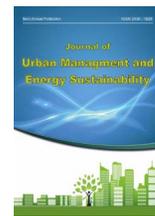


Journal of Urban Management and Energy Sustainability (JUMES)

Homepage: <http://www.ijumes.com>



ORIGINAL RESEARCH PAPER

Indoor thermal comfort and high residential buildings (Case study: two high-rise buildings in two different microclimates in Tehran city)

Mehdi Khakzand*, Saeid Chahardoli

School of Architecture and Environmental Design, Iran University of Science and Technology, Tehran, Iran

ARTICLE INFO

Article History:

Received 2021-05-14

Revised 2021-10-07

Accepted 2021-11-10

Keywords:

Cross ventilation

Computational Fluid Dynamic

Solar chimney

Microclimate

Residential buildings

ABSTRACT

Thermal comfort in the building sector is a major concern, especially in high residential buildings which have become common in cities. In this regard, an adequate ventilation strategy can be an alternative technique to create better thermal conditions in these buildings. The impacts of microclimates in cities have also been taken into account recently to determine their influence on indoor thermal conditions. This study aims to investigate thermal comfort in two high-rise buildings located in two different microclimates (Artesh highway and Mojahedin Eslam Street) in Tehran with the use of cross ventilation to determine the impacts of NV and Microclimates on the level of occupant thermal comfort. In addition, Solar Chimney (SC) systems are installed on buildings to enhance NV through buildings via buoyancy forces, and the CFD method is employed to simulate cross ventilation and SC in these buildings. Furthermore, the occupants' level of thermal satisfaction is investigated by conducting a survey. The results indicate that SC can decrease approximately 2 °C of room temperature by boosting NV which improves the thermal comfort zone inside the houses. According to the survey, 23.1% and 7.5% of residents are respectively dissatisfied with the non-response of the cooling system and the stillness of the air. Hence, the use of SC can significantly increase indoor thermal comfort zone and residents' satisfaction.

DOI: [10.22034/JUMES.2021.553631.1075](https://doi.org/10.22034/JUMES.2021.553631.1075)

Running Title: Indoor thermal comfort and high residential buildings



NUMBER OF REFERENCES

42



NUMBER OF FIGURES

5



NUMBER OF TABLES

19

*Corresponding Author:

Email: mkhakzand@iust.ac.ir

Phone: +9821-77240467

ORCID: <https://orcid.org/0000-0001-9390-3433>

1. Introduction

In the contemporary world, hasty population growth and urbanization have led to raise energy demand all over the globe. Although saving energy is a critical matter in everyday life, maximizing human comfort is another important issue for highly populated cities and metropolitans. One of the most important elements of comfort is the sense of convenience and relaxation at home and in offices. Doubtlessly, thermal comfort is the most essential parameter in our state of living. Whether in the hot summer times, where home cooling becomes a great and energy consuming need or in the cold winters when heating is critical, the design of houses and buildings becomes crucial to provide a reasonable degree of thermal comfort with minimum consumable energy (Monghasemi and Vadiiee, 2018). Moreover, thermal comfort is one of the most immediate necessities of modern buildings and also for people who live in them. While it is an important parameter for users, it could lead to great energy savings especially in high-rise buildings (Aflaki et al., 2016). Recently, the configuration of the buildings, especially the high-rise structures has been designed in a way that NV would lead to energy saving and desired thermal comfort. Typically, buildings are affected by environmental parameters such as wind speed, air pressure, and density (Lotfabadi, 2014). However, the intensity of its impact is different from area to area owing it to climate diversity. One of the most significant parameters for NV is climate which shows whether NV is possible or not because in some areas NV is almost implausible. Arid climates in the world like Middle East because of large diurnal temperature range have a great potential for night ventilation (Chen et al., 2017; Lotfabadi, 2014). Besides, in beach cities, temperature and humidity play a significant role for NV simultaneously (Tong et al., 2017). Moreover, in most climate types, night ventilation strategies have been shown that are practical (Solgi et al., 2018). In addition, NV due to the pressure difference leads to increase air velocity and; therefore, ventilation creates a comfortable internal microclimate inside a building and saves energy by reducing the use of mechanical ventilation (Baxevanou et al., 2017). Acceptable rate of thermal comfort using NV is higher than mechanical HVAC

systems (Kumar et al., 2021). Additionally, NV leads to increase indoor air velocity and; consequently, it provides a comfortable area for users (Schulze and Eicker, 2013). However, the performance of NV can be adversely affected by some obstacles such as strip apartments in rows, high-rise buildings with large podium bulk and enclosed city blocks (Guo et al., 2017). NV is also reliable on local climate conditions and experimental settings (Zhang, Yang, et al., 2021). For example, in warm climates, single-sided ventilation has the poorest function in providing thermal comfort (Ahmed et al., 2021). Designers have employed some strategies in order to fortify NV. One of the most common strategies is exploiting ventilation shafts within the high-rise buildings as an efficient and energy saving method to achieve desired level of thermal comfort in tall residential buildings (Prajongsan and Sharples, 2012). Another strategy which has been used in high-rise buildings is using SC in order to improve NV due to the direct correlation between airflow distribution and the wall- SC (Park and Battaglia, 2015). However, it's concluded that the height of the chimney, width and heat flux have a significant impact on the function of the SC (Layeni et al., 2021). As the height of the chimney increases, the capacity of the ventilation experiences a rise in amount. The same occurs to the ventilation rates when the air inlet is moved upwards (Zhang, Tao, et al., 2021). It is also considered that ventilation has a remarkable impact on the recent COVID pandemic as well. Therefore, SC with different configurations in different climates is being observed. In Hong Kong, a single SC ventilator (SVC) with different tilt angles was examined and the observations showed that various tilt angles in different times of the day can enhance the performance of the SCV (Cao et al., 2021). Some features called "Phase Change Materials" (PCMs) are exploited to save thermal energy or control the temperature variation in a certain range (Kasaeian et al., 2017; Souayfane et al., 2016; Wang et al., 2019). Employing the PCM storage in SC can ameliorate the free ventilation in the evening and night (Rashidi et al., 2021). Moreover, the design of the chimney can enhance rate of the ventilation in almost every hour of a day in an actual building (He et al., 2021). Furthermore, the performance of SC is based on some fundamental points such

Table 1. Summary of the reviewed articles

Authors and publish date	Concern	Location	Methodology	Simulation software
[Dong-XueZhao Bao JieHe (2017)]	Effect of architectural shapes on wind pressure distribution especially on tall buildings.	-	Measurements, model geometry and computational domain, simulation	CFD
[Wei You Jialei Shen Wowo Ding (2017b)]	The remarkable impact of height on NV	China	Building configuration description, simulation	ANSYS-Fluent CFD
[Wei You Jialei Shen Wowo Din, (2017a)]	The noticeable effect of building parameters as: length, spacing and stagger placing of building on NV	China	Building configuration description, measurement, simulation	CFD
[Pimolsiri Prajongsan*, Steve Sharples (2012)]	Enhancing NV and thermal comfort by using ventilation shaft.	Thailand	evaluated the ventilation shaft's ability, simulation	CFD
[Shakila Pathirana - Asanka Rodrigo-Rangika Halwatura (2019)]	Direct correlation between thermal comfort and building features like: building shape, orientation.	Tropical area	Case study models, simulation	CFD
[Sara Omrani, Veronica Garcia-Hansen, Bianca R. Capra, Robin Drogemuller (2017)]	In comparison with single-sided ventilation, cross ventilation operation was found to lead to more comfort zones for indoor thermal conditions.	Australia	Utilizing a case study and evaluating indoor thermal comfort, measurement	-
[Wang Liping and Wong Nyuk Hien (2007)]	Developing façade design in order to increase indoor air velocity and subsequently thermally comfortable	Singapore	Climatic environment analyses. ASHRAE Standard, measurement	-
[Jun Cheng, Dahai Qi, Ali Katal, Liangzhu (Leon) Wang, Ted Stathopoulos (2018)]	The correlation between critical ventilation coefficients and factors such as wind incidence angles and building heights for reducing energy consumption.	Canada	The empirical formulas and series of simulations	CFD
[Catherine Baxevanou, Dimitris Fidaros, Aris Tsangrassoulis (2017)]	Creating a comfortable internal microclimate inside a building and saving energy by NV	Europe	Experimental measurements in wind tunnel, simulation	CFD
[Xudong Cheng, Long Shi, Peng Dai, Guomin Zhang, Hui Yang, Jie Li (2018)]	The design of SC has been examined on a reduced platform to optimize smoke exhaustion and NV	-	Experimental procedure and scenarios, measurement system	-
[S. Omrani, V. Garcia-Hansen, B. Capra, R. Drogemuller (2017)]	Proposing a model to evaluate the integration of NV design into the overall building design for multi-story constructions.	-	Analytical and empirical methods, computational simulation, experimental methods	CFD
H. Zhang, D. Yang, V. W. Y. Tam, Y. Tao, et al. (2021)	The effectiveness of combined NV strategies in building design	-	Review	-
[Till Pasquay (2004)]	Double façade configurations have a desirable effect on NV in high-rise buildings	Germany	Measurement, comparative, simulation	CFD

Continued Table 1. Summary of the reviewed articles

Authors and publish date	Concern	Location	Methodology	Simulation software
[James O.P. Cheung, Chun-Ho Liu (2011)]	NV in high rise buildings is sensitive to wind direction, and building disposition.	-	Experimental measurements, simulation	CFD
[Chaobin Zhou, Zhiqiang Wang, Qingyan Chen, Yi Jiang, Jingjing Pei (2014)]	Optimizing NV in high-residential buildings by adjusting building orientation, creating wind path into internal zone.	China	Field measurements, simulation	CFD
[Ardalan Aflaki, Norhayati Mahyuddin, Mohamad Rizal Baharum (2016)]	Building orientation and height are significant for ventilation in high-rise buildings.	Tropical climate (Malaysia)	Analyzing data, SPSS (statistical package for social science) , simulation	CFD
[Fei Guoa, Peisheng Zhu, Shiyuan Wang, Dongwen Duan and Yun Jin (2017)]	NV performance is being hampered by strip apartments in high-rise buildings with large podium bulk	China	Numerical simulation analysis of morphology optimizing	CFD
[D.J. Harris , N. Helwig (2007)]	Increasing the efficiency of such structures on south-facing buildings by SC inclination angle	-	Climate studied calculation procedure, simulation	CFD
[M.A. Hosien S.M. Selim (2017)]	Parameters such as incident solar radiation and wind dimensions of the SC height influence the performance of SC	Egypt	Measurements, description of the system and model approach, simulation	CFD
[A.B.Kasaeian , Sh.Molana , K.Rahmani , D.Wen (2017)]	Large- scale SC due to economical beneficial is more acceptable than small sizes	Iran	Experimentally and theoretically, simulation	CFD
[Long Shi, Guomin Zhang, Wei Yang, Dongmei Huang, Xudong Cheng, Sujeeva Setunge (2018)]	Parameters such as configuration and installation conditions affect the performance of SC	-	Statistics of experimental studies	Mathematical models
[Francine Battaglia (2015)]	The correlation between air flow distribution and the wall-solar chimney	-	Numerical Methodology, simulation	CFD software ANSYS FLUENT
H. Zhang, Y. Tao, K. Nguyen, F. Han, J. Li and L. Shi (2021)	Studying the airflow characteristics inside a wall SC with various configurations in multi-zone buildings	-	Numerical (and Experimental)	FDS (Fire Dynamics Simulator) and experimental model
Y. Cao, F. Aldawi, N. Sinaga, H. Moria, H. S. Dizaji and M. Wae-hayee. (2021)	Investigate the applicability of a single SC ventilator from ventilation, electrical energy consumption and environmental viewpoints	Hong Kong	Experimental and Numerical	ANSYS Fluent 18.1 Designing a 3D Model of a SC
S. Rashidi, J. A. Esfahani and E. Hosseinirad (2021)	Evaluated the progress related to the exploitation of PCMs in SC power plants	-	Review	-
G. He, Q. Wu, Z. Li, W. Ge, D. Lv and L. Cong (2021)	Examine the potentials of a SC in an actual house	Hangzhou	Field Performance and Literature Review	-

as geometrical and operational parameters. For instance, incident solar radiation, inclination angle, ambient temperature, wind speed, material usages and dimensions of the SC height are crucial parameters being employed (Harris and Helwig, 2007; Hosien and Selim, 2017; Shi et al., 2018).

Based on the above table, we can pick out some worthwhile information about NV projects which take place in the whole world. First, Southeast Asia is one of the most common zones in the entire world where have been done numerous studies on NV in high-rise buildings by researchers, since high-rise buildings have tremendous potential for NV. Moreover, Tehran as a metropolitan is favorable for NV due to the large diurnal temperature range during summers, and the number of high-rise buildings has been increased. For this purpose, two high-rise buildings, located in two different places in Tehran, were chosen while both use cross ventilation. Second, one of the most popular methodologies for researching the NV field is experimental tests and simulation as well. Third, Computational Fluid Dynamics (CFD) is one of the most favorable methods to simulate NV, indoor air quality, and stratified ventilation since they are a little bit hard to be predicted with other models. For calculating indoor thermal comfort in the two high-rise buildings, temperature and relative humidity were measured by Dataloggers. After that, 50 LEED surveys were conducted from the residents to investigate the impact of building direction on residents' satisfaction. Lastly, an SC was added to each building to calculate how it can boost NV and decrease indoor temperature. The turbulent flow is simulated by RNG $K-\varepsilon$ model, and also Discrete Ordinates (DO) model is employed to calculate incident radiation.

2. Material and Methods

In this section, for calculating the effects of two different microclimates in Tehran city and SC on occupants' thermal comfort, firstly the microclimate data of Tehran collected from the climatic conditions of the Mehrabad synoptic station is used as the nearest station to both study areas of buildings. Then, governing equations for the fluid flow inside buildings and radiation is studied. Third, two selected buildings which are located in two different places are described.

Besides, in each building, one room from the fourth floor is selected then Data Loggers are employed in order to collect temperature and wind velocity data from the rooms. Then, conditions inside the rooms were performed using CFD simulation in Ansys software 18.2 (Ansys, Inc. Canonsburg, PA, USA). Lastly, a survey based on LEED occupant comfort is created, and it is filled by both residential buildings' occupants.

2.1. Microclimate data

The city of Tehran is located at 51 degrees and 6 minutes to 51 degrees and 38 minutes east longitude and 35 degrees and 34 minutes to 35 degrees and 51 minutes north latitude and its height above sea level is between 1800 meters in the north to 1200 meters in the center and 1050 meters in the south is variable. Tehran is located between two mountain and desert valleys and on the southern slopes of the Alborz Mountain range. The amount of rainfall in Tehran is mostly low, measuring 245.8 mm during the year and the number of frosty days is 36 days per year. In 45 years, the highest temperature in Tehran is 43 degrees Celsius and the lowest temperature is -15 degrees Celsius. The average relative humidity in Tehran was 40% and in Shemiran 46%. The prevailing wind in Tehran is from west (270 degrees) and its average speed is 5.5 meters per second. At night, a cool breeze blows down from the mountain (mountain wind) and during the day, a reverse breeze blows from the plain (plain wind). Due to the foothills of Tehran and its large size, this city has a variety of climates in different parts of the city. Based on this, 2 buildings in 2 different parts of the city were selected and the NV of these 2 buildings on a summer day was evaluated. The reason for evaluating on a summer day is that given the climatic conditions of the area, this is the best time to properly evaluate NV. Additionally, according to the climate data in Table 2 maximum average temperature is related to June, July, August and September.

2.2. Numerical model

A numerical model is developed to simulate the turbulent flow, energy and the radiation associated with the solar chimney. The simulation is utilized to solve steady state governing equations of mass, momentum, energy conservation and

Table 2. Annual frequency of average temperature, relative humidity, average air velocity, Tehran, Iran.

Month	January	February	March	April	May	June	July	August	September	October	November	December
Average temperature °C	3	4	10	16	21	28	29	30	25	17	11	5
Relative humidity%	60	56	49	38	34	21	25	24	25	38	49	62
Average air velocity m/s	2	2	3	4	3	3	2	1	2	3	2	1

the equation of radiation for the 3D flow domain of the room and the solar chimney. The steady state governing equations were solved using the CFD solver FLUENT 18.2. SIMPLE Algorithm is employed to treat the pressure-velocity coupling.

At the inlet and the outlet of the chimney, atmospheric pressure condition was imposed. The two walls of the channel were put under mixed boundary conditions. The interior surface (to the building) of the wall was assumed to have a mixed boundary condition with the room at constant temperature of 298 K. The mathematical modelling of the flow and the temperatures inside the chimney involved solving the Reynolds Averaged Navier-Stokes (RANS), the energy equation and the radiative transfer equation within the domain. In addition, the Discrete Ordinates (DO) model is used as the applied radiation model. The DO resolving the Radiative Transfer Equation (RTE) is an appropriate model for semi-transparent material' s simulation. The mathematical models can be driven as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \cdot \vec{V}) = 0 \tag{1}$$

Eq. (1) Shows Continuity equation.

$$\frac{\partial}{\partial t} (\rho \vec{V}) + \nabla \cdot (\rho \vec{V} \vec{V}^T) = -\nabla p + \nabla \cdot \left(\mu \left[(\nabla \vec{V} + \nabla \vec{V}^T) - \frac{2}{3} \nabla \cdot \vec{V} I \right] \cdot \vec{V} \right) + \rho \vec{g} \tag{2}$$

Eq. (2) Presents Momentum equation, and also Energy equation is:

$$\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\vec{V} (\rho E + P)) = \nabla \cdot \left(\left(K_{eff} \nabla T - e \vec{j}_j + \left(\mu \left[(\nabla \vec{V} + \nabla \vec{V}^T) - \frac{2}{3} \nabla \cdot \vec{V} I \right] \cdot \vec{V} \right) \right) \right) + S_h \tag{3}$$

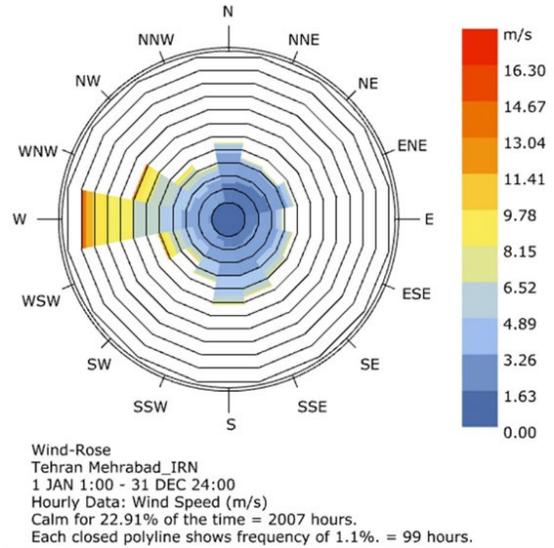


Fig. 1. Wind rose for annual frequency percentages, Mehrabad, Tehran

2.3. Building description in Tehran city

In recent years, high-rise buildings (more than 10 floors) have become popular. Therefore, two high-rise buildings were selected, one in the northeast and the other in the southeast. In order to make a comparison of these two buildings, the last floor units of each building were examined, and also both are southern units.

In the path of the sun (Figure 3), the only front that is optimally exposed to radiation in winter is the southern front. In summer, radiation from the west and east adversely helps to heat the building.

Figure 4 shows the high-rise building also known as Royal Complex which is located near the Artesh highway, in the north-eastern parts of Tehran city. On the other hand, the Behnam tower

is located on the Mojahedin Eslam street, in the south-eastern part of the city.

2.4. Data acquisition and experimental layout

Data loggers were installed in the units in the middle of summer because at this time of year we have the highest energy consumption for cooling homes. The data logger was placed on

the fourth floor of both buildings, 12:30 to 2 pm, the cooling systems of both stories were turned off, and windows were opened according to calculate the effect of natural ventilation through houses. The purpose of this was to measure the wind speed and air temperature inside the units using NV. Since these two buildings are located in two different parts of the city, the amount of

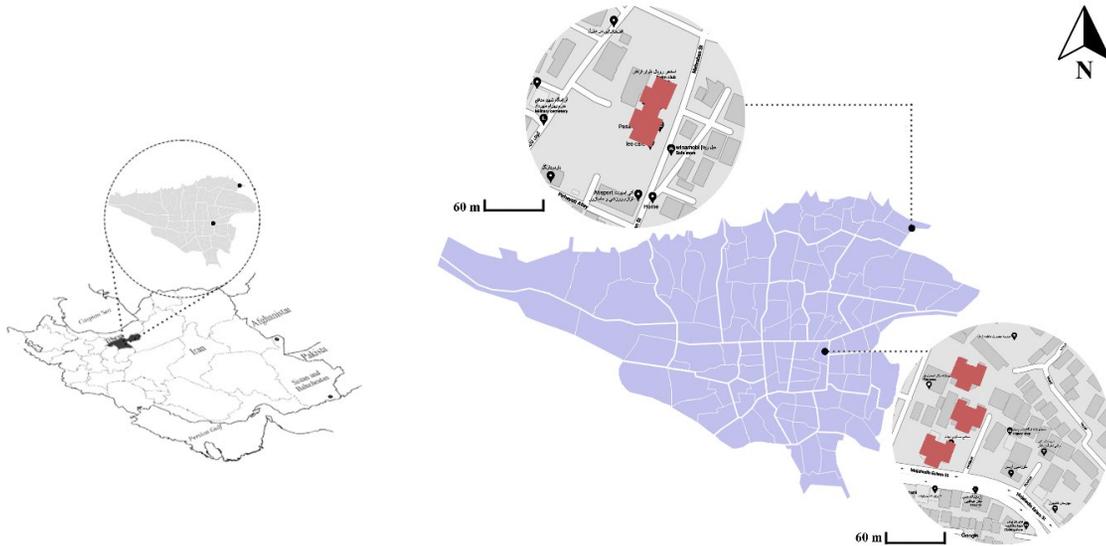


Fig. 2. The location of the buildings in Tehran- Iran. The Royal Tower (left), and the Behnam Tower (right)

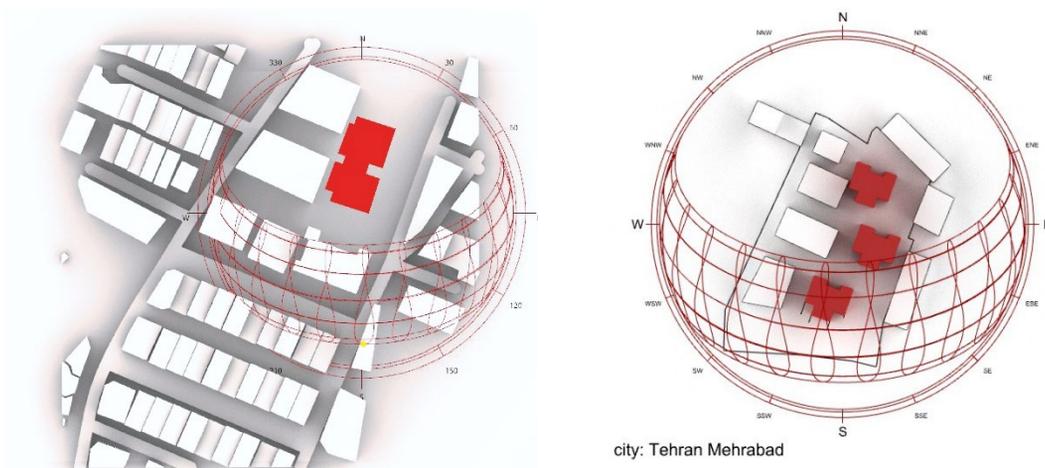


Fig. 3. Sun path Analysis of the Royal Tower (left), and the Behnam Tower (right).

Indoor thermal comfort and high residential buildings



Fig. 4. View of the buildings, the Royal Tower (left), and the Behnam Tower (right).



Fig. 5. Data logger for collecting data at both rooms

wind and ambient temperature were different from each other. Both data loggers were located in the southern part of the unit and the living room. It is also important to note that they are not exposed to direct sunlight and are not located near the windows. The high-rise building has relatively more open environment, which means that its ventilation potential is better than the building which is surrounded by other buildings. The outside temperature was 35 degrees Celsius and the wind speed was 3 meters per second, according to the meteorological station. The wind entered both rooms with a speed of about 3 meters per second from the northern window, due to the openness of the rooms and the openness of the southern window, the airflow entered the living room.

2.5. Occupant Thermal Comfort Survey

LEED uses ASHRAE thermal comfort to judge the thermal comfort of the occupants and if more than 20% of them are dissatisfied, the owner must prepare a corrective plan. Zarrabi et al. (2017) studied the thermal comfort of 500 occupants of an office building through an LEED survey in North Carolina and conducted that occupant surveys can prepare a systematic measure to evaluate

office spaces and increase the thermal comfort. A thermal comfort questionnaire was taken for the residents of the two studied buildings (two high-rise buildings). The questions of this questionnaire were extracted from the thermal comfort survey form of LEED residents (Altomonte and Schiavon, 2013; Lee, 2011; Lee and Guerin, 2009). The purpose of this study was to evaluate the thermal comfort of building occupants indoors. Poll questions help the performance of indoor ventilation rates. The results help to evaluate the improvement of thermal comfort conditions for the occupants of the building.

3. Results

3.1. Survey's data

After surveying the residents, we compared the results and these are the outcomes: Table 3 shows 85% of the residents of buildings with a medium height, and also 80% of the residents of the Royal Complex (northeast of the city) were satisfied with of the temperature of their house. Among people who were not satisfied with the temperature of their house, they stated the reasons for their dissatisfaction as follows. 5% who were the residents of Royal Complex stated that their reason was the stillness of the air. 5%

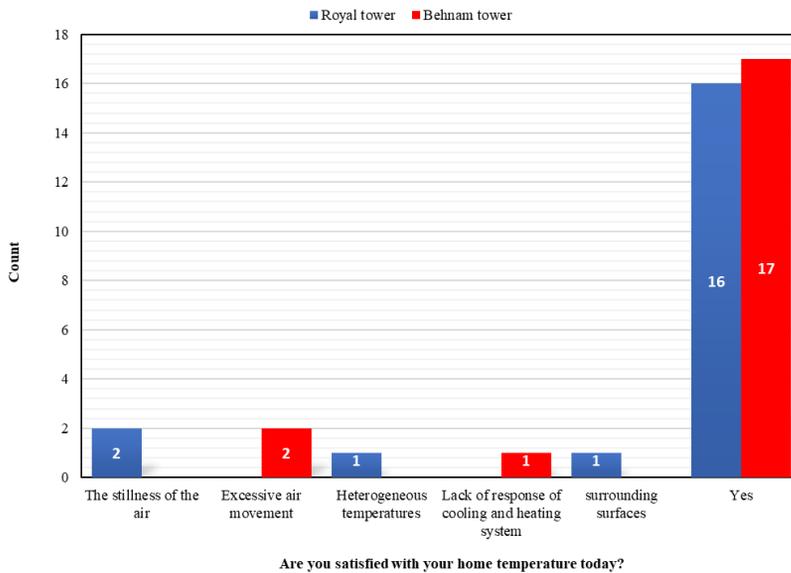


Fig. 6. Frequency distribution comparing the residents in terms of satisfaction or dissatisfaction today with the temperature of the house and stating the reason for dissatisfaction

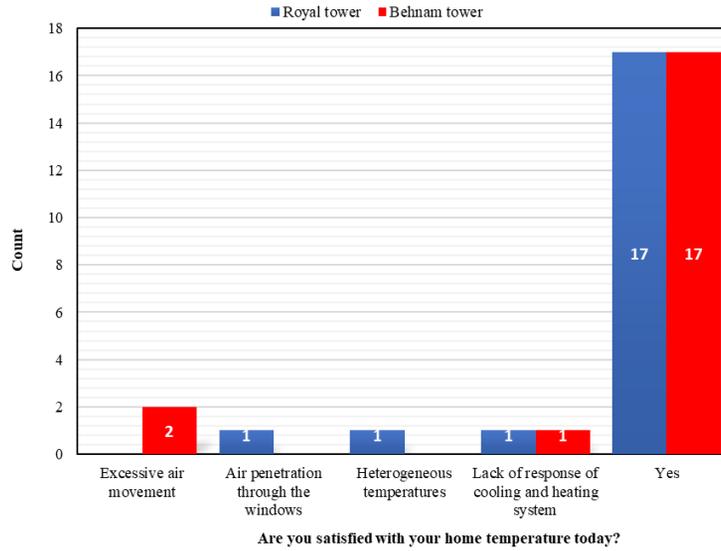


Fig. 7. Frequency distribution comparing the residents in terms of satisfaction or dissatisfaction today with the temperature of the house and stating the reason for dissatisfaction

who lived in buildings with medium height stated that their reason for dissatisfaction was the high amount of movement of the air. 2.5% who lived in the Royal Complex attributed the heterogeneous temperature. 2.5%, who lived in buildings with medium height were dissatisfied with the temperature of their house due to non-response of the heating /cooling systems. 5%, who lived in the Royal Complex said that the reason for their dissatisfaction was the surrounding surfaces.

According to the information in Table 4, in both types of buildings (high-rise buildings and mid-rise buildings), the residents were 85% satisfied with the temperature of their house in the cold seasons. Among those who were dissatisfied with the temperature of their home in the cold seasons. 5% living in medium-height buildings attributed the excessive air movement. 2.5% who were the residents of the Royal Complex attributed the infiltration of air from the windows. 2.5% living in Royal Complex were dissatisfied with the temperature of their house in the cold seasons due to the heterogeneous temperature. 5% said that the reason for their dissatisfaction was the non-response of the heating /cooling system, which was in both types of buildings.

According to the question “in warm-season are you satisfied with the temperature of your

house?”, the satisfaction rate for the residents of the Behnam building and the residents of Royal Complex who were satisfied with the temperature of their house in hot seasons account for 2.36% and 75%, respectively. Among people who were dissatisfied with the temperature of their house in hot seasons, 23.1% stated that the reason was the non-response of the cooling/heating system, the majority of which lived in buildings with medium height, and 7.7% are the residents of Royal Complex said that the reason was the level of surrounding surfaces.

According to the information in Table and Chart (4), most people have reported that windows were used to obtain ventilation (19 people for Behnam Tower and 14 people for Royal Tower). The number of people stating this in Behnam Tower is more than Royal complex (1 person for Behnam tower and 5 people for Royal Tower).

Based on these results, we proposed 2 hypotheses and examined them according to the results of the questionnaire

Hypothesis 1: There is a significant difference in the level of satisfaction with NV of the building occupants. The results of Mann-Whitney test to compare the average ranking of residents’ satisfaction with NV of the residential building and it’s also achieved that the P-Value of the

test is 0.76 and above 0.05. As a result, the research hypothesis is rejected and the level of residents' satisfaction with NV in buildings is not significantly different and is at the same level. The data in Table 5 show that the average rank of the occupants of buildings with an average height of 20 is close to the average rank of the occupants of Royal Complex with 21.

Hypothesis 2: There is a significant difference in the level of satisfaction with NV among the residents based on the floor in which the residents live in the complex.

The results of Kruskal-Wallis' s test to compare the average rate of residents' satisfaction with NV of the building based on their residential floor and based on the information in Table 6, it could be the significance level of the test is 0.72 and above 0.05. As a result, the research hypothesis is rejected and the level of residents' satisfaction with the natural air conditioning in the building does not differ significantly based on their residential floor and is at the same amount. The data in Table 6 show that the average rank of residents' satisfaction in floors up to 5 floors is 18.93 and close to the average rank of residents' satisfaction in floors 6 to 10 is 21 and close to the average rank of residents' satisfaction in floors 11 to 15 is 22.57. As a result, the floor in which

the residents live does not affect the residents' satisfaction with NV in the complex.

3.2. Ventilation performance in rooms

As shown in the picture, the wind speed increased slightly when leaving the room. The greatest increase in wind speed occurs in the front part of the kitchen counter because due to its location and shape, it causes the wind to be directed to that area more. Furniture and arranging home appliances are also applied in simulation. Moreover, the geometry of the plan affects the air circulation inside the unit, as we can see in Figure 6, the wind changes its direction due to the location of the walls and in some areas causes a vortex, which is not acceptable for the thermal comfort of the residents.

Around the southern window, due to direct sunlight, we see a decrease in air concentration, so this area has different pressures. On the other hand, the air temperature under the window is much higher than other areas. In the building located in the northwest of the city, like the first building, the data logger was placed in the south of the unit, and the windows were opened as shown in Figure 7, so that the air could flow naturally. According to the meteorological station, the air temperature flowing through the windows is 32

Table 3. Ranking of residents' satisfaction with NV in the complex

Variable		Number	Average ranking	Total rating
Residents' satisfaction with NV in the complex	Behnam Tower	20	20	400
	Royal Complex	20	21	420
	total	40		

Table 4. Ranking of the residents' satisfaction based on the residents' floor in the complex

Variable		Number	Average Ranking
Satisfaction of residents based on the residents' floor in the complex	up to level 5	15	18.93
	level 6 to 10	18	21
	level 11 to 15	7	22.57
total		40	

Table 5. Table of statistical results of the Kruskal-Wallis's test

Results	Satisfaction based on the resident floor of the complex
Test value	0.63
P-Value	0.72

°C and the wind speed is 3 meters per second. The southern windows have a much higher temperature than the northern windows due to exposure to direct sunlight, and this temperature difference causes the airflow to occur.

According to Figure 8, the air temperature under the windows reaches about 40 °C, while the temperature of the northern windows is about 27 °C. An increase in temperature causes an increase in the movement of air molecules.

Due to the closure of the southeast window, the air moves diagonally from the northeast of

the unit to the southwest. As can be seen in the image below, the highest wind speed occurs in the middle of the unit. In general, the airflow condition in this unit is acceptable.

3.3. Ventilation with SC

In this article, after examining the current condition of the two buildings, an SC is recommended for both. The results of the new design simulation will be compared with the current situation. The purpose of this proposal is to improve the airflow inside the house, so that

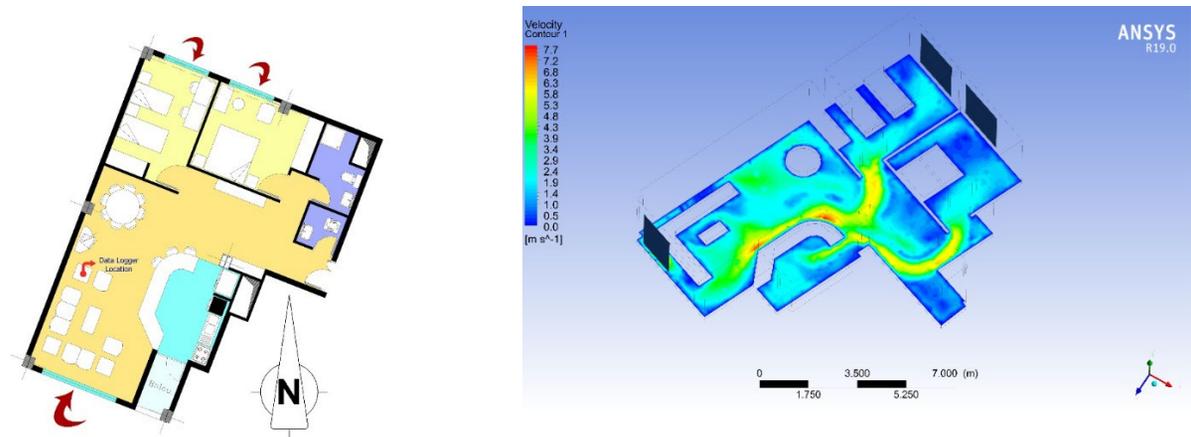


Fig. 8. Plan of one unit of Royal Tower on the left- the simulation of wind flow inside the unit on the +1 m right

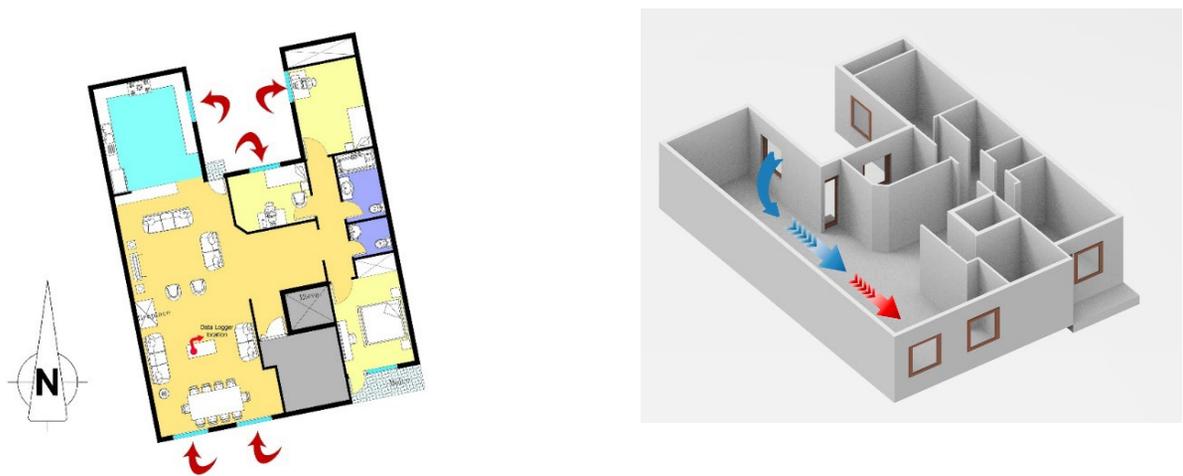


Fig. 9. Cross-ventilation in a unit of the Behnam Tower building

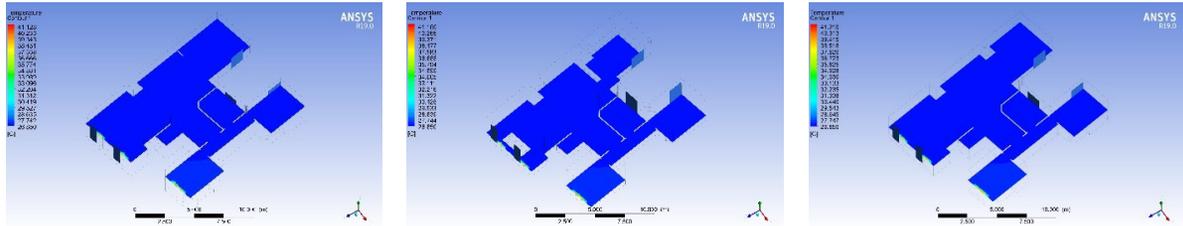


Fig. 10. Section temperature contour from three different section at x/z plan 0.7, 1.5, and 2 m.

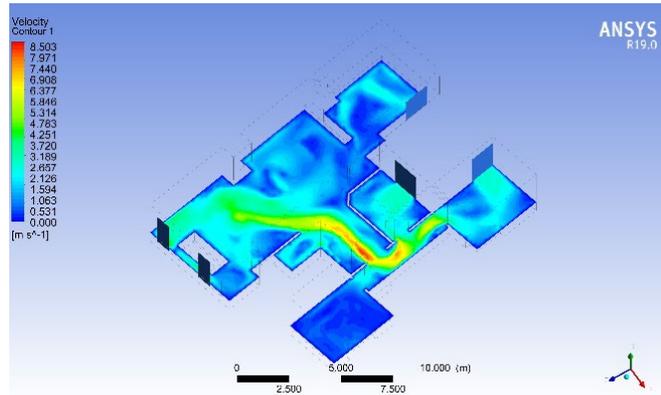


Fig. 11. Velocity contour of the Behnam Tower at 0.7 m high

adequate airflow causes the thermal comfort of the residents. The airflow is mainly due to the pressure difference between the two spots and the air moves from high-pressure areas to low-pressure ones. The southern window of the unit is exposed to direct sunlight, on the other hand, the northern window is in the shade, therefore, we see different temperatures between these two windows, followed by airflow. After receiving the information from the loggers, the simulation of two units in ANSYS software 18.2 was started immediately and the simulation results were compared with the data of the data loggers. In both units, there is a relative convergence between the simulation results and the data logger information. After this step, an SC is proposed for each building in the southern part of the building according to the pictures below.

After adding the SC, we check the air concentration in the new condition and compare it with the air concentration when there is no SC. The chimney inlet is located in the upper



Fig. 12. The illustration of Royal Tower after adding SC

part (below the ceiling of each floor). We set the simulation exactly the same as the day we left the data logger at home, on a sunny summer day when

the temperature is around 32 °C from 1:30 to 2:30 pm. Figure 11a shows the air concentration in the house without a chimney (current state). Figure 11b shows the air concentration in the house with the integrated SC. As shown in the picture, the concentration of air inside the chimney due to being under direct sunlight is about 1.1557 kg/m³ and is less concentrated than in other areas of the house. Other areas have concentrations between 1.1734 and 1.1787 kg/m³, and as we move away from the chimney, the air concentration increases.

It's obvious that due to the different heat capacities of different materials, they behave differently towards heat reflection. For instance, the wind on the beach during the day is from the sea to the land because the heat capacity of water is higher than the sands of the beach. This means that the beach heats up faster than water. Figure 12a is related to the air pressure in the

0.4 Pa contour. As we can see, the air pressure inside the chimney is lower than other areas due to the low concentration of air. When the air pressure decreases, the wind speed increases. It is necessary to mention that in this output, the purpose is to reduce the pressure compared to the normal pressure. Therefore, the air pressure is 0.55 Pascal less than the normal atmospheric pressure. Figure 12b shows air pressure status without an SC at the same section which shows lower pressure than Figure 12a.

Now we check the temperature inside the house. As shown in Figure 14, the indoor air temperature varies between 26.3 to 27 degrees. When we compare this temperature with the data obtained from the data logger, we see that the air temperature has decreased by about 2 degrees Celsius with the addition of the SC. This amount of temperature variation can also be altered by

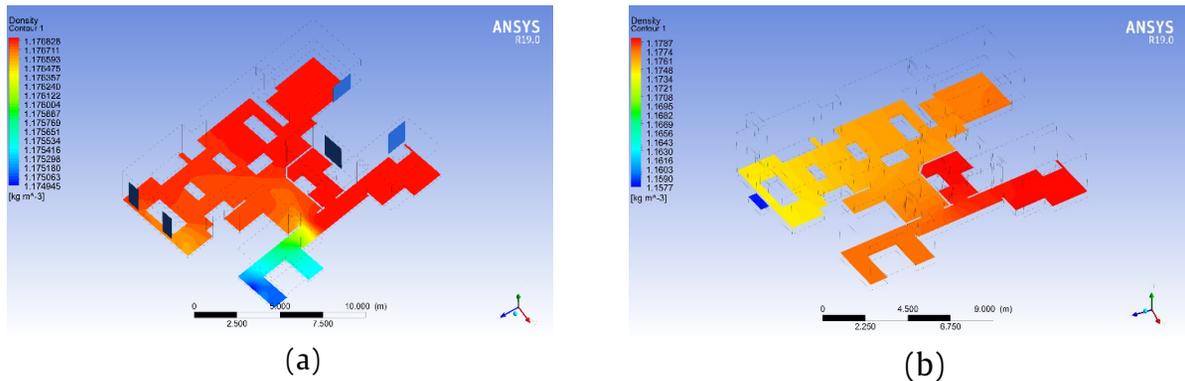


Fig. 13. Density contour plot at mid-rise building's house in 0.7 m plan height.

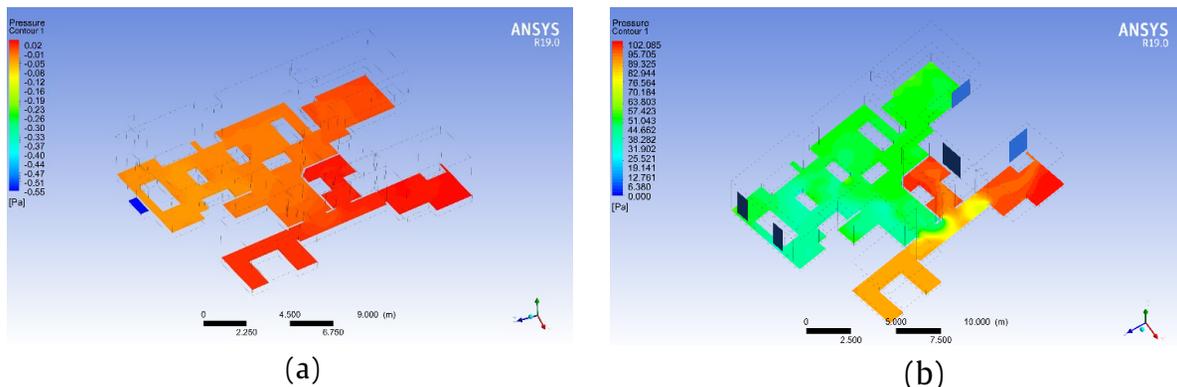


Fig. 14. Pressure contour plot in Behnam Tower's house in 0.7 m plan height.

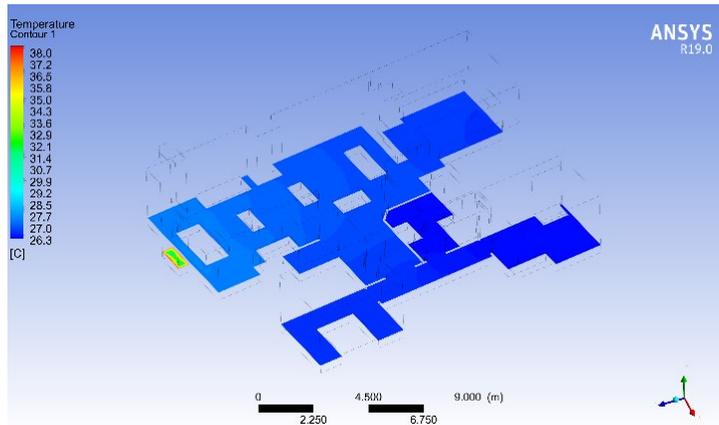
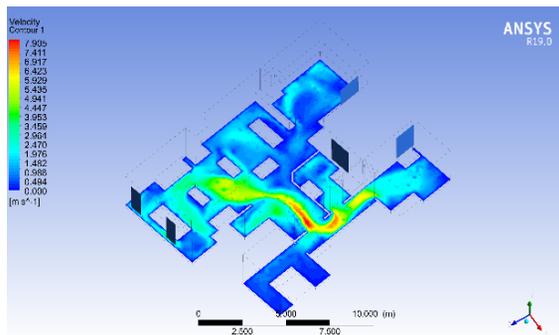
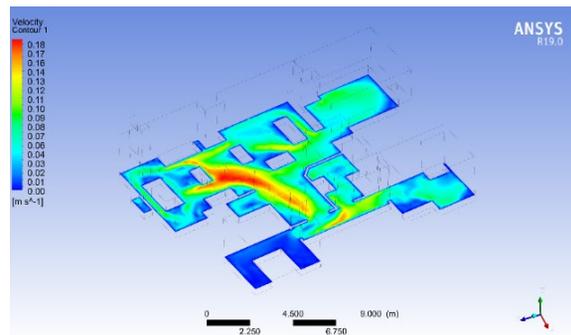


Fig. 15. Air temperature plot at Behnam Tower's house in 0.7 H plan height.



(a)



(b)

Fig. 16. Velocity contour plot at Behnam Tower's house in 0.7 m plan height.

changing the dimensions of the chimney.

Figure 14a and b are related to the wind speed inside the house. The comfort range of wind speed for humans is between 0.3 to 0.7 meters per second. If air comes through the windows into the house, the wind speed also increases, so, as the wind speed increases, the air temperature inside the house decreases. The wind speed inside the SC with the increase of height gradually increases. Compared with Figure 14b which shows the wind velocity without the SC, with the addition of the SC the wind speed increases in a large part of the house.

The purpose of adding an SC is to improve the thermal comfort of residents. Although it is possible to increase the air velocity inside the house by increasing the dimensions of the

chimney, increasing the wind speed causes inconvenience for the residents, and as a result, our main goal, which is to improve the thermal comfort of the residents, is questioned. Therefore, it does not make sense to increase the wind speed at any cost. 2.4 Contour is an important contour, according to figure 17, the temperature is in the range of 26 °C, which is in the normal range for human comfort at this time of the year (summer). It should be noted that the height of the SC is considered 3m higher than the roof of the last floor. The reason for this is to comply with city rules and regulations. If we raised the height of the SC, we could increase the wind speed and as a result, the temperature inside the house would decrease more.

The air concentration decreases from north to

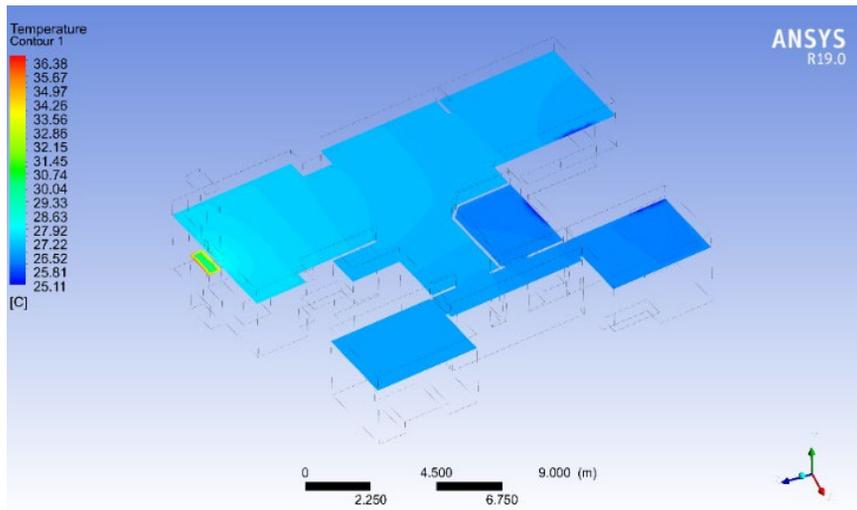


Fig. 17. The temperature distribution inside the house

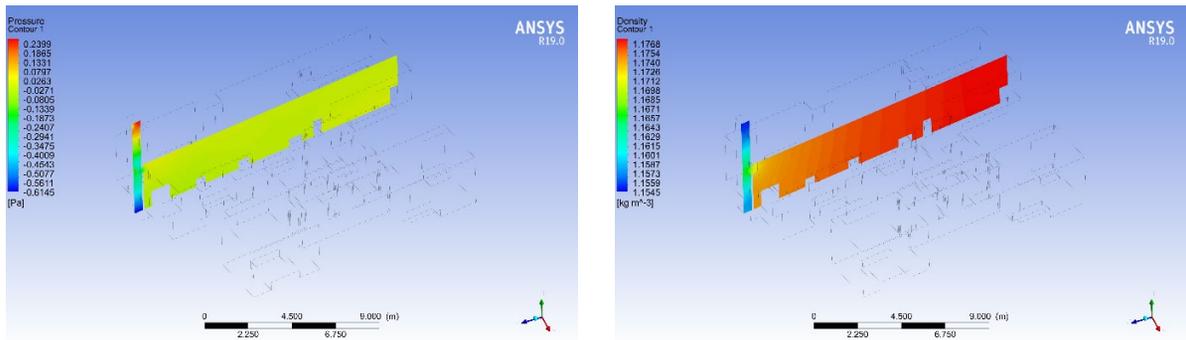


Fig. 18. The picture of pressure distribution on the left and density contour on the right

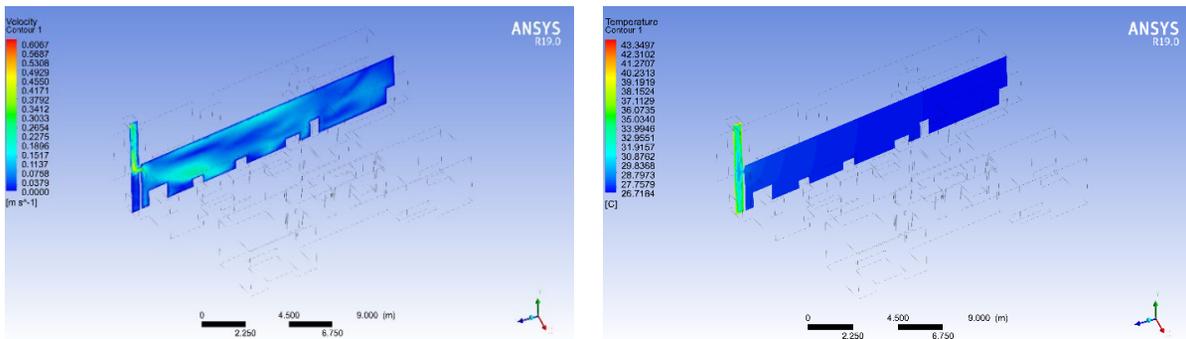


Fig. 19. Wind speed and temperature inside the house and the chimney

south of the house. While inside the chimney from bottom to top, the concentration is first low, then gradually increases until it reaches the chimney cavity, then the concentration decreases. The same occurs inside the house which is desirable for the occupants. If the pressure inside the house is not uniform, residents may experience discomforts such as ear cramps or wheezing.

Adding SC to the building can help increase the speed of airflow inside the units. In an SC, airflow is created by the buoyancy force; that is, the hot air inside the duct moves upwards and out and is replaced by cooler air in a closed system. In order to increase heat absorption and ventilation rate, the southern wall of the SC is considered to be glass and the inner part of other walls is considered as absorption walls. Numerous factors affect the performance of the SC, such as the dimensions of the chimney, location, height and etc.

4. Discussion and conclusion

This paper studies cross-ventilation in the two high-rise buildings in two different microclimates in Tehran city. To examine the perception of thermal comfort and behavioral adaptation of residential building occupants in two different microclimate zones in Tehran city, a comparison was made between two different districts, Artesh highway and Mojahedin Eslam street. The residents in the two districts registered differing thermal sensation, and their thermal sensitivity varied across the season throughout summer season (Jeong et al., 2022). The wind speed and temperature of the city are respectively considered 1.5 m/s and the temperature 32 °C, which are related to one of the sunny summer days at 1:30 to 2:30 pm. Second, the LEED occupant comfort survey database is used to determine how much buildings' occupants are satisfied with their home temperature and wind speed. Then, an SC is added into each building, and CFD approach is employed to determine the impact of SCs on thermal comfort for the occupants.

Cross ventilation in hot and arid climates is an effective way for NV as it can increase thermal comfort zone during the hot days. In comparison with building with outcross ventilation, it can also reduce buildings' energy demand by decreasing

air temperature and boosting wind velocity.

Investigation the results occurred in the fourth story of the buildings show that after adding an SC to Behnam Tower with cross ventilation these buildings have a significant effect on ventilation system performance.

The sufficient wind flow can remove heat air successfully through cross ventilation (Aflaki et al., 2016). SC integrated on mid-rise building, reduces indoor air temperature by about 2 °C in comparison with experimental data caught with Data Logger and simultaneously boosts air velocity. Furthermore, it has a significant effect on the reduction of energy consumption in buildings. Based on data in Table 3, 7.5% of occupants are dissatisfied with the stillness of the air and lack of responsive cooling system while using SC is effective to decline the number of occupants who are dissatisfied. Another improvement in residents' satisfaction could be the reduction of dissatisfied residents (27%) with the non-response of the cooling/heating system because SC enhances NV through houses.

Since adding an SC to the building does not cost too much, it is very cost-effective to add an SC to the southern side of the buildings in Tehran because they can reduce energy consumption and improve indoor thermal comfort. Moreover, development of a residential adaptive comfort model for high-rise buildings will help designing houses to more closely meet occupants' comfort needs. An adaptive comfort model will also assist in setting more reasonable cooling and heating thermostat settings within the housing comfort/energy rating tools, hence contributing to improved energy efficiency in the residential building sector.

References

- Aflaki, A., Mahyuddin, N., Baharum, M. R. (2016). The influence of single-sided ventilation towards the indoor thermal performance of high-rise residential building: A field study. *Energy and Buildings*, 126, 146-158. <https://doi.org/https://doi.org/10.1016/j.enbuild.2016.05.017>
- Ahmed, T., Kumar, P., Mottet, L. (2021). Natural ventilation in warm climates: The challenges of thermal comfort, heatwave resilience and indoor air quality. *Renewable and Sustainable Energy Reviews*, 138, 110669. <https://doi.org/https://doi.org/10.1016/j.rser.2020.110669>
- Altomonte, S., Schiavon, S. (2013). Occupant satisfaction in

- LEED and non-LEED certified buildings. *Building and Environment*, 68, 66-76. <https://doi.org/https://doi.org/10.1016/j.buildenv.2013.06.008>
- Baxevanou, C., Fidaros, D., Tsangrassoulis, A. (2017). Management of Natural Ventilation in High-Rise Building – a CFD Study. *Procedia Environmental Sciences*, 38, 428-435. <https://doi.org/https://doi.org/10.1016/j.proenv.2017.03.128>
- Cao, Y., Aldawi, F., Sinaga, N., Moria, H., Dizaji, H. S., Wae-hayee, M. (2021). Single solar chimney technology as a natural free ventilator; energy-environmental case study for Hong Kong. *Case Studies in Thermal Engineering*, 26, 101173. <https://doi.org/https://doi.org/10.1016/j.csite.2021.101173>
- Chen, Y., Tong, Z., Malkawi, A. (2017). Investigating natural ventilation potentials across the globe: Regional and climatic variations. *Building and Environment*, 122, 386-396. <https://doi.org/https://doi.org/10.1016/j.buildenv.2017.06.026>
- Cheng, J., Qi, D., Katal, A., Wang, L., Stathopoulos, T. (2018). Evaluating wind-driven natural ventilation potential for early building design. *Journal of Wind Engineering and Industrial Aerodynamics*, 182, 160-169. <https://doi.org/https://doi.org/10.1016/j.jweia.2018.09.017>
- Cheng, X., Shi, L., Dai, P., Zhang, G., Yang, H., Li, J. (2018). Study on optimizing design of solar chimney for natural ventilation and smoke exhaustion. *Energy and Buildings*, 170, 145-156. <https://doi.org/https://doi.org/10.1016/j.enbuild.2018.04.016>
- Cheung, J. O. P., Liu, C.-H. (2011). CFD simulations of natural ventilation behaviour in high-rise buildings in regular and staggered arrangements at various spacings. *Energy and Buildings*, 43(5), 1149-1158. <https://doi.org/https://doi.org/10.1016/j.enbuild.2010.11.024>
- Guo, F., Zhu, P., Wang, S., Duan, D., Jin, Y. (2017). Improving Natural Ventilation Performance in a High-Density Urban District: A Building Morphology Method. *Procedia Engineering*, 205, 952-958. <https://doi.org/https://doi.org/10.1016/j.proeng.2017.10.149>
- Harris, D. J., Helwig, N. (2007). Solar chimney and building ventilation. *Applied Energy*, 84(2), 135-146. <https://doi.org/https://doi.org/10.1016/j.apenergy.2006.07.001>
- He, G., Wu, Q., Li, Z., Ge, W., Lv, D., Cong, L. (2021). Ventilation performance of solar chimney in a test house: Field measurement and validation of plume model. *Building and Environment*, 193, 107648. <https://doi.org/https://doi.org/10.1016/j.buildenv.2021.107648>
- Hosien, M. A., Selim, S. M. (2017). Effects of the geometrical and operational parameters and alternative outer cover materials on the performance of solar chimney used for natural ventilation. *Energy and Buildings*, 138, 355-367. <https://doi.org/https://doi.org/10.1016/j.enbuild.2016.12.041>
- Jeong, B., Kim, J., Chen, D., de Dear, R. (2022). Comparison of residential thermal comfort in two different climates in Australia. *Building and Environment*, 211, 108706. <https://doi.org/https://doi.org/10.1016/j.buildenv.2021.108706>
- Kasaeian, A. B., Molana, S., Rahmani, K., Wen, D. (2017). A review on solar chimney systems. *Renewable and Sustainable Energy Reviews*, 67, 954-987. <https://doi.org/https://doi.org/10.1016/j.rser.2016.09.081>
- Kumar, R., Farhan, H. A., Nayak, S., Paswan, M., Achintya. (2021). Building design on wind driven natural ventilation with different simulation air model. *Materials Today: Proceedings*, 46, 6770-6774. <https://doi.org/https://doi.org/10.1016/j.matpr.2021.04.336>
- Layeni, A. T., Waheed, M. A., Adewumi, B. A., Nwaokocho, C. N., Sharifpur, M., Tongo, S. O., Okeze, R. C., Mboreha, C. A. (2021). Computational and sensitivity analysis of a dual purpose solar chimney for buildings. *Materials Today: Proceedings*. <https://doi.org/https://doi.org/10.1016/j.matpr.2021.07.292>
- Lee, Y. (2011). Comparisons of Indoor Air Quality and Thermal Comfort Quality between Certification Levels of LEED-Certified Buildings in USA. *Indoor and Built Environment - INDOOR BUILT ENVIRON*, 20, 564-576. <https://doi.org/10.1177/1420326X11409453>
- Lee, Y., Guerin, D. (2009). Indoor Environmental Quality Related to Occupant Satisfaction and Performance in LEED-certified Buildings. *Indoor and Built Environment - INDOOR BUILT ENVIRON*, 18, 293-300. <https://doi.org/10.1177/1420326X09105455>
- Liping, W., Wong, N. H. (2007). Applying Natural Ventilation for Thermal Comfort in Residential Buildings in Singapore. *Architectural Science Review*, 50, 224-233.
- Lotfabadi, P. (2014). High-rise buildings and environmental factors. *Renewable and Sustainable Energy Reviews*, 38, 285-295. <https://doi.org/https://doi.org/10.1016/j.rser.2014.05.024>
- Monghasemi, N., Vadiiee, A. (2018). A review of solar chimney integrated systems for space heating and cooling application. *Renewable and Sustainable Energy Reviews*, 81, 2714-2730. <https://doi.org/https://doi.org/10.1016/j.rser.2017.06.078>
- Omriani, S., Garcia-Hansen, V., Capra, B., Drogemuller, R. (2017). Natural ventilation in multi-storey buildings: Design process and review of evaluation tools. *Building and Environment*, 116, 182-194. <https://doi.org/https://doi.org/10.1016/j.buildenv.2017.02.012>
- Omriani, S., Garcia-Hansen, V., Capra, B. R., Drogemuller, R. (2017). Effect of natural ventilation mode on thermal comfort and ventilation performance: Full-scale measurement. *Energy and Buildings*, 156, 1-16. <https://doi.org/https://doi.org/10.1016/j.enbuild.2017.09.061>
- Park, D., Battaglia, F. (2015). Application of a Wall-Solar Chimney for Passive Ventilation of Dwellings. *Journal of Solar Energy Engineering*, 137(6). <https://doi.org/10.1115/1.4031537>
- Pasquay, T. (2004). Natural ventilation in high-rise buildings with double facades, saving or waste of energy. *Energy and Buildings*, 36(4), 381-389. <https://doi.org/https://doi.org/10.1016/j.enbuild.2004.01.018>
- Pathirana, S., Rodrigo, A., Halwatura, R. (2019). Effect of building shape, orientation, window to wall ratios and zones on energy efficiency and thermal comfort of naturally ventilated houses in tropical climate. *International Journal of Energy and Environmental*

- Engineering, 10. <https://doi.org/10.1007/s40095-018-0295-3>
- Prajongsan, P., Sharples, S. (2012). Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts. *Building and Environment*, 50, 104-113. <https://doi.org/https://doi.org/10.1016/j.buildenv.2011.10.020>
- Rashidi, S., Esfahani, J. A., Hosseini, E. (2021). Assessment of solar chimney combined with phase change materials. *Journal of the Taiwan Institute of Chemical Engineers*, 124, 341-350. <https://doi.org/https://doi.org/10.1016/j.jtice.2021.03.001>
- Schulze, T., Eicker, U. (2013). Controlled natural ventilation for energy efficient buildings. *Energy and Buildings*, 56, 221-232. <https://doi.org/https://doi.org/10.1016/j.enbuild.2012.07.044>
- Shi, L., Zhang, G., Yang, W., Huang, D., Cheng, X., Setunge, S. (2018). Determining the influencing factors on the performance of solar chimney in buildings. *Renewable and Sustainable Energy Reviews*, 88, 223-238. <https://doi.org/https://doi.org/10.1016/j.rser.2018.02.033>
- Solgi, E., Hamedani, Z., Fernando, R., Skates, H., Orji, N. E. (2018). A literature review of night ventilation strategies in buildings. *Energy and Buildings*, 173, 337-352. <https://doi.org/https://doi.org/10.1016/j.enbuild.2018.05.052>
- Souayfane, F., Fardoun, F., Biwolé, P.-H. (2016). Phase change materials (PCM) for cooling applications in buildings: A review. *Energy and Buildings*, 129, 396-431. <https://doi.org/https://doi.org/10.1016/j.enbuild.2016.04.006>
- Tong, Z., Chen, Y., Malkawi, A. (2017). Estimating natural ventilation potential for high-rise buildings considering boundary layer meteorology. *Applied Energy*, 193, 276-286. <https://doi.org/https://doi.org/10.1016/j.apenergy.2017.02.041>
- Wang, F., Lin, W., Ling, Z. (2019). A comprehensive review on phase change material emulsions: Fabrication, characteristics, and heat transfer performance. *Solar Energy Materials and Solar Cells*, 191, 218-234. <https://doi.org/10.1016/j.solmat.2018.11.016>
- You, W., Shen, J., Ding, W. (2017a). Improving wind environment design based on assessing spatial distribution of ventilation efficiency in regional space. *Energy Procedia*, 142, 2923-2929. <https://doi.org/https://doi.org/10.1016/j.egypro.2017.12.418>
- You, W., Shen, J., Ding, W. (2017b). Improving Wind Environment of Residential Neighborhoods by Understanding the Relationship between Building Layouts and Ventilation Efficiency. *Energy Procedia*, 105, 4531-4536. <https://doi.org/https://doi.org/10.1016/j.egypro.2017.03.972>
- Zarrabi, A., Azarbayjani, M., Day, J. K., Thariyan, E., Stearns, E., Dale, B. (2017). Visual qualities and perceived thermal comfort-results of survey studies in a lead platinum office building.
- Zhang, H., Tao, Y., Nguyen, K., Han, F., Li, J., Shi, L. (2021). A wall solar chimney to ventilate multi-zone buildings. *Sustainable Energy Technologies and Assessments*, 47, 101381. <https://doi.org/https://doi.org/10.1016/j.seta.2021.101381>
- Zhang, H., Yang, D., Tam, V. W. Y., Tao, Y., Zhang, G., Setunge, S., Shi, L. (2021). A critical review of combined natural ventilation techniques in sustainable buildings. *Renewable and Sustainable Energy Reviews*, 141, 110795. <https://doi.org/https://doi.org/10.1016/j.rser.2021.110795>
- Zhao, D.-X., He, B.-J. (2017). Effects of architectural shapes on surface wind pressure distribution: Case studies of oval-shaped tall buildings. *Journal of Building Engineering*, 12, 219-228. <https://doi.org/https://doi.org/10.1016/j.jobbe.2017.06.009>
- Zhou, C., Wang, Z., Chen, Q., Jiang, Y., Pei, J. (2014). Design optimization and field demonstration of natural ventilation for high-rise residential buildings. *Energy and Buildings*, 82, 457-465. <https://doi.org/https://doi.org/10.1016/j.enbuild.2014.06.036>

COPYRIGHTS

©2021 The author(s). This is an open access article distributed under the terms of the Creative Commons Attribution (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, as long as the original authors and source are cited. No permission is required from the authors or the publishers.



HOW TO CITE THIS ARTICLE

Khazand, M., Chahardoli, S. (2021). *Indoor thermal comfort and high residential buildings (Case study: two high-rise buildings in two different microclimates in Tehran city)*. *J Urban Manage Energy Sustainability*, 2(4): 39-57.

DOI: [10.22034/JUMES.2021.553631.1075](https://doi.org/10.22034/JUMES.2021.553631.1075)

