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The Impact of the Combination of Positive and Negative Spaces on the Performance of Solar Chimney; Case Study: Office Buildings in the Hot and Dry Climate of Shiraz*

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ABSTRACT

Given the intense rise of the world's population and ever-increasing energy consumption, the application of passive solutions is of paramount importance to the development of countries. A large share of energy consumption is attributed to the construction industry and office buildings, whose consumption levels can be significantly reduced through passive solutions such as solar chimneys. Solar chimneys, also known as thermal chimneys, greatly contribute to reduced energy consumption and thus can be employed for building ventilation, as well as heating and cooling by absorbing and storing solar energy. The present study aims to examine the effect of the solar chimney on ventilation and indoor temperature of office buildings in the hot and dry climate of Shiraz City, where buildings have different urban forms. In this study, a room with a solar chimney, in five different urban forms, is considered as a case study. The simulation is performed using ANSYS Fluent and Comsol Multiphysics software. By measuring the mean ambient temperature, inlet air velocity of the chimney and the amount of exhaust air pressure and comparing them in all four seasons of the year, it is found that the best performance in terms of ventilation is related to the summer season. Also, in cold seasons, the chimney should be closed so that the heat absorbed from solar radiation by the chimney keeps the environment warm. The values of temperature, velocity and pressure are only slightly varying in the models, but the findings indicate that the more the inlet air and the outlet air pressure, the higher the ventilation rate and the air change rate. With a slight difference, in the summer, the central courtyard is the most optimal urban form, which offers the highest increase in ventilation rate and decrease in energy consumption by being connected to a solar chimney, followed by the shaded courtyard on the north side and then the two-courtyard form.

Keywords: Solar Chimney, Air Conditioning, Combination of Negative and Positive Spaces.

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1. INTRODUCTION

Currently, the issue of energy is of paramount importance all over the world. Buildings consume 45% of the world's energy, while also producing 30% of greenhouse gases in the US (Zhai & Previtali, 2010). Among reasons for the ever-increasing energy consumption of buildings are climate change, increased household electricity demand, increased frequency of buildings, growth in the use of household appliances, shifts in the industry, high energy consumption in existing buildings and lack of government oversight (Yao & Zhu, 2011). Residential buildings are one of the main sources of energy consumption, which itself is strongly impacted by the climate of the region (Zhang, 2004). The hot and dry climate is characterized by two important characteristics of high temperature and dry air (Kasmaei, 2003). Owing to the significance of fossil fuels and the risk of their depletion, alternative solutions should be pursued to preserve as many natural resources as possible.

In the hot and dry climate of Iran, passive methods have been historically employed for airflow and ventilation (Sahebzadeh, Dalvand, Sadeghfar, & Heidari, 2018). Passive solar systems refer to systems that accumulate and store solar energy without the involvement of any secondary energy, to be exploited later when required. In this way, different components of the building simultaneously meet the expectations and standards set up in the field of architecture, provide statics and safety and optimize energy consumption in a building or urban texture (Gholami, Mofidi Shemirani, & Fayaz, 2018). These systems are considered to be the most efficient among other solar systems in cases where harnessing the energy and reducing equipment and implementation costs are among the top design priorities (Gilani & Kari, 2011). It is possible to gain a better understanding of these systems by performing more studies on strategies of the past (Nasab, Pilechiha, & Hajian, 2019) and evolve them using modern technologies. Among passive methods, the double-skin facade (Pilechiha, Mahdavinejad, Mirhosseini, & Ahmadi, 2019) and solar chimneys are rather notable.

Solar chimneys are usually consisted of glass, apertures and an absorber surface, and is a passive solar system for ventilation using the stack effect. This system is similar to conventional chimneys, except that the south-facing wall is made of glass and is made of glass, apertures and massive walls to harness solar energy. Solar rays pass through the glass, are absorbed on the surface of the wall and heat the air inside the chimney. As the air gets warm and its density decreases, it arises owing to the stack effect, creating a driving force and causing the lower air inside the room to replace it. Thus, natural ventilation increases and causes air pollution to escape from the interior (Miyazaki, Akisawa, & Kashiwagi, 2006).

One of the most important factors affecting chimney ventilation is the temperature difference between the interior and the exterior. In summer, the temperature difference between inside and outside is not significant, and thus exploiting the buoyancy effect in a conventional chimney that uses the rules of chimney stack ventilation would not be sufficient. Studies reveal that the combination of radiation and convection in a solar chimney leads to significant air displacement and thus increased ventilation (Khanal & Lei, 2011). During the day, the absorber wall acts as heat storage and allows the solar chimney to continue functioning for long hours after sunset, or even used exclusively for night-time ventilation. This approach can be widely applicable to the hot and dry climate (Pantavou, Theoharatos, Mavrakis, & Santamouris, 2011). The solar chimney operates like a Trombe wall and follows the simple law of thermodynamics, in that, sunlight, i.e. the flux of solar radiant heat, after passing through a transparent glass or wall, hits the absorber plate and causes it and the surrounding air to heat up and hence rise due to its density (Lee & Strand, 2009).

2. RESEARCH BACKGROUND

In recent years, understanding consumption trends and proposing methods for their optimization has been greatly considered in the residential sector by researchers and energy managers. In this regard, Swan & Ugursal (2009) reviewed the literature regarding different techniques employed for modelling energy consumption in the residential sector (Swan & Ugursal, 2009). Dong et al. used a neural network algorithm to predict building energy consumption in tropical areas (Dong, Cao, & Lee, 2005). Hirst et al. reviewed survey data of temporary energy consumption on a national level to study household energy consumption, including total energy consumption, electricity consumption, and the use of primary space heating fuels (Hirst, Goeltz, & Carney, 1982).

Jaber and Ajib have evaluated the optimum building orientation, window size and the thickness of thermal insulation for a residential building in the Mediterranean region and suggested that about 27-29% of annual energy consumption can be saved by employing the best direction, the optimal size of windows, canopies and optimal insulation thickness (Jaber & Ajib, 2011). Atashinjabin and Yazdani have studied the effect of building form on building energy consumption by analyzing volumes in the climate of Kish Island and concluded that the building form plays a significant role in reducing consumption (Atashinjabin & Yazdani, 2016). Studying the effect of solar radiation upon building form on energy consumption in Shiraz, Barzegar and Heydari concluded that the most optimal building forms in terms of solar energy absorption are vertical bodies and if the building orientation is optimal, absorbing this type of radiation can readily enable architects to design low-consuming houses in all areas such as heating, cooling, and lighting among others (Barzegar & Heidari, 2013).

The first studies in the field of solar chimneys were conducted in 1993 by Bansal and colleagues. Through mathematical model, they proved that the ventilation of buildings will be enhanced by employing solar chimneys and correctly designing a permanent system (Bansal, Mathur, & Bhandari, 1994). Khedari et al. (2002) studied different types of solar chimneys and concluded that chimneys are effective in ventilation and air change (Khedari, Boonsri, & Hirunlabh, 2000). Chungloo and Limmeechokchai (2009) experimentally examined the effect of the solar chimney on indoor air ventilation in the presence or absence of a cool ceiling and concluded that the external chimney can reduce the indoor temperature by 1 to 3.5 degrees, depending on the ambient temperature and the level of solar radiation (Chungloo & Limmeechokchai, 2009).

Comparing a solar chimney and a regular chimney, Afonso and Oliveira (2002) showed the effect of solar energy on increased ventilation (Afonso & Oliveira, 2000). Charvat et al. concluded that by increasing the thermal mass, the air velocity increases at night hours. Moreover, their findings indicated that using a solar chimney during the day increases the airflow by 25% (Charvat, Jicah, & Stetina, 2004). Using a numerical study of the airflow in a solar chimney, Khanal & Lei showed that total air mass flow rate in a vertical solar chimney is heavily influenced by the reverse flow and air temperature at the outlet of the aperture (Khanal & Lei, 2012).

Miyazaki et al. (2006) examined the performance of a solar chimney in an office building under the Japanese climate and concluded that using natural ventilation from a solar chimney, the daily energy required in some months of the year is reduced by approximately 90% (Miyazak, 2006). Chantawong analyzed the performance of a glass solar chimney in the tropical climate of Thailand and concluded that the heat transfer from glass walls into the home can be reduced through increased air circulation (Chantawong, Hirunlabh, Zeari, Win, 2006). Punyasompun et al. studied the performance of a thermal chimney in a multi-story building in Bangkok using experimental and numerical methods and concluded that its performance improves in cases where the solar chimney is attached to all stories (Punyasompun, Hirunlabh, Zehat, 2009).

Chen et al. studied the air gap as well as the inclination angle of the chimney, the results of which revealed that the maximum airflow is achieved at an inclination angle of 45 degrees for a 200 mm air gap and 1.5 m height chimney (Chen, Bandopadhayay, Halldorsson, Byrjalsen, Heisel & Li, 2003). Moshfegh and Sandberg investigated the properties of flow and heat transfer resulting from the buoyancy effect behind photovoltaic solar panels (Moshfegh & Sandberg, 1998). Bassiouny et al. tested a passive solar house for heating, cooling and ventilation in a composite climate. The air supply capacity of solar chimneys in this study was predicted by calculations and then confirmed by laboratory measurements (Bassiouny & Korah, 2009).

Saghafi & Fakhari compared the performance of solar chimney on building ventilation in four different climates and concluded that the solar chimney has the most optimal performance in hot and dry climates (Saghafi & Fakhari, 2012). Comparing the abovementioned studies in terms of methodology, it is found that the studies on the solar chimney can be done using three methods of observation, simulation and computation. However, owing to various limitations such as the impossibility of measuring the temperature within a real solar chimney and performing field visits, in the present study, quantities such as temperature and air movement patterns were calculated and analyzed through numerical calculations and computational fluid dynamics simulation using computer simulation software (ANSYS Fluent and Comsol Multiphysics).

2.1. Solar Chimney

In a solar chimney, the airflow is generated by the buoyancy force, that is, the warm air inside the shaft moves upwards and is ventilated out, and hence is replaced by cooler air in a closed system. Usually, to optimize the heat absorption and ventilation rate, the south wall of the solar chimney is made of glass and the inner part of the other walls is dark-coloured while the outer part is heat insulated. Several factors must be considered in designing a solar chimney, including atmospheric conditions, location, direction and size of the building (Shamsai, Mahmoudi, Sarlak, & Vosoughifar, 2011). Solar chimneys are divided into two categories, namely, electricity generator, and ventilator. The former is usually made on a large industrial scale, while the latter has residential applications. The former consists of three main elements: the solar collector area, the tower or the chimney and the wind turbine. The hot air required for a solar chimney is generated by the greenhouse effect in an area covered with plastic or glass and placed a few meters above the ground. Approaching the base of the tower, the height of the covered area increases to alter the direction of airflow vertically with minimal friction. In the middle of this transparent roof is a vertical chimney or tower. Warm air moves to the top of the tower as it is lighter (creating suction at the bottom of the tower). The solar radiation in this tower generates an upward suction and the energy resulting from this suction is first converted into mechanical energy by several turbines mounted on the tower, and then, into electricity. The power generation capacity of a solar chimney is highly proportional to the volume achieved from the height of the tower and the collector area, that is, it is possible to generate the same amount of electricity using a tall tower with a small area or a short tower with a large area (Ghiabaklou, 2013). As mentioned earlier, different types of solar chimneys can be combined with other passive solutions to use for different applications in different climates in hot and cold seasons. It is noteworthy that the latter types of solar chimneys are rather similar to conventional chimneys, except that their south wall is made of

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glass. A solar chimney is the air ventilation, in which the airflow is stirred through thermal buoyancy, and is consisted of glass, apertures and bulky walls to absorb solar energy (Miyazaki, Akisawa, & Kashiwagi, 2006). Saghafi and Fakhari compared the performance of solar chimneys in four different climates of Iran and, and compared several cities in the best climate, the results of which revealed that the highest yields are observed in hot and dry climates. The performance of solar chimneys varies in different climates. Studies conducted on the three cities of Isfahan, Tabriz and Bandar Abbas, each having a unique climate, indicated that Isfahan has the highest air volumetric flow rate during the day and night, and the lowest of which pertains to the city of Bandar Abbas. Accordingly, the volumetric flow rate, the outlet air temperature, the ventilation rate and the outlet air temperature of the solar chimney vary among climates. Three cities of Isfahan, Yazd and Shiraz in hot and dry climate were compared, the results of which showed that Shiraz has the highest performance (Saghafi & Fakhari, 2012). The solar chimney is usually used to provide ventilation for cooling, while for heating, the chimney aperture can be closed and the heated air inside the chimney can be directed to the building using fans. In designing a chimney, factors such as the height, width, and depth of the aperture, type of glass, type of absorber, insulation and heat storage material (such as brick, concrete, stone and any material with high heat capacity) affect the performance of the chimney (Khamse, 2010).

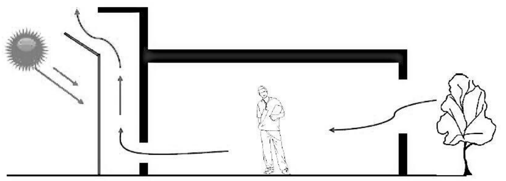

Fig. 1. Operation of a Solar Chimney with a Closed Aperture in Winter

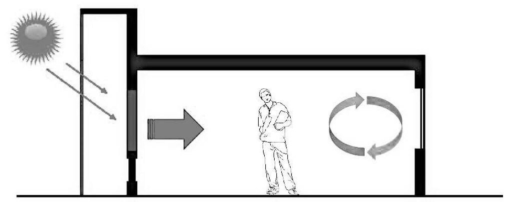

Fig. 2. Operation of a Solar Chimney with an Open Aperture in Summer

3. METHOD

Given the intense rise of the world's population and ever-increasing energy consumption, the application of passive solutions is of paramount importance to the development of countries. A large share of energy consumption is attributed to the construction industry and office buildings, whose consumption levels can be significantly reduced through passive solutions such as solar chimneys. Since this research aimed to examine the effect of the solar chimney on ventilation and indoor temperature in office buildings in the hot and dry climate of Shiraz in which buildings have different urban forms, five hypothetical office buildings with courtyards, which are common in Iran, were modelled. Since solar radiation is required to optimize the performance of the solar chimney, buildings with office or school use, where working hours are from morning to late noon, are the best options for implanting a solar chimney. As stated earlier, the highest performance of solar chimneys was observed in Shiraz City, so, office space in the climate of Shiraz was modelled. The dimensions of the rooms in the simulated models were 8 × 6 meters and 2.7 meters of height. The rooms were equipped with a solar chimney. One air inlet of 2 × 1.3 meters was devised for each room. The air inlet to the chimney is through an aperture of 0.5 m height, 1.5 m width located 0.3 m above the floor on each storey. The depth of the chimney is 1 meter and its height is 1 meter above the ceiling of the room, i.e. 4 meters. The materials used in the research model was concrete for floors and concrete and insulation layer for the roof. The chimney was made of double-glazed glass (two colourless glass layer, and 13 mm of argon gas between them), the outer wall is composed of 10 cm of concrete and 5 cm of insulation, from outside to inside, respectively, while the wall between the room and the chimney is consisted of 5 cm of insulation and 10 cm of concrete, from inside to outside, respectively. The model proposed in Saghafi and Fakhari (2012) was adopted to validate the results in the early stages.

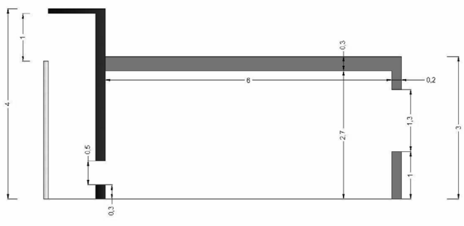

Fig. 3. Model Geometry and Dimensions

3.1. Simulation of Models

The simulation was performed using ANSYS Fluent and Comsol Multiphysics. Fluent is an engineering computer software in the field of computational fluid dynamics and used for modelling fluid flow and heat transfer in highly complex geometries. The required calculations for each form per hour were performed using Comsol software. The simulation was hourly performed on equinoxes and solstices (i.e. start of every season) during working hours, from 8 am to 4 pm. According to previous studies, the hot and dry climate in Shiraz has the highest rate of ventilation (Saghafi & Fakhari, 2012). Since the building form can influence the energy consumption of the building, five different forms with a shaded courtyard were considered to determine the best form (Fig. 4). To improve the quality of the inlet air, it can be supplied from the shaded courtyards with green space so that it becomes cooler and more humid.

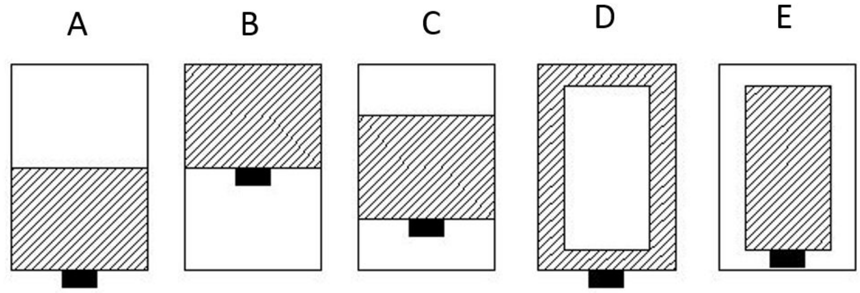

Fig. 4. Different Positions of the Solar Chimney in Five Forms of Positive/Negative Space

All combinations of positive and negative spaces, i.e. the models, have the same area. Model A is a north-facing building with a courtyard on the north side. Model B is the same as Model A, but the courtyard is on the south side; Model C is a north-facing building in the middle of the ground with two courtyards on both north and south side. Model D is in the form of a central courtyard, and in model E, the courtyard is built all around the building.

ANSYS Fluent was used to model each form (Fig. 5) and materials and other necessary specifications were applied to the desired geometric model (Fig. 6). In the simulation, courtyard walls were considered equal to the room height. In model meshing, the more important points have denser meshes to increase the accuracy of the modelling (Fig. 7). The boundary conditions were calculated based on latitude (Fig. 8). Finally, the contour plot of mean ambient temperature (Fig. 9), the contour plot of temperature at air inlet and outlet (Fig. 10), the contour plot of inlet air velocity (Fig. 11) and the contour plot of outlet air pressure (Fig. 12) were obtained. Figures in this section are presented as examples just for summer.

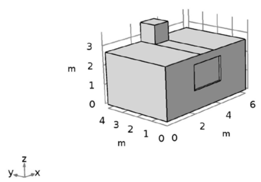

Fig. 5. Geometric Form of the Model

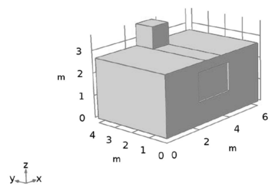

Fig. 6. Points Applied to Air and Material in These Areas

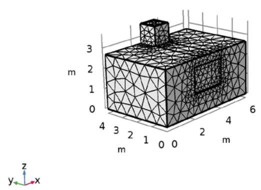

Fig. 7. System Mesh

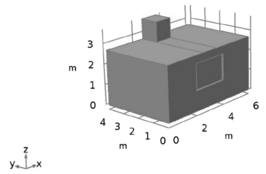

Fig. 8. Boundary Conditions Based on Latitude

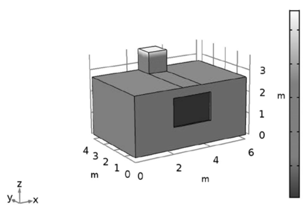

Fig. 9. Contour Plot of Mean Ambient Temperature (ºC)

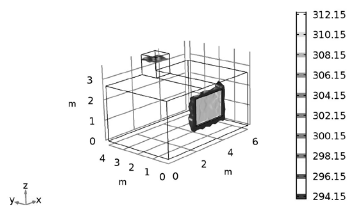

Fig. 10. Contour Plot of Temperature at Air Inlet and Outlet (ºC)

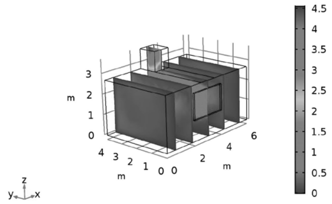

Fig. 11. Contour Plot of Inlet Air Velocity (m/s)

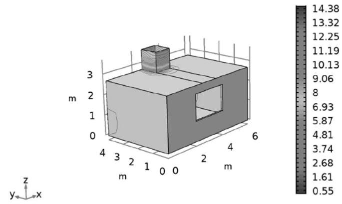

Fig. 12. Contour Plot of Outlet Air Pressure (Pa)

4. ANALYSIS OF MODELS

Comparing ventilation flow rates in different models indicated that under similar conditions, different combinations of positive and negative spaces have different effects on the performance of the solar chimney. The data regarding temperature, velocity, and pressure in four seasons are compared in the following.

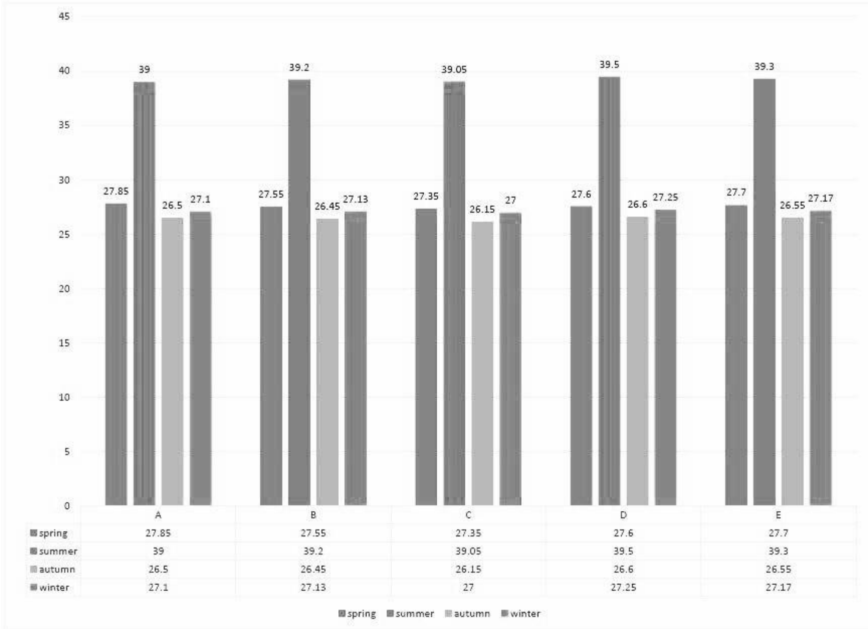

Fig. 13. Mean Temperature in Four Seasons (Celsius)

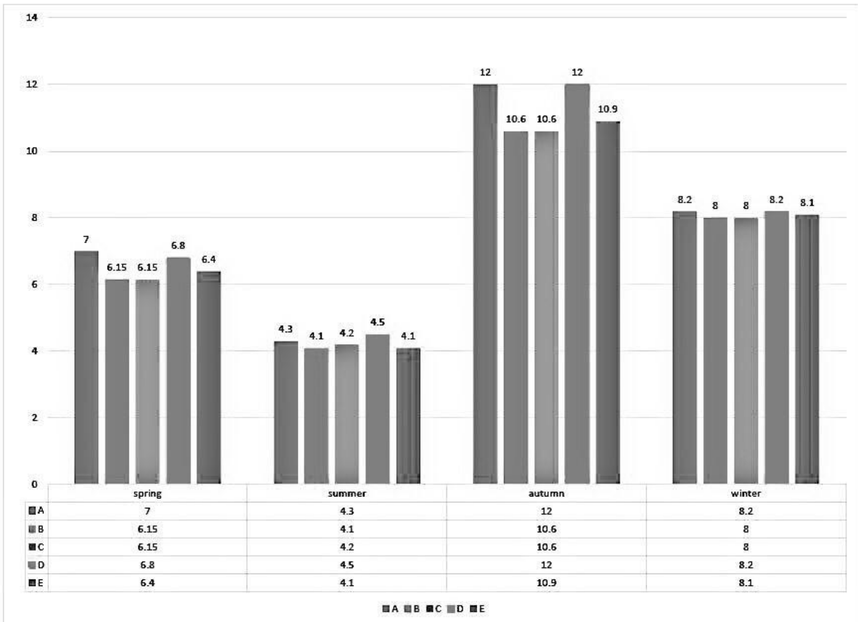

Fig. 14. Inlet Air Velocity in Four Seasons (m/s)

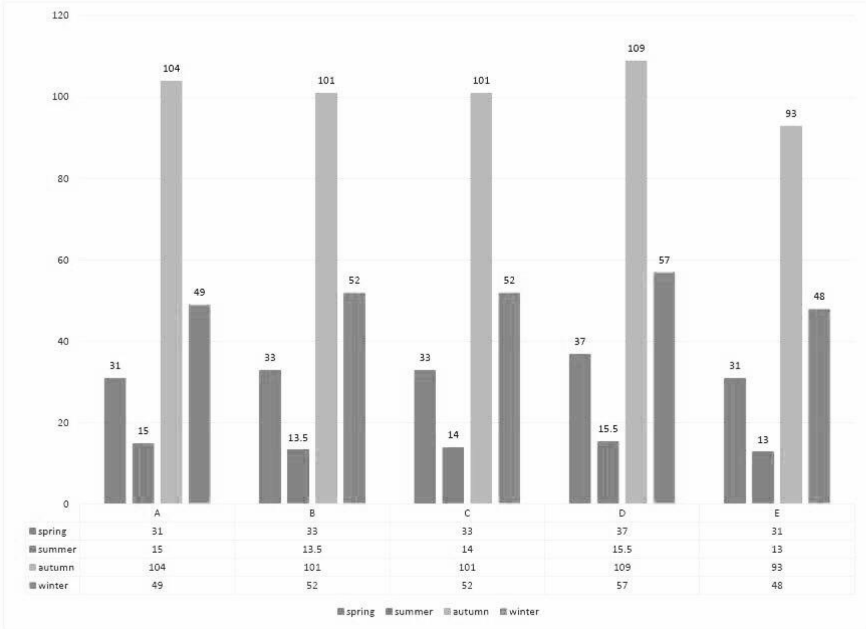

Fig. 15. Outlet Air Pressure in Four Seasons (Pascal)

Comparing the diagrams shows that, as a system for ventilation and cooling of the interior, the solar chimney has an acceptable performance only in summer and does not perform optimally in other seasons. Owing to the higher rate of airflow created in the environment during the colder seasons, the comfort of people working in the room is hindered as the environment gets very cold (Figs. 14 & 15). Therefore, the solar chimney is only used in summer, and in other seasons, as mentioned in the literature, the aperture is closed to keep the heat absorbed from the solar radiation and trapped in the chimney within the environment and thus make it warm. Due to the optimal operation of the chimney in summer and hotter weathers, fossil fuel consumption can be greatly saved by circulating air and cooling the environment.

In the following, the performance of the solar chimney in summer is examined in more details. In Figure 16, the five models are compared in terms of average ambient temperature on the first day of summer, i.e. June 20. The results show that model D had the highest temperature in this season followed by models E, A, B and C, respectively.

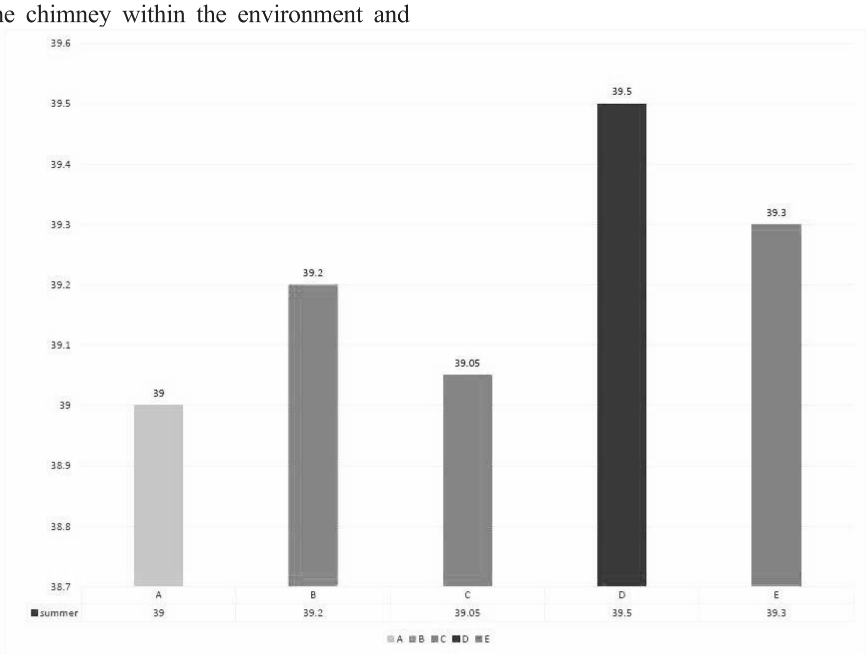

Fig. 16. Mean Temperature in Summer (Celsius)

Correspondingly, the five models are compared in terms of the velocity of inlet air to the environment in Figure 17, which reveals that model B had the highest velocity while models A, C, B and E had the lowest velocity on the first day of summer (i.e. June 20), respectively. Moreover, models B and E had similar velocity values (Fig. 17). Comparison of the five models in terms of the outlet air pressure on the first day of summer (Fig.18) indicates that Model D had the highest pressure, while models C, B, A and E had the lowest pressure, respectively.

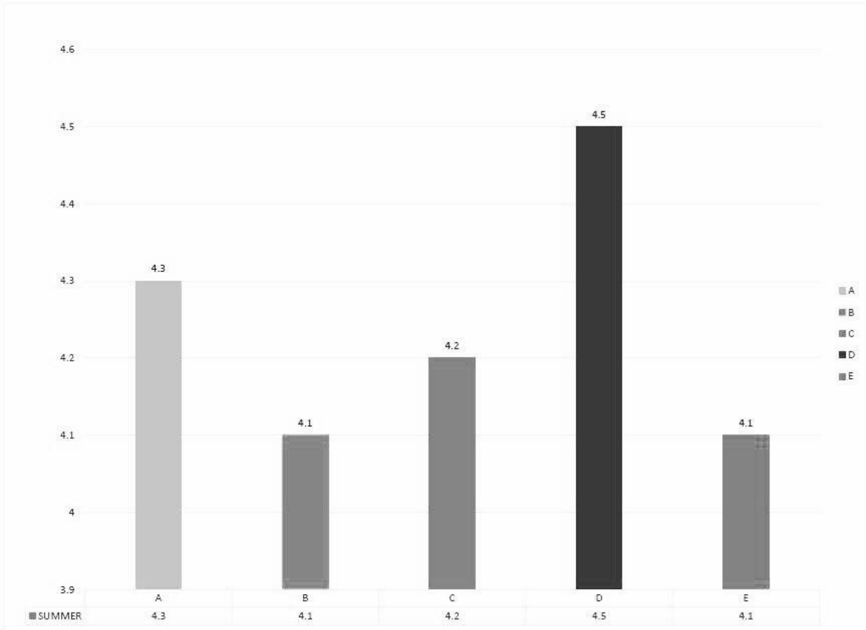

Fig. 17. Inlet Air Velocity in Summer (m/s)

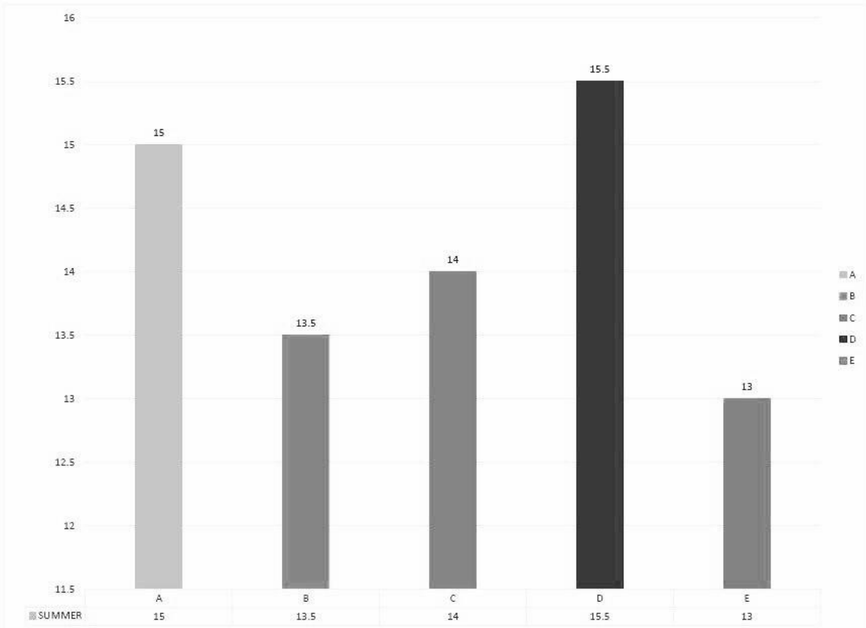

Fig. 18. Outlet Air Pressure in Summer (Pa)

5. DISCUSSION AND CONCLUSION

Previous research revealed that among efforts to conserve energy, using passive methods, such as solar chimneys can greatly contribute to ventilation, heating and cooling of buildings. Solar chimneys operate better in hot and dry climates compared to other climates (summer in particular). In this study, according to the better performance of the chimney in Shiraz, five models of positive and negatives spaces combination were compared in terms of ventilation, average ambient temperature, the inlet air velocity and the outlet air pressure in summer.

The difference between the models in terms of mean ambient temperature in summer was very small. The difference between the central courtyard model (D) and the south-facing building model (A), i.e. the two models with the highest and lowest mean ambient temperature, respectively, was only 0.5 °C. This is true for the inlet air velocity, meaning that the difference between the two central courtyards (D) and north-facing building (B), with the highest and lowest inlet air velocities, respectively, was only 0.4 meters per second. However, the differences between the models in terms of outlet air pressure were significant, as the central courtyard model (D) had the highest outlet air pressure, and the difference between it and Models (A) and (E) (with the lowest outlet air pressure) was 0.5 and 2.2 Pa, respectively.

Comparing the models in summer, the central courtyard model (D) has the best performance, followed by model A (northern-shaded courtyard), model C (with 2 northern and southern courtyards), and model B (with the southern courtyard and without shading due to facing the sunlight), and Model E (with the lowest performance due to the extensive north-south elongation), respectively. The greater the volume of inlet air to the room, the greater the suction created and thus the more pressure by which the air leaves the chimney, ultimately leading to better ventilation and more air change. As the ventilation rate increases, more comfort is provided for the residents. Therefore, in the hot and dry climate of Shiraz and during summer, the central courtyard model (D), which is considered the traditional Iranian architectural model in this area, has the most optimal performance in terms of ventilation when being combined with the solar chimney.

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