Energy Reports 10 (2023) 2174–2193

Contents lists available at ScienceDirect

Energy Reports

journal homepage: www.elsevier.com/locate/egyr

Research paper

The effect of geometry and location of balconies on single-sided natural ventilation in high-rise buildings

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ARTICLE INFO

Article history:
Received 31 December 2022
Received in revised form 29 August 2023
Accepted 3 September 2023
Available online 12 September 2023

Keywords:
Balcony
Natural ventilation
High-rise buildings
Computational Fluid Dynamics
Sustainable Development
Energy
Zero Energy Building

ABSTRACT

The demand for housing and the expansion of urbanization have increased the price of land and vertical growth of buildings, resulting in converting the courtyard and porch to balconies. Nowadays, semi-open spaces, which play a critical role in providing optimal indoor air and thermal conditions, are neglected. In addition, the area of such spaces is regarded as limited and sometimes even the balcony is eliminated, leading to improper thermal behavior and increased energy consumption, while such elements can be used for better natural ventilation of spaces and utilization of natural energy, resulting in reducing energy consumption in addition to controlling the pressure created by the wind in the case of correct design. The purpose of the current paper is to evaluate the performance of balconies on the high-rise buildings using single-sided ventilation in the harsh hot-arid climate of Hamdan in Iran, which there has not been studied already A general basic model is presented according to field studies and criteria. Field survey indicates that most of the high-rise buildings in Hamedan have single-sided natural ventilation, as well as are located on the south side, have a rectangular shape, are enclosed on three sides, and have recessed balconies. Based on the climate data of Hamedan, July is considered the hottest month of the year, during which natural ventilation should be applied. Simulation is conducted by computational fluid dynamics (CFD) method and ANSYS software. Based on the results, 4.5 m width and 1.5 m depth are regarded as the best geometry of the balcony for Hamedan providing a mass flow rate up to 1.38 kg/s. In addition, the position of the balcony in the wall of the building should not be symmetrical. The usage of a balcony in the middle of the façade could provide higher ventilation rate and reduce cooling energy up to 7% compared with the base case. Through a meticulous balcony design, wind could path through the larger spaces then it is led towards the opposite window, and finally exits the building in a single-sided ventilation mode. This causes the air to flow in most of the interior spaces, leading to better ventilation than other methods.

1. Introduction

An increase in energy consumption to provide thermal comfort in the building and the adverse effects of environmental pollution including the emission of greenhouse gases are among the critical concerns in the field of building and energy. There are significant elements in the architectural body of buildings in the past architecture of Iran, which meet thermal needs. Some of these elements can act as static elements although they have been neglected in contemporary architecture due to lack of scientific investigations. In addition, the buildings have been isolated due to the spread of air conditioning systems, leading to an energy crisis and environmental obstacles (Memarian et al., 2017).

Using passive systems in building cooling is among the methods to reduce the cooling load of electric air conditioners and to optimize energy consumption in the building. Openings and their accessories in the façade of the building play a critical role in natural ventilation and air flow inside the building (Ziabari and mozaffari Ghadikolaei, 2018). The balcony is among the significant components of the building, which is considered as a semi-open and in-between space and connects the inside and outside of the building (closed and open space) (Ebrahimi Asl et al., 2017). Obviously, two-sided natural ventilation (i.e.,

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https://doi.org/10.1016/j.egyr.2023.09.030

cross-ventilation) is considered more appropriate for the building than the single-sided one. However, the present study aims to assess single-sided ventilation since the density in urban life is regarded as high and most houses have single-sided ventilation in the modern world. According to scientific information data bases (e.g., Scopus and Web of Science) comparing the amount of the research published on the topic of single-sided vs cross-ventilations is really insignificant at an equal period from 2019 to 2023 that is around 7%. A very recently published review paper has emphasized this point and the authors have referred to the limitation of the cross-ventilation due to growing and clustered cities, instead, single-sided natural ventilation becomes an alternative mode in wind driven natural ventilation strategies for clustered urban buildings (Zhong et al., 2022)

As indicated, the main role of semi-open spaces such as balconies has been neglected with the development of construction in the country. In addition, few studies have been conducted in their field, leading to unconscious neglect of such critical element in the design of buildings by experts.

This study emphasizes that balconies affect the external shell of the building significantly. In fact, such elements lead to a better distribution of wind and its pressure on the building shell and reduce or increase the wind pressure in different parts (Montazeri and Blocken, 2013). The present study seeks to evaluate the effectiveness of the balcony geometry and location in single-sided natural ventilation in high-rise buildings in Hamedan by examining the critical parameters in the formation and optimal design of the balcony.

A large number of studies have been conducted on the effect of the details related to the façade of the building and balconies on factors such as thermal comfort, air flow, natural ventilation, and sound. The studies conducted during 1988–2023 are discussed as follows.

In one study, the effect of the details related to the façade of the building was assessed by applying the wind tunnel method. To this aim, balconies with different widths were tested and no significant difference was observed in the measured pressures. Based on the results, balconies in short buildings do not affect the wind pressure on the wall significantly (Stathopoulos and Zhu, 1988). In another study, the optimal amount of protrusion from the façade to save energy consumption in the air conditioning system was reviewed. The results indicated that the load on the cooling system during the summer reduces through the shade created from the balcony under the climatic conditions of Iran. In addition, there was a significant increase in winter heating demand (Raeissi and Taheri, 1998).

Chand et al. evaluated the effect of balconies on natural ventilation. Based on the results, a change was reported in the pressure distribution on the windward side, while no significant change was observed on the back side of the wind. The balcony, as an architectural element, creates a significant change in the air flow in and around the building and improves the performance of natural ventilation (Chand et al., 1998a). In addition, Prianto and Depecker examined the combined effects of balconies and openings on two-sided ventilation in buildings. The results indicated that an increase in the height of the balcony ceiling does not affect the overall ventilation while installing the balcony increases natural ventilation significantly. Further, they investigated the combined effect of the balcony, opening design, and internal divisions of the plan in a two-story building in a similar climate (hot and humid). Based on the results, the balcony improves indoor thermal comfort and increases air velocity and indoor comfort conditions for stationary activity. Comfort conditions for sitting activity are regarded as acceptable, despite being little (Prianto and Depecker, 2002, 2003).

Zhiyi et al. (2021) evaluated the potential of cross-ventilation channels in an ideal-typical apartment using CFD. The paper argued the difficulties of high-density buildings in urban spacing caused to utilize a single elevator hall in the apartments. The issue is amplified when the apartment is on the leeward side and the wind pressure ventilation is low. The authors tried to predict the effect of implementing horizontal airflow channels in 7 different climates in China. They proved that the horizontal airflow channel can obviously improve the ventilation capacity of the leeward apartment, especially for south-side apartments up to 5%. In a similar study, the authors evaluated the performance of a newly designed cross-ventilation technique in a building and improved the ventilation rate by 215% on an annualized basis when applied and simulated in typical conditions from 10 different cities in China (Zhiyi et al., 2021).

Kosutova et al. (2019) studied the cross-ventilation of an isolated building equipped with louvers on its opening. The 3D steady Reynolds-averaged Navier–Stokes (RANS) simulations are performed with three turbulence models (RNG k-ε, SST k-ω, RSM) and validated with the wind-tunnel experiments. The authors validated their results using a wind-tunnel experiment and based on their results, the largest velocities occur in a building with openings in the upper part of the façade and the highest dimension-less flow rate would reach 0.69. The highest air exchange efficiency (45%) is achieved for a building with louvered openings in the center of the façade (Kosutova et al., 2019).

There are also studies done recently coupling CFD modeling of cross-ventilations with Machine Learning by Ding and Lam (2019) to reduce the robustness of CFD analysis at the early stage of design.

Furthermore, Niu evaluated the balcony as a useful architectural model in residential buildings, which can improve indoor air quality significantly and reduce energy consumption in buildings. The results reported by Niu et al. were consistent with those of Stathopoulos and Zhu (1988) regarding residential buildings in China. The demand for air conditioning is reduced during the summer by shading the façade of the building with façade projections (Niu, 2004).

da Graca et al. (2021) evaluated the performance of a flow in the form of single-sided pumping and cross-sided ventilation using experimental and numerical modeling in Corner rooms with two or more open windows (da Graca et al., 2021). Arinami et al. (2019) single-sided natural ventilation for a generic building model, so as to investigate the impact of guide vanes (GVs) and adjacent obstacles on the air change rate and ventilation efficiency (Arinami et al., 2019).

In another study, the effect of balconies on single-sided natural ventilation was reviewed. The results indicated that the combination of the balcony and opening plays a critical role in creating internal airflow. The indoor airflow alters with the change of the height from the ground level and location of the building block significantly (Yu et al., 2008). In another study, the balcony was defined as a transitional space to control and create natural ventilation and internal and external turbulences in high-rise apartments in Malaysia. Based on the results, the corridors and balconies channel the wind and bring the airflow to the required areas of the building (Mohamed et al., 2009).

There are also some studies which have assessed the ventilation in dense cities with a balcony in order to reduce air pollutants from the city recently which proved balconies have significant impacts on the ventilation and pollutant dispersion inside the street canyon (Karkoulias et al., 2020; Sin et al., 2023).

Kim and Kim studied the effect of balcony removal on healthy daylight in some residential apartments in South Korea and argued that removing the balcony prevents blocking the intense and excessive light of the sun, leading to annoying radiation and penetration of ultraviolet rays (Kim and Kim, 2010). In another study, a residential apartment in Hong Kong was analyzed. The results indicated that residential apartments with different orientations can save a lot of energy in the air conditioning system due to the shading of the balcony (Chan and Chow, 2010). In addition, Ai et al. assessed the effect of balconies on thermal comfort and natural ventilation in short buildings. Based on the results, the balcony improves comfort by increasing the uniformity of indoor air distribution and provides a greater range of thermal comfort for naturally ventilated buildings (Ai et al., 2011).

In another study, natural ventilation in high-rise residential buildings was examined by creating a balcony on the façade. The results indicated that the performance of single-sided ventilation can be improved by applying façade components such as balconies compared to flat buildings, and the appropriate combination of balconies and single-sided ventilation strategy can improve ventilation performance in high-rise buildings (Mohamed et al., 2011). In order to reduce the adverse wind in the balconies, various measures can be taken such as closing the balcony, adding partition walls, and the like. Recently, the idea of a new façade was presented by the ELD group (Eld Partnership, 2011). Such a semi-open façade is considered as the second shell of the façade, which acts as a wind shield for the balconies. Further, Montazeri et al. investigated the performance of the above-mentioned data and claimed that the concept of the second shell improves comfort for a large part of the western façade and a part of the southern one (Montazeri et al., 2012b).

There are also studies that have added the effect of balconies on thermal performance and added energy equations associated with flow analysis in order to calculate convective heat transfer at the façade with balconies for a multi-story building. According to their results in the presence of the balconies, the surface-averaged convective heat transfer coefficient (CHTC) is reduced by about 17.5% at the windward facade, while it is reduced by 35.2% at the leeward façade (Tao et al., 2023).

According to Ghadikolaei et al. the balcony can change the pattern of airflow inside and outside the building significantly and can be used to improve the performance of natural ventilation in the building (Ghadikolaei et al., 2013). Omrani et al. evaluated the effect of balconies in high-rise residential buildings in subtropical climates utilizing the CFD method and reported that the implementation of semi-enclosed balconies in such buildings can improve ventilation performance (Omrani et al., 2015). In addition, Hilliaho et al. studied the effect of glass balconies on the energy consumption of buildings in northern climate conditions and found that single-pane balcony glass with inlets and openable glass is regarded as an appropriate option for balconies, especially in conditions like Finland (Hilliaho et al., 2015).

Omrani et al. developed their studies on the effect of balconies on natural ventilation and thermal comfort in high-rise buildings. To this aim, different case studies were conducted based on two balcony types, four balcony depths, two ventilation modes, and four wind angles, indicating that an open balcony increases indoor air velocity compared to a semi-enclosed one, and single-sided natural ventilation can improve up to 80% with ventilation through the open balcony. In fact, the highest indoor air velocity is observed when the wind blows perpendicular to the openings, while the lowest one is observed when the prevailing wind blows parallel to the openings, indicating the significance of building construction towards the prevailing wind direction to improve natural ventilation. According to sensitivity analyzes, both single- and two-sided ventilation modes are considered highly sensitive to the change of wind direction among the wind angle and balcony depth and type, indicating the significance of proper design in case of single-sided ventilation. Comparing single- and two-sided ventilation under similar conditions demonstrates that natural ventilation performs extremely better in the case of the cross-ventilation type. However, analyzing different parameters indicates that single-sided ventilation is considerably more sensitive to the change of parameters compared to two-sided ones (Omrani et al., 2017). Here, the findings provide solutions to improve the design of single-sided ventilation through the appropriate selection of the balcony since two-sided ventilation cannot be implemented easily, especially in dense urban areas.

In another study, the effectiveness of the balcony as one of the components in the building facade in reduction of energy consumption was reviewed, indicating that the balcony can provide appropriate effects in improving internal natural ventilation, reducing air conditioning energy consumption, and decreasing the external noise of the building, which is regarded as a common challenge in applying natural ventilation (Ziabari and mozaffari Ghadikolaei, 2018). Furthermore, Mozaffari et al. used a fin wall in the balcony as a solution for the facade to strengthen the single-sided ventilation performance in mezzanine apartments and asserted that fin walls located near double windows in the middle or corner of the balcony can improve the indoor ventilation performance significantly. Various parameters have been assessed for types of fin walls, as a new part in balcony design. A fin wall in the middle of the balcony performs better than that in the corner significantly. In addition, the results indicated that the fin wall angle deviation up to 22.5° leads to better results than the standing one at a wind angle of 45° (Mozaffari Ghadikolaei et al., 2020).

In one study, the effect of balcony geometry on single-sided natural ventilation and thermal comfort was evaluated. To this aim, five openings and nine different depths were defined as the basic simulation model. The results indicated that smaller openings lead to better thermal comfort than other models, while smaller depths lead to a non-uniform and unstable indoor air distribution in the living room connected to the balcony. Comparing the findings and the theoretical literature indicates that the effect of the depth of the balcony on average depends on the direction of the buildings significantly (Izadyar et al., 2020). In another study, the effect of building balcony geometry on the average wind speed in the balcony spaces and the average surface pressure created by the wind on public high-rise buildings was examined by focusing on the balconies that span the entire width of the building facade. Based on the results, the balcony geometry can affect the average wind speed in the balcony spaces and the average wind pressure coefficient of the facade. Generally, adding five partition walls can reduce the wind speed in the balcony spaces compared to that without such walls (Zheng et al., 2021).

According to the research conducted from 1998 to 2021 on the balcony and its effect on natural ventilation, we find that the process of studies has been such that first the effect of the balcony on improving natural performance, thermal comfort, and reducing noise pollution has been investigated and then the details of this issue have been discussed in different climatic conditions and different types of balconies with different geometries. Considering the vertical growth of buildings and the transformation of courtyards into balconies in today's residential buildings, and the fact that no research has been done on the effect of the dimensions and optimal design of the balconies of high-rise buildings in Hamedan, this research, by examining the important parameters in the formation and the optimal design of the balcony, the effectiveness of the dimensions of the balcony and its location in one-way natural ventilation in tall buildings in Hamedan city are investigated. Besides, the main purpose of this is to evaluate the capacity and performance of balconies in order to improve natural ventilation in a location where it has not been studied already and it can provide initial points for future investigations.

2. Theoretical foundations

2.1. Natural ventilation

Natural ventilation is considered as an environmentally friendly method to provide fresh air although its performance depends on external environmental factors such as wind conditions and the shape of the building including openings (Linden, 1999). Natural ventilation means utilizing the process of moving air inside the building or fresh air outside without applying mechanical facilities, which saves fossil energy consumption. During the aforementioned process, the air inside the building, which has become heavy due to exhalation, skin breathing, odors from cooking, smoking, and the like, is replaced with fresh and light air outside (Etemad Sheikholeslami, 2011).

Generally, three significant factors are used to describe and classify the concepts related to natural ventilation. The first factor includes the natural driving force utilized to create ventilation, which can be wind, buoyancy force, or a combination of both methods (Kleiven, 2003). The second factor contains the type of strategy applied to ventilate a space. The principles of ventilation determine the method of connecting the air flows inside and outside and that of using natural driving forces for the ventilation of the building (Aflaki et al., 2015). The third factor includes the type of elements utilized to realize natural ventilation. Generally, various instruments such as wind towers, chimneys, windows, ventilation valves, wind deflectors, solar chimneys, fin walls of double-shell facades, atriums, and built-in ducts can be applied by designers for natural ventilation in buildings (Mozaffari Ghadikolaei et al., 2020; Aflaki et al., 2015; Kopec, 2017; Passe and Battaglia, 2015; Nasrollahi, 2009; Allard and Ghiaus, 2012).

Airflow is considered a critical requirement in the overall process of ventilation during the design of the building wall, form, openings, and orientation (Kopec, 2017). In addition, the airspeed outside the building can affect the air movement inside the building due to the difference in air pressure created through the building walls using the appropriate placement of openings and passive design strategies (Memarian, 2008). Overall, the effective use of natural ventilation to create airflow depends on utilizing various architectural elements and techniques in buildings (Passe and Battaglia, 2015). Design parameters that change indoor airflow patterns include the type, size, and location of openings, interior layout, height and orientation of building facade, and exterior additions such as balconies (Kopec, 2017). There are different methods to create natural ventilation including applying architectural elements in the facade or roof of the building or a combination of both. The balcony is among the most critical building elements in shaping the exterior and volume composition. Today, the significance of creating a balcony as a semi-open space is increasing due to industrialization, urbanization, and building houses with a closed environment without an open private one.

2.2. Balcony

The balcony is defined as the covered surface in the floors of the building with at least one side open. The semi-open high level is connected to the exterior of the building, which is surrounded by a short wall or fence (Mahmood and farahani, 2013). According to the general requirements of the building, spaces such as balconies and verandas, which can be accessed from inside the building and are connected to the open air with at least one side open, are considered as semi-open spaces. Today, the balcony is among the critical components of the building in Iranian architecture, especially in residential buildings. In addition, the balcony is regarded as a semi-open and intermediate space from the visual point of view, which connects the inside and outside of the building (open and closed space) (Ebrahimi Asl et al., 2017).

2.3. High-rise building

To introduce high-rise buildings, no official definition can be found in which there is a consensus among all national and international official authorities, which may be related to the fact that high-rise building is defined based on the conditions of time, place, and different standards (Khodaveysi et al., 2019). Generally, high-rise buildings can be defined based on the following two indicators.

2.3.1. Height limit

The height of the building is affected by issues such as the method of providing services during a fire and building facilities. Environmental factors such as wind, flood, and earthquake are considered effective in the above-mentioned definition, as well. The aforementioned definition changes over time because the height of fire ladders may change with technological progress, resulting in decreasing its acceptability (Karimimoshaver et al., 2020).

The above-mentioned definition is based on the characteristics of the building or its location in the city and region. According to the Council of High-rise Buildings and Urban Housing in America, a high-rise building without specifying the height or the number of floors is defined as one, whose height affects one of the aspects of using the space or its construction planning significantly. Such a definition appears more practical and acceptable due to the features of the region and the location of such buildings in different cities (Etemad Sheikholeslami, 2011). According to the study conducted and considering the sample base (most buildings in Hamedan have two and three stories) and definition number one of the Council of High-rise Buildings and Urban Habitat, as well as the Center for Studies and Planning of Hamedan Municipality, a high-rise building is described as one taller than seven stories which are regarded as taller than those around significantly (Ghiasvand et al., 2020).

3. Materials and methods

Fig. 1 depicts the overall research process. Through the figure it is seen that the study contains three main steps; first, reviewing of the related studies to the research scope, second, field study to categorize the main variables influencing the flow performance of the balconies in Hamadan, and third, the simulation step (Fig. 1). During the field study, it tried to clarify the main balcony components such as orientation, geometry, type, enclosure, placement, dimensions and type of balcony wall, and its type of ventilation are investigated. This step generally provided a basic model configuration in the next step of simulation.

To conduct the simulation part, the performance of balcony ventilation is checked in different modes, and a general optimal model is presented. In the next step, simulation focuses on the change of balcony location in the plan, and the effect of each parameter is studied. Finally, the results of the simulations are analyzed.

To investigate the effect of the desired components, it is necessary to define models for simulation; In order to determine the appropriate model for this research, first of all, it is necessary to explain the features and characteristics of models and evaluation methods, and in the next step, we will simulate and examine the behavior of basic models.

In the field survey, the orientation of the desired buildings was checked, the common typologies of balconies in Hamadan city were classified and the most frequent types were identified. The configuration of the balconies was examined in terms of direction, geometrical shape, type of enclosure, and indentation or protrusion of the balcony, as well as the depth and opening

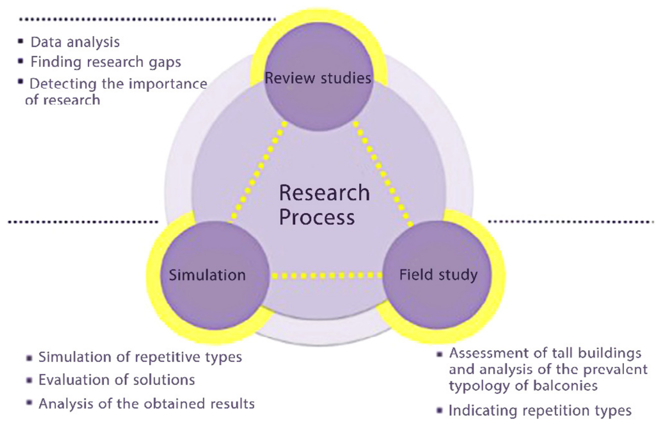

Fig. 1. The process of research.

of the balcony. Finally, the optimal direction in the simulation of the fixed base model is considered. In order to design the basic simulation model, the balconies of the high-rise buildings in Hamedan were investigated. The existing buildings include 35 buildings (8 floors and above), and it was found that 74% of them have balconies and they often have a north–south direction leaning to the east, 91% are rectangular. The ventilation type of 77% of them is one-way, 70% are recessed and 65% are enclosed on three sides and have no cover.

3.1. Climatic study of the research platform

Hamedan is located in the mountainous region of Alvand, which is located in the high foothill climate. Hamedan is placed 1741.5 m above sea level with latitude of 34.52 north and longitude of 32.48 east (Etemad Sheikholeslami, 2011). The appropriate wind from the southeast and southwest should be utilized at maximum due to the efficiency of natural ventilation during about 4 months of the year provided that relative humidity exists (Malekhosseini and Dargahi, 2010).

3.2. Orientation of the building

The most appropriate direction of the main front of the building is measured in relation to the two factors of sun radiation and wind flow. Facing south with rotation to the east, which receives the most heat during the winter and receives less during the summer is considered the best orientation of the building considering the radiant heat received by the window during different months. The cold wind during the winter flows from the southwest, and the southeast and southwest are regarded as the appropriate wind direction of the Hamedan www.worldweatheronline.com. In addition, three ranges of the need for shade in two seasons, need for shade in one season, and need for sunshine in two seasons are obtained which determines the optimal orientation of the building when the temperature of 21°, as the boundary of the need for shade and sunshine, is matched from the calendar of climatic needs on the map of the path of the sun at the latitude of 36° north which is regarded as the latitude of Hamedan. Generally, 21° to the southeast is considered as the most appropriate orientation of the building in Hamedan in terms of shade design with the optimal overlap of the shadow detector and achieved chart (Etemad Sheikholeslami, 2011).

In fact, EPW weather data files are related to a 12-year period of the climate in a region, the accuracy of which is reliable to a large extent. The considered weather file contains information such as dry air temperature, humidity percentage, direct and indirect radiation, geographic location, dew point temperature, and the like. According to the climate data, July is regarded as the hottest month of the year with 21 °C, and the 12-year average wind speed during this month equals to 9.8 m/s based on the World Meteorological Site www.worldweatheronline.com (Fig. 2 and Table 1).

4. Simulation procedure

The simulation was conducted by applying CFD and ANSYS software. To this aim, ANSYS SpaceClaim, ANSYS Meshing, ANSYS Fluent, and CFD-POST software were used to model the design geometry, generate grid and mesh, analyze the airflow behavior, and process the results, respectively. Fig. 3 demonstrates the simulation steps.

4.1. The grids independence test

Before conducting any CFD simulation it is necessary to be sure regarding the sensitivity of the solutions on the mesh numbers and qualities. To this end, the base model has been considered for the grid analysis. In order to conduct the mesh independence test, a basic model has been chosen. Fig. 4 shows the considered model and defined conditions for the test. The detailed information related to the model will be discussed in Section 4.2.1.

The model is one of four cases that has been selected for the analysis. Since the domain selected for the study is a horizontal analysis, the model has a dimension of 8 m $*$ 12 m. The lower dimension is the windward face. Based on the assumptions, the wind speed is considered at the height of 12 m. Thus, due to the wind speed gradient formula (z^(1/4)) derived from a valid benchmark study (Stathopoulos, 1984; Murakami, 1990), the speed value was calculated at 1.86 m/s and used for the simulation. The flow is an external flow around an obstacle, the Reynolds number was calculated in the order of $50 * 10^4$ to $150 * 10^4$ for this study (Streeter et al., 1998). At the outlet, zero static pressure is specified.

Fig. 4 shows the base model dimensions, considered boundary conditions, and computational domains used for grid tests. According to the references it is proven that RANs models can calculate the flow and its characteristics using time-average governing equations (Zheng et al., 2020; Hu et al., 2008; Lakehal and Rodi, 1997) and the referred modes (i.e., RANS) are able to simulate natural ventilation for either simple or complex geometries such as building with a reasonable range of precision (Ramponi and Blocken, 2012; Evola and Popov, 2006). Additionally, more detailed information regarding the best-fitting turbulence model has been discussed in the papers (Shirzadi et al., 2020a; Zhang et al., 2020) where the authors have discussed and compared the properties, settings. and capacities of each model for the specific application. This fact also was proven and applied the recent studies (Perén et al., 2015; Montazeri et al., 2013). According to these studies (Montazeri et al., 2013; Blocken et al., 2007a), the use of k-e type of turbulence models wall functions can yield difficulties in simulating a horizontally homogeneous atmospheric boundary layer, this data is required at the upstream part of the computational domain (Blocken et al., 2007a), this means that regarding the performance of the turbulence models for the prediction of indoor and outdoor airflow, that is RNG k-e models that could show better performance and be reliable for the similar studies. For this simulation according to the suggestions of the authors k-e realizable has been selected (Zhang et al., 2020; Shih et al., 1995; Shaheed et al., 2019; Ai et al., 2013; Murena and Mele, 2016; Shirzadi et al., 2020b).

Table 1
Wind speed in the hot months of the year.
Source: Statistical data of Nojeh Hamadan synoptic station (2009–2020).

Month	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	Ave
Sep	8.7	6.5	8.7	8.5	9.4	9.4	7.7	10.9	7.5	10.9	10.1	7.9	8.9
Jul	8.5	8.1	9	9	8.4	10.2	11	9.6	11	12	11	9.8	9.8
Oct	8.3	6.4	8.8	9.2	8.9	8.5	9.8	9.8	11.5	10.6	9.9	10.1	9.3
Jun	8.6	8.5	10.5	9.9	8.9	10.7	8.7	13.2	11.6	10.4	9.1	10.8	10.1
May	9.6	9.5	11.2	13.1	11.6	10.4	15.9	12.9	12.4	10.3	10.9	14.2	11.8

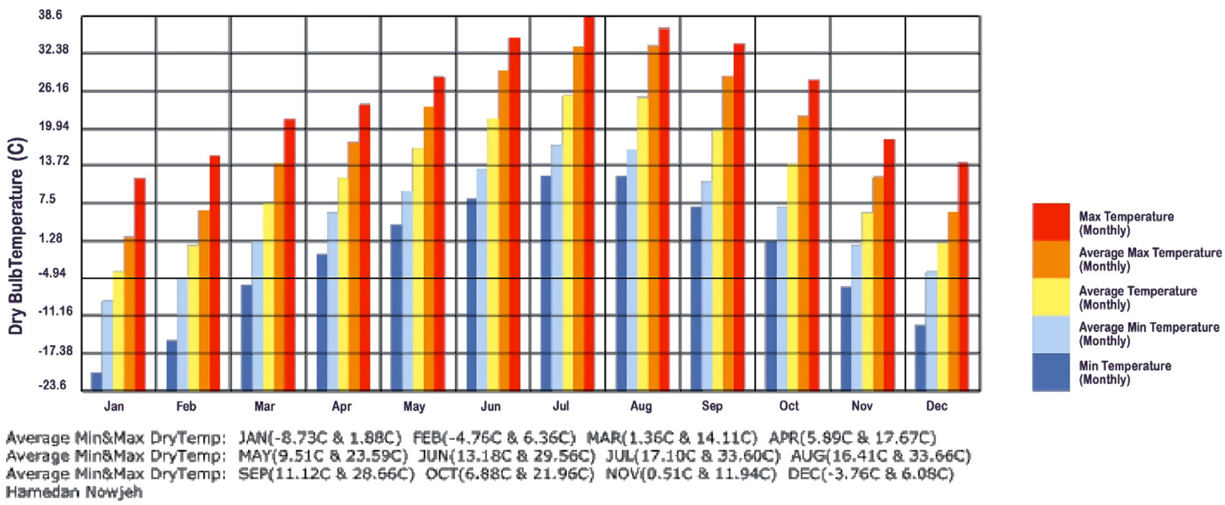

Fig. 2. Minimum and maximum monthly temperature chart.
Source: Statistical data of Nojeh Hamadan synoptic station (2009–2020).

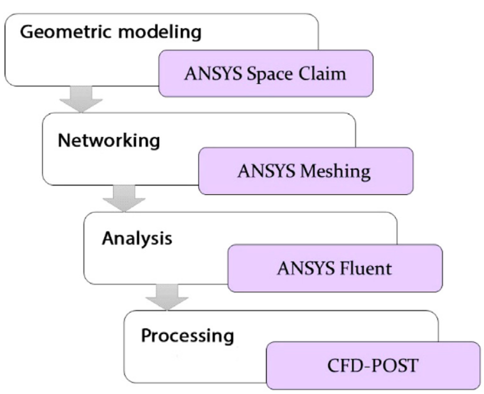

Fig. 3. Steps of research simulation.

In this research, the regarded turbulence model has been chosen due to some main points, as a main approach is to refer to similar studies from literature, which is likely due to widely employed to simulate natural ventilation showing excellent performance compared with other models (Izadyar et al., 2020). From theoretical and simulation points of view, based on Richards and Hoxey (1993), it was stated that in computational models of wind engineering problems within the atmospheric surface layer, the approach flow should normally be modeled as a homogeneous flow; velocity and turbulence profiles associated with the k-ε turbulence model are proposed which produce homogeneous conditions. With similar characteristics, the RANS models such as the k-ε model could show good performance in predicting Cp on the windward façades with balconies (Stathopoulos and Zhu, 1990). Among all the k-ε models, the realizable variant contains a new formulation for the turbulent viscosity compared with the k-ε standard model; Cμ is not a constant in the turbulent kinetic energy equation like in the standard model but a variable (Cμ equal to 0.09) (Zheng et al., 2021). The second difference is a new transport equation for the dissipation rate, ε, that is derived from an exact equation for the transport of the mean-square vorticity fluctuation. Consequently, the model would provide more improved predictions for the cases with the spreading rate of jets and more importantly where the models have more apparatus (as seen in our cases), because it can capture the mean flow of complex geometries and also cases with rotation, boundary layers under strong adverse pressure gradients, separations, and re-circulations. It is seen that almost all the mentioned characteristics could be involved in our simulation. The mentioned information and also more details are found in the paper Shih et al. (1995) and, Murakami (1990). As a result, k-ε realizable mainly gives a superior ability to capture the mean flow of complex structures and for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and re-circulation, as we faced such flows in our case. Finally, as mentioned by Murakami (1990), in the building aerodynamic problems, the Reynolds number is high owing to the large length scale imposed; this makes it hard to set mesh interval near the solid walls fine enough to solve viscous sublayers. Therefore, we needed the first grid point from the wall to be located at an area of lower than 200 by the value of the wall (Y+). As k-ε realizable does use wall functions, so, it has to be assured that the Y+ values in the first cell near the wall should not excessively exceed the referred values. Through that, it is possible to reduce mesh numbers and have less computational time provided by the model. However, it is necessary to create high-quality grids. For all these reasons the authors have chosen the regarded turbulence model for the simulations.

In order to enhance the accuracy of the results near the wall/surface the enhanced wall-treatment has been selected in wall

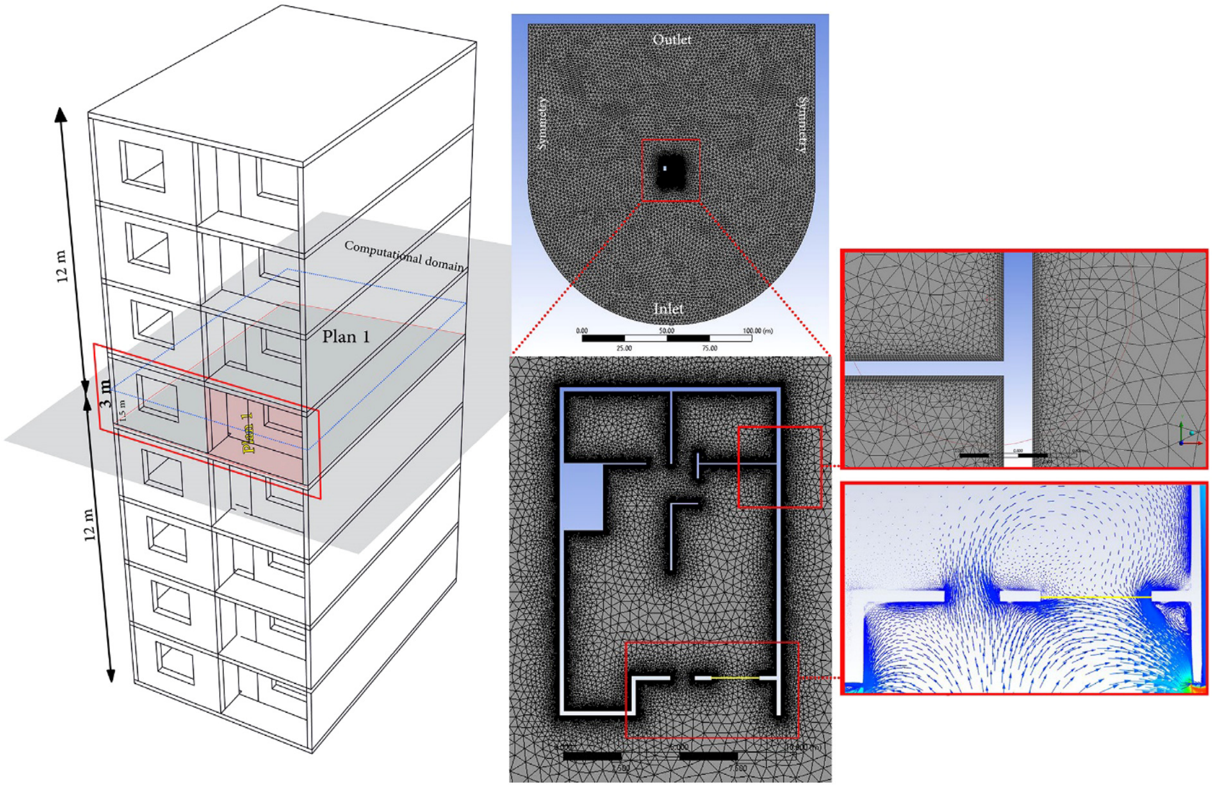

Fig. 4. The base case model dimensions and considered computational domain for grid independent test analysis: the yellow line is depicted as the reference position for the velocity as the indicator. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

regions. Fluent Release 1.ver (2021) also used a modified wall-function with the two-layer model at the near-wall regions; this approach would improve the estimating viscous sublayer with higher accuracy resulting in improving and capturing complicated flows but increasing calculations considerably (Fluent Release 1.ver, 2021). It should be stated that only mass and momentum equations have been solved using the CFD tool and the energy equation was not considered. Fig. 1 shows the base model and considered boundary conditions at each surface. According to the outdoor wind modeling procedure, the domain is a critical subject that it should be careful when dealing with. Based on conducted researches (Omrani et al., 2017; Papakonstantinou et al., 2000) considering H as the height of the building, 3H, 15H, and 6H are reasonable values for Upstream, Downstream, and Height of the domain respectively. However, due to available hardware limitations, it was tried to use a smaller domain since the surrounding obstructions were not included. The sizes of the domain at the upstream, downstream, and lateral sides characteristics were discussed completely in the study (Blocken, 2015). It is clear inclusions and exclusions of the surroundings would affect the airflows but, since the considered situation is similar for all the cases, the comparative study will be reasonable and would not detract from the results (Omrani et al., 2017; Malkawi and Augenbroe, 2004).

For this study, 5 types of mesh configurations were selected starting with 88,000 (the Coarsest case) to 1,410,000 (the Finest case) grid numbers. As shown in Fig. 4. (118,8000, 355,000, 804 000) the average velocity at the selected line (i.e. yellow line) has been plotted. For the grid types, a hybrid mesh with tetrahedral cells has been selected due to the complexity and adaptability of such a method for more complex cases. Also, according to Shirzadi et al. (2021) unstructured tetrahedral mesh configurations with significantly lower cell numbers can provide comparable results with structured hexahedral mesh configurations (to improve the accuracy of the results near the walls), the mesh density got higher, and a refinement was applied by Fluent refinement algorithm. The overall quality of meshes is from 0.71 up to 0.80 (Fluent Release 1.ver, 2021). The maximum skewness of the meshes had a range from 0.16 to around 0.55; thus it is depicted that the skewness is at an acceptable range to start the simulation. The simulation was conducted using SIMPLE algorithms for Pressure–Velocity coupling, Second Order schemes are used for both the convection terms and viscous terms of governing equations recommended by Omrani et al. (2017) and Montazeri et al. (2013). More detailed descriptions regarding the CFD simulation settings and assumptions will be discussed in the following section. Double precision has been checked to improve the accuracy of the results. All the residuals were set to 10^{-5} for the convergency criteria. All the simulations converged after around 10 000–12 000 iterations. Fig. 5. Shows the average velocity values in the middle of the window for each 5 types of grid configurations.

According to the figure it is seen while the number of the grids increases, the range of the average velocity variations get smoother although it had an incrementing characteristic. With a deeper look, it is seen when the numbers exceed 400 000, the relative differences between the results have met a reduction in a way the differences between the finest mesh (800 000–1 400 000) are almost negligible which is less than 2%. Thus, in order to the utilize more efficient setting the cases with the range of 800 000–900 000 grid numbers have been selected for the next analysis.

4.2. CFD model validation

The prediction of the wind and its loads on a building surface is not a trivial task and it gets more complicated when appurtenances are added to the models. This is due to the random

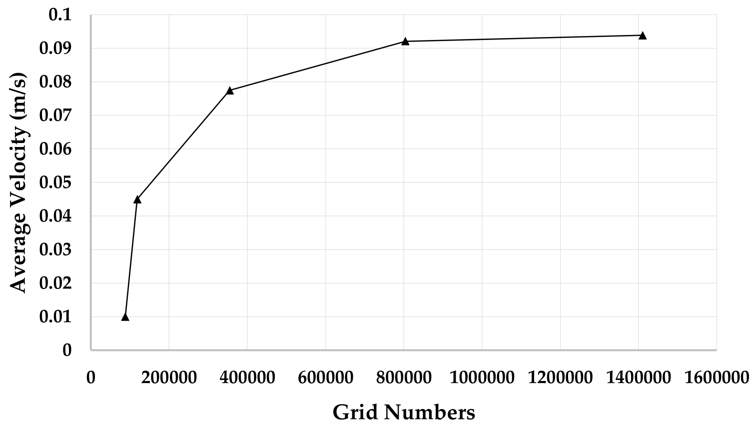

Fig. 5. Grid independence test.

nature of the approaching flow. According to the experimental data (Stathopoulos and Zhu, 1990) the wind pressures are only affected by the existence of the appurtenances compared with the walls without these appurtenances. The exception points are at the upper zones of the windward and the lower zone of the side and leeward zones. In the literature, most cases have different kinds of roughness and its application would make it doubtful and it is of interest to examine the suitability of these provisions. However, in the wind tunnel models, it is commonly assumed that the surfaces of buildings are simulated as smooth ones. According to Stathopoulos and Zhu (1990) and Omrani et al. (2015) there has been only a limited number of experimental studies related to the wind-induced pressures on buildings with appurtenance. There are statements by the researchers (Blocken and Carmeliet, 2008) regarding the lack of experimental neither for a particular model nor for very similar configurations, thus it was tried to utilize a generic sub-configuration validation approach. This would make it hard to access more credible data for validation purposes. It is known that validation/verification of the used model is one of the obligatory steps of any simulation study and it is worth conducting an empirical or experimental study by the authors for their specific study, however, there are some issues preventing this task due to the lack of sources and also required measurement equipment (Chen, 2009) to conduct a fully-validated study. To this end, the authors utilized the literature to fill this gap using the available data. The main reasons for choosing a study for the validation task are the purpose of the study and the availability of enough data as a benchmark which assures the credibility of the study and the level of the model's complexity. The validity could be implied by the number of citations of the utilized study and its large-scale utilization by the previous researchers. Based on Chand et al. (1998b) the results of pressure distributions on the windward would meet an altercation and no significant changes on the leeward would occur. Although their experiment was on a model without openings and balconies, it can be also used for CFD validation and subsequent evaluation of the effect of balcony provision on indoor ventilation performance (Chand et al., 1998b). Considering the similar approach and available data in hand at the time of operating the research, the study done by Murakami (1990) has been selected and the calculated pressure coefficients on the windward and leeward walls have been compared. The study also has been used for the validation and modeling settings in recent studies (Omrani et al., 2017; Zheng et al., 2020; Murena and Mele, 2016; Zheng et al., 2021). Having considered the available data related to a cubic form, it is possible to attribute the results analogous to the real cases based on the other research from literature for example; based on some experimental data done by Newberry and Easton for the windward face of the Cp values for rectangular-clad buildings should be increased slightly in the presence of balconies (Newberry and Eaton, 1974).

The following validation study reported by the Ref and the considered solver and computational domain setups will be discussed in advance. The reference used for the validation is a well-known study used by many researchers so far (Zheng et al., 2020; Bangalee et al., 2012).

4.2.1. Experiment model and boundary conditions descriptions

It should be stated that the geometry and flow characteristics of the wind tunnel have been based on economic and space availability considerations and due to the available computational capacities instrument, it was tried to describe the problem in non-dimensional expressions as stated by Murakami (1990).

Fig. 6 shows the schematic model of a cubic block in the domain in 2D by defining vertical and horizontal planes. All the details of the experimental models are found in Ref. Murakami (1990). In the current study, the vertical cross-section of the flow was not our interest, and we only tried to evaluate the flow in a horizontal section as shown in Fig. 6(a), the red line depicts the exact height of the plane (Hb/2, Hb = Building Height) where all the results have been compared with the experimental data. In the (b) section of the figure, the red/green/blue dots on the model denote the wind/leeward walls where the results were compared with each other. Based on Fig. 6(a and b) and experimental data, the wind direction is perpendicular on one side of the building with the considered wind profile.

4.2.2. CFD solver settings

Having finalized grid properties (it has been discussed in Section 4.1) proposed by Murakami (1990), a grid independence test was also conducted before starting the main simulations. All the airflow properties were considered in the range of Reynolds Number 36-115e5. Regarding dealing with boundary layer flow, the mesh interval adjacent to the model is Hb/6 and the mesh interval adjacent to the walls around the windward corners is Hb/24 (Murakami, 1990). In addition, it was also checked the results with Y plus 1 provided a grid with high resolution (88e4-100e4 cells). There have been some parameters were checked such as K-e models (look in Section 4.1 for the CFD) and pressure–velocity discretization scheme (Franke et al., 2007; Tomboulides et al., 1993; Tominaga et al., 2008a). Based on the results, the K-e and K-w models provided similar results, but for the discretization methods, the SIMPLE method could provide better results than the Quick scheme, for the rest of the discretization method, the second-order upwind performed better. According to the Refs. Omrani et al. (2017), Montazeri et al. (2013), Blocken (2015)

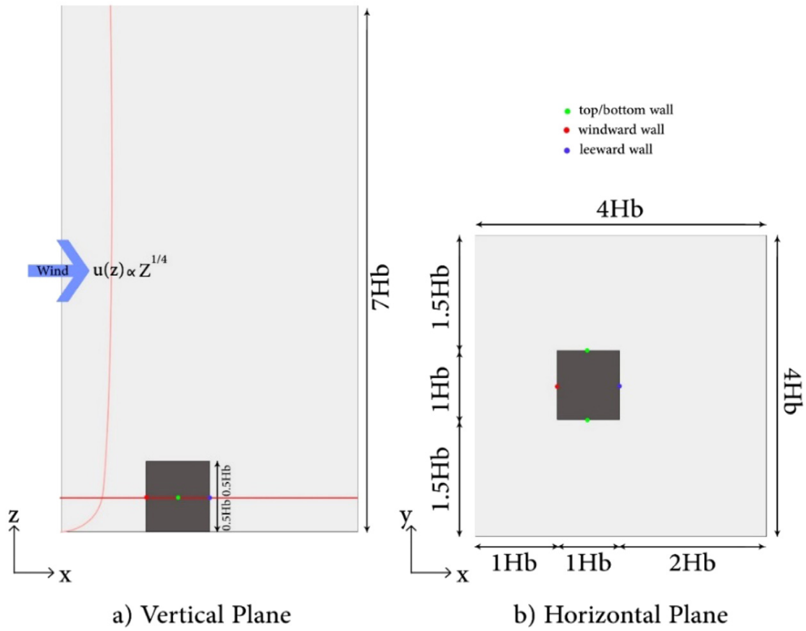

Fig. 6. Schematic view of the modeled in the experiment and CFD tool. . (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

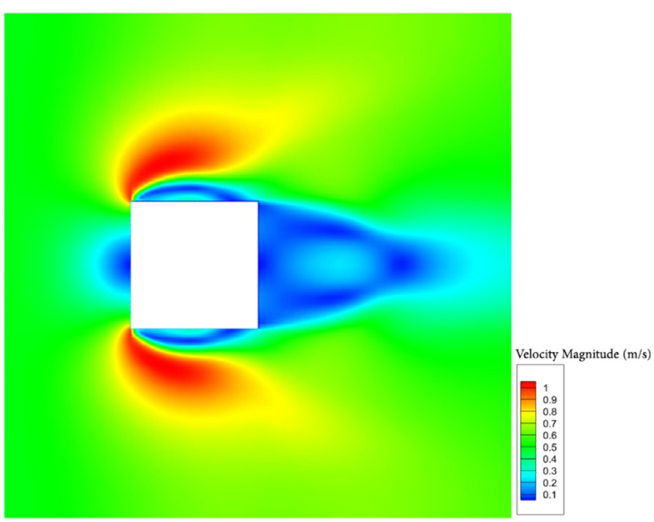

Fig. 7. Iso-Velocity contours showing the flow magnitude around the cubic building layouts (m/s).

and Blocken and Carmeliet (2008) the surfaces were assumed smooth. All the residuals considered for the convergency criteria were set 10e−6 as already elaborated in Section 4.1.

4.2.3. Velocity contours and flow pattern vs. Experiment

Fig. 7 shows the velocity vector based on the considered boundary conditions. It should be stated the simulation was done in steady-state and this could be considered one of the main limitations of this study.

In order to make the comparison with the experimental data, the flow pattern and streamlines of the simulation were plotted and compared with experimental and CFD simulation results in Fig. 8.

According to Fig. 7, it is clear the general flow pattern around the cube is more likely following the pattern reported in Murakami (1990). It is seen that the flow around the side walls in the horizontal section, observes a reversed flow which is a bit faded in the experiment results due to the lower resolution. Since the flow in the windward is almost constant, the pattern is the same as in the experiment, however, in the leeward, due to the transient manner of the flow and producing the eddies (i.e., von Karman vortex street, repeating pattern of swirling vortices, caused by a process known as vortex shedding, which is responsible for the unsteady separation of flow of a fluid around blunt bodies) and they get varied in the back side of the cube. It could show its difference in the quantity of the pressure coefficient to some extent which would be normal. But what matters that is the two main eddies are the same as the experiment and simulation reported in Ref compared with our simulation. And the similarity in size and positions of the eddies are so close.

4.2.4. Pressure coefficient vs. Experiment

In order to quantify the comparison between the simulation results and the experiments, pressure coefficients on the regarded position were plotted in Fig. 9.

Based on Fig. 7, it is seen that the magnitude of the calculated Cp on the wall of the building has followed a similar pattern and it depicts a similar variation as those of the experiment. As seen in Fig. 7 there are some discrepancies between the results and experiment values. These discrepancies could be related to some possible reasons; (first) as the k-type turbulence model wall function has been used in this study and it can yield difficulties in simulating horizontal homogeneous atmospheric boundary layer (Blocken and Carmeliet, 2008) to tackle this issue, it is needed a specified upstream part characteristic of the computational domain Blocken et al. (2007a) which is not available for the most of experimental studies. More details regarding the turbulence models on the CFD modeling of building balconies can be found in Ref. Zheng et al. (2020) comparing RANs and LES turbulence models. (Second) It should be noted that the profile used for the simulation is on a horizontal plane and as referred to in the studies (Franke et al., 2004; Blocken et al., 2011) the absence of streamwise gradients in vertical profiles of mean speed and turbulence quantities in the region is not disturbed by the presence of building models. For the CFD simulation, it is necessary to satisfy the relation between physical roughness

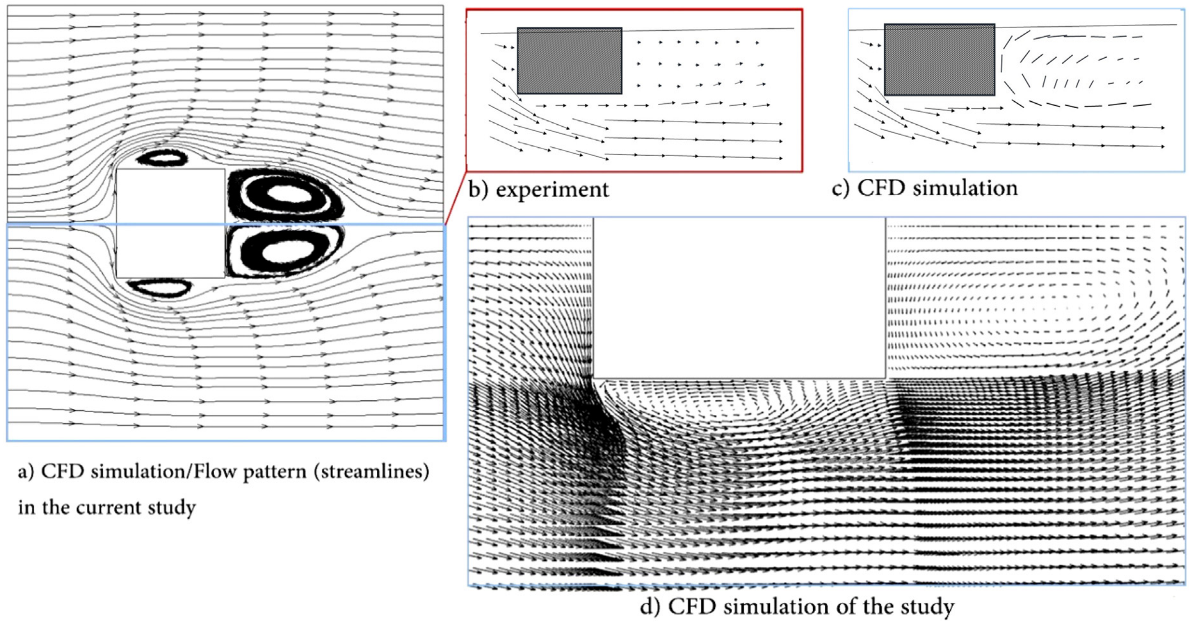

Fig. 8. Flow pattern around the cube: (a) CFD simulation in our study, (b) experimental data (c) CFD simulation done by Murakami (1990), (d) the highlight section of the CFD simulation in the current study.

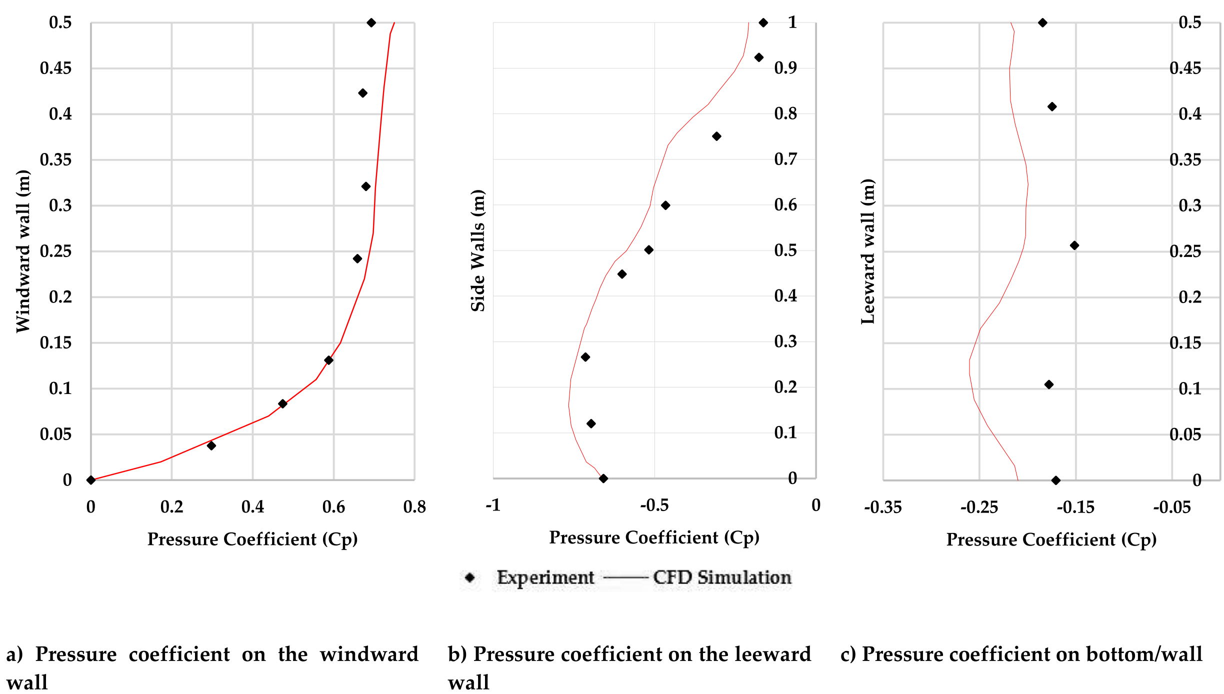

Fig. 9. Comparison of the pressure coefficient between the experimental data (Murakami, 1990) and CFD simulations.

height, aerodynamic roughness length, and roughness constant. This value has not been mentioned in this study but Fluent does not allow physical roughness to be larger than aerodynamic roughness (Blocken and Carmeliet, 2008). (Third) Regarding to the results on the different parts of the form, it is clear that the results on the windward are satisfied (improving mesh quality from 0.81–0.9 and reduction of residual values) and the results are very close to the measurements (5% relative accuracy error). The less accurate results are related to the leeward section (down steam) which is around 15%–20%. This range of variation was also reported in the literature (Blocken et al., 2007b). This deviation is mostly related to the used turbulence model downstream where the Refs. Montazeri et al. (2013), Franke et al. (2007) and Montazeri et al. (2012a) noted that the steady RANS CFD is generally deficient in reproducing the wind-flow pattern downstream of the windward facades. Also, according to the Refs. Murakami (1990), Montazeri et al. (2013), Franke et al. (2007), Blocken et al. (2007b) and Murakami (1993) this deviation is still significant which is due to the mostly the numerically predicted back pressure levels depicting a recovery than the experiment results and this is due to the weaker wake structure behind the buildings in CFD simulations. Additionally, what matters is the application of the results of each part for the present study purpose; at least in the positions where the CFD results have enough accuracy (i.e., windward) the highest relative accuracy error is around 5% because the wind speed at the windward faces rather than the leeward faces are on the focus of the present study and it has the highest importance for the simulation; the CFD model provides some confidence that the wind condition in those positions can be modeled numerically with satisfactory accuracy. It is also a common approach referring to the results where at least the highest values and variations are concerned and the other positions such as leeward and sidewalls due to not placing the balconies are less important (Montazeri et al., 2013; Blocken and Carmeliet, 2008) and also the wind speed at those positions (leeward) is much lower to be contributed. This was also stated in the previous studies (Janssen et al., 2013; Blocken et al., 2012). There are also some issues that are worth stating here regarding the probable deviations between the results; since the flow is a transient-based phenomenon, simulating it in a steady-state condition would cause some inevitable errors. Such shortage was mostly due to the limitation of hardware sources during the simulation process. Another reason could be attributed to the nature of the flows in this specific problem, because the flow is a 3D inherited phenomenon, and degrading it in a 2D would not expect similar results due to some inaccuracies of forces coefficients associated with flows, although 2D simulations are a great starting place, simulation run times are low, allowing for lots of testing (Blocken, 2015). Also, as the flow is transient and turbulent in the experiment it is clear that it is not possible to catch more accurate data due to the variations of fluctuation of the velocity and pressure especially downstream, additionally, there were some missing data regarding the turbulence intensities and turbulence dissipation rate in the report which was needed to reevaluate different values to provide the best solution constants. Finally, a part of the discrepancies could also be related to some numerical errors as discussed in the Murakami (i.e., diagnostic system for numerical simulation section) (Murakami, 1990) study in detail. But what matters, that is the simulation and considered solver setting based on the current information was satisfactory enough to conduct the rest of the simulation with high attention, and the calculated data in those sections shows an agreement with the experiments.

4.3. Mesh quality

The meshing simulation of this research was done in ANSYS meshing software. In order to achieve the right quality in the Ansys Fluent grid, we must consider the aspect ratio quality and the skewness quality and start the grid based on these patterns.

The aspect ratio number is the aspect ratio of the cell, which is defined as the ratio of the longest side of the cell to its shortest side. Mesh with a high aspect ratio causes low accuracy and a slow convergence rate. This value must be below 49, which is 3 in the meshing of this research, and the skewness is the amount of the mesh lying down (the meshing should not be sharp), which should be between zero (the best case) and 1 (the worst case) (Bakker, 2006), which in this research it is around 0.16–0.5.

In order to get to a decent flow simulation in the model, it must have extra attention to the walls adjacent where it could be expected complex vortices affecting the whole area of airflows. One of the most important places where the grids need to be fine enough is the boundary layer. For this purpose, the Boundary Layer Mesh could be used. In this method, multilayers of small cells, which are usually organized, are considered on the walls of the object, so that the intense current gradients inside the boundary layer and especially in the direction perpendicular to it are correctly calculated. Outside the boundary layer and far from the surface of the body, larger cells are used.

In this research, for the accuracy of the simulation, finer meshing has been created in the critical parts, such as inside the unit and the openings that show the inlet and outlet of the airflow (Fig. 10).

4.4. Numerical modeling, assumptions and boundary conditions

In order to conduct CFD simulation, the paper has used the best practice guidelines provided by Franke et al. (2004, 2007) and Tominaga et al. (2008b). The geometrical domain modeling and the size of computational models was chosen by the Refs. Zheng et al. (2020) and Murakami (1993) with the main domain around 10 times each facing surface size in order to minimize surface negative influence on the flow behavior due to boundary layer contacts.

All the simulation of the house was conducted in a steady state. The inlet boundary conditions (i.e., turbulent kinetic energy k, turbulence dissipation rate e, mean wind speed $U = 9.81$ m/s), were considered constant. In the outlets, the pressure outlet boundary condition was adopted and it was assumed equal to the normal ambient pressure. For the side walls, the symmetry boundary conditions were set. Due to hydrodynamical necessities, the paper has utilized the model of Zhang et al. (2007) to provide best-practicing assumptions of turbulent models. Thus, a realizable k-ε model, with standard wall function options has been set for the turbulence model which is considered as another subset of k-ε turbulence ones. Generally, RNG and realizable models provide better results than the standard mode in cases where the flow is under strong rotation, vorticity, and curvature. In addition, the considered setting and turbulence models have been utilized and confirmed by Montazeri et al. (2013) and Montazeri and Blocken (2013) in similar studies. According to climate data, the wind speed during July equals 9.8 m/s. Finally, the coupling of speed and pressure equations was conducted using the coupled algorithm. The SIMPLE algorithm was used for pressure velocity coupling, pressure interpolation was second-order, and second-order discretization schemes were used for both the convection terms and the viscous terms of the governing equations. Fig. 11 shows the 3D view of the modeling features including determined boundary conditions, and modeled cases.

Convergence was assumed to be obtained when all the scaled residuals leveled off and reached a minimum of 10^{-6} for x, y momentum, 10^{-5} for y momentum, and 10^{-4} for k, e, and continuity (Montazeri and Blocken, 2013). All the assumptions considered for the simulations have been addressed in Table 2.

5. Results and discussions

In order to continue the study, high-rise buildings in Hamadan were studied, collected, and categorized by applying the field study method, and the most frequent pattern was identified (Table 2). Then, the configuration of the balconies was examined in terms of direction, geometric shape, type of enclosure and recess or protrusion, as well as depth and opening. In order to design the basic simulation model, the balconies of the high-rise buildings in Hamadan were analyzed. Based on the survey 35 cases of buildings with different balcony types were classified. As seen in Fig. 8, schematic configurations are shown clearly. Based on the Fig. 6 basic morphologies of the surveyed building were classified. In order facilitate the simulation, a typical residential plan of the Hamadan was derived from the literature. Since the purpose of the study to show the performance of the balcony in terms of ventilation, all the house plans were set fixed and it was only the balcony configurations were varied. The results

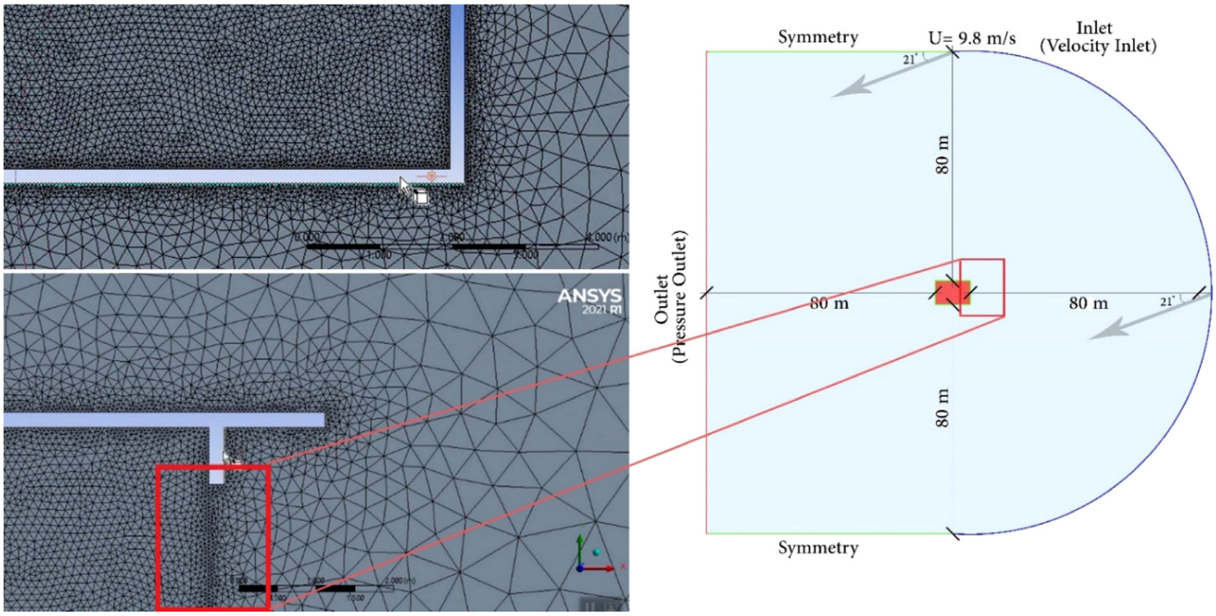

Fig. 10. The meshing simulation in ANSYS software.

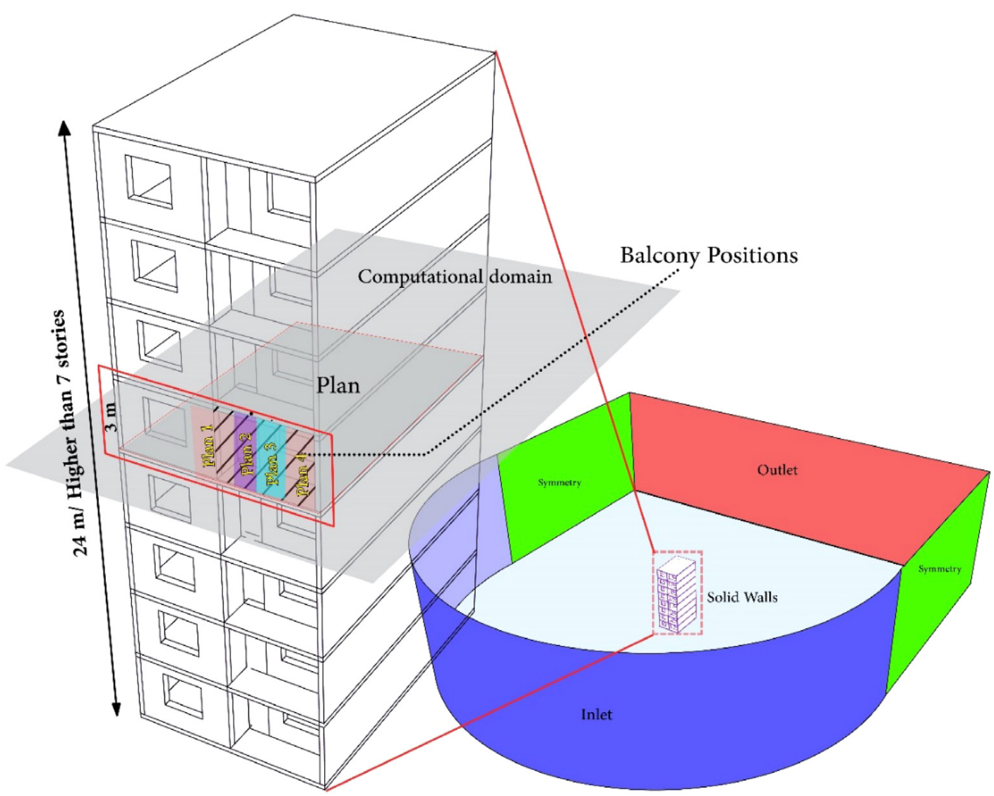

Fig. 11. A 3D schematic view of the model and computational domain used for the simulation.

indicated that 74% of the buildings have balconies with a north–south direction inclined to the east. In addition, 91% are regarded as rectangular and the ventilation type of 77% is considered as single-sided. Finally, 70% are regarded as recessed and 65% are considered as enclosed on three sides without cover (see Table 3). During the simulation, the changes in the depth of the balcony

Table 2
CFD simulation setting and assumptions.

Geometry modeling	Base case balcony
Environment	2D Simulation
Solver	Pressure Based
Scheme	Steady-state
Density (Fluid/Air)	Density = Constant (1/204 kg/m^3)
Turbulent model	Realizable k-ε, Enhanced wall treatment (for wall function) $Y^+ \geq 1$
Pressure–velocity coupling method	SIMPLE
Discretization methods	PRESTO for pressure discretization method Second-order for the rest of the discretization
Boundary conditions	
Wind direction/value	θ = 21°, 9.8 m/s
Inlet	Velocity inlet
Outlet	Pressure outlet
Solid walls (no internal mass)	No-slip condition
Side walls	Symmetry

Table 3
Investigating the dimensions of balconies in high-rise buildings in Hamedan.

The dimensions of the balcony according to the field study	Frequency	Dimension (m)
	14.2%	1.5
Balcony width	**66.6%**	1
	19%	0.8
	4.7%	6
	9.5%	3
	42.8%	2
	19%	1.5
Balcony length	**23.8%**	1

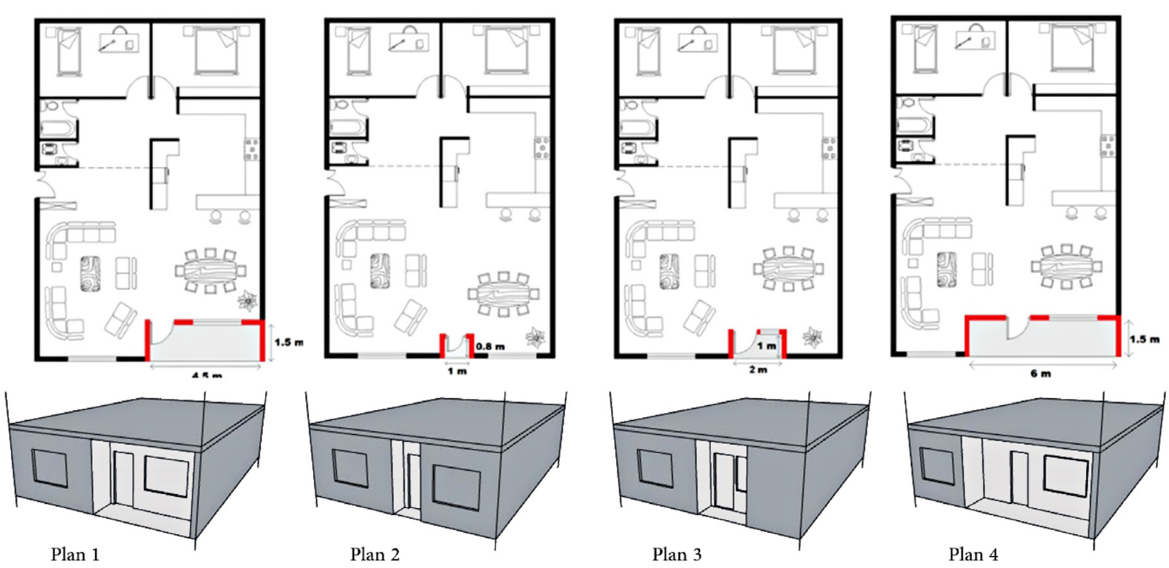

Fig. 12. Various changes in the depth and opening of the balcony.

were reviewed in three modes including the depth of 0.8, 1, and 1.5 m due to the current standards in construction and field studies. The maximum allowed depth of the balcony in public passages with a width of 12–20 m and passages with a width of more than 20 m equals to 0.8 and 1.2 m, respectively. Generally, the cantilevers larger than 1.5 m are not constructed as much as possible. In addition, the changes in the balcony opening were assessed based on the criteria and field study in four modes of 1, 2, 4.5, and 6 m. Fig. 12 demonstrates the configurations related to different openings and depths of the balcony for simulation.

A house with four different balconies was examined to evaluate the single-sided natural ventilation by the balcony. To this aim, the balcony openings were regarded as air inlet and outlet, the doors of the rooms were opened, and the entrance door and that of the toilet and bathroom were closed. Finally, the geometry was drawn in the Space Claim software and the drawn geometries were entered in the ANSYS meshing software.

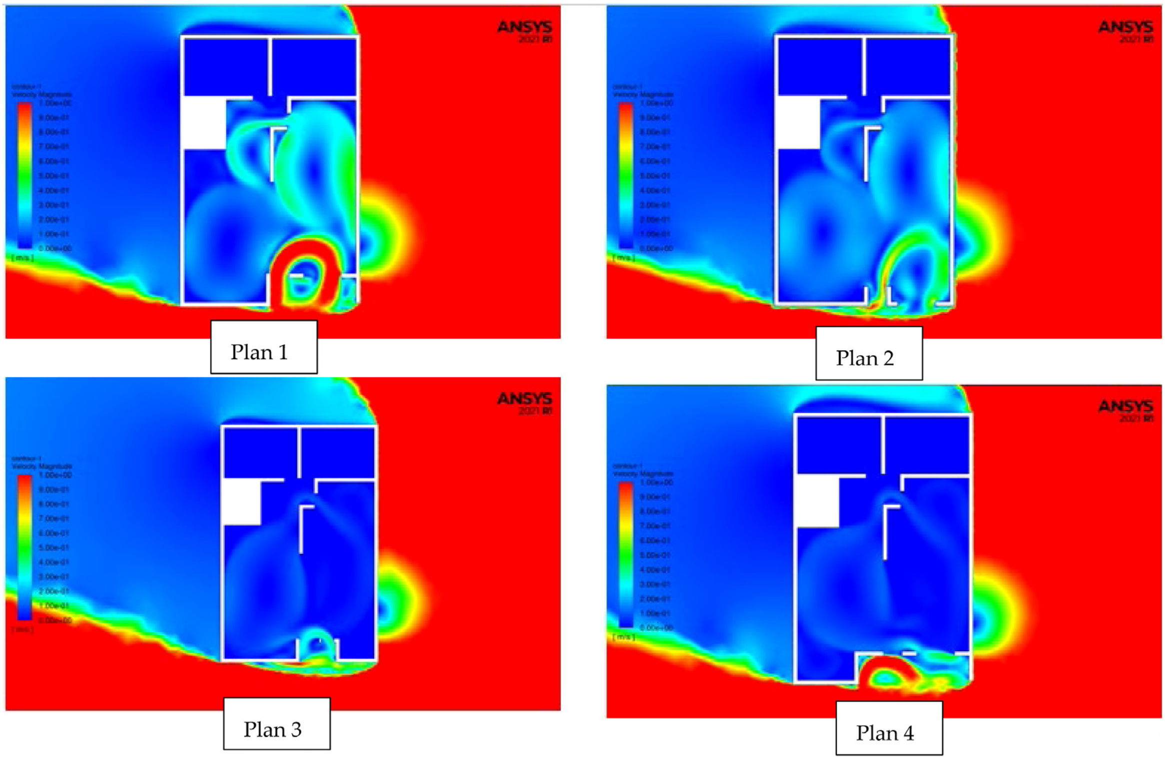

Fig. 13. Airflow speed contours (m/s).

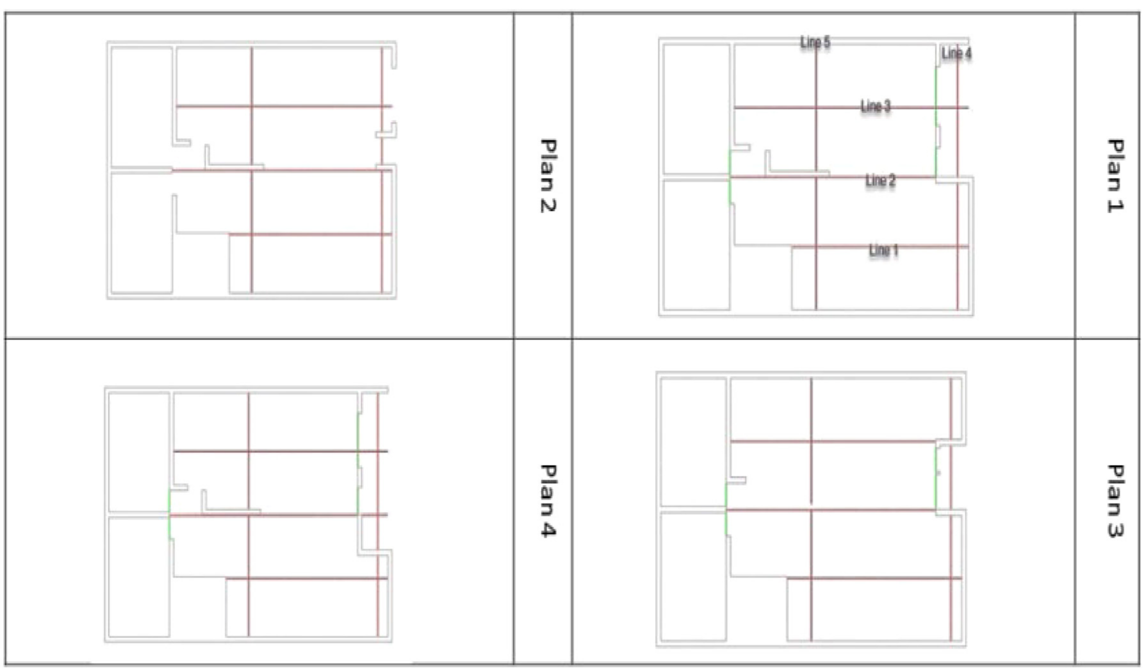

Fig. 14. Position of guidelines to explain airflow speed in plan 1 to 4.

Finally, through the first step analysis, the flow rate and conservation of mass for all cases have been checked. It is seen the same amount of entering flow is almost equal to the amount extracting from the building; this would show the mass is in balance.

Fig. 13, indicates the iso-velocity contours of all 4 cases As Table 4 indicates, flow differs for different maps.

To understand and observe the explanation of the speed as a chart, five lines were drawn in critical places in the plans. Fig. 14 shows the lines drawn on each map (the number of lines is demonstrated in maps)

Based on the results, map No. 1 is regarded as better than all of the maps for air rotation and circulation in the house. As observed, the flow rate entering and leaving the building in map No. 1 is several times that of other modes. In addition, the speed is considered as higher in most lines than in other maps. According to the contours, the air circulates much better than other conditions in map No. 1 and circulates in all parts of the

Table 4
The flow rate of the entrance and exit of the building.

Number of plan	Mass flow rate of balcony door [kg/s]	Mass flow rate of windows [kg/s]
1	−1.3824594	1.3824594
2	0.33108425	−0.33108425
3	0.20663354	−0.20663354
4	0.074936693	−0.074936693

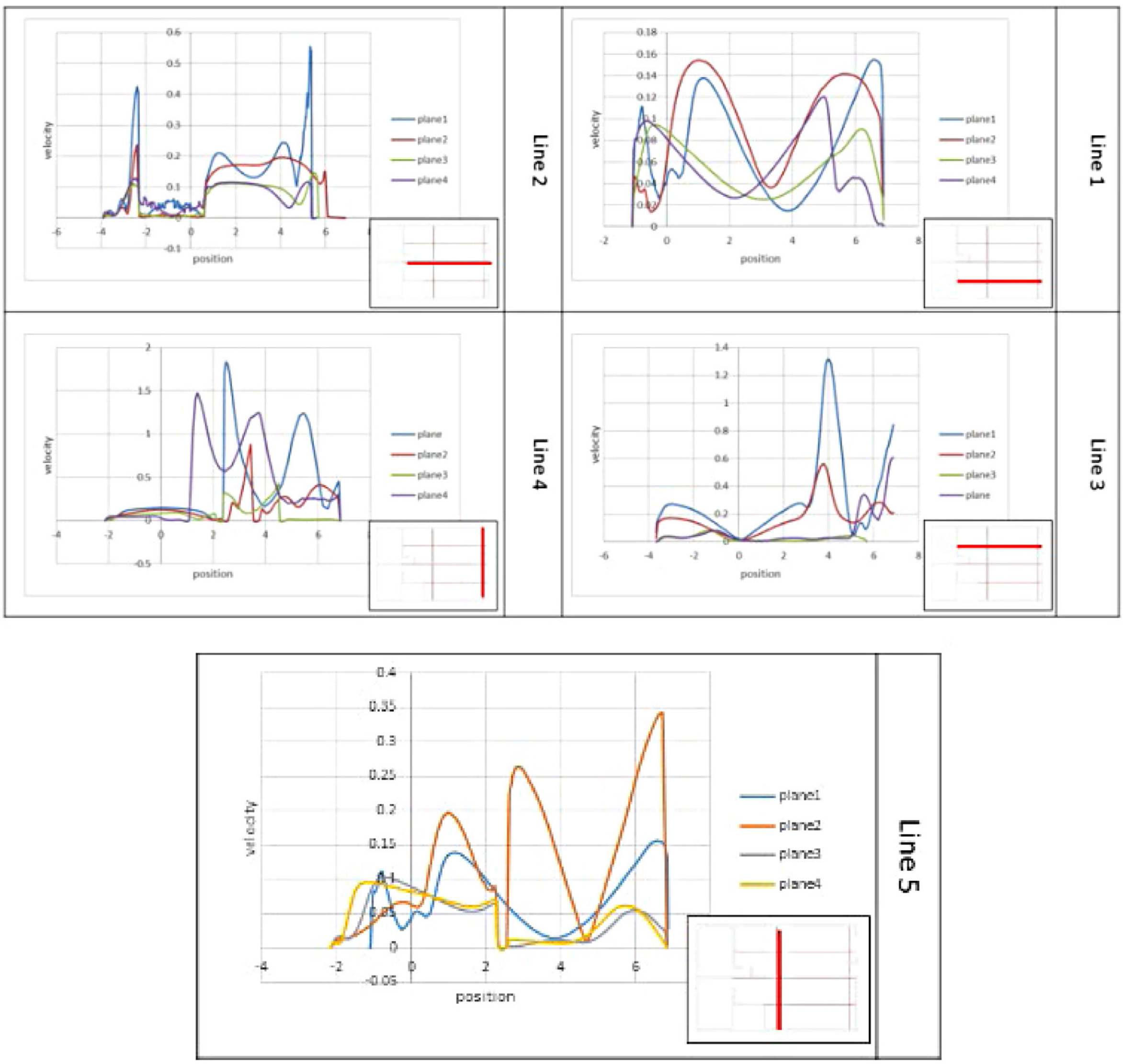

Fig. 15. Airflow speed in the lines specified in the plans 1–4.

house, meaning would provide better ventilation and flow rates consequently (Fig. 15).

According to the figure (Fig. 15) the highest variation of the velocity is related to the line 3 which depicts the flow regime coming through the balconies and the lowest variation belongs to Plan 4 and the highest velocity in the room could only be around 0.02 which is very low. Almost in all of the cases, this is Plan 1 the air velocity has improved and it could reach up to 2 m/s in the middle of the room and it reduces to 0.3 m/s. this shows that at the side of the room far from the window we could have sufficient airflow for ventilation purposes.

In order to find the best type of balcony to improve single-sided natural ventilation, the balcony of Map No. 1 was investigated in three different positions. Finally, the same amount of entering flow left the building. As Table 5 represents, flow differs for different maps (Fig. 16).

To understand and observe the explanation of the speed as a chart, five lines were drawn in critical places. Fig. 17 demonstrates the lines drawn in each plan (the number of lines simulates the previous step).

Comparing the speed contour in plans 1, 5, and 6 indicates that plan NO. 6 is regarded as better than all of the plans for air circulation in the house. According to the table of flow rates, the

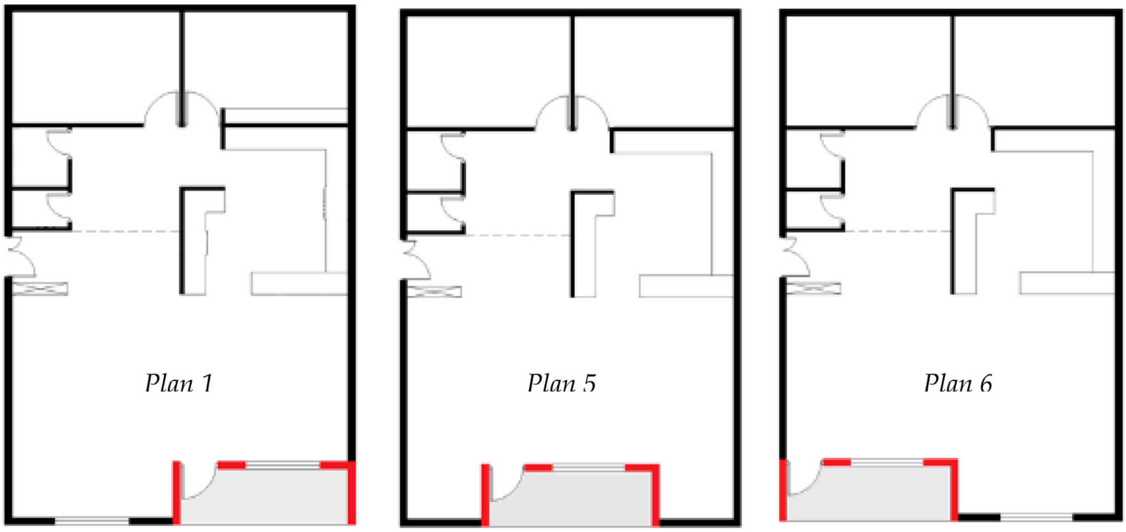

Fig. 16. Different changes in the position of the balcony in the plan 1, 5, and 6.

Table 5
The flow rate of the entrance and exit of the building.

Number of plan	Mass flow rate of terrace door [kg/s]	Mass flow rate of windows [kg/s]
1	−1.3823857	1.3823857
5	−1.3859148	1.3859148
6	−0.76666986	0.76666986

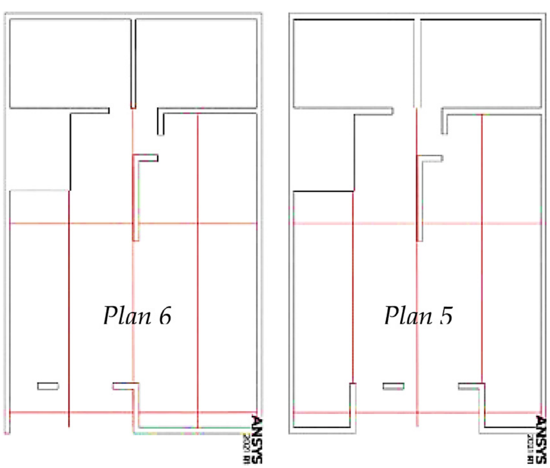

Fig. 17. Position of guidelines to explain the speed of plans 5 and 6.

inlet flow rate is considered better for maps 1 and 5 (Fig. 18). However, the contours of the flow speed show that the air quickly leaves the window after the flow enters the door in the above-mentioned maps, while the air enters the room appropriately and circulate extremely better than before in map No. 6 (Fig. 19).

In order to provide an overall indication of the performance of each case (Plans 1, 5, and 6), compared to each other, it has to conduct a comprehensive energy and flow analysis at the same time which can be the subject of an independent study in the future. To depict the benefits of each case Table 6 shows the ventilation rate and energy-saving capacities of the mentioned cases for an assumed summer condition scenario. Since the mass flow rate is available, it could be possible to estimate an energy balance through the building by assuming temperature differences between indoor and outdoor conditions. In this scenario, the temperature difference of 5 °C was considered due to the maximum temperature differences on a typical summer day in Hamadan (see Table 6).

As seen in Table 6 considering the balcony with the dimensions of 4.5 m in 1.5 m, could have a significant effect on the ventilation rate when it is located at the corner of the building's main front (Plan 1) compared with the cases with the balconies located in the middle of the façade (Pan 6). It is observed that the differences between the case 1 and 5 are not very significant (around 0.2–0.4%) but noting this amount of efficiency would be very valuable in the large scale. In addition, it seems that considering the balconies with the regarded configuration could be very efficient compared to the rest of the cases because the difference between the flow rate and energy-saving capacities of such cases (4.5 m in 1.5 m) could reach even 45% higher than the cases with small balcony areas which are located at the middle section of the façade; this means that utilizing simple treatments on balcony locations and sizes could provide significant energy and flow impact on the performance of the buildings.

6. Conclusion

As indicated, the present study seeks to present critical parameters in the formation and design of the balcony and achieve its optimal pattern in order to provide single-sided natural ventilation. To this aim, the basic simulation models were modeled and studied by conducting the aforementioned studies. The results indicated that the balcony with a depth of 1.5 m and an opening of 4.5 m demonstrates a more appropriate performance. Moving air inside the building depends on two factors including the air pressure around and the inertia of the moving air inside. Based on the dynamic principle, the air flows from the pressure area to the suction one when the openings are opened. After entering, the air moves in its original direction until it hits the wall, its speed reduces, moves towards the opposite window, and exits the building, which makes the air flow in most of the interior spaces, leading to better ventilation than other modes.

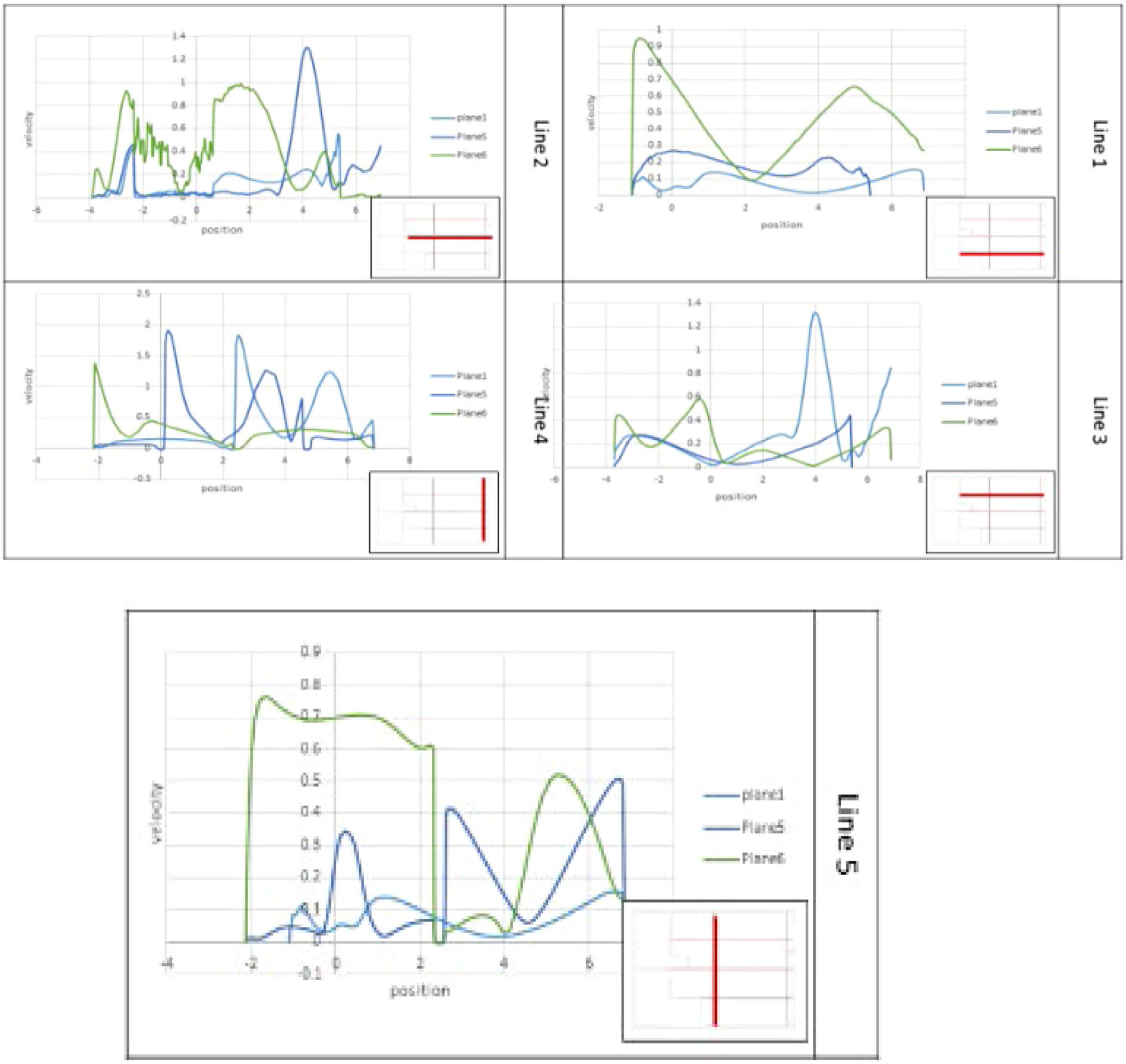

Fig. 18. Speed contour in plans 1, 5 and 6.

Table 6
Ventilation rate and energy saving (cooling) capacity of the cases.

Cases	Ventilation rate (ACH)	Difference (%)	Energy balance (kJ)	Difference (%)
Plan 1	14.94	Ref	6.95	Ref
Plan 5	15	+0.40	6.96	+0.21
Plan 6	8.2	−45.11	3.82	−45.12

Positive pressure occurs on the side facing the wind and negative one or suction occurs on the opposite side when the wind hits the surface of the building. The wind enters the space with the same impact direction when it blows perpendicularly to the surface of the building, the opening is regarded as symmetrical with respect to the impact surface, and the balcony is placed in the middle. However, the wind deviates towards the smaller length and enters the space, resulting in making natural ventilation more appropriate when the opening is considered asymmetric due to the increase in pressure in the longer part of the surface.

Declaration of competing interest

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

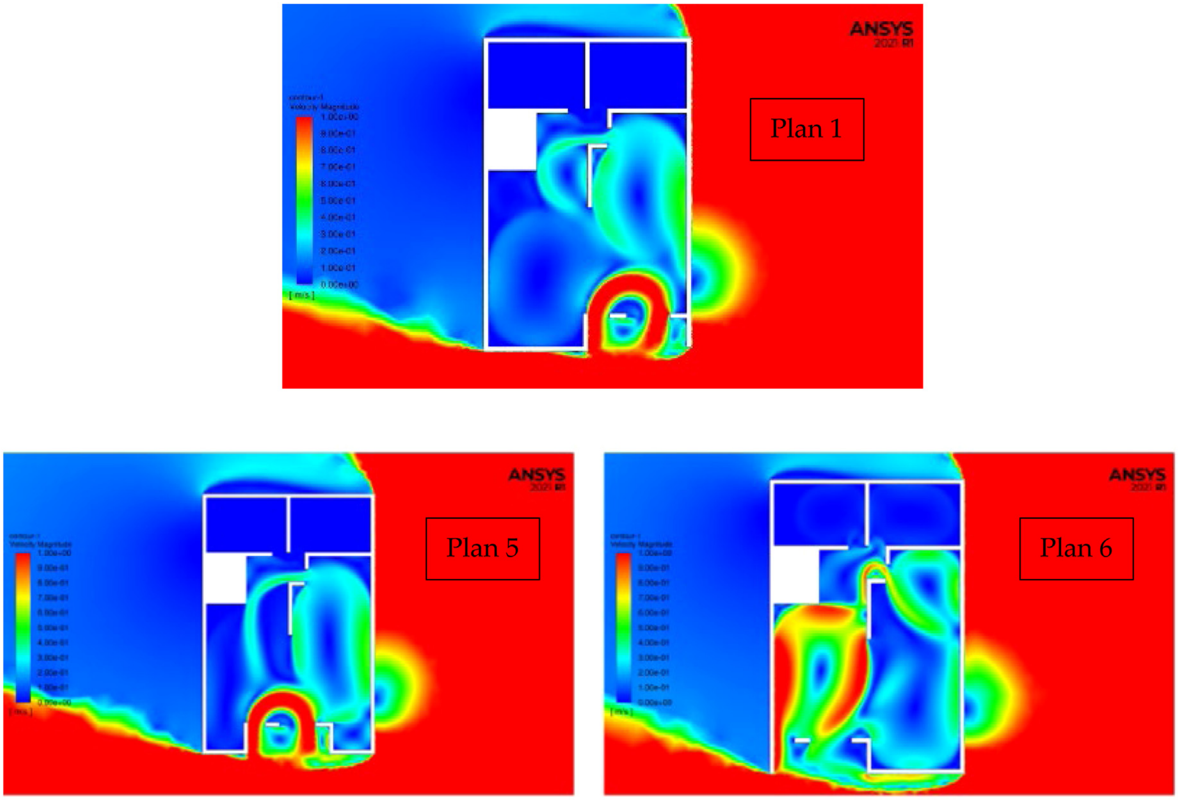

Fig. 19. Speed contour in plans 1, 5 and 6.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

Data availability

Data is available via the corresponding authors upon reasonable requests for academic purposes.

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