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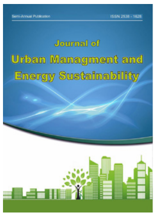

CASE STUDY RESEARCH PAPER

Observing Temperature Changes and Wind Speed Variations in an Urban Canyon of Shiraz at Different Heights Using CFD Simulation

Shoeleh Shoara[1], Seyed Majid Mofidi Shemirani[2]*, Seyed Kamaleddin Shahriari[3], Zahra Sadat Saeideh Zarabadi[4]

1 Ph.D. Candidate, Department of Civil engineering, Faculty of Art and Architecture, Science and Research Branch, Islamic Azad University, Tehran, Iran
2 Associate Professor, Department of Urban Design, Faculty of Art and Architecture, Iran University of Science and Technology, Tehran, Iran.*
Assistant Professor, Department of Civil engineering, Faculty of Art and Architecture, Science and Research Branch, Islamic Azad University, Tehran, Iran
Associate professor, Department of Urban Planning, Faculty of Art and Architecture, Art and Architecture, Science and Research Branch, Islamic Azad University, Tehran, Iran.

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ABSTRACT

The utilization of natural ventilation in urban canyon plays a substantial role in lessening energy consumption and heat island effects. Therefore, the determination of suitable street canyon form is very influential. Due to rapid urbanization, industrial activities and massive construction in Shiraz during the recent years, it is inevitable to investigate the new development effects. The aim of this study is to investigate how strategic urban design can influence natural urban ventilation through the analysis of wind flow simulations, with the goal of informing urban planning. This study aims to numerically simulate air flow, heat transfer and solar radiation over a large-scale building at different altitudes in Hosseini Al-Hashemi Expressway, Shiraz, Iran by using Ansys Fluent. According to the solution method of this research, after obtaining the initial solution using the k-ε model, the problem was switched to the LES method, and the final solution was solved by this method. In addition, convective, conductive, and radiation flows were calculated through the governing equations of fluid dynamics using Monte Carlo model. The results show that the blocked flow at 2 m height was released at 25 m height due to a large eddy. It can be concluded that the design of the urban canyon located next to the busy highway, effectively repels heat and has good ventilation.

Running Title: Temperature Changes and Wind Speed Variations in an Urban Canyon

NUMBER OF REFERENCES	NUMBER OF FIGURES	NUMBER OF TABLES
43	05	00

*Corresponding Author:
Email: *s_m_mofidi@iust.ac.ir*
Phone: +989125116488
ORCID: https://orcid.org/0000-0001-5388-7045

INTRODUCTION

Urbanization is increasing rapidly as a large portion of the world's population moves from rural to urban areas (Rezaei et al., 2019; Roshan et al., 2020). The widespread expansion of built-up areas is one of the most typical symbols of urbanization, which accompanies the development of urban form. This process leads to land use and land cover changes on limited horizontal land resources and increases in vertical building heights (Sun et al., 2020), which directly affects the local microclimate and urban thermal properties (Hu et al., 2022). In one hand, accompanied by rapid global population growth, unplanned urban sprawl characterized by low density and single–use, may lead to excessive energy consumption, traffic congestion and environmental degradation (Yu et al., 2023). On the other hand, impermeable surfaces and high-rise buildings can nevertheless impede natural ventilation, reduce wind speed(Tian et al., 2023), and absorb thermal energy in urban areas, resulting in an overall Urban Heat Islands (UHI) effect (Darbani et al., 2023). Previous studies have shown that frequent high temperature events doesn't only affect energy consumption and carbon emissions, but also cause cardiovascular and respiratory diseases. Therefore, urban planners and policy makers urgently need to find UHI mitigation strategies to improve the cities' resilience to climate change (Tian et al., 2023).

Contrary to previous studies (Bakarman and Chang, 2015), heat transfer simulation and numerical solution of fluid flow were used to study the daily heat cycle at the city scale. In fact, in this study, unstable simulations with solar, wind and heat loads are solved simultaneously. In contrast to previous studies (Yaghoobian and Kleissl, 2012; Nazarian and Kleiss, 2016) wind speed and direction (Blunn et al., 2022) and inlet temperature was considered realistic and time-varying in this study. In addition, the use of full-scale building heights was another innovation in this study.

In this study, firstly, the case study model was modelled in Autocad 2021. Then, the airflow was simulated in Ansys Fluent 2021R1. Based on the solution strategy of this study, the problem was switched to the LES method after obtaining the initial solution by using the RANs model and the final solution was also solved by this technique.

The research presented in this study aims to investigate the impacts of urbanization on local microclimate and thermal properties in Shiraz, focusing on the effects of built-up areas, land use changes, and vertical building heights on natural ventilation and heat dissipation. By utilizing heat transfer simulation and numerical fluid flow solutions, this research provides insights into underscoring the importance of urban design to mitigate Urban Heat Island effects in rapidly urbanizing environments. The innovative approach of considering realistic and time-varying wind conditions, solar radiation, and building heights sets this study apart from previous research efforts, offering valuable findings for urban planners and policymakers seeking effective UHI mitigation strategies in this area.

Literature Review

According to the United Nations, the world population is rise from 55 % to 68 % of the total population by 2050 (Tian et al., 2023; Nasrollahi et al., 2021; Xi et al., 2024). Due to this population growth and continued global warming, urban heat islands (UHIs) have become a major issue for humanity as a consequence of urbanization and industrialization (Fadhil et al., 2023; Nasrollahi et al., 2021). Rapid advances in the built environment and increasing urbanization are changing ecosystems and climate; and surface temperature is one of the most influential variables, with increasing energy consumption in the urban environment contributing directly to the rise in land surface temperature. Due to urbanization and human activities, the UHI effect, which is caused by an increase in surface temperature, is one of the most serious problems in urban areas (Irfeey et al., 2023).

UHI is a phenomenon characterized by urban areas retaining more heat than surrounding rural areas, creating significant temperature differences (Dimoudi et al., 2013; Vardoulakis et al., 2013; Busato et al., 2014; Musco, 2016; Salehi and Naeemayi, 2021). Studies have demonstrated that temperature differences can range from a few degrees Celsius in small cities to more than 10 degrees Celsius in large cities. The consequences of UHI vary, ranging from localized effects such as increased energy demand and human discomfort (Moulai et al., 2019). to broader impacts such as water scarcity and severe respiratory diseases (Elmarakby and Elkadi, 2024; Elmarakby et al., 2020). Therefore, recent studies have emphasized the importance of the stochastic properties of turbulence at different altitudes using computational fluid dynamics based on unsteady simulations. For example, Ikegaya et al. performed LES of airflow around isolated buildings and block arrays to determine the wind speed (Ikegaya, 2020; Li et al., 2024).

Urban geometry plays an important role in affecting the microclimate of urban canyons (Madani et al., 2021). Stewart and Oke (2012) describes the microclimate effects of various factors related to urban geometry, including the aspect ratio (height to width) (H/W), sky view factor (SVF), which is directly related to H/W, and street orientation (Mohajeri et al., 2019; Nasrollahi et al., 2021). An urban canyon is a typical urban structure, consisting of buildings and the spaces between them (Mei et al., 2019A; 2019B; Fu et al., 2017). Rational placement of buildings within the city can increase self-ventilation capacity and reduce the pollution level in the canyon. Therefore, many studies have been conducted on the influence of various factors within cities on canyon airflow and the global distribution of traffic pollutants. In contrast to field observations, numerical simulation techniques can quickly and cost-effectively simulate more complex conditions (Zhao et al., 2022).

Here, numerical simulation is the preferred method to solve atmospheric environmental problems (Jon et al., 2023). Moreover, the geometry of the urban canyon formed by the height and spacing of buildings is one of the most important parameters influencing the quantity and quality of radiation reaching an urban block and energy consumption of buildings (Nasrollahi and Rostami, 2023).

The study of wind flow in urban areas is conducted at four scales: regional scale (horizontal scale of about 100 to 200 km), city scale (horizontal scale of about 10 to 20 km), neighborhood scale (horizontal scale of up to 1 to 2 km) and street scale (horizontal scale less than 100–200 m) (Lateb et al., 2016; Wang et al.,2023). However, studies on the urban-scale ventilation in street networks are still rare and difficult, as field measurements are inappropriate and wind tunnel experiments are prohibitively expensive for such a large scale. Over the past few decades, the capacity, storage, and affordability of high-speed computers have increased dramatically, making highly accurate computational fluid dynamics (CFD) technology an important means of controlling ventilation in cities (Zikanov, 2019; Wang et al.,2023). Therefore, the efficient design of urban wind flow has proven to be an important factor in promoting the healthy, green, and sustainable development of urban cities (Xi et al., 2024).

Middel et al. (2014) used ENVI-Met to measure the changes in wind speed and temperature in the built environment. Some other software such as Integrated Environmental Solution IES-VE and Energy-Plus are more focused on internal thermal parameters and performance. The software has been developed mainly to simulate the microclimate parameters in urban space coverage. ANSYS-FLUENT is a high-flexibility application in air flow modelling and can consider a wide range of parameters related to fluid flows in microclimate.

In general, the turbulence models of the LES and RANS have been utilized simultaneously only in a few studies. Based on research conducted by Toparlar et al. (2017), only in 2 cases among 183 studies, LES and RANS models were employed at the same time. The computational cost of LES models is one of the most important reasons. The work flow of the presented work is illustrated in figure 1.

In the next sections of this study, the research theory, data, and methods, including the overall problem, input data and boundary conditions are introduced. Then, the results of the research are discussed and finally, the case study is argued.

MATERIALS AND METHODS

In this study, there are 6 variables including pressure (P), temperature (T), density (ρ), and wind velocity in the x-direction (u), velocity in the y-direction (v), velocity in the z-direction (w). Three variables related to velocity were simulated by the Navier-Stokes equation. According to the solution method of this research, after obtaining the initial solution using the k-ε model, the problem was switched to the LES method, and the final solution was solved by this method.

In addition, convective, conductive, and radiation flows were calculated through the governing equations of fluid dynamics. To this end, the solar radiation during the June 21st Summer Revolution was simulated by a Monte Carlo model. Note that this problem has common variables, so the equations must be solved simultaneously. The analytical methods are summarized in Table 1.

Since there are 5 equations and 6 unknowns, equation1 is used to solve this problem. Where P (pressure), V (volume), n (number of moles of gas), T (temperature), and R are the universal gas constant (Equation1).

$$PV = nRT \quad \text{(Equation1)}$$

The height of the computational domain was 6H (Nazarian and Kleissl, 2016) to achieve a fully-developed flow field, where H represented the height of the buildings. In this study, input data were considered based on the city of Shiraz with hot and dry climates. In addition, the effect of gray concrete on temperature change were investigated. The concrete specifications according to Radhi et al. (2014) include a density of 2050 kg/m3, conductivity of 0.719 w/mK, specific heat capacity of 890 kJ/kgK and infrared emissivity of 0.9. Furthermore, the computational fluid dynamics solver was based on the finite volume method (Versteeg, 2007).

Introducing data

For this study, the weather data for June 21 (the longest day of the year) in Shiraz was chosen to drive the simulation process. Figure 2 shows time-dependent boundary conditions for (a) temperature, (b) velocity along the X-axis, and (c) velocity along the Y-axis.

Boundary conditions

This model used symmetric boundary conditions to simulate an urban area. In addition, the velocity-inlet was considered as the inlet boundary condition and the mass flow as the outlet boundary condition. Furthermore, the no-slip boundary condition of the stationary wall was employed for the top view.

Research theory

The Navier-Stokes equations can be used to derive the Reynolds Averaged Navier-Stokes (RANS) equations, while in Large Eddy Simulation (LES), turbulence scales are filtered out to focus on resolving the largest energy-containing scales. Additionally, the conservation of energy equation plays a crucial role in modelling heat transfer and compressible flows by determining the fluid temperature and density. In the following, the related theories will be explained.

Table 1: Summary of Analysis Methods

The main components of the solution	Description
Geometry	Geometry consists of several 30-meter-tall building
Solid domain	Gray concrete
Fluid	Air ideal gas density formula
Turbulent flow model	For the Initial solution is used k-ε model and for the exact solution is utilized LES model
Radiation model	Monte Carlo
Solver type	Transient

Filtered Navier-Stokes Equations

The governing equations employed for LES are obtained by filtering the time-dependent Navier-Stokes equations in either Fourier (wave-number) space or configuration (physical) space. The filtering process effectively filters out the eddies whose scales are smaller than the filter width or grid spacing used in the computations. The resulting equations thus govern the dynamics of large eddies. A filtered variable (denoted by an overbar) is defined by

$$\overline{\varnothing}(\mathrm{x}) = \oint_{\mathrm{D}} \varnothing(\mathrm{x}')\,\mathrm{G}(\mathrm{x},\mathrm{x}')\,\mathrm{dx}' \qquad \text{(Equation2)}$$

where D is the fluid domain, and G is the filter function that determines the scale of the resolved eddies. In Ansys Fluent, the finite-volume discretization itself implicitly provides the filtering operation:

$$\overline{\varnothing}(\mathrm{x}) = \frac{1}{V}\oint_{D} \varnothing(\mathrm{x}')\,\mathrm{dx}', \mathrm{x}' \in v \qquad \text{(Equation3)}$$

where V is the volume of a computational cell. The filter function, , implied here is then

$$G(x,x') = \begin{cases} 1/\mathrm{V}, \mathrm{x}' \in \mathrm{v} \\ 0, \mathrm{x}' \text{ otherwise} \end{cases} \qquad \text{(Equation4)}$$

The LES capability in Ansys Fluent is applicable to compressible flows. For the sake of concise notation, however, the theory is presented here for incompressible flows.

Filtering the Navier-Stokes equations, one obtains

$$\frac{\partial\rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho\bar{\mathrm{u}}_i) = 0 \qquad \text{(Equation5)}$$

and

$$\frac{\partial\rho}{\partial t}\left(\rho\bar{u}_i\right) + \frac{\partial}{\partial x_i}\left(\rho\bar{u}_i\bar{u}_j\right) = \frac{\partial}{\partial x_i}\left(\sigma_{ij}\right) - \frac{\partial\bar{p}}{\partial x_i} - \frac{\partial_{T_{ij}}}{\partial x_i} \qquad \text{(Equation6)}$$

where is the stress tensor due to molecular viscosity defined by

$$\sigma_{ij} \equiv \left[\mu\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right)\right] - \frac{2}{3}\mu\frac{\partial\bar{u}_i}{\partial x_j}\delta_{ij} \qquad \text{(Equation7)}$$

and T_{ij} is the subgrid-scale stress defined by

$$T_{ij} \equiv \rho\overline{u_i u_j} - \rho\bar{u}_i\bar{uj}$$

Heat Transfer Theory (The Energy Equation)

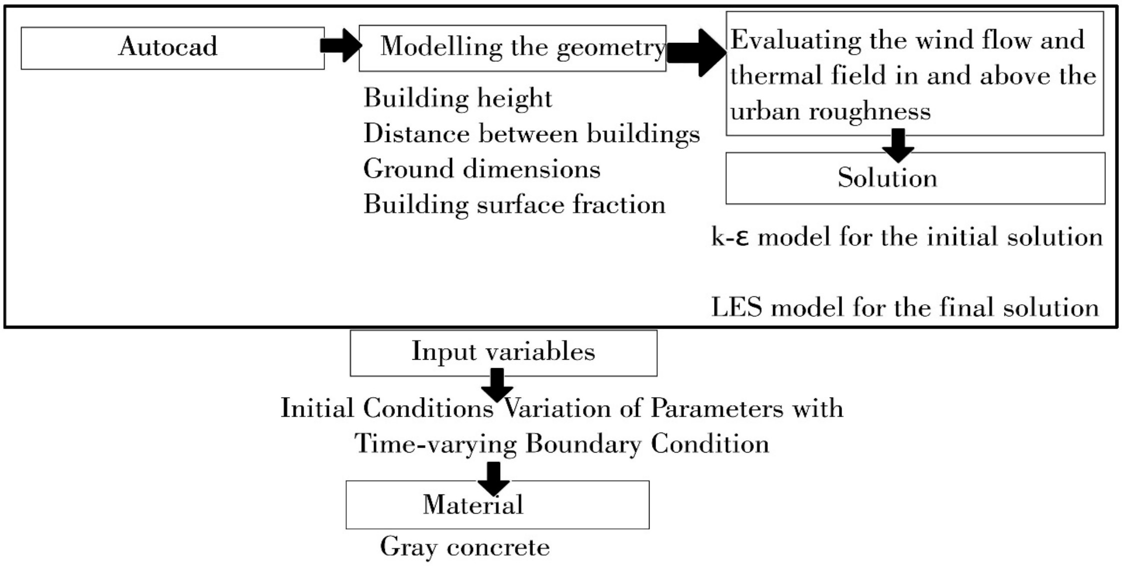


Figure1: The work flow of the presented work

Ansys Fluent solves the energy equation in the following form:

$$\frac{\partial}{\partial t}(\rho E)+\nabla.\left(\vec{\upsilon}(\rho E+p)\right)$$

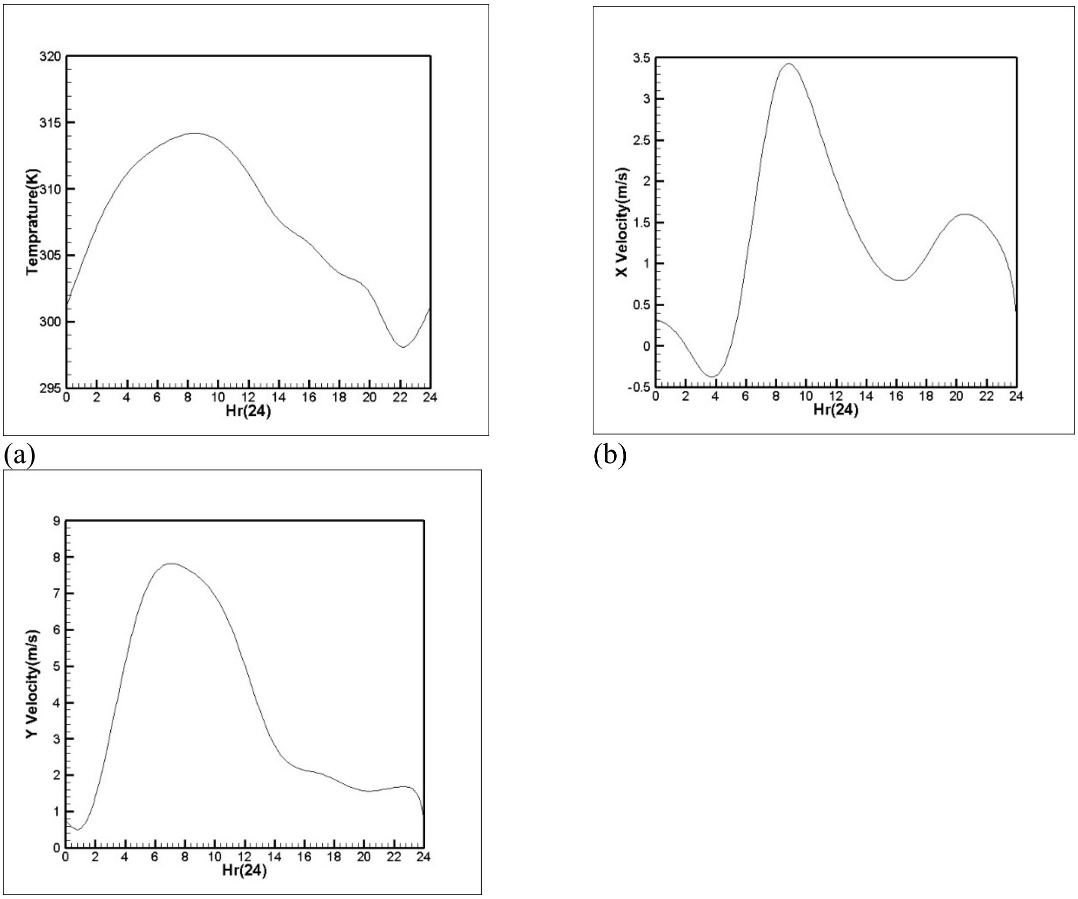
$$=\nabla.\left(k_{eff}\nabla T-\sum_{i}h_{j}\vec{j}_{i}+\left(\overline{\overline{T}}_{eff}.\vec{\upsilon}\right)\right)+S_{h}$$

(Equation8)

where k_{eff} is the effective conductivity $(\mathrm{k}+\mathrm{k}_t)$, where k_t is the turbulent thermal conductivity, defined according to the turbulence model being used), and $\vec{j}_i$ is the diffusion flux of species i. The first three terms on the right-hand side of Equation (3-3-2) represent energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. S_h includes the heat of chemical reaction, and any other volumetric heat sources you have defined.

Case study: Shiraz city

A real large - scale building in Hosseini Al-Hashemi Expressway, located in district 10 of Shiraz, has been chosen for this case study. The location was selected due to the unique construction characteristics in the area, with separate buildings and no surrounding constructions. This makes it an ideal model for urban planners to study and plan future construction projects in this district. The three-dimensional model of this area was created using AutoCAD software (3c), based on a satellite map (3a,3b) of the location.

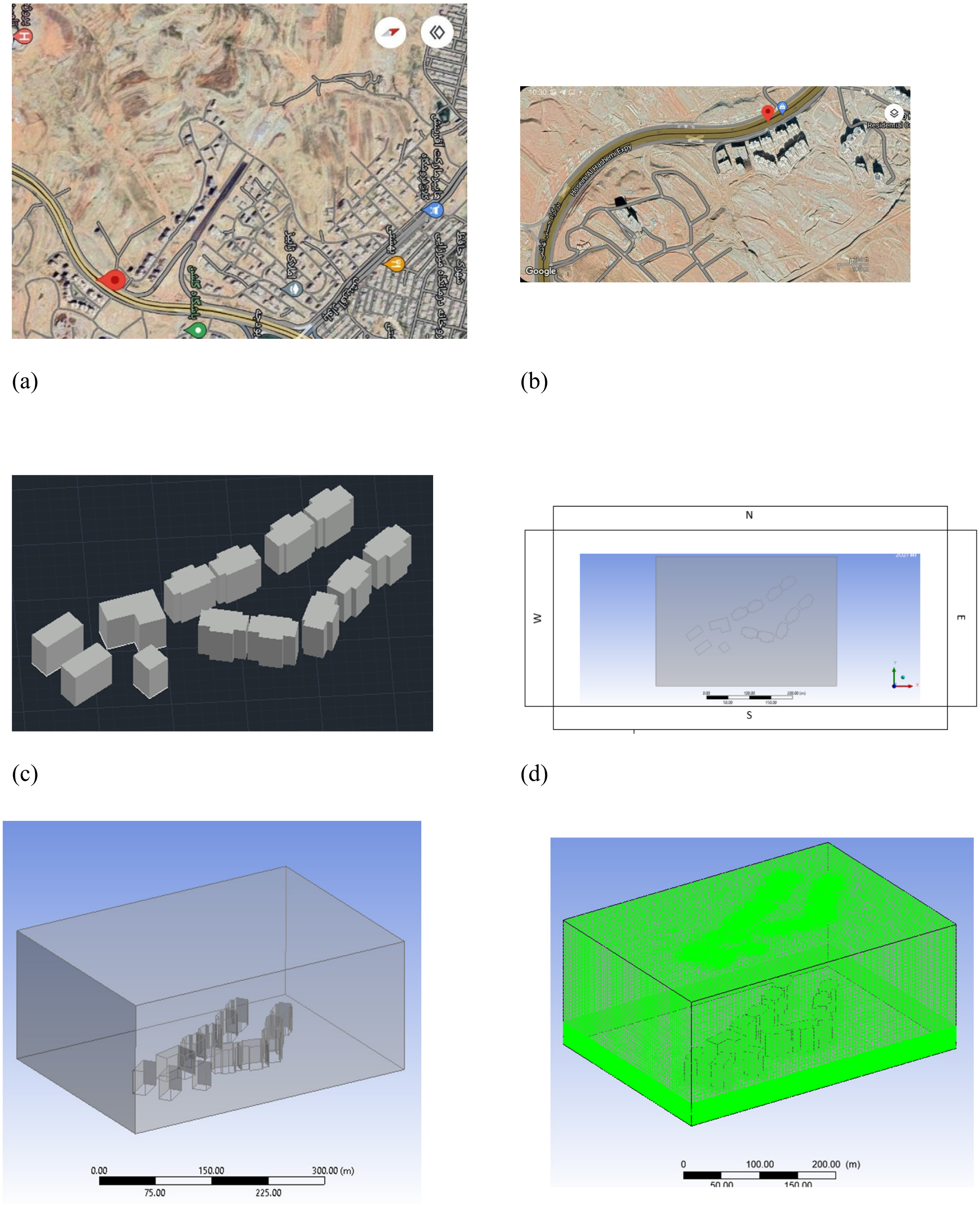


(a)

(b)

(c)

Figure2: Time-varying boundary condition for (a) Temperature (b) velocity along the X axis (c) velocity along the Y axis



(a)

(b)

(c)

(d)

(e)

(f)

Figure 3: model of the Shiraz City case study (a,b) The Satellite map of the urban canyon (c) Simulation in AutoCAD (d) Geographical orientation of the model (e) Geometry designed in ANSYS Design Modeler (f) mesh of the case study.

The urban canyon is situated in the north - western part of Shiraz and comprises several 30-meter-tall gray concrete high-rise buildings. The zone covers a land area of 420 meters by 300 meters. To ensure a fully developed flow field for simulation purposes, symmetric boundary conditions were applied in both streamwise and spanwise directions. The height of the fluid field was set at 180 meters, which is six times the height of the buildings in the area. The simulation of this area in Shiraz involved detailed analysis of the geographical orientation of the model (3d), the geometry designed in ANSYS Design Modeler (3e), and the mesh of the case study (3f). By running simulations on this specific urban canyon, insights can be gained into optimizing airflow, heat transfer, and solar radiation in similar urban environments. This research aims to provide valuable data for urban planners and designers to enhance natural ventilation and mitigate heat island effects in rapidly growing cities like Shiraz.

DISCUSSION AND FINDINGS

Figure 4 shows the temperature contours and Figure 5 indicates the velocity contours at heights of 2m to 25m. Figure 4 provides a comprehensive visual representation of the temperature contours, revealing a notable reduction in temperature non-uniformity distribution and heat traps as altitude increases. The alignment of the dominant flow temperature with the prevailing air temperature at higher altitudes indicates a more harmonized thermal environment. The deliberate design of the urban canyon shape plays a crucial role in enhancing airflow dynamics by facilitating the expansion of pre-existing eddies at elevated altitudes. This phenomenon contributes to improved air circulation and heat dissipation within the urban setting.

Upon closer examination of Figure 5, a distinct shift in airflow patterns becomes apparent between different heights within the urban canyon. The comparison highlights the release of previously blocked airflow at 2m height (represented by the circle in Figure 5a), now facilitated by the presence of larger eddies at 25m height. This observation underscores the significance of considering vertical variations in airflow behavior when assessing urban ventilation strategies. By employing Large Eddy Simulation (LES)-based methods, researchers were able to accurately capture the intricate flow characteristics induced by turbulence. The utilization of advanced simulation techniques not only enhances our understanding of urban airflow dynamics but also underscores the importance of detailed analysis in optimizing urban design for mitigating heat accumulation and enhancing ventilation.

The findings from the temperature and velocity contours analysis underscore the positive impact of thoughtful urban planning on mitigating heat accumulation and enhancing natural ventilation. The progressive reduction in heat traps and improved airflow patterns with increasing altitude emphasize the effectiveness of the designed canyon shape in promoting efficient air circulation within the urban environment. By leveraging LES-based methods, researchers gained valuable insights into flow magnitude and length-scale variations, shedding light on the complex interplay between turbulence and urban microclimate. These insights are instrumental in guiding future urban development strategies aimed at creating more comfortable and energy-efficient living spaces.

RESULT AND CONCLUSION

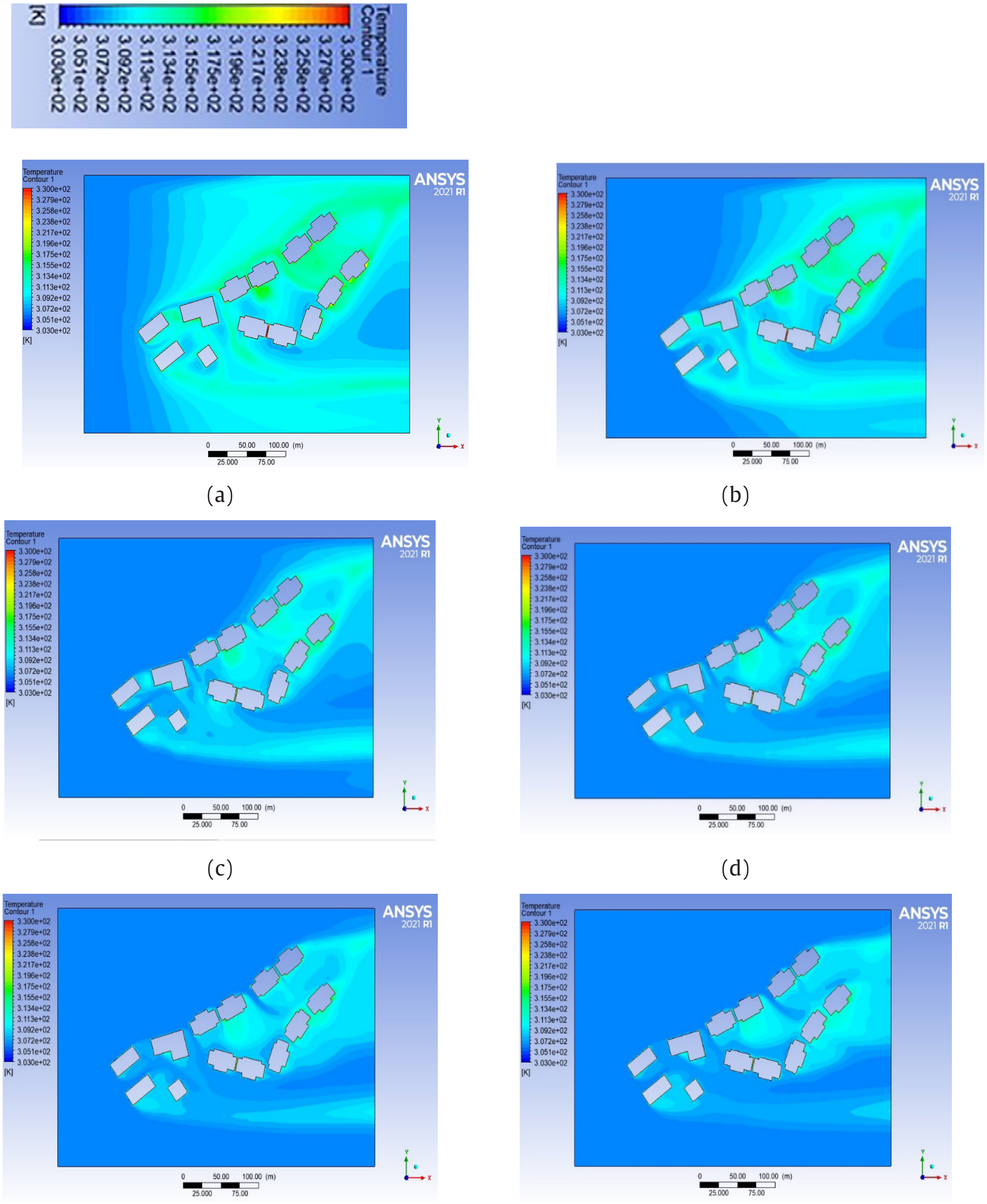
Various topography features affect wind velocity, direction, and air pressure. To study the wind flow characteristic in a real urban canyon, including buildings in an urban area (Hosseini Al-Hashemi Expressway), various modelling approaches, including CFD were employed. The wind flow characteristics (wind velocity and wind pressure) were simulated using the CFD technique.

The study's findings provide compelling evidence of the effectiveness of the city block's design near a busy highway in Shiraz in mitigating heat accumulation and enhancing ventilation. Through a meticulous analysis of temperature and velocity contours at various heights, the research revealed a notable reduction in heat traps and improved airflow patterns as altitude increased. The deliberate widening of eddies within the canyon structure played a pivotal role in promoting enhanced air circulation, facilitating efficient heat dissipation throughout the urban environment. This emphasis on airflow dynamics highlights the critical role of urban design in fostering natural ventilation and combatting thermal challenges.

The transition from the conventional k-ε model to the more advanced LES method marked a significant advancement in understanding the intricate flow dynamics within the urban setting. By leveraging sophisticated simulation techniques, the research was able to delve deeper into the complexities of airflow behavior, shedding light on the nuanced interactions between turbulence, heat transfer, and urban microclimate. This shift towards more detailed and accurate assessments underscores the importance of adopting state-of-the-art methodologies to inform urban planning decisions in built environments.

In conclusion, the study serves as a compelling testament to the transformative potential of natural ventilation strategies in urban canyons for reducing energy consumption and mitigating heat island effects. By examining real-world scenarios in Shiraz, the research showcases how thoughtful urban design interventions can positively influence airflow patterns within dense urban areas. The successful management of heat and ventilation near a busy highway exemplifies the tangible benefits of urban planning practices in creating more livable and energy-efficient urban landscapes.

Selecting the locations of residential zones near urban respiratory arteries is crucial for urban planning and urban designers, as they impact air quality and human behaviour. Simulating wind flow can help understand airflow patterns affected by obstacles, ultimately influencing human health and safety. Wind engineers should utilize practical simulations to forecast wind speed and pressure and air temperature considering the impact of various topographical features and barriers on wind flow in extensive areas. By employing suitable simulation methods, such as computational fluid dynamics, experts can accurately predict how wind behaves in urban environments like the Hosseini Al-Hashemi Expressway, aiding in better urban planning decisions.



(a)

(b)

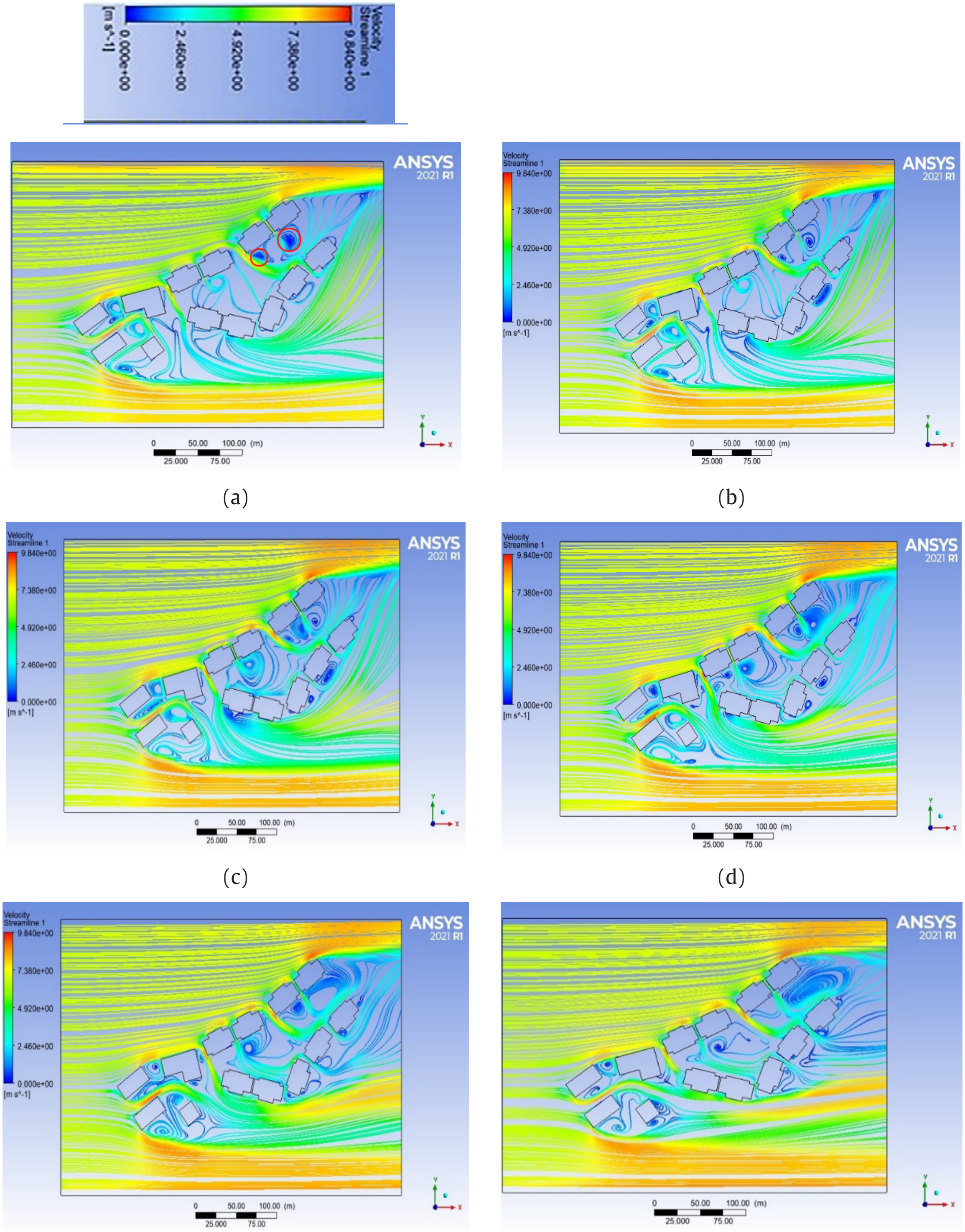
(c)

(d)

(e)

(f)

Figure 4: Temperature contour at a height of (a) 2m, (b) 4m, (c) 10m, (d) 15m, (e) 20m, (f) 25m



(a) (b) (c) (d) (e) (f)

Figure 5: velocity contour at a height of (a) 2m, (b) 4m, (c) 10m, (d) 15m, (e) 20m, (f) 25m

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