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CFD ANALYSIS ON HVAC SYSTEM FUNCTIONALITY IN AN AMPHITHEATER

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ABSTRACT

Heating, Ventilation and Air Conditioning (HVAC) is an important part of residential structures such as single-family homes, apartment buildings, hotels, and medium to large industrial and office buildings such as skyscrapers and hospitals, on ships, submarines, and in marine environments. This paper investigates the characteristics of the performance HVAC system at the KUET auditorium, regarded as an amphitheater, for various internal and external conditions. A 2D model of the longitudinal section of the auditorium was drawn using ANSYS-Fluent software in Design Modeler to simulate the various functionality of the HVAC system for both the summer and winter seasons. In this research, both the indoor and external conditions of the KUET auditorium were considered, with the entire spectacle of the hall being occupied by people. The main aim of this study was to observe the air temperature, air velocity, and relative humidity for each case. The results are represented comparatively as graphs and spectra for various mass flow rates and indoor-outdoor temperatures. It was observed that the HVAC system provided sufficient human comfort conditions in terms of air flow and relative humidity recommended by the American Society of Heating, Refrigerating and Air Conditioning Engineers (AHRAE) in the amphitheater for both the summer and winter seasons.

Keywords: *HVAC system; Numerical simulation; Amphitheater; Relative humidity; Human comfort.*

1. INTRODUCTION

Humans have been searching for ways to improve interior temperature conditions and create better, more pleasant living spaces since the dawn of humanity. The majority of the ancient civilizations, including the Egyptians, Greeks, Chinese, and Romans, are examples of simple and crude technology that were able to gently alter and manage the thermal conditions inside enclosed spaces and buildings. Since then, providing some heating during the cold season and cooling the environment throughout the summertime have been the two fundamental issues that humans have sought to solve. The handling of relative humidity was occasionally a useful additional measurement. People employed fire for heating at the beginning. Since then, providing some heating during the cold season and cooling the environment throughout summertime have been the two fundamental issues that humans have sought to solve. The handling of relative humidity was occasionally a useful additional measurement. People employed fire for heating at the beginning of recorded history. The quality of indoor air emerged as the second issue. There were suggested guidelines for ventilation by the late 1880s (McDowall, 2007). "Air conditioning" or, far better yet, "full air conditioning" (McDowall, 2007) today refers to and identifies complete control over the temperature, relative humidity, air movement, airborne particle filtration. The requirements for contemporary construction are enormous. A significant part of designing and managing a facility is providing fresh air, cooling, and heating. Heating, ventilation, and air conditioning systems are offered in order to satisfy the customer's needs for comfort, cost, efficiency, and aesthetic appeal. The complexity of developing an HVAC system is increased by a generally sustainable system. Buildings must lower their energy usage without reducing the services they offer in a sustainable manner to guarantee a comfortable interior environment for people. Setting energy targets should focus mostly on the HVAC system. Enhancing energy efficiency is the most effective strategy to reduce energy usage. Due to the extreme weather, buildings need to cool down more frequently in order to maintain a suitable indoor climate. Enhancing energy efficiency is the most effective strategy to reduce energy usage. Due to the extreme weather, buildings need to cool down more frequently in order to maintain a suitable indoor climate. Using a radiant cooling system with a large surface area at relatively high temperatures is a good strategy for sustainable cooling. It is important to keep in mind that, whereas space cooling almost always involves some sort of dehumidification procedure, space heating may or may not include the humidification of air.

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Additionally, the methods and technologies that were commonly employed to heat and cool a structure were very different (and frequently still are). For these reasons, the following section of this paragraph should assess the heating and cooling systems individually as mentioned for summer and winter. Particular emphasis will be placed on the overall layouts of the installations as well as the kind and customary temperatures of the fluid carriers.

Simulation has recently exerted a profound influence on the design of HVAC systems, with a burgeoning surge of simulation activities now prevalent in contemporary practice. CFD modeling is a computational approach used to simulate and analyze fluid flow and heat transfer. Uyttenhove *et al.* (2004) simulated CFD-modeling of Temperature and Humidity Distribution for the St. Pieter's Church. They carried out an investigation into the environmental conditions within the church and applied CFD techniques to understand how temperature and humidity are distributed within the church, which could be essential for preserving the historical artifacts and structural integrity. Mahu *et al.* (2012) used CFD simulations to evaluate and analyze HVAC systems, which are critical components of indoor environmental control in buildings. CFD modeling allows researchers and engineers to gain insights into airflow patterns, temperature distribution, and other factors influencing the performance of HVAC systems. The paper's focus on CFD modeling suggests that it explores how this computational tool can be employed to optimize HVAC system design and operation. This research could contribute to improved energy efficiency, indoor comfort, and sustainability in buildings.

Popovici and Hudișteanu (2016) employed computational fluid dynamics (CFD) techniques to simulate and analyze airflow, temperature distribution, and indoor air quality within a sociocultural building. The simulation outcomes offered valuable insights into the performance of the building's HVAC system, demonstrating its capability to maintain optimal indoor conditions, including temperature and air quality. These assessments took into account factors such as occupancy patterns and external environmental variables. Mohammadshahi *et al.* (2016) delved into the enhancement of ventilation and heat transfer within traditional HVAC systems, using Shavadoon as a specific case study. The authors utilized numerical simulations to thoroughly investigate and propose enhancements to the existing HVAC system in this particular context. Their analysis encompasses crucial factors such as airflow, heat distribution, and thermal comfort .Through these numerical simulations, the authors pinpoint strategies for optimizing ventilation and heat transfer, which are pivotal for maintaining both indoor air quality and temperature control in traditional HVAC configurations. These findings offer actionable solutions aimed at overall system performance improvement.

The findings of this research not only shed light on the HVAC system's effectiveness but also present opportunities for implementing energy-saving measures and enhancing system design. Such improvements have the potential to significantly elevate comfort levels and sustainability in sociocultural spaces. Studies on the impact of indoor climate on air flow within different buildings are becoming more and more important in the literature (Viswambharan *et al.,* 2014, Thiyagarajan and Kumar, 2015; Popovici and Hudișteanu, 2016) . These analyses are often carried out with the aid of specialist tools for transient (Gustafsson *et al.,* 2014) or steady (Mohammadshahi *et al.,* 2016) state. Analyzing the impact of exterior air circulation on internal climate (Peri *et al*., 2011; Mahu *et al.,* 2012) is also of interest. Another area of development is in the medical industry, where this method of approach offers preliminary data on the atmosphere in the operating room or emergency room (Bhaskoro *et al.,* 2012; Balocco *et al.,* 2014). The efficiency of the HVAC system and other building services is a top priority for all types of structures, but it is even more crucial in areas with large population densities.

Some research works dealt with analysis on thermal comfort in the HVAC system (Liu *et al*., 2019 and Darlis *et al*., 2021) under specific conditions. Liu et al. (2019) conducted numerical simulations to assess the impact of of a particular method with a radiant HVAC system on local thermal comfort around the human body. The study of Darlis *et al.* (2021) opted for numerical simulations to analyze airflow and temperature distribution within the Proton Exora passenger compartment. Ahmed *et al.* (2022) facilitated the numerical analysis of airflow within this 2D room. User Defined Functions (UDFs) coded in C language and integrated into ANSYS Fluent were utilized The study focused on analyzing velocity fields and temperature distributions under specified boundary conditions in an indoor environment and signified the complexity of optimizing HVAC systems and the impact of various parameters on achieving thermal stability while considering energy consumption.

In the current study, the HVAC system functionality for the KUET auditorium, which is also available as a conference hall, was investigated under steady state conditions both in summer and winter seasons. We thoroughly analyzed the HVAC system's performance in terms of temperature, relative humidity, velocity in different seasons, and visualize critical flow characteristics. This approach will provide valuable physical insights to comprehend both energy efficiency and occupant thermal comfort within the building. This type of analysis can be used for a variety of building engineering tasks, even at the design phase in order to achieve the best outcomes during implementation and execution of the installation.

2. CASE DESCRIPTION

One significant challenge faced by socio-cultural buildings like the KUET auditorium is the rapid accumulation of heat and water vapor, necessitating effective evacuation solutions. The focus of this study revolves around the HVAC system's functionality in managing these issues within the actual structure of the KUET auditorium. Specifically, the study concentrates on the Main Hall, accommodating the entire audience during events. This space is sizable, approximately 10 meters in height, 15 meters in width, and 50 meters in length. The model is constructed using the monument's real dimensions and incorporates the airflow characteristics of the HVAC system.KUET auditorium can hold roughly 1000 people, however it's frequently full during performances. The conditions of the interior climate are quickly changed by this urbanisation. Instead, in order to remove the extra heat and humidity and maintain the ideal degree of comfort inside the structure, the HVAC system must operate with the same reaction speed. The comfort of the occupants and the preservation of artwork and architectural features are the two most crucial objectives of the HVAC system.

Geometry of the auditorium was designed using ANSYS 19.2 student version as well as solidworks 2017 in two dimension format. The dimension was provided from KUET engineering section. The geometry of the auditorium is a simplified one (shown in Figure 1), for the longitudinal section only, assuming a 2D model.

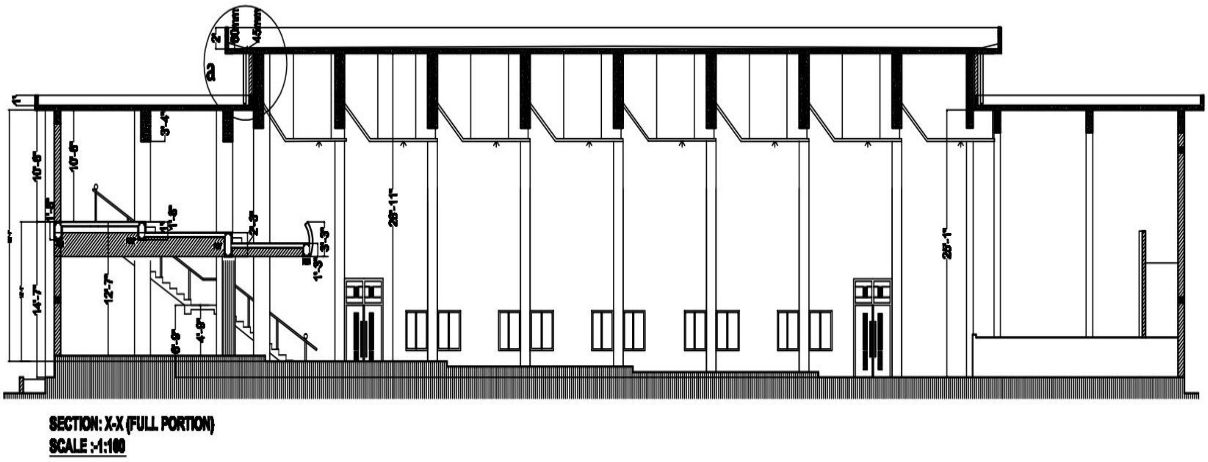


Figure 1: CAD drawing of KUET auditorium Elevation

The depiction in Figure 2 presents a lateral or right-hand side view of the KUET Auditorium, a versatile space also utilized as a conference hall. This particular view offers an illustration or graphical representation of the auditorium's structure and layout from a lateral perspective.

Figure 2: Right hand side view of KUET auditorium.

3. MODELING HVAC SYSTEM

3.1 Modeling

The research employed steady-state simulations, with a turbulent flow model known as the k-ε model, which is suitable for assessing airflow and heat transfer within enclosed spaces (Schwarz and Marchal, 2009). The outcomes of these simulations pertain to temperature and velocity data within an amphitheater. To accomplish this, numerical simulations were conducted using the CFD software ANSYS-Fluent, which allowed for the resolution of the differential equations related to heat transfer and fluid mechanics according to ANSYS Fluent guide.The problem is further simplified by considering a steady flow which does not change with time and by limiting the forces to only those associated with the pressure.

$$\frac{\delta}{\delta t}(\rho\vec{v}) + \nabla\rho(\overrightarrow{\vec{v}v}) = -\nabla p + \nabla(\overline{\overline{\tau}}) + \rho\vec{g} + \vec{F} \tag{1}$$

Where, the sum of the kinetic and potential energy at an initial time will be equal to the sum of the kinetic and potential energy at any other time.

$$\frac{\delta}{\delta t}(\rho E) + \nabla.\left(\vec{v}(\rho E + p)\right) = -\nabla\left(\textstyle\sum_j h_j J_j\right) + S_h \tag{2}$$

The law of conservation of mass states that in a closed system, the mass of the system cannot change over time.

$$\frac{\delta p}{\delta t} + \nabla.(\rho\vec{v}) = S_m \tag{3}$$

The transported variables are the turbulence kinetic energy (k) and the rate of dissipation of turbulence energy epsilon (ε), which are explained in Eq. (4) and (5) (Ali et al. 2007). Unlike earlier turbulence models, k-ε model focuses on the mechanism that affect the turbulent kinetic energy.

For turbulent kinetic energy

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{u_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + 2\mu_t E_{ij}E_{ij} - \rho\varepsilon \tag{4}$$

For dissipation ε

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{5}$$

Where, u_i represents velocity component in corresponding direction, E_{ij} represents component of rate of deformation, μ_t represents eddy viscosity

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{6}$$

Where, C_μ is the eddy viscosity coefficient for the standard k-ε model. The semi-empirical model k-ε was used to represent the turbulence, and it was considered to be adequate for simulating air flow inside huge domains.

For finer meshing the geometry was sub divided into 5 split facing. All the grids are quadrilateral shaped. The mesh generated shown in Figure 3 has a total of 145907 nodes and 144292 elements. For the models, energy equation was turned on also standard k-ε, standard wall Function was turn on in the viscous model. The researchers employed the Fluent software's species model tool to simulate relative humidity. In this model, the properties of the "mixture species" were defined to include H_2O (water vapor) and air, with H_2O as the top component. For properties like density, thermal conductivity, and viscosity, the "volume-weighted" approach was selected. Additionally, the "mass-weighted" method was chosen for these properties. The longitudinal section of the KUET Auditorium with inlets and outlet conditions for the solver setting is illustrated in Figure 4.

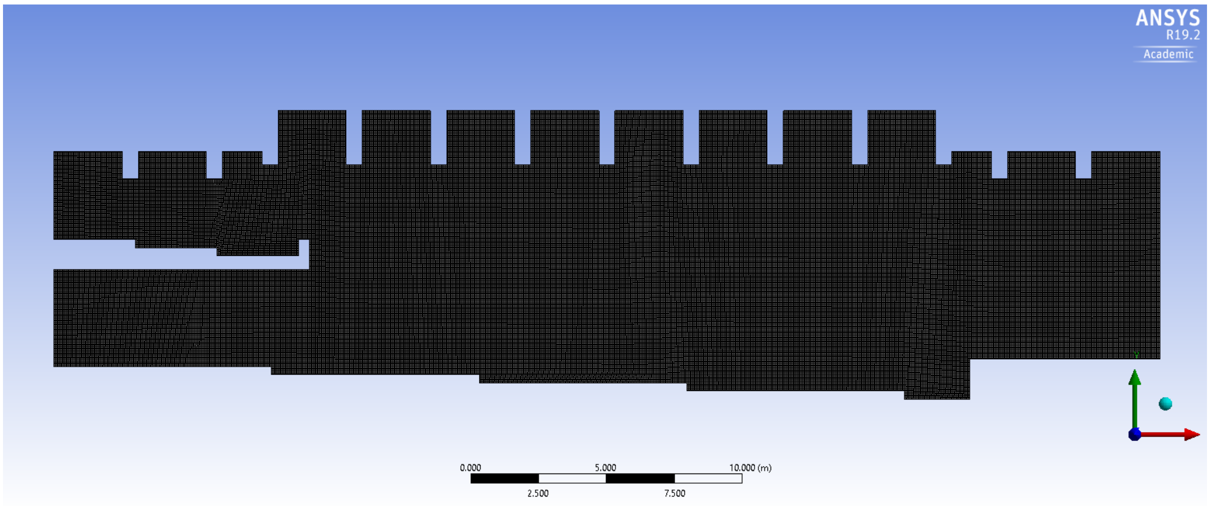


Figure 3: Meshing of geometry

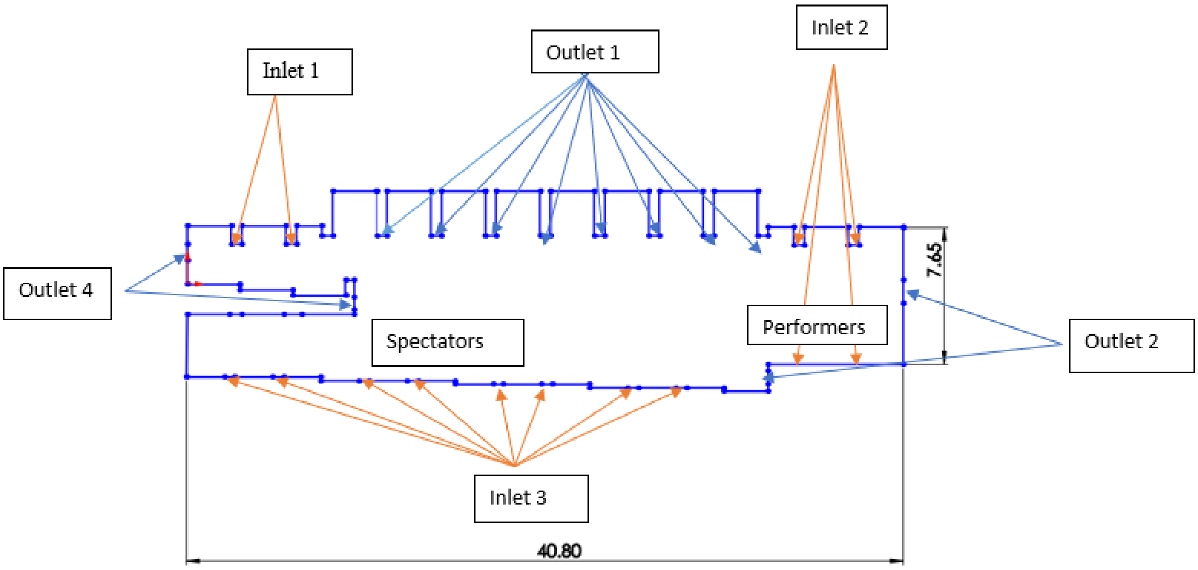


Figure 4: Longitudinal section – position of inlets and outlets.

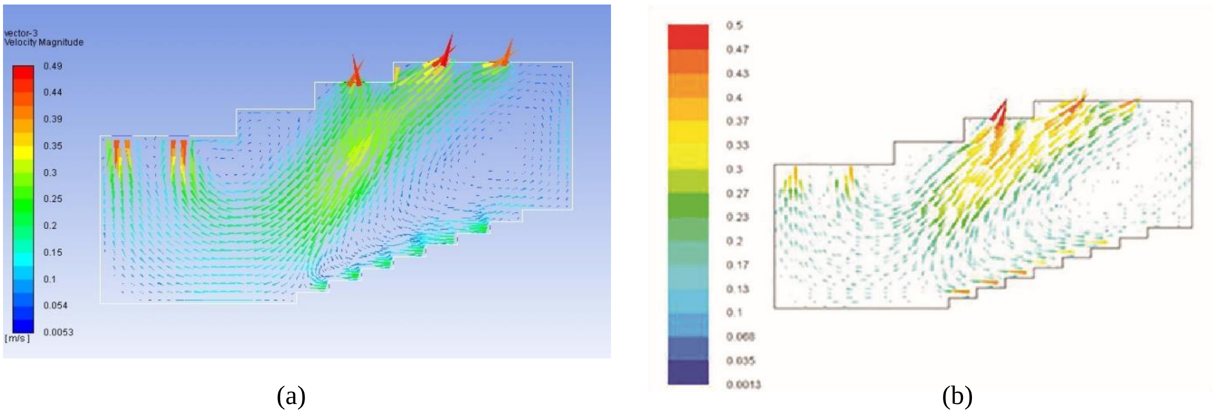
The horizontal and vertical dimensions of the amphitheater is 40.80 m and 7.65 m respectively.and By utilizing this approach, the researchers were able to establish the moisture mass fraction at the inlet and make predictions regarding the relative humidity at the outlet, facilitating a comprehensive analysis of the HVAC system's performance. The boundary conditions have been described in Table1.

Table 1: Boundary conditions for the HVAC functionality simulation.

Conditions	During Summer	During Winter
Inside Temperature	23ºC	22ºC
Free stream temperatures	35ºC	15ºC
Heat transfer coefficient	12 W/m^{2}k	24 W/m^{2}k
Heat generation rate	100 W/m^3	100 W/m^3
Mass Fraction of H_2O at inlet	0.01, 0.0105, 0.0115	0.087, 0.095 0.01
Flow rate	10000 m^3/hr	6000 m^3/hr
Direction Specification Method	Normal to boundary	Normal to boundary
Turbulence specification method	k- ε	k- ε
Density of air	1.225 Kg/m^3	1.225 Kg/m^3
Viscosity	1.7894×10^{-5} kgs/m^2	1.7894×10^{-5} kgs/m^2

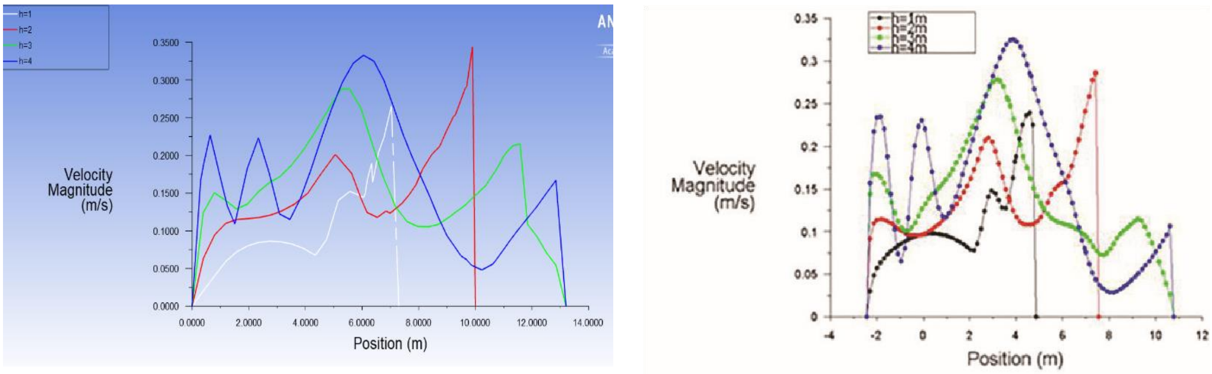
3.2 Model Validation

In order to validate the numerical model and solutions, the current model was applied in the case of previous published work that was done by Popovici and Hudisteanu (2016) , from Faculty of Civil Engineering and Building Services, "Gheorghe Asachi" Technical University of Iasi, 13 Dimitrie Mangeron, Iasi, 700050, Romania. Figure 5 represents a comparison of velocity vector bewteen the current simulation model and the numerical results from Popovici and Hudisteanu (2016). The present model is found to be in very good agreement with the literature. Figure 6 illustrates the velocity magnitude of air at different heights (h=1m, h=2m, h=3m, h=4m) inside the amphithater vicinity for current model and literature of the same study mentioned above. The velocity magnitude is found to be highest almost 0.33 m/s at height h=4m in the current model which validated the result from published literature. All the presented results for validation are very much comparable except little variation in velocity magnitude between the current model and literature at height h=3m inside the amphitheater.



(a) (b)

Figure 5: Validation of (a) the present model with (b) the numerical result (Popovici and Hudisteanu 2016) considering velocity vector.



(a) (b)

Figure 6: Validation of (a) the present model with (b) the numerical result (Popovici and Hudisteanu 2016) considering velocity magnitude

4. RESULTS AND DISCUSSION

The analysis investigated indoor temperatures during both summer and winter seasons within an auditorium setting. We aimed to examine temperature patterns, airflow velocities, and humidity distributions in this space. This exploration involved creating visual representations, such as contour plots showcasing temperature variations, airflow, and humidity levels across different sections of the auditorium. Specifically, we compared these factors across various horizontal heights within the auditorium, spanning from h=1 meter to h=4 meter and beyond. By examining these diverse heights, we intended to discern how these factors fluctuate vertically within the auditorium for the understanding of HVAC system functionality. The simulation results provided data used to generate visual representations like contour plots, offering insights into temperature distributions, airflow patterns, and humidity variations. Additionally, we plotted graphs displaying velocity magnitude at different horizontal heights within the KUET auditorium. These findings were interpreted to grasp the variations in temperature, airflow, and humidity within the auditorium across seasons and various horizontal heights. These results will be presented through graphical representations and detailed explanations, offering valuable insights into how indoor environmental conditions differ during summer and winter across different heights within the auditorium.

4.1 Velocity contour

Figures 7 and 8 provide visual representations of velocity contours under distinct indoor conditions: one for summer at an indoor temperature of 23˚C and the other for winter at 22˚C. These contours visually display how air velocities vary within the auditorium during these seasons.A significant observation arising from the velocity contours is the disparity in airflow velocities between the lower inlet ducts and the upper return ducts. The lower inlet ducts show higher airflow velocities compared to the upper return ducts, indicating a significant contrast in the airflow dynamics within these regions. However, this pattern is not consistent across the entire space. Areas like the stage and upper floor display a different airflow pattern, showcasing a reversal in the observed velocity distribution. An important factor influencing these velocity patterns is the mass flow rate, which is higher during summer. This higher mass flow rate directly contributes to the increased velocity magnitude observed during summer compared to the winter conditions. Essentially, the higher the mass flow rate, the greater the airflow velocity within the auditorium, leading to distinct differences in airflow dynamics between the two seasons.

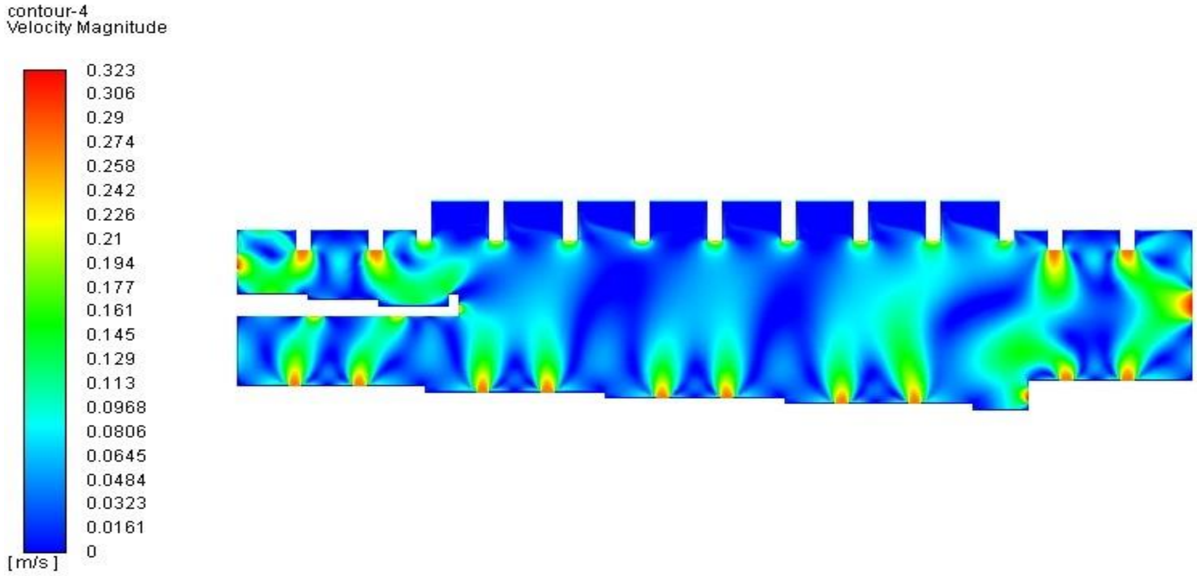


Figure 7: Velocity contour at summer

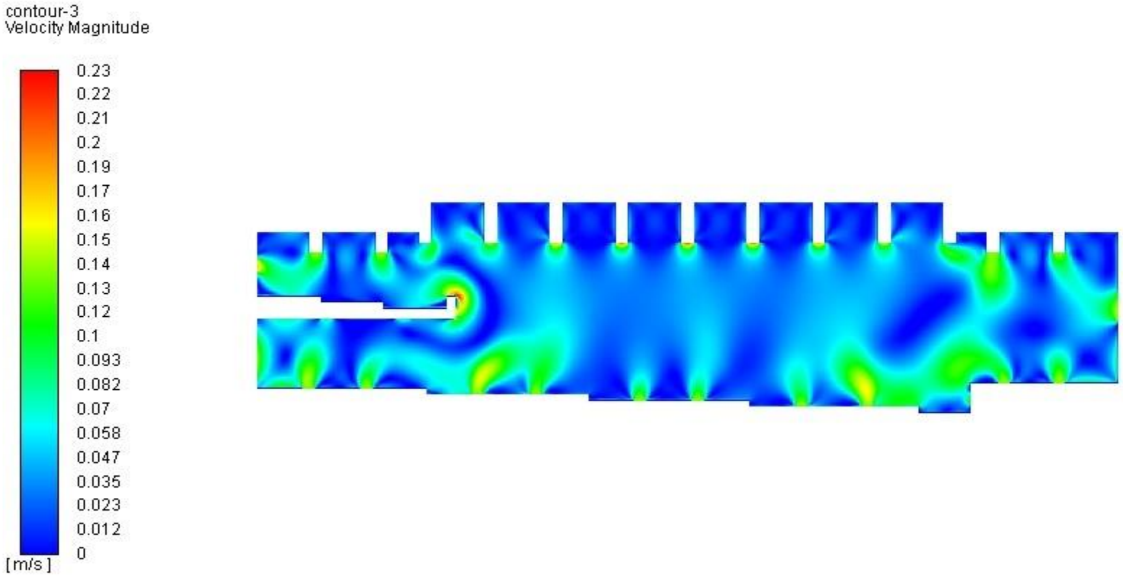


Figure 8: Velocity contour at winter

4.2 Temperature contour

Figures 9 and 10 showcase temperature contours for both summer and winter conditions. These contours were examined under specific indoor temperatures: 23˚C for summer and 22˚C for winter. The purpose is to visually represent how temperatures distribute within the auditorium during these seasons. A notable finding from these temperature contours is that the temperature remains relatively constant across most of the auditorium space, both in summer and winter. However, there are noticeable deviations along the internal and external walls where convection processes occur. These deviations indicate variations in temperature due to heat exchange happening at these surfaces. During the summer season, higher temperatures are observed within the auditorium. This rise in temperature is influenced by several factors. Firstly, it's impacted by the temperature of the inlet air introduced into the auditorium. Additionally, external heat transfer, likely from sunlight or external environmental conditions, contributes to the higher temperatures. Furthermore, internal gains from occupants, such as the heat generated by people, also play a role in elevating the temperatures during the summer season.

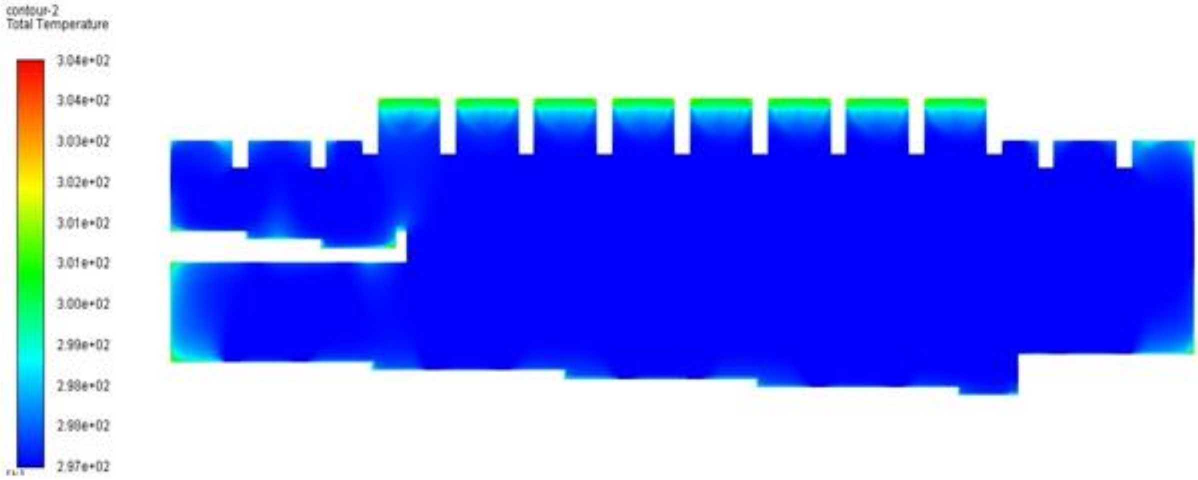


Figure 9: Temperature contour at summer

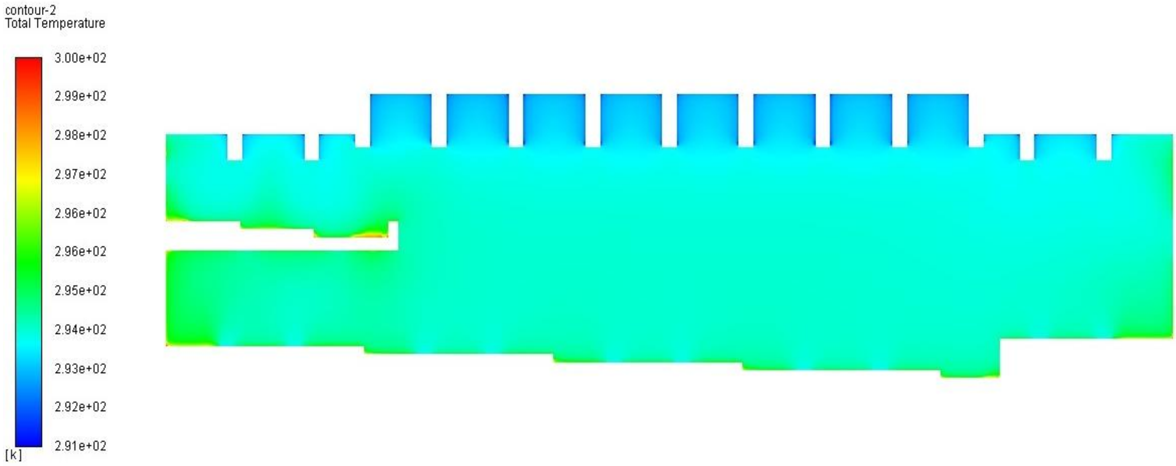


Figure 10: Temperature contour at winter

4.4 Relative Humidity contour

Figure 11 and Figure 12 exhibit relative humidity contours for both summer and winter seasons. These contours visually represent the distribution of relative humidity levels within the auditorium during these distinct seasons.

A clear observation derived from these humidity contours is that the relative humidity levels fall within the range of human comfort for both summer and winter. Throughout the auditorium space, the relative humidity remains within acceptable comfort levels for occupants. During summer, the relative humidity varies within a range of approximately 59% to 70%, while in winter, it fluctuates within a range of about 49% to 60%. These observed ranges align with the thermal comfort zone guidelines set by ASHRAE 1997, ensuring that the relative humidity levels maintain conditions that are comfortable for individuals occupying the space. These ranges indicate that the humidity levels are conducive to providing a comfortable indoor environment for occupants during both summer and winter seasons.

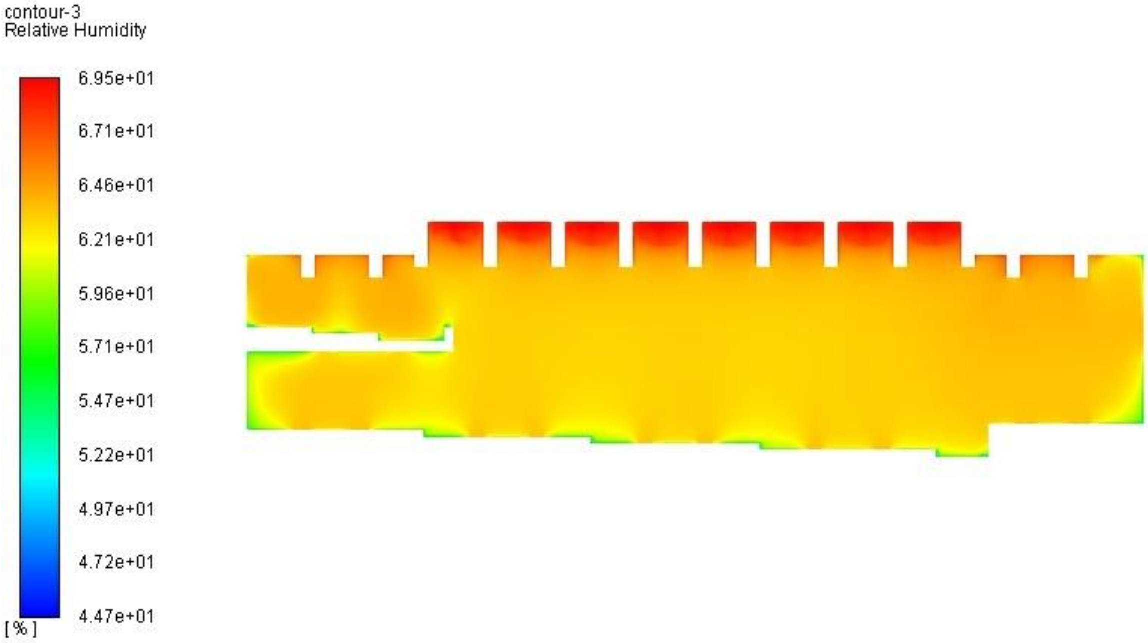


Figure 11: Relative humidity contour at summer

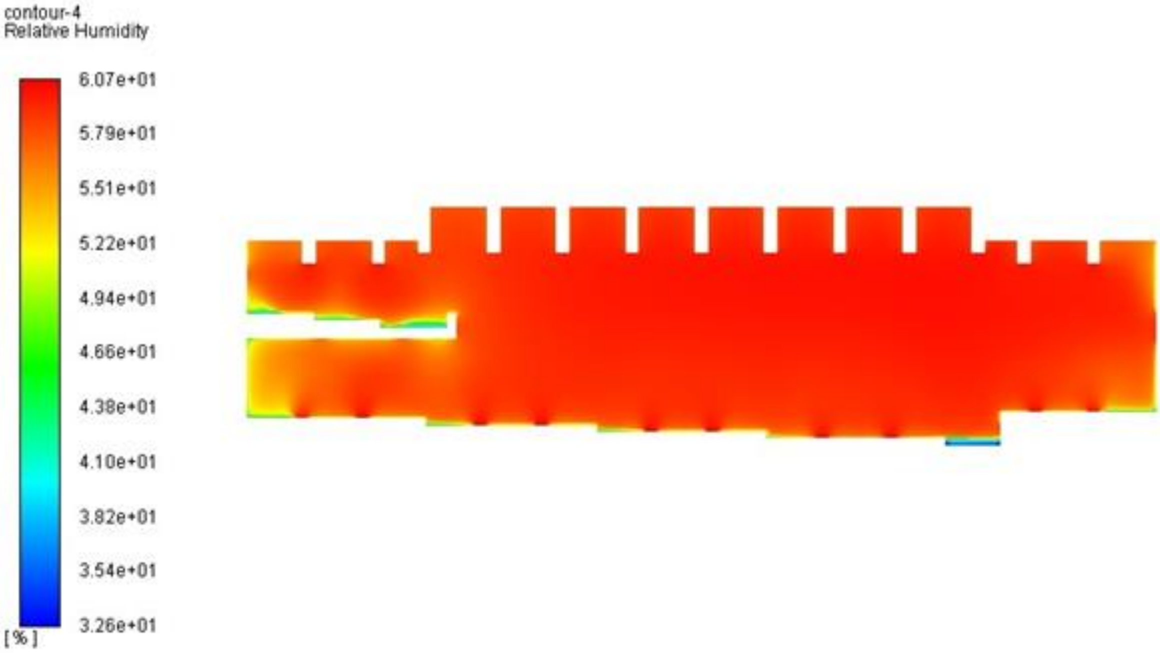


Figure 12: Relative humidity contour at winter

4.5 Velocity Vector

The velocity vectors, depicted in the vector plots, illustrate the airflow characteristics within the auditorium. Figure 13 represents the velocity vectors for the summer condition, while Figure 14 displays the vectors for the winter condition. Similar to the velocity contour, the velocity vectors showcase the magnitude of airflow at various points within the vicinity. Additionally, they provide directional information, indicating the pathways of the airflow. These vectors visually represent both the speed and the direction in which the air is moving within the auditorium. An evident point gleaned from these vector plots is that the maximum airflow velocity is notably higher during the summer season in comparison to the winter season. This difference in maximum velocity indicates a more vigorous airflow during summer, likely due to factors such as higher mass flow rates or increased external influences impacting airflow dynamics. The contrasting velocities between seasons suggest variations in air movement patterns and intensities, reflecting the seasonal differences in the indoor airflow dynamics.velocity vectors are described in the vector plotting. The summer condition velocity vectors are shown in Figure 13 and the winter condition velocity vectors are shown in Figure 14. Similar to the velocity contour, the velocity vector shows the velocity magnitude at different point in the vicinity. It also shows the direction of air being directed. It can be noticed that maximum velocity is higher during summer compared to winter season.

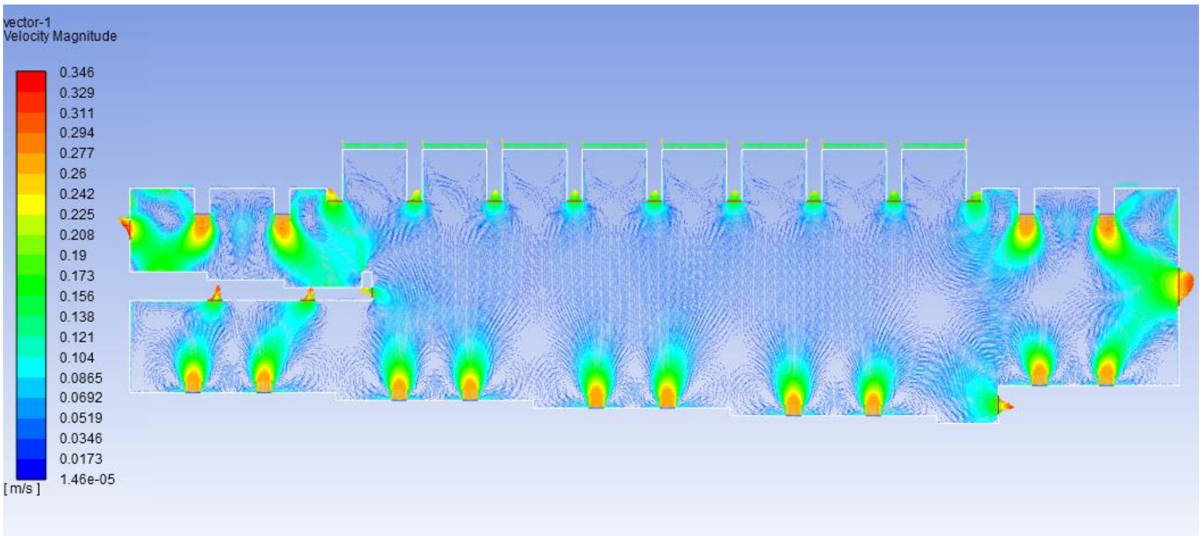


Figure 13: Velocity vector during summer

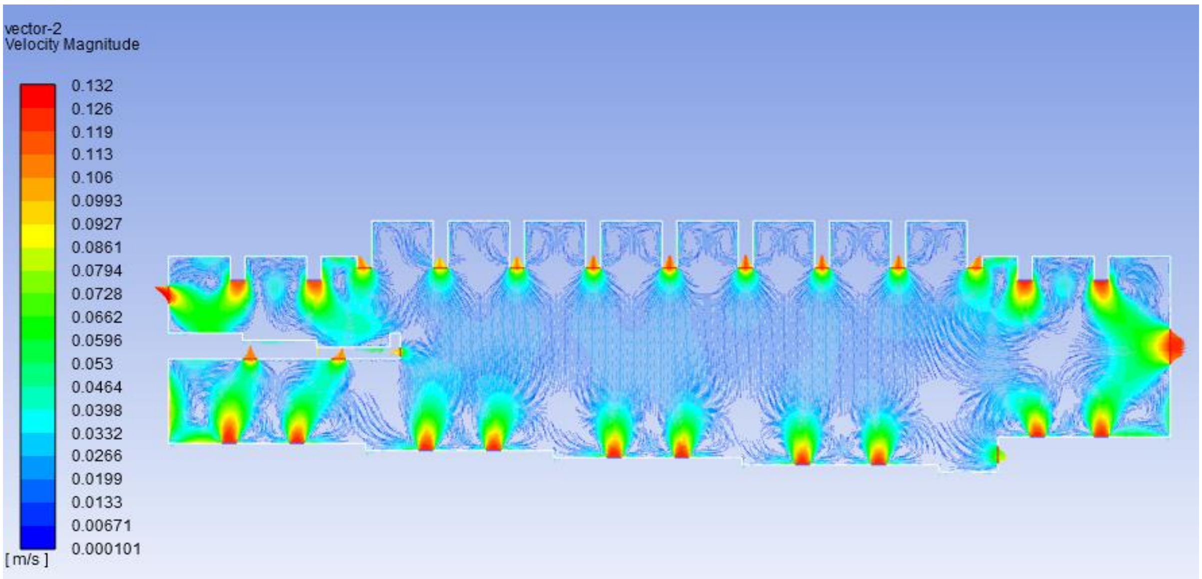


Figure 14: Velocity vector during winter

4.6 Graphical representation of velocity magnitude vs position

Velocity magnitude is analyzed with respect to several horizontal heights such as h= 1 m, h=2 m, h=3 m and h=4 m and also has been compared. The outside temperature of the amphitheater is considered as constant and indoor temperature as well as mass flow rate is varied. Two indoor temperatures at summer 22˚C and 23˚C also for winter 21˚C, 22˚C have been taken into consideration for the analysis. Figures 15 and 16 show the velocity magnitude vs horizontal position at different heights h for summer season at inside temperature 22˚C and 23˚C respectively. The velocity magnitude shows maximum of 0.28 m/s at height h=1 m face for 22˚C and 0.30 m/s at height h=1 m at 35 m and 38 m respectively from the left face.

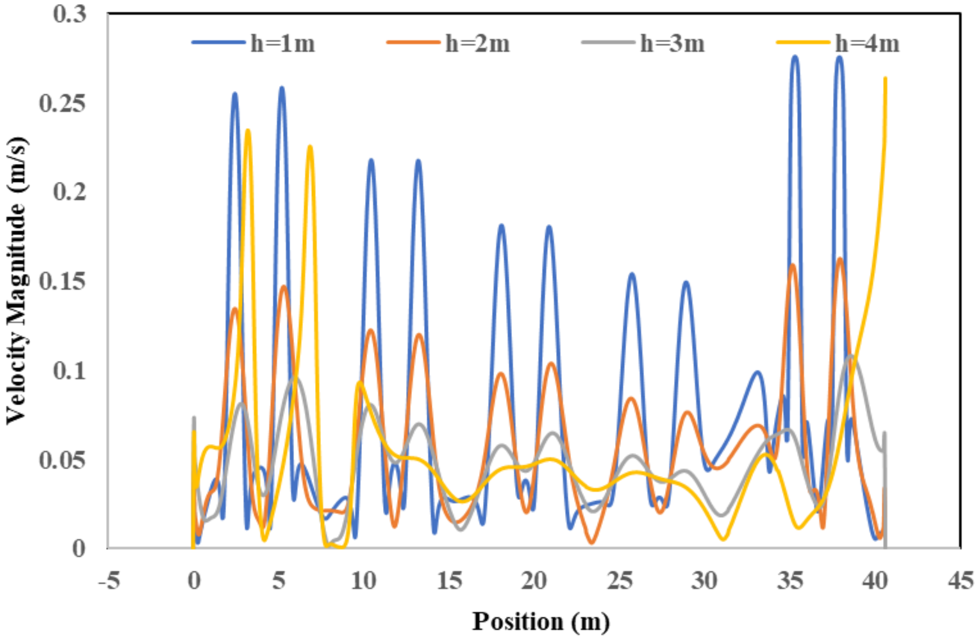


Figure 15: Velocity magnitude vs Position graph at 22˚C room temperature

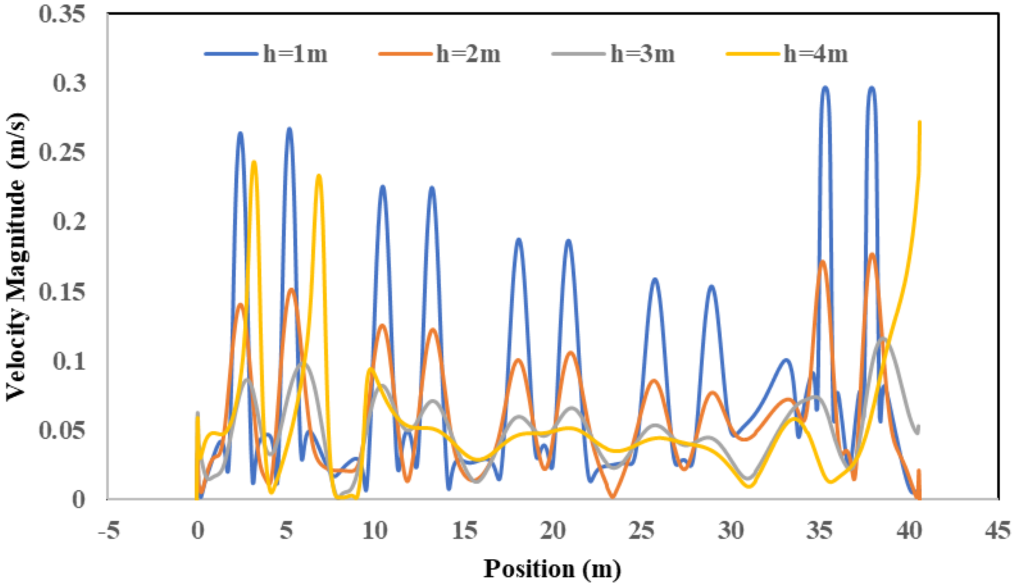


Figure 16: Velocity magnitude vs Position graph at 23˚C room temperature

Figures 17 and 18 depict the velocity magnitude vs horizontal position at different heights h for winter season at inside temperature 21˚C and 22˚C respectively. The velocity magnitude shows maximum of 0.14 m/s at height h=1 m face for 21˚C and 0.17 m/s at height h=1 m at 3m, 35 m and 37 m, respectively from the left face.From the velocity magnitude and position graphs for both summer and winter it can be seen that velocity at different horizontal heights changes quite frequently due to the various position of inlet and outlet ducts.Maximum velocity during Summer is measured 0.30 m/s and during winter it is 0.16 m/s which is within the acceptable range of velocity of air inside an auditorium or theatre according to ASHRAE.

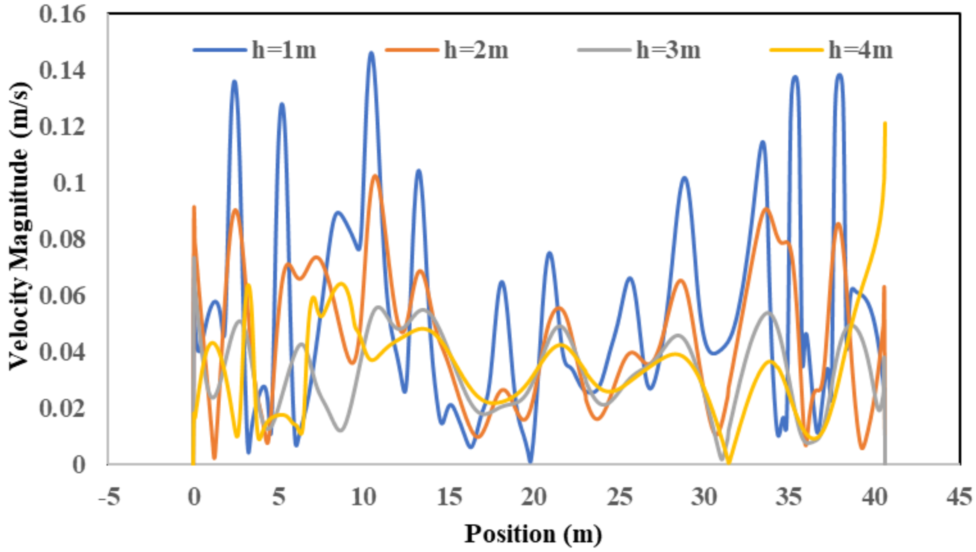


Figure 17: Velocity magnitude vs Position graph at 21˚C inside temperature

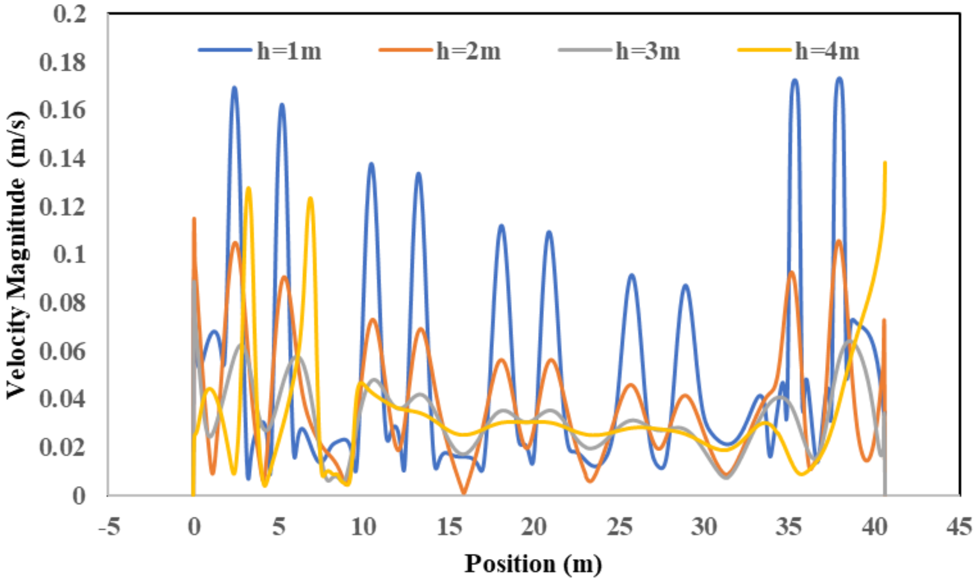


Figure 18: Velocity magnitude vs Position graph at 22˚C inside temperature

5. CONCLUSIONS

The study aimed to utilize ANSYS-Fluent, a specialized program, to simulate the HVAC system's performance in different summer and winter conditions. The primary focus was on creating a 2D model of an auditorium's geometry and simulating internal conditions. Overall, the findings indicate that the theater maintains adequate comfort levels throughout both the summer and winter seasons. Although slightly higher airflow is required in summer, the average velocities don't impact the occupants' comfort as the indoor spaces remain comfortable. Additionally, the humidity changes minimally between seasons. A noteworthy observation is the significant temperature and humidity variation near the walls due to convection with the external environment. Despite this variation, the interior comfort remains unaffected. This type of analysis isn't limited to theater spaces but can be applied broadly to building engineering tasks, especially during the design phase. It can aid in achieving optimal outcomes during the installation and execution of HVAC systems to ensure comfort and efficiency in indoor spaces.

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NOMENCLATURE

p - Pressure (Pa)
α - convective heat transfer coefficient (W/m^2K)
v - Overall velocity vector (m/s)
ε - Dissipation rate of turbulence energy epsilon
g - Gravitational acceleration (m/s^2)
k - Turbulence kinetic energy
h_0 - Standard state enthalpy of formation (energy/mass, energy/mole)
J - Mass flux; diffusion flux (kg/m2s)
S_m - Source of mass added to the continuous phase
T_{ext} - Temperature of external air (°C)
F - Force vector (N)
E - Total energy (J)
h - Enthalpy (J/kg)
t - Time (s)
ρ - Density (kg/m3)
τ - Shear stress (Pa)
S_h - Source of heat added

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