The Implication of Solar Chimney for Enhanced Stack Ventilation

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Abstract

In this study the effect of a solar chimney in enhancing the stack ventilation in an e-Bike Prototype Assembly building is analyzed. The Study area is Birgunj, Nepal. Natural ventilation in the existing plans is studied and compared with an alternate scenario of incorporating a solar chimney. Various parameters like temperature (Air, operative and radiant), pressure and velocity distribution, and comfort parameters (PPM and PPD) are compared. The DesignBuilder software is used to analyze natural ventilation. DesignBuilder internal CFD analysis is used to study the effect of solar chimney as a part of the building on the natural ventilation. Results show that there is significant improvement in ACH and air movement inside the building with incorporation of Solar Chimney. The PPD analysis results show that the comfort aspect is not only related to a single parameter like the air flow, temperature and pressure differential but a combination of these. The design of solar chimney should not only focus to improve a single aspect but a combination of the entire parameters for overall comfort. The study also shows that internal CFD analysis can be effectively used to predict internal condition of a building. The performance of Solar Chimney can be measured either or wholly in terms of air movement/air flow, temperature and velocity distribution and also thermal comfort parameters like PPD and PMV.

Keywords: *Passive Stack Ventilation, Solar Chimney, CFD Simulation, Thermal Performance*

Introduction

Ventilation and air conditioning have an increasing impact on the total energy consumption of buildings. As a result, natural ventilation and passive cooling have attracted people's attention. Wind-driven (single-sided and cross) ventilation and buoyancy-driven stack ventilation are two passive ventilation strategies, the effective working of the former is dependent on the mercy of wind while the latter can be used independently of site wind conditions.

Studies show that the wind-driven cross ventilation is a superior force to buoyancy-driven stack ventilation causing airflow inside a building, (Papadakis et al., 1996), therefore more designers are inclined towards cross ventilation strategies to induce airflow in a building (DeKay & Brown, 2013). But there are certain limits of wind-driven ventilation like the presence of wind capable of inducing airflow, denser built environment leading to stagnant air, therefore enhanced stack ventilation by use of devices like a solar chimney, cooling tower, etc. can significantly increase airflow even in absence of external wind force. The most common form of natural ventilation in residential buildings is passive stack ventilation. Passive stack ventilation is based on the chimney effect produced by the temperature difference between the temperature inside and outside the building. The solar chimney represents an option to improve the passive ventilation performance of the chimney when it is hot and sunny when the temperature difference between indoor and outdoor air is very small (Charvat et al., n.d).

A solar chimney is a passive device that uses solar radiation to ventilate buildings in summer. Solar chimneys can increase the ventilation of buildings by increasing the chimney effect every time the sun shines. It is especially valuable on days when there is no wind, hence increasing the stack effect. Solar chimneys use the sun to heat the air and increase its buoyancy. The air then rises faster, expelling more warm air, which in turn pushes more cold air into lower buildings (Lechner, 2015). Computational fluid dynamics deals with the flow of fluids under various conditions governed by the laws of physics. Computational fluid dynamics or CFD is the most popular method for solving and numerically analyzing the laws of control of fluid dynamics. Solve complex partial differential equations on a grid (or grid) and simplify the process by dividing the geometric domain into small volumes. CFD enables analysts to simulate and understand the world of fluid flow in new ways without the need for instruments that measure multiple flow variables at the desired location. (Kalkan & Dagtekin, 2015)

CFD as a sophisticated airflow modeling tool is widely used to predict various aspects like wind flow and heat transfer around and within a building envelope (Zhai, 2006). CFD can help architects and engineers to relate the design to respond to the site microclimate by overviewing the thermal performance of the building and its various elements.

The study uses DesignBuilder as CFD simulation software, DesignBuilder employs energy plus as the calculation engine. The main objective of the study is to understand how efficiently solar chimney systems enhance passive stack ventilation for the climatic condition of Birgunj.

Methodology

The study is quantitative and based on a positivist approach. To arrive at the objective of the research, the works are planned based on three main parts: a study of relevant literature, the study of climate and project site, and finally design and analysis of solar chimney for the considered site. The review of literature includes the study of the historical development of natural stack ventilation along with its development over the years. Current trends in stack ventilation strategies and examples from all over the world are also studied. Relevant key theories that will guide the research are also studied. Previous research findings in a similar field of study have been carried out that help in pointing out key variables and factors to be considered for the study. A Methodological review is also carried out that demonstrates different methods that past researchers have employed, this helps in choosing appropriate methods most relevant for the study. Another part of the research is the study of the climate of Birgunj. The EPW format weather data for Birgunj was collected from the available online source. The collected data is used for simulation in the DesignBuilder Software. Climate Consultant, a graphic-based computer program will be used to understand the local climate by feeding the created weather file in EPW format. Recommendations drawn from the various literature along with the climatic study of Birgunj will be used for modeling of Solar Chimney for the analysis.

Literature Review

Most of the research works on solar chimney studies have followed three approaches and/or a combination of these three approaches, namely experimental studies, Numerical modeling studies, and Analytical studies. Experimental investigations aid in the demonstration and validation of various chimney models and equations. These experimental studies are carried out on either a full-scale model or a small reduced-scale model. Numerical Modeling Studies increased with the development and improvement of computational calculation power. Computational tools are employed to study solar chimney models; this negates the need to construct a physical model for study. Simulation-based results obtained are in close conformity to the real models. Various researchers have resorted to numerical modeling studies for the analysis of solar chimneys. In analytical studies, mathematical models are developed for the prediction of solar chimneys' performance. Experiments are usually performed, to validate the models (Gontikaki et al., 2010).

Bansal et al. (1993) developed a steady-state mathematical model for a solar chimney and studied the effect of solar radiation, opening size, and ambient temp on airflow rate. Bouchair (1994) studied ventilation-induced due to cavity on a full-scale model under steady-state conditions. A solar chimney significantly increases the ventilation rate as compared to a conventional chimney (Afonso & Oliveira, 2000). The possibility of reducing heat gain in a house by incorporating the solar chimney was experimentally investigated by Khedari et al. (2000). The effect of variable chimney dimensions, solar chimney heat flux, and inclination angle on airflow rate was investigated by Chen et al. (2003) on an experimental solar chimney model. Ong and Chow (2003) experimentally verified the mathematical model of solar chimney proposed to predict the performance under varying ambient and geometrical features. Airflow rate due to lightweight construction and thermal mass construction on the solar chimney was experimentally studied by Charvat et al. (2004). Mathur et al. (2006) conducted experimental investigation on nine different configurations of solar chimney dimensions. Nugroho et al. (2006) found that air ventilation is induced by solar chimney in a terrace house. Gontikaki et al.

(2010) identified SC dimensions and material properties as influential parameters on the performance of SC. Tan and Wong (2013) investigated the effect of solar chimney parameters on interior air temperature and airspeed and found SC width as the most significant factor. Lal et al. (2013) conducted an experimental investigation of SC for the climatic condition of Kota city in India and recorded ACH satisfying BIS requirements. Mahdavinejad et al. (2013) investigated effect of SC inclination angle on airflow rate for different climates of Iran. Natural ventilation across chimney was studied using CFD by De la Torre and Yousif (2014). Nugroho and Ahmad (2014) found that the average indoor temperature of a terrace house in the city of Malang was within the acceptable comfort range for the whole day when the passive cooling technique of indoor cooling assisted by solar chimney and green vertical landscape was integrated into the building. Chung et al. (2015) used CFD in Design Builder software to study the optimized length and width gap of solar chimney that could induce optimum air velocity and thermal performance in the indoor environment. Kalkan and Dağtekin (2016) demonstrated solar chimney using FLUENT software. Mekkawi and Elgendy (2016) studied the effect of introducing a solar chimney on thermal performance in a prototype residential building in Alexandria, Egypt. Nakielska and Pawłowski (2017) analyzed the impact of solar chimneys on the thermal comfort of rooms based on experimental studies on solar chimneys located in Poland. Godoy-Vaca et al. (2017) studied the performance of SC in different climates of Ecuador. Baxevanou and Fidaros (2017) developed a CFD model for the examination of natural ventilation in a two-store building with a solar chimney. Dietrich (2018) presented general design rules for the geometry of solar chimney systems that could be adapted to existing or newly erected buildings in hot and humid locations. PM and Harish (2018) analyzed various parameters of Solar Chimney by developing a mathematical model. Cheng et al. (2018) explored the application of solar chimneys for smoke exhaustion which otherwise is primarily utilized for natural ventilation. Suhendri et al. (2018) investigated the potential of the buoyancy-driven ventilation strategy for the hot and humid climate by employing Computational Fluid Dynamics. Danesh (2018) simulated the effect of the solar chimney on the heating load of the building using DesignBuilder software. Prima and Prima (2019) pointed out the potential use of passive ventilation using a wind catcher and the solar chimney to solve thermal problems. Salehi et al. (2019) established the time of the year when Solar Chimney can effectively provide thermal comfort under different climates of Bandar-Abbas (hot and humid), Yazd (hot and arid), Paris (mild and humid) and Toronto (cold and humid). Shi et al. (2020) investigated design of solar chimney considering both energy-saving and fire safety. Sakhri et al. (2021) experimentally investigated the potential of renewable energies [wind-catcher (WC), solar chimney (SC), and earth to air heat exchanger (EAHE)] to ameliorate thermal comfort and reducing energy consumption in building sectors.

Case Study Simulation

Birgunj Climate Study

Data Source

The weather information for Birgunj was obtained from http://climate.onebuilding.org. (Climate.OneBuilding.Org, 2020) The meteorological files on this page were created using the TMY/ISO 15927-4:2005 methods and hourly data from ISD (US NOAA's Integrated Surface Database). Individual year files for ISD are generated utilizing the IWEC's general concepts (International Weather for Energy Calculations). Various climate aspects are shown, understood, and studied using Climate Consultant software. The Climate Consultant program uses the yearly TMY 8760-hour EPW format climate data to produce charts and graphs for climatic research.

Climate Condition

Birgunj experiences a sub-tropical monsoon climate with a hot and humid summer. The average yearly temperature is between 23.8 and 24.5 degrees Celsius. The average annual rainfall is 1,800 mm, with a range of 1,300 to 2,800 mm. The months of June, July, August, and September see the most precipitation. Köppen and Geiger Climate of Birgunj is classified as Cwa.

Prototype Description

The building considered for this study is the e-Bike Assembly Building. The Built-up area of the assembly block is 312.5 m2. As shown in Figure 1, the plan has a rectangular form having an aspect ratio of 1:2. The building is oriented with its longer axis in an East-West direction. The Building is an open floor plan and is divided into various zones as shown in Figure 1. The inventory space is for storing parts, the assembly line is where the bike is assembled, holding cell is where assembled e-Bike is kept before dispatching to the warehouse. The Building has a blank façade on the East and West. The southern Façade has a window with a WWR of 40%. There are two 9m2 metal doors on the northern façade one each for entry and exit. The building has a fly roof that shades the actual flat roof of the building from direct sun exposure.

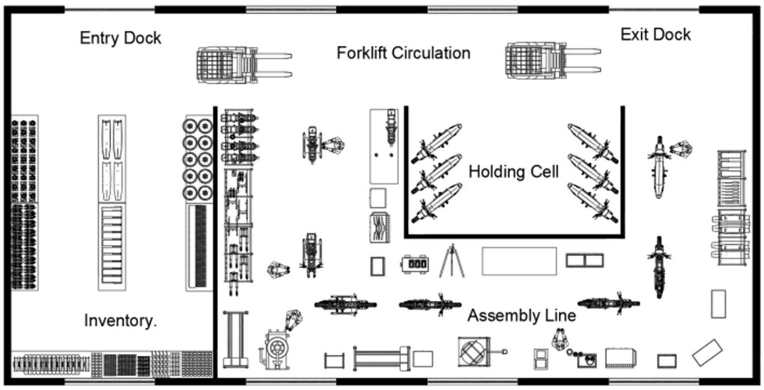


Figure 1: Floor Plan of e-Bike Assembly Building

Design-Builder Settings

Out of the two general approaches to natural ventilation modeling in DesignBuilder, the Calculated module is used instead of the Scheduled module. In the calculated module natural ventilation is calculated based on window opening, buoyancy, and wind-driven pressure differences. For this study, the effect of wind is excluded (wind factor set to 0) from calculated natural ventilation so that the results obtained truly reflect the buoyancy-driven ventilation. Thermal simulation is conducted for the typical summer design week, which is from 3-9 June. The calculation for the thermal simulation (Energy plus engine) takes into account building geometry, materials, and input *epw* weather file of Birgunj. These thermal simulation results are used to define the boundary condition for the internal CFD Analysis. CFD analysis is conducted on June 7, 12 noon.

Base Case Scenario

The prototype e-Bike assembly building was modeled into DesignBuilder (Figure 2). This is the Base case scenario with no changes made. Ventilation takes place through the windows on the south and north façade. These windows have a bottom open aperture of 50% (only 50% of the entire window is open on the bottom).

Figure 2: Base Scenario Model without Solar Chimney

Solar Chimney Scenario

In this scenario, a solar chimney is modeled as shown in Figure 3. In this model, a solar chimney block is added to the south façade. The length of the chimney block is the same as that of the building (25m), it is 1.5m wide and the chimney extends 3m above the roof of the existing assembly building. The Inlet vent (21.974 m2) for the solar chimney is placed on the south side internal wall (common wall between the assembly building block and solar chimney block), outlet vent (12.34 m2) is placed on the roof surface of the solar chimney block. The upper Southside outer wall of the solar chimney is made up of 6mm clear glazing, the interior is a 6” concrete wall with the inside surface exposed to the sun on the south side painted black to absorb the solar radiation.

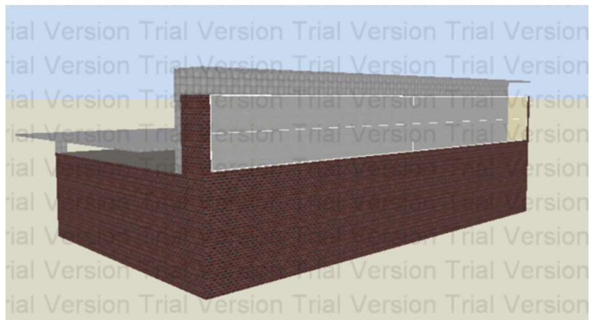


Figure 3: Solar Chimney Scenario

Results and discussion

Figure 4 shows the zone radiant and air temperature CFD slice (Across elevation) for the base scenario. The air temperature in the case of the base case scenario is fairly constant around 31°C. There is a slight variation in the radiant temperature from various surfaces. Windows have slightly higher radiant temperatures than compared walls, floors, and ceiling surfaces.

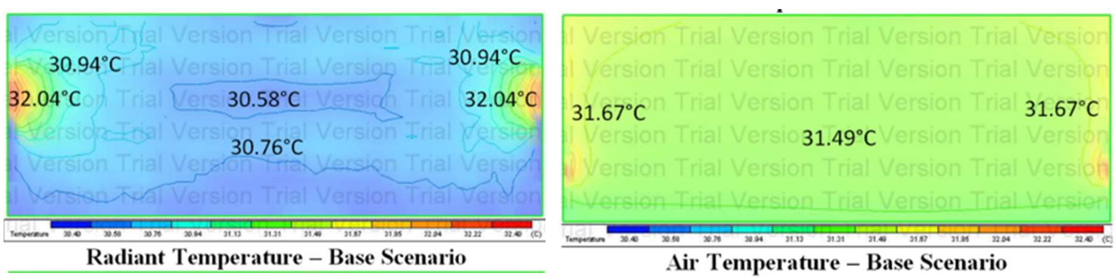


Figure 4: CFD slices (elevation) showing the radiant and air temperature of the base scenario.

In the Solar chimney Scenario (Figure 5) the air temperature is fairly constant at around 32°C in the assembly building zone whereas the air temperature in the solar chimney cavity is higher by about 1°C. There is a slight variation in the radiant temperature from various surfaces. Windows have slightly higher radiant temperatures than compared with walls, floors, and ceiling surfaces. The radiant temperature of the solar chimney is higher as compared to the assembly building zone by about 1°C.

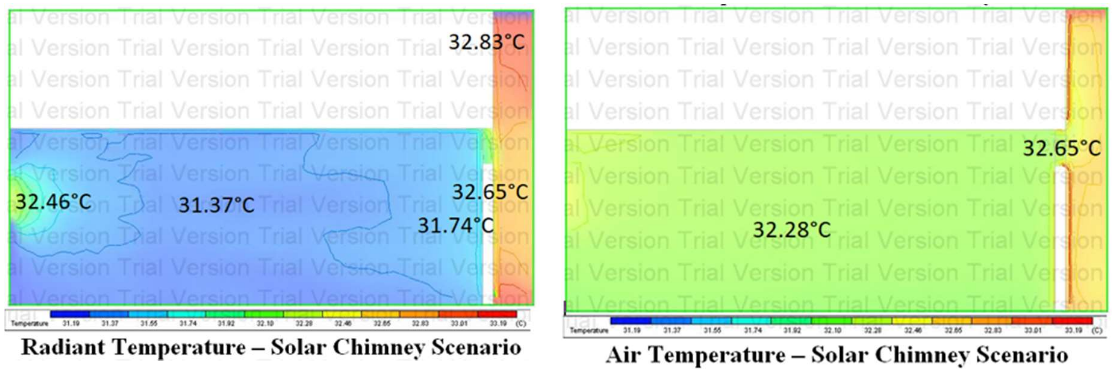


Figure 5: CFD slices (elevation) showing the radiant and air temperature of the Solar Chimney scenario.

Figure 6 shows the velocity distribution across the zone elevation for the two cases with and without a solar chimney. For the base case scenario, the velocity vectors at and around the window elevation are slightly higher than that of the rest of the room in the range of 0.11-0.13 m/s. At the center of the room, the velocity is nearly approaching 0 suggesting no air movement. For the Solar Chimney Scenario, the velocity vector shows flow from the window towards the inlet of the solar chimney. The velocity is also higher near the outlet of the solar chimney. There is the movement of air from the inlet at the north side window towards the outlet vent on the south side of the room which eventually moves out of the building through the vent placed above the solar chimney.

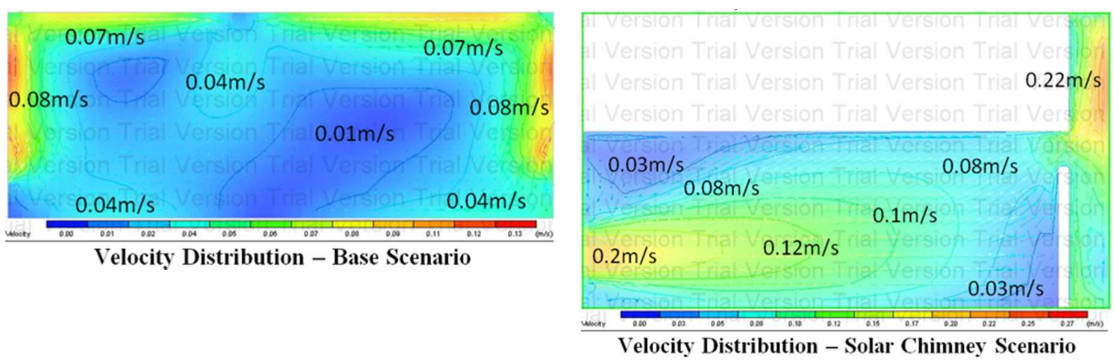


Figure 6: CFD slices (elevation) showing velocity distribution of base and solar chimney scenario

Figure 7 shows the pressure distribution across the zone elevation for the two cases with and without a solar chimney. For the base scenario, there is linear pressure distribution across the zone elevation higher positive value (around 0.7 Pa) at the ceiling level and a lower negative value (0.82 Pa) at the floor. In the Solar chimney Scenario, the velocity vectors at and around the window elevation are slightly higher. There is linear pressure distribution across the zone elevation higher positive value (around 1 Pa) at the ceiling level and a lower negative value (0.94 Pa) at the floor level. The pressure gradient follows a similar pattern in the solar chimney as well, with a higher positive value (around 2 Pa) at the top and a lower negative value (0.94 Pa) at the floor level.

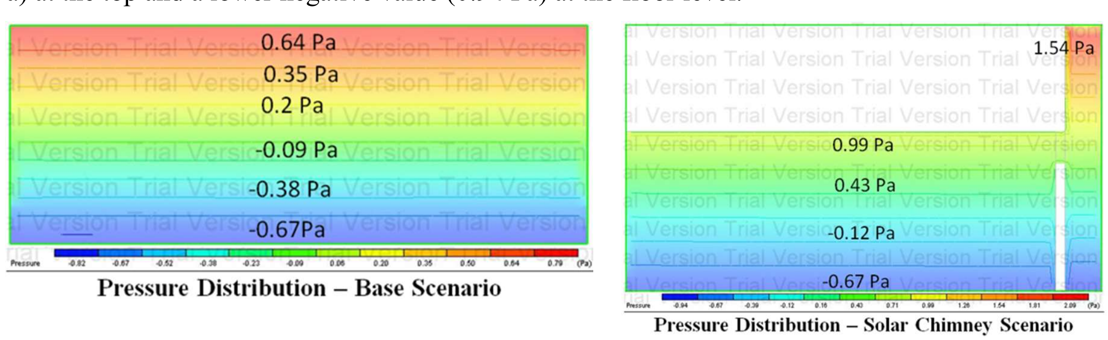
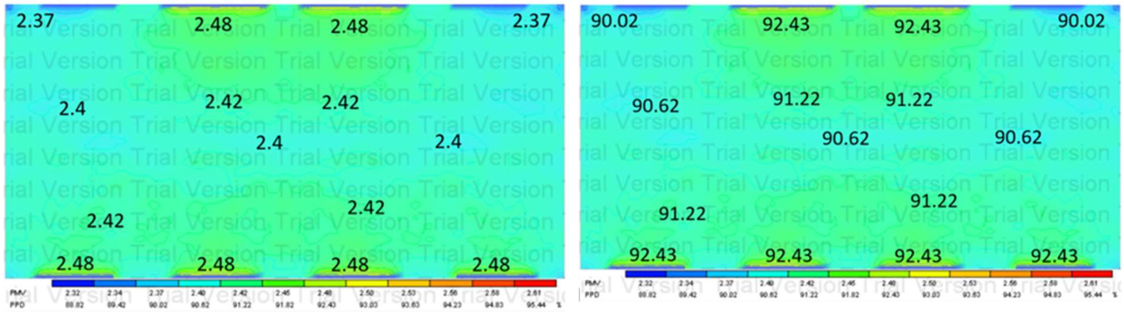


Figure 7: CFD slices (elevation) showing the pressure distribution for the base and Solar Chimney scenario

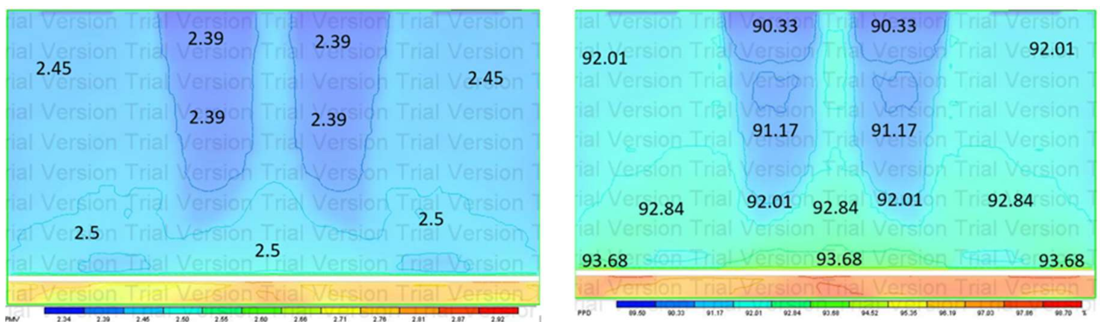
Figure 8 shows the PPD and PMV distribution for the base scenario. For the base case scenario the Percent of people dissatisfied with the thermal condition of the zone ranges from 90-92.5 percent i.e. majority number of people are dissatisfied with the comfort of the zone. The Predicted mean vote ranges from 2.4-to 2.48 i.e. most people feel the zone to be slightly warm to hot.



a PMV - Base Scenario b PPD - Base Scenario

Figure 8: CFD slices (plan) showing PPD and PMV for Base Scenario

Figure 9 shows the PPD and PMV distribution for the solar Chimney scenario. In the Solar chimney scenario, the Percent of people dissatisfied in the zone ranges from 89-to 99 percent i.e. nearly all the people are dissatisfied with the comfort of the zone. The Predicted mean vote ranges from 2.34-to 2.92 i.e. most people feel the zone to be warm to hot.



a PMV - Solar Chimney Scenario b PPD - Solar Chimney Scenario

Figure 9: CFD slices (Plan)) showing the PPD and PMV distribution of the Solar chimney scenario

Conclusion

Internal CFD analysis can be effectively used to predict the internal condition of a building. The performance of a Solar Chimney can be measured either or wholly in terms of air movement/airflow, temperature and velocity distribution, and also thermal comfort parameters like PPD and PMV. The findings show that the internal air temperature in the case of the solar chimney scenario is slightly higher by about 1°C than compared with the base scenario. The airflow in the case of the base scenario is due to cross-ventilation, and it was observed that airflow occurred only near the openings and most of the interior space had stagnant air with no air movement. In contrast, the airflow improved significantly with the incorporation of the solar chimney as there was no stagnant air and the air moved from the windows flowed through the room and escaped from the vents of the solar chimney. The Thermal performance results however showed that the thermal condition deteriorated with the incorporation of the solar chimney; although larger airflow occurred, the temperature of external air was above the thermal comfort region causing discomfort.

In summary, although the airflow is improved with the incorporation of the solar chimney, the cooling aspect does not improve. The comfort aspect is not only related to a single parameter like the airflow, temperature, and pressure differential but a combination of these. The design of a solar chimney should not only focus to improve a single aspect but a combination of the entire parameters for overall comfort.

Further studies are required to determine the optimum construction details for the specific climatic condition of Birgunj. The potential of pre-cooling of air with other passive technologies is also a matter for further studies to improve the thermal comfort aspect by using a solar chimney.

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