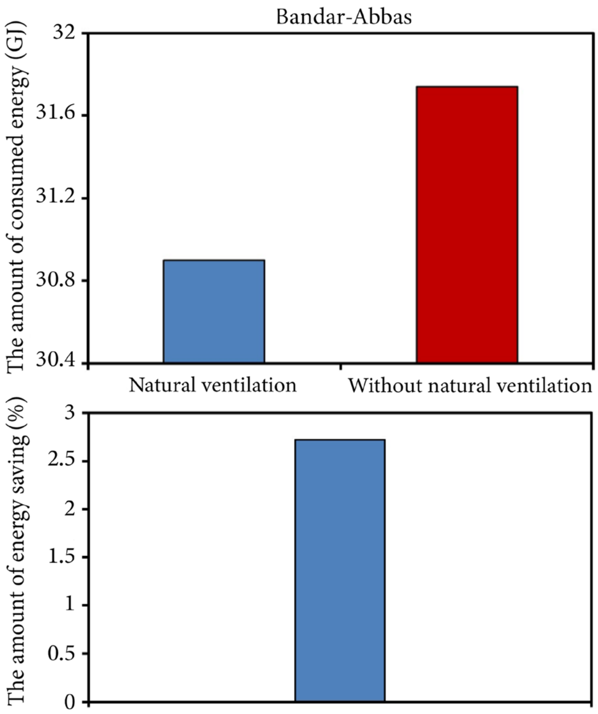

Figure 7. The amount of energy savings using natural ventilation in Bandar-Abbas.

season is lower than the inside temperature in comparison with the other three cities. As a result, natural ventilation can be used to establish thermal comfort conditions inside the building and there will be no need for mechanical ventilation. Due to this, the amount of reduction in energy consumption in Tabriz is less than other cities. On the other hand, in Bandar Abbas, in the warm seasons, the outside air temperature is higher than room setting temperature and therefore natural ventilation will be less efficient in this city compared to the other cities.

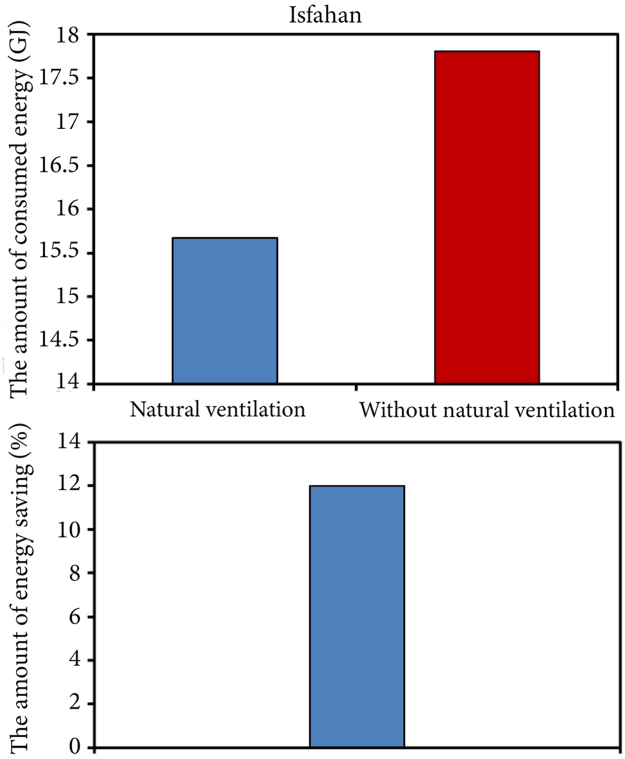

Figure 8. The amount of energy savings using natural ventilation in Isfahan.

5. Conclusions

In this paper, the potential of natural ventilation in reducing of energy consumption for cooling is examined. For this reason, a combined cooling method is employed for a three-zone building in four different climate zones in Iran. Also, the energy analysis is conducted by Energy Plus software applying the Air Flow Network model (AFN). The results show that the most energy saving is for Tabriz with cold and dry climate and the lowest amount is for Bandar-Abbas with hot and humid climate. Energy Plus software has been used to analyze and estimate energy consumption. So, in the first case, the amount of energy consumption without considering natural ventilation is evaluated. Afterward, in the second case, by considering a combined mode (the combination of mechanical cooling system and natural ventilation), the amount of energy consumption is estimated and compared with the first case. The results of this study are summarized as below:

- In general, the amount of consumed energy for cooling, without using natural ventilation, in Bandar-Abbas with hot and humid climate is the highest one. Also, the amount of consumed energy for cooling in Tabriz with cold and dry climates is the lowest amount;
- The amount of energy savings using natural ventilation in the cities of Tehran, Tabriz, Isfahan and Bandar-Abbas is 10, 18, 12 and 3 percent, respectively. The most energy savings is for Tabriz with cold and dry climate and the lowest amount is for Bandar-Abbas with hot and humid climate. According to Figure 3, the average air velocity in Tabriz is higher than other cities. Since, wind speed plays a very important role in natural ventilation, so one of the reasons for the highest energy savings in Tabriz could be related to high wind speed.

Nomenclature

P	Pressure (Nm^{-3})
V	Velocity of airflow (ms^{-1})
g	Gravity acceleration (ms^{-2})
y	Elevation (m)
k	Constant value depending on the terrain type (n.d.)
a	Constant value depending on the terrain type (n.d.)

z	Height of the reference point (m)
C_p	Pressure coefficient (n.d.)
C_d	Discharge coefficient (n.d.)
$\dot{m}$	Airflow (kgs^{-2})
Y	Height of neutral plane (m)
H	Height of the openings (m)
W	Width of the openings (m)
C_{p0}	Pressure coefficient when the wind angel is zero (n.d.)
U_{ref}	Local wind speed (ms^{-1})
U_{wind}	Measured wind speed by the meteorological station in a standard height of the 10m in an open field (ms^{-1})
G	Natural logarithm of the ratio of the width of the wall with an opening to the width of the adjacent wall (n.d.)
Subscribes	
n	Entry node
m	Exit node
0	Reference elevation ($y = 0$)
w	wind
Greek symbols	
ρ	Air density (kgm^{-3})
θ	Wind angle,
Abbreviations	
NPL	Neutral Pressure Plane

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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