*Int. J. Urban Manage Energy Sustainability, 4(4): 142-153, 2023*

Journal of Urban Management and Energy Sustainability (JUMES)

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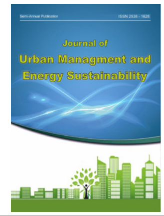

CASE STUDY RESEARCH PAPER

# Investigating inlet height effect on natural ventilation efficiency in vernacular house solar chimneys

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ARTICLE INFO

*Article History:*
Received 2023-08-29
Revised 2023-11-14
Accepted 2024-01-20

*Keywords:*
Air quality, Computational Fluid Dynamics (CFD), inlet height, Natural ventilation, solar chimney.

DOI: 10.22034/ijumes.2024.2010371.1158

ABSTRACT

Natural ventilation has long been acknowledged as a viable method for regulating indoor temperatures. The use of solar chimneys (SCs), a passive architectural feature in modern building design, has been shown to significantly reduce energy consumption. However, there are differences in the design of natural ventilation devices between traditional and contemporary approaches, particularly in terms of inlet location. While conventional SCs have their inlets at ceiling level, modern SCs have them at floor level. This study aims to investigate the impact of inlet location on SC performance in airflow, in order to enhance the efficiency of passive natural ventilation. On June 15, 2022, at 15:00 (the warmest time of the day), simulations were performed using the ANSYS FLUENT software on a hypothetical three-story building to investigate the impact of inlet location on SC performance in airflow and enhance the efficiency of passive natural ventilation. Two possible inlet locations, ceiling and floor level, were considered. The results showed that the floor level inlet had a stable airflow with an average airspeed of 0.11 m/s, while the airflow at the ceiling-level inlet fluctuated with an average airspeed of 0.15 m/s. These findings suggest that conventional beliefs about SC efficiency may not be accurate, and that ceiling-level inlets may be more suitable for achieving SC efficiency in line with Iranian traditional architecture.

*Running Title: Inlet height effect on natural ventilation efficiency in vernacular house solar chimneys*

NUMBER OF REFERENCES 38

NUMBER OF FIGURES 07

NUMBER OF TABLES 05

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## INTRODUCTION

Global warming and its environmental effects compel designers to use more passive methods and tools to address thermal comfort issues. Numerous factors affect indoor air quality, and natural ventilation is one strategy for improving the quality of indoor air in buildings. Air ventilation is highly dependent on openings and air leakage; therefore, passive ventilation methods can reduce energy consumption and environmental pollution (Mirrahimi et al., 2016). Optimizing energy consumption in buildings is a primary and crucial goal in urban planning today (O.j. Farzaneh,2020). Passive solar methods' performance in a similar structure, including the driving force that controls the airflow rate, is the buoyancy effect, where the airspeed is due to the air temperature difference and density differences at the inlet and outlet (Thibault Quentin et al.,2016). SC as one of the inactive methods, supports natural ventilation with the manner of thermosiphon solution (Pantavou et al., 2011). Converting thermal energy and kinetic energy is a mutual and two-way equation; therefore, the SC can be used for cooling and heating purposes (Jafari & Poshtiri, 2017). The air in the chimney is then heated by convection and radiation from the absorber. The decrease in density experienced by the air causes it to rise, whereupon it is replaced by air from below, i.e. from the attached room. The rate at which air is drawn through the room depends upon the buoyancy force experienced (i.e dependent upon the temperature differential), the resistance to flow through the chimney, and the resistance to the entry of fresh air into the room (Harris & Helwig, 2007; Lee Kun Hong, 2020). However, a wind exchanger performs better in terms of airflow velocity across the buildings than a wind catcher and Taremeh. Additionally, using natural ventilation and sunshades, models might establish 38% of the year's pleasant hours (Mehdi Khakzand, Saeid Chahardoli. et al. 2023). Results show SC's ability to increase air temperature from 25°C to 48°C (TV Nguyen,2021). Studying the potential design and operating parameters influencing the SC performance for natural ventilation (NV) compared to the electrical high-energy technologies to sustain acceptable indoor climatic conditions is important. Combined enhanced cooling/heating energy systems based on the solar chimney are considered an effective strategy for low-energy consuming buildings (Panel Hussein,2022). Their energy demand is calculated to choose the best constructive solutions by simulation techniques and not by trial-and-error experimental techniques (Yair Schwartz,2021).

Detailed parameters including physical features such as air gap width, the height of the stack, opening areas, material, and chimney tilt angle can be simulated through a simulation method (Hweij et al., 2017, Ruijun Zhang et al., 2021). Miyazaki has investigated "the effect of the SC on thermal load mitigation of an office building under the Japanese climate" using the CFD method and they have revealed that the fan shaft power requirement was reduced by about 50% in annual total due to the natural ventilation. Additionally, the SC was beneficial to reduce the heating load by about 20% during the heating season. The annual reducing thermal loads was estimated at 12% by taking the increase in the cooling load into account (Miyazaki et al., 2006). The benefits of SCs include 1) keeping residents' privacy, 2) thermal comfort with less air movement in internal space since natural ventilation makes noise and intolerable conditions if the air velocity exceeds 1 m/s,3) preventing unwanted factors such as dust,4) increase in thermal comfort during cold dry nights of windless summer when the natural ventilation is of less power (Asadi et al, 2016). Solar chimneys' function has been frequently scrutinized using experimental and simulation tools (Chung et al., 2015; Omer, 2018). Most of the analysis and model configurations are based on the assumptions that are common among most of the studies (Harris & Helwig, 2007; Kasaeian et al., 2014). These studies have greatly contributed to the current understanding of SCs and can be roughly classified into three categories: (a) Study based on small-scale models, (b) Study based on large-scale and full-size models, (c) Study based on an indoor laboratory setting (Khanal & Lei, 2011). Some general factors affecting the efficiency of the SC include the location, climate, orientation, and size (Harris & Helwig, 2007). They examined the SC effect on natural ventilation through an experimental and numerical method in the context of Iraq that an SC with a side entrance gives better thermal performance; also, integrating SC with PCM (Phase Change Material) extended the ventilation period hours after sunset. A comparison between the numerical and the experimental results shows fair agreement. (Karima & SaifWatheq, 2012). Found that the air change rate (ACH) with solar chimneys throughout the year was more than the desired ventilation standards in the enclosure space (Hosien & Selim, 2017; M. Dhahri, 2020).

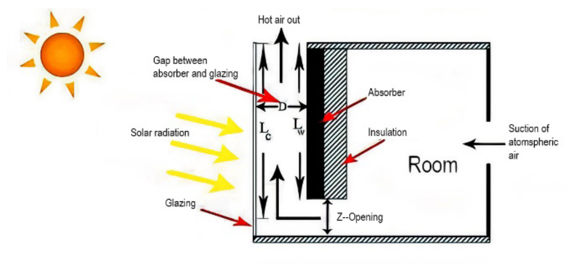


Figure 1: The graphical layout of a solar chimney's function (Hosein & Selim, 2017)

In most studies, the height of the air inlet has assumed a fixed height (near the floor). (Table 1) As mentioned before, most of these studies have been carried out by mechanical engineers and subsequently, the human scale is neglected.

Computational Fluid Dynamics (CFD) simulation is a common method to predict airflow patterns, speed, temperature, etc. (Ramponi et al., 2015). This method greatly contributes to

Table 1: The assumption of different studies

| Authors | computational domain | Air gap (m) | Chimney inlet (m) | Chimney height (m) | Inlet position | Channel width |
|---|---|---|---|---|---|---|
| Hosien&Selim, 2017 | 3m*3m*3m | 0.1m to 0.5m | 0.2m*0.2m | 2m | floor level | 0.6m |
| Haghighi&Maerefat, 2014 | 4m*4m*3.125m | 0.2 m | 1.0 × 0.3<br>1.0 × 0.2<br>1.0 × 0.1 | 3.125 m, | floor level | 4m |
| Imran et al., 2015 | 2m*3m*2m | 50-100-150 mm | 0.25m | 2m | floor level | 2m |
| Park &Battaglia, 2015 | 1m*1m*1m | 0.1m -0.2m- 0.3 m | 0.1m -0.2m- 0.3 m | - | floor level | - |
| Mokheimer et al., 2017 | - | 0.3 m | - | 3 m | floor level | 1 m |
| Hosseini et al., 2017 | - | 175mm | - | 1m | - | - |
| Tan & Wong, 2014 | 64.2*21.0*14.2 m | 0.3 m | 0.5*0.7 m | - | 2.5 m above floor | 1.0 m |
| Imran, 2017 | - | 0.1, 0.15, 0.2 m | 0.2×1 | 2 m | floor level | 1 m |
| Asadi et al., 2016 | 8×6 m at 2.7 m height | H/11-2 m | 0.5m*1.5m | 22 m | 0.3 m above the floor | 2 m |

the architects and engineers reaching the optimum choice of architectural device forms and geometries (Lal et al., 2016). CFD enables building designers to choose the best constructive solutions by simulation techniques and not by trial-and-error experimental techniques, which need much time and economic resources to be performed. Nevertheless, CFD simulations have to be validated to ensure that the results are reliable (Mora-Pérez et al., 2015). The increasing number of simulations contributes to the outcome optimum solution for enhancing natural ventilation by examining different parameters (Asadi et al., 2016). Detailed parameters including physical features such as air gap width, the height of the stack, opening areas, material, and chimney tilt angle can be simulated through a simulation method. In the past decade, an increasing number of studies have been done examining the mentioned factors via theoretical, numerical, or simulation tools (Hweij et al., 2017). Miyazaki has investigated "the effect of the SC on thermal load mitigation of an office building under the Japanese climate" using the CFD method and they have revealed that the fan shaft power requirement was reduced by about 50% in annual total due to the natural ventilation. It was also found that the SC was beneficial to reduce the heating load by about 20% during the heating season. The annual thermal load mitigation was estimated at 12% by taking the increase in the cooling load into account (Miyazaki et al., 2006).

Therefore, in comparison with natural ventilation, designers will be convinced to use these SC tools. The operation of SC is a vertical element exposed to the south rays of the sun, which, by absorbing southern solar rays, warm the inner air of the chimney. Due to the chimney effect, the air is warmed and contracted less, which makes it move upward (Pasumarthi & Sherif, 1998). During the daytime, the heat inside a mass wall is reserved for the SC effect continuation after sunset and nighttime or cloudy hours (Aboul-Naga & Abdrabboh, 2000). The simple structure of the SC does not mean that performance is neglected. The different layout of the SC creates a different ventilation rate. (Fluri & Backström, 2008). The design of the SC is crucial in providing an optimum airflow rate for the occupants. Many factors affect the efficiency of the SC, including the location, climate, orientation, and size of the building (Harris & Helwig, 2007). The function of the SC is greatly influenced by the height of the chimney, its width, and the heat flux (Layeni et al.,2021). Increasing the chimney height leads to an increase in ventilation capacity, and moving the air inlet higher also results in higher ventilation rates, as noted by (Rujiin,Zhang, et al., 2021). The different layout of the SC creates a different ventilation rate (Fluri & Backström, 2008). It is crucial to mention that natural ventilation in coastal cities heavily relies on the levels of temperature and humidity (Tong et al., 2017). Additionally, it is indicated that a higher amount of particle deposition fraction (ca. 0.71) is obtained when the outlet valve is located on the top of the wall (Forough Farhadi, et al,2023). In addition, NV due to the pressure difference leads to increased air velocity; therefore, ventilation creates a comfortable internal microclimate inside a building and saves energy by reducing the use of mechanical ventilation (Baxevanou et al., 2020).

In the traditional architecture of Iran, several houses in the hot climate of Tehran use a vertical structure similar to a SC for ventilation, with gates located near the ceiling level. However, modern architecture proposes a fixed height for the inlet of the SC near the floor due to mechanical theories (Hosien & Selim, 2017). Unlike modern architecture, vernacular and traditional architecture in Iran rely on passive technology for indoor ventilation (Foruzanmehr, 2015). However, traditional passive ventilators like Wind Catcher depend on outdoor wind flow. The advantages of traditional passive ventilators are described by Maleki in his paper titled "Wind Catcher: Passive and Low Energy Cooling System in Iranian Vernacular Architecture"

(Maleki, 2011). This study is helpful for designers in understanding the impact of roof types on improving outdoor air quality around buildings, numerically investigates the influence of building shape on improving outdoor air quality around buildings using the RNGk−ε turbulence model (Saeid Chahardoli, et all.2023). Ghadiri et al investigated the effectiveness of natural ventilation using a two-sided traditional ventilator called Wind Catcher through CFD simulation. This study focused solely on mean air velocity and airflow rate as the primary parameters for evaluating natural ventilation. The study was conducted on a simplified building geometry and a two-sided isolated wind catcher.(Ghadiri et al., 2013).

In this paper, the aim is to analyze the placement of solar chimneys in three traditional Iranian cities and investigate the impact of entrance location on air speed fluctuation on the hottest day of the year by simulating a three-story house with a solar chimney. Many studies have been carried out by mechanical engineers, focusing solely on airspeed rate without considering the impact on human comfort and only measuring airspeed rate instead of analyzing air velocity at the human scale. Therefore, the main aim of this study is to simulate different heights of inlets and their effect on air velocity at different levels, especially at the human scale, to determine the optimal height for the air inlet in an SC in modern architecture. This research aims to provide valuable insights into the optimal positioning of the air inlet in solar chimneys for modern architecture.

## MATERIALS AND METHODS

In the present study, natural ventilation was analyzed through simulation methods. The model's features were derived from traditional houses in Tehran, which will be further described. Ansys Fluent software was utilized for CFD simulation. CFD studies have increasingly been employed for indoor ventilation research (Calautit &Hughes, 2014). Ansys Fluent is one of the most validated software programs used for CFD simulation purposes, and its validation has been proven in numerous studies (Hughes et al., 2012). Therefore, ANSYS FLUENT 18 is used for simulation purposes in this study.

*Selected Iranian Traditional House*

Building species, as cells of this concept (morphology), determine the degree of energy efficiency (H. Karamouzian et al., 2021). One might mention the purity and non-polluting qualities of renewable energies, which eliminate greenhouse gas emissions, offer free costs and availability, safety, and ultimately reduce the usage of fossil fuels (Safavi, 2019). Indoor ventilation is one of the main principles of Iranian traditional architecture. Thus, some traditional houses were selected from different cities in Iran to scrutinize their ventilation structure. The height of the ventilation gate was inspected as the main focus of this study. Three cities were selected, which are well-known for their traditional houses, including Tehran, Isfahan, and Kashan. 21 houses were selected for this purpose. In this study, a 3-story residential building is modeled, which is shown in the following picture.

Figure 2: The main model

The model has a typical plan. In each story, the location of the SC is at the front of the kitchen and Living Room. This space has dimensions of 14 m in length, 5.1 m in width, and a height of 2.9 meters. There is a ventilation gate located on the northern side for air-flow purposes, with a dimension of 1.5*2 meters. The inlet of the SC on the southern side is taken into consideration with two different heights. Initially, the inlet is located at 0.4 meters of floor level with a dimension of 0.5*1 m, then the inlet is placed at a height of 1.7 m from floor level. These two hypotheses are driven by frequent studies of the SC and the ventilation gate of the traditional house of Tehran, Iran, which was described in the previous section. The cross-section of the models has 1.3 meters of depth since Bouchair (1994) introduced the h/10 as an optimum proportion and proposed the dimension of this study as close to his introduced optimum dimension and 0.6 meters of width. The height of the SC is considered 20 meters in total (it is 10 meters higher than the last floor). On the first floor, three outlet channels with a width of 0.5m and 2 meters in height, and on the second floor, three outlet gates are considered with a width of 0.5m and 3 meters in height. It is worth mentioning that to avoid disturbing sound and smell, the channels are considered separately. All environmental parameters are calculated at the level of 1.4 meters.

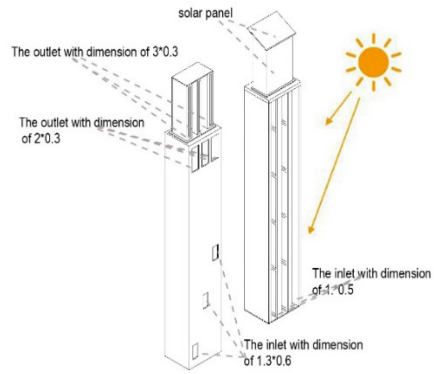


Figure 3: The structure of the modeled SCs

## DISSCOUSION AND FINDINGS

*Natural ventilation in Iranian traditional architecture*

According to the methodology section, 22 traditional houses from three cities were selected to be assessed in terms of ventilator height. Seven houses in Tehran, Iran (the capital city of Iran) were evaluated to extract the height of the ventilation gate called Goljam in the Persian language. Based on traditional houses in Tehran, almost all ventilation gates are located above one-third or near the ceiling level.

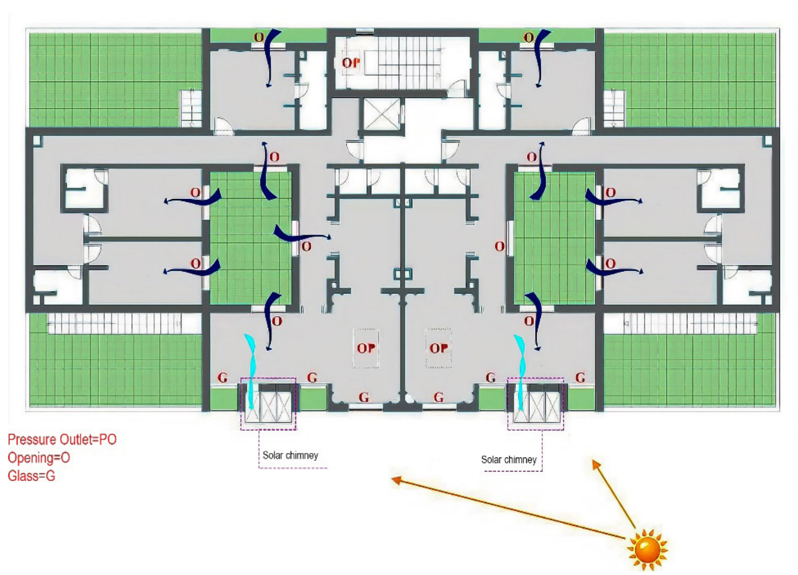


Figure 4: The architectural plan of the third floor

Nine traditional houses of Isfahan are chosen to assess the level of ventilation gates, almost all gates are placed near to ceiling of above one-third level.

For the final city, the six traditional houses of Kashan City, Iran opted to be taken into consideration in terms of the ventilation gate's level:

According to the above, in traditional houses in Kashan, Iran, ventilation gates are placed above one-third or near the ceiling level. Based on this data, it can be concluded that ventilation gates in traditional houses are not located at floor level, which is contrary to modern architecture. However, it is important to consider the human level. Therefore, three levels of the inlet of the SC including (1) Floor level, (2) Near to ceiling, and (3) above one-third level are simulated and compared in the next section.

Table 2: The level of ventilation gate (Goljam) in Tehran's traditional houses

| Name of house | Level of gate | archaism |
|---|---|---|
| Mostofi-Al-Mamalek house | Near to ceiling | Qajar dynasty |
| Jalale Ale Ahmad house | Above one third | Qajar dynasty |
| Ayat Allah Kashani house | Near to ceiling | Qajar dynasty |
| Imam Jomeh house | Near to ceiling | Qajar dynasty |
| Ghavam-Al-Doleh house | Near to ceiling | Qajar dynasty |
| Mirza Bozorg-e- Noori house. | Above one third | Qajar dynasty |
| Zahir-Al-Islam house | Above one third | Qajar dynasty |

Table 3: The level of the ventilation gate (Goljam) in Isfahan's traditional houses.

| Name of house | Level of gate | archaism |
|---|---|---|
| Haj Hasan-e- Ghafori house | Above one third | Qajar dynasty |
| Charmi house | Above one third | Qajar dynasty |
| Yadolahi House | Above one third | Qajar dynasty |
| Dr-Alam house | Near to ceiling | Qajar dynasty |
| David house | Near to ceiling | Safavi dynasty |
| Haj Mansour-e- Maleki house | Near to ceiling | 250 years ago |
| Karimi house | Above one third | Qajar dynasty |
| Akafzade& Sharif house | Above one third | Qajar dynasty |
| Sheikh-e- Harandi house | Above one third | Qajar dynasty |

Table 4: The level of ventilation gate (Goljam) in Kashan's traditional houses

| Name of house | Level of gate | archaism |
|---|---|---|
| Bakuchi house | Above one third | Qajar dynasty |
| Sharifian house | Near to ceiling | 1941 |
| Vosogh-e- Ansari house | Above one third | Qajar dynasty |
| Karkhaneh Chi house | Near to ceiling | Qajar dynasty |
| Atarha house | Near to ceiling | Qajar dynasty |
| Abasian House | Above one third | Qajar dynasty |

*1.2 CFD simulation*

The paper examines the speed and pressure of airflow within 1.4 meters of the floor (human scale). The physical properties of the fluid (air) following the weather conditions at 15:00 (the warmest hour of the day) on June 15, 2022 are also considered. In this study, the fluid (air) condition is considered incompressible flow, and the study is done in a steady uniform flow condition.

Table 5: input parameters

| Initial parameters | value |
|---|---|
| Air temperature | 304 K |
| Initial speed | 0.2 m/s |
| Initial air pressure | Pressure of atmosphere |

*Floor level inlet:*

In this step, the air inlet is considered at the floor level. Air velocity flow is considered the most important factor in solar and natural ventilation, thus airspeed analysis is conducted in the first step. The chart below shows a constant speed in the first 10 meters. At the first 0.5 m, there is a slight decrease in the rate of air, and then it reaches a constant value of 0.13 m/s in a decreasing manner. However, the chart experiences some variation in the final meters due to openings, which cause pressure differences. At a distance of 11 metres, there is fluctuation due to the pressure difference, and the chart hits 0.15 m/s and drops to 0.05 m/s at a distance of 12 metres, then starts growing and hits the value of 0.25 m/s at a distance of 14 metres. According to the chart below, the average air velocity is 0.11 m/s in the floor-level inlet.

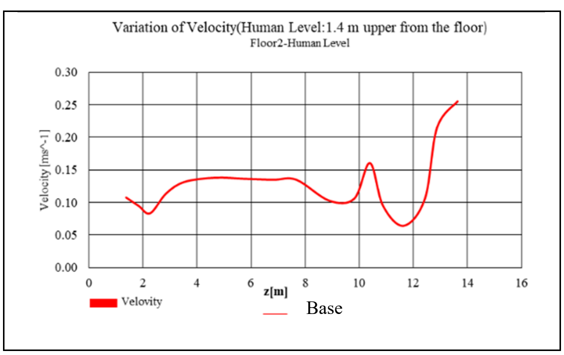


Figure 5: Variation of velocity ( floor lever inlet)

The chart of air temperature experiences a downward trend and starts with 305K and reaches 300.75 K. For the first 8 meters, the chart shows a constant decrease and reaches 304K; but after that, it experiences a sharp drop to 300.75 K. It means that by getting away from the inlet, the indoor environment experiences a cooler condition.

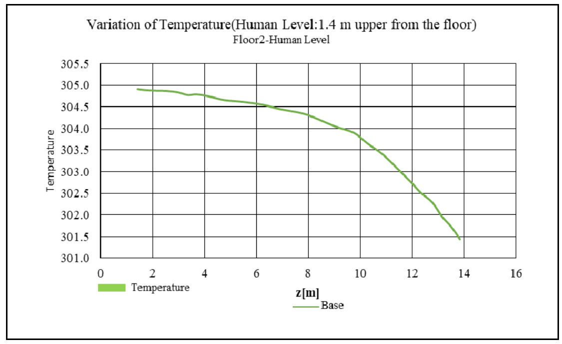


Figure 6: Variation of air temperature (floor lever inlet)

*Close to the ceiling inlet:*

In the second step of the simulation, the inlet level is placed at the ceiling level. Overall, the chart has some fluctuation at some point despite the steady chart that the previous condition has. The CFD results show that the initial airspeed is more than 0.2m/s, and the chart hits 0.25 m/s at a distance of 1 meter. The air moves quickly to the floor level after exiting the inlet and reaches the floor at a distance of 1 meter. From a distance of 1 up to 3 meters, the distance experiences a downward trend and reaches the value of 0.05 m/s, and the chart starts growing with slight growth up to the distance of 7 meters, hitting 0.15 m/s. At the distance of 7 meters, the chart experiences a downward trend symmetrically, reaching again the value of 0.05 m/s. Due to the openings and pressure differences, which create a good potential for reaching a higher airspeed, the chart experiences a rapid surge to the value of 0.15 and with a little fluctuation. At a distance of 14 meters, the chart hits its maximum value of 0.25 m/s again. According to the chart below, the average air velocity is 0.15 m/s at the ceiling level inlet.

When it comes to the air temperature of the ceiling-level inlet simulation, it is approximately equal to the floor-level inlet simulation. The entered air becomes cooler when moving through the floor due to the heat exchange between the entered air and the air on the floor. The equal results of the air temperatures in both conditions of the simulations demonstrate that the thermal sensation of the setters is more affected by air velocity on an equally typical day.

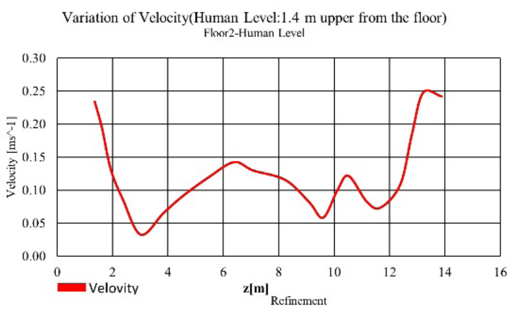


Figure 5: Variation of velocity (ceiling lever inlet)

The equal results of the air temperatures in both conditions of the simulations demonstrate that the thermal sensation of the setters is more affected by air velocity than other factors on a typical day. The comparison of the CFD results demonstrates that despite many typical studies, ceiling-level inlets have better airflow results and would create a cooler environment in terms of airflow. Air temperature contours in both simulation conditions are similar. However, when it comes to air velocity, the results are different. Airflow velocity in the ceiling-level condition is closer to the desired airflow rate. The airflow in the ceiling-level inlet is superior to that of the floor-level inlet, as shown in Fig. 6. At rest points on the floor, the ceiling-level condition has higher airspeed. However, at human level, the floor-level inlet provides a steadier environment in terms of airspeed. It is worth noting that ventilation gates in Iranian traditional architecture are placed at the ceiling level. This study confirms that following this tradition by locating the inlet of the SC at the ceiling level would optimize natural ventilation. The goal of creating temperature differences, pressure differences, and airflow rates is to enhance natural ventilation efficiency, and therefore, we recommend using the ceiling-level inlet for better natural ventilation.

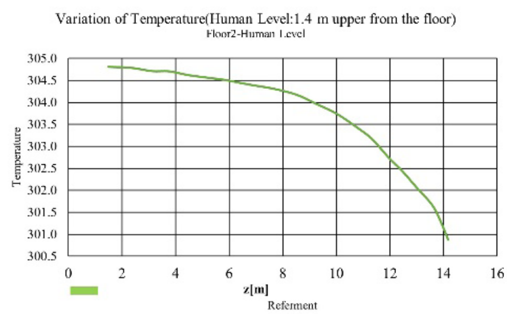


Figure 6: Variation air temperature (ceiling lever inlet)

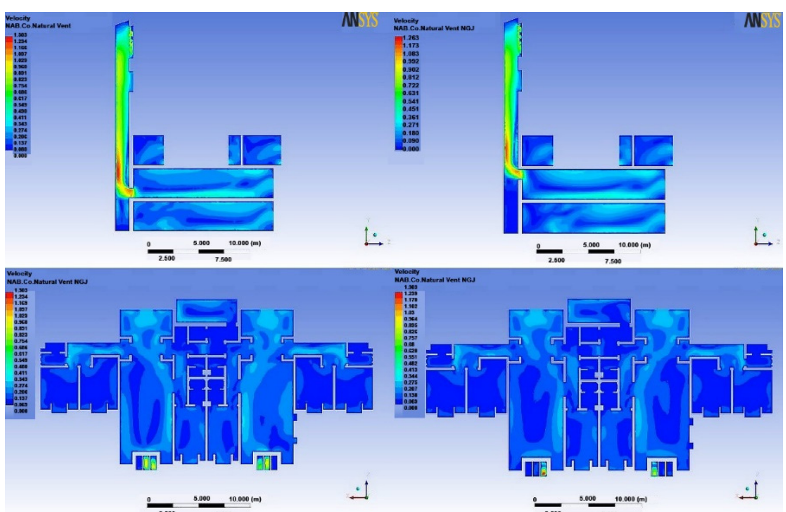

Figure 7: Comparison of the air velocity

## CONCLUSION AND RESULTS

In recent decades, natural ventilation has been a major concern for researchers, and various solutions have been proposed to promote it. Studies in mechanical engineering and architectural surveys have shown that enclosed spaces often exceed desired ventilation standards throughout the year in terms of air change per hour (ACH) (Hosien & Selim, 2017; M. Dhahri, 2020). Proposed methods have considered variations in pressure loss coefficient for different flow conditions at the chimney outlet and have been demonstrated to be valid for predicting induced airflow rates with or without reverse flow (Yicun Hou, 2019; Marco S. Fernandes, 2020). Findings indicate that different chimney designs can increase airspeed by 17% to 23% and boost electricity production by 64% to 95% (Parisa Rahdan et al.,2021). The use of solar chimneys has been found to lower room temperature by approximately 2 degrees Celsius, improving indoor thermal comfort and increasing residents' satisfaction (Mehdi Khakzand & Saied Chahardoli, 2021). Traditional Iranian architecture has long prioritized natural ventilation, with modern studies recommending floor-level inlets for improved airflow. However, simulations have demonstrated that ceiling-level inlets, following traditional architectural approaches, may be more suitable for natural ventilation. This study addresses the accuracy of these two conditions, demonstrating that a floor-level inlet provides steady airflow at the human level with an average airspeed of 0.11 m/s and a cooler temperature as air moves away from the inlet. On the other hand, a ceiling-level inlet shows fluctuating airflow with an average airspeed of 0.15 m/s and similar air temperature values to the floor-level inlet. The suitability of the traditional architectural approach in natural ventilation is proven, and a ceiling-level inlet is recommended as a proper inlet despite typical studies and assumptions. Further research is suggested to explore the relationship between temperature and natural ventilation or the combination of cooling materials in the walls of solar chimneys and their effect on the change in airspeed.

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HOW TO CITE THIS ARTICLE
Khakzand, M., Ashrafi, N., & Yaghoubi, M. (2024). Investigating the impact of inlet height in the solar chimney in vernacular houses on the indoor natural ventilation efficiency. Journal of Urban Management and Energy Sustainability, 4(4), 142-153.
DOI: 10.22034/JUMES.2024.2010371.1158