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Solar Chimney for Enhanced Stack Ventilation, a Case of e-Bike Prototype Assembly Building in Birgunj, Nepal

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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 however show that with the incorporation of solar chimney the Percent of people dissatisfied with thermal condition of the building increases from 56 percent to 92 percent. Although the study shows that the solar chimney can effectively work to enhance the stack effect, the comfort ventilation aspect shows no improvement.

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

1. 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 former is dependent on the mercy of wind while the latter can be used independent of site wind conditions.

Studies show that the wind driven cross ventilation is superior force to buoyancy driven stack ventilation causing airflow inside a building [1] , therefore more designers are inclined towards cross ventilation strategies to induce airflow in a building [2]. But there are certain limits of wind driven ventilation like presence of wind capable of inducing airflow, denser built environment leading to stagnant air, therefore enhanced stack ventilation by use of devices like 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 [3].

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 [4].

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 [5].

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 [6]. CFD can help architects and engineers to relate the design to respond to the site microclimate by over viewing 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 climatic condition of Birgunj.

2. Methodology

The study is quantitative, based on positivist approach. To arrive at the objective of the research, the works are planned based on three main parts: study of relevant literature, 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 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 similar field of study have been carried out that helps 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 researches have employed, this helps in choosing appropriate methods most relevant for the study.

Another part of research is the study of climate of Birgunj. The EPW format weather data for Birgunj collected from 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 literatures along with the climatic study of Birgunj will be used for modeling of Solar Chimney for the analysis.

3. Literature Review

Most of the research works on solar chimney studies have followed three approaches and/or 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 full scale model or small reduced scale model. Numerical Modeling Studies increased with 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 analysis of solar chimney. In analytical studies mathematical models are developed for the prediction of the solar chimneys' performance. Experiments are usually performed, in order to validate the models [7].

Bansal et al. [8] developed steady state mathematical model for a solar chimney and studied effect of solar radiation, opening size and ambient temp on airflow rate. Bouchair [9] studied ventilation induced due to cavity on a full scale model under steady sate condition. Solar chimney significantly increases the ventilation rate as compared to conventional chimney [10]. The possibility of reducing heat gain in a house by incorporation of solar chimney was experimentally investigated by Khedari et al [11]. The effect of variable chimney dimensions, solar chimney heat flux and inclination angle on airflow rate was investigated by Chen et al. [12] on an experimental solar chimney model. Ong and Chow [13] experimentally verified mathematical model of solar chimney proposed to predict the performance under varying ambient and geometrical features. Air flow rate due to lightweight construction and thermal mass construction on solar chimney was experimentally studied by Charvat et al. [14]. Mathur et al. [15] conducted experimental investigation on nine different configurations of solar chimney dimensions. Nugroho et al. [16] found that air ventilation is induced by solar chimney in a terrace house. Gontikaki et al. [7] identified SC dimentions and material properties as influencial parameters on performace of SC. Tan and Wong [17] investigated effect of solar chimney parameters on interior air temperature and air speed and found SC width as the most significant factor. Lal et al. [18] conduted experimental investigation o f SC for the climatic condition of Kota city in India, and recorded ACH satisfying BIS requirements. Mahdavinejad et al. [19] 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 [20]. Nugroho and Ahmad [21] 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 passive cooling technique of indoor cooling assisted by solar chimney and green vertical landscape was integrated into the building. Chung, et al. [22] 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 [23] demonstrated solar chimney using FLUENT software. Mekkawi and Elgendy [24] studied effect of introducing a solar chimney on thermal performance in prototype residential building in Alexandria, Egypt. Nakielska and Pawłowski [25] analyzed the impact of solar chimneys on the thermal comfort of rooms based on experimental studies on solar chimney located in Poland. Godoy-Vaca, et al. [26] studied the performance of SC for different climates of Ecuador. Baxevanou and Fidaros [27] developed a CFD model for the examination of natural ventilation in a two store building with a solar chimney. Dietrich [28] 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 [29] analyzed various parameters of Solar Chimney by developing a mathematical model. Cheng, et al. [30] explored application of solar chimney for smoke exhaustion which otherwise is primarily utilized for natural ventilation. Suhendri, et al. [31] investigated the potential of the buoyancy-driven ventilation strategy to the hot and humid climate employing Computational Fluid Dynamics. Danesh [32] simulated the effect of solar chimney on heating load of building using DesignBuilder software. Prima and Prima [33] pointed out the potential use of passive ventilation using a wind catcher and the solar chimney to solve thermal problems. Salehi, et al. [34] 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. [35] investigated design of solar chimney considering both energy-saving and fire safety. Sakhri, et al. [36] 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.

4. Case Study Simulation

4.1 Birgunj Climate Study

4.1.1 Data Source

The weather data for Birgunj has been derived from the website http://climate.onebuilding.org. [37]. The meteorological files here are derived from ISD (US NOAA's Integrated Surface Database) with hourly data through 2018 using the TMY/ISO 15927-4:2005 methodologies. ISD individual year files are created using the general principles from the IWEC (International Weather for Energy Calculations). Climate Consultant, a graphic-based computer program is used to visualize, understand and study various climatic factors. The annual TMY 8760 hour EPW format climate data is fed into the Climate Consultant software to generate charts and graphs for the climatic study.

4.1.2 Climate Condition

The climatic condition of Birgunj (Koppen climate Classification Cwa) is sub-tropical monsoon with a very hot and humid summer. The mean annual temperature ranges from 23.8 to 24.5°C. The annual rainfall ranges from about 1,300 to 2,800 mm with an average of 1,800 mm. Majority of the precipitation occurs during June, July, August and September [38].

4.2 Prototype Description

The building considered for this study is e-Bike Assembly Building. The Built up area of the assembly block is 312.5 sqm. As shown in Figure 1, the plan has a rectangular form having aspect ratio of 1:2. The building is oriented with its longer axis along East-West direction. The Building is an open floor plan and is divided into various zones as shown in Figure . The inventory space is for storing of parts, assembly line is where the bike is assembled, holding cell where assembled e-Bike is kept before dispatching to warehouse. The Building has a blank façade on East and West. The southern Façade has window with WWR 40 percent. There are two 9 sqm. 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.

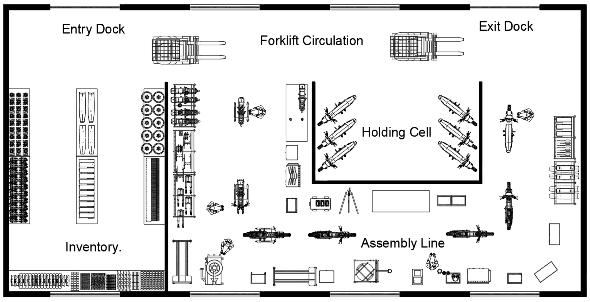

Figure 1: Floor Plan of e-Bike Assembly Building

4.2.1 DesignBuilder Settings

Out of the two general approaches to natural ventilation modeling in DesignBuilder, Calculated module is used instead of Scheduled module. In 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 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. This thermal simulation results is used to define the boundary condition for the internal CFD Analysis. CFD analysis is conducted for June 7, 12 noon.

4.2.2 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 bottom open aperture of 50 percent (only 50 percent of the entire window is open on the bottom).

Figure 2: Base Scenario Model without Solar Chimney

4.2.3 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 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. Inlet vent (21.974 sqm) for the solar chimney is placed on the south side internal wall (common wall between assembly building block and solar chimney block), outlet vent (12.34 sqm) is placed on the roof surface of the solar chimney block. The upper South side outer wall of solar chimney is made up of 6mm clear glazing, the interior is ” concrete wall with the inside surface exposed to sun on the south side painted black to absorb the solar radiation.

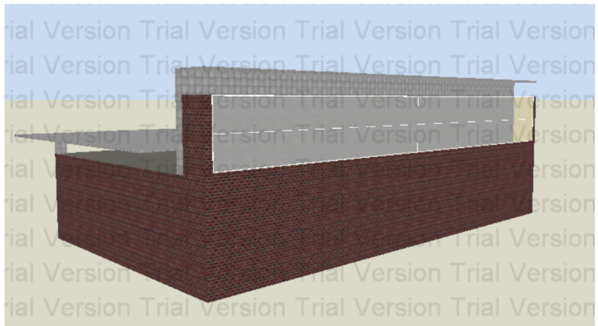

Figure 3: Solar Chimney Scenario

5. Results and Discussion

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

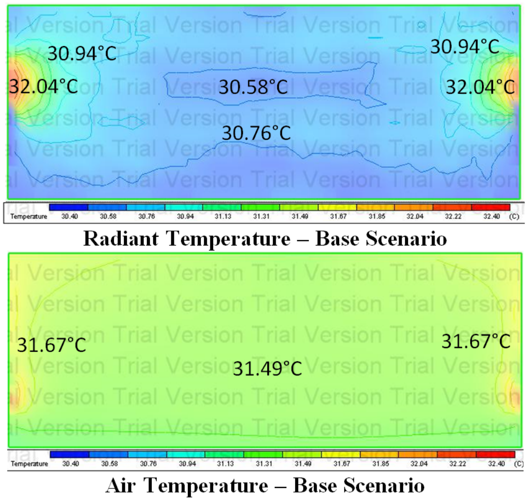

Figure 4: CFD slices (elevation) showing the radiant and air temperature of base scenario

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

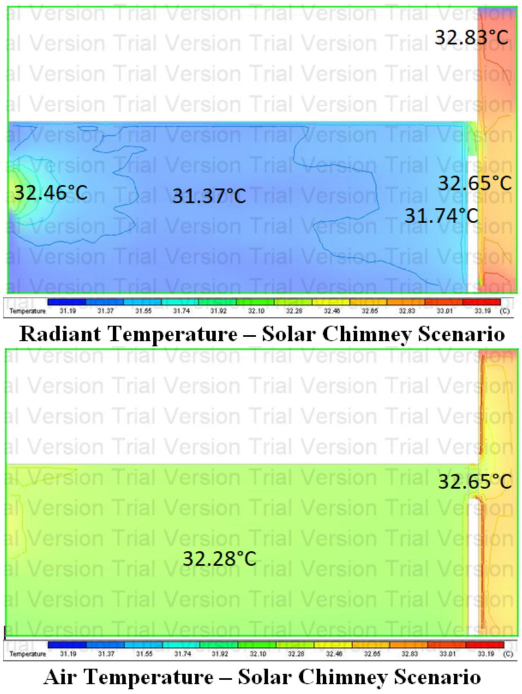

Figure 5: CFD slices (elevation) showing the radiant and air temperature of Solar Chimney scenario

Figure 6 shows the velocity distribution across the zone elevation for the two cases with and without solar chimney. For the base case scenario the velocity vectors at and around the window elevation is slightly higher than that of 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 window towards the inlet of solar chimney. The velocity is also higher near the outlet of solar chimney. There is movement of air from inlet at north side window towards outlet vent at south side of room which eventually moves out of the building through vent placed above solar chimney.

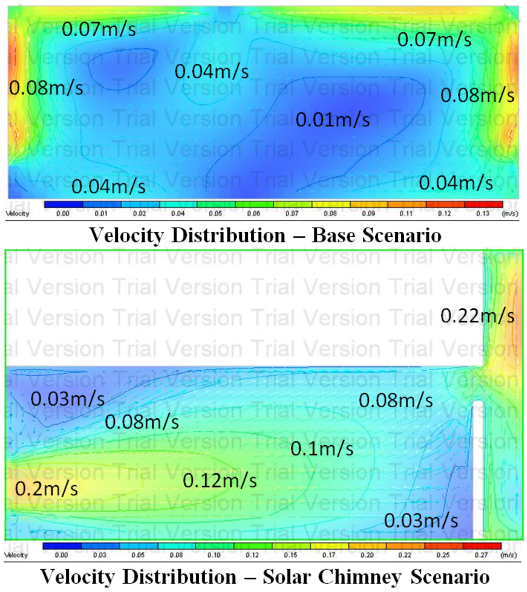

Figure 6: CFD slices (elevation) showing velocity distribution of base and solar chimney scenario

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

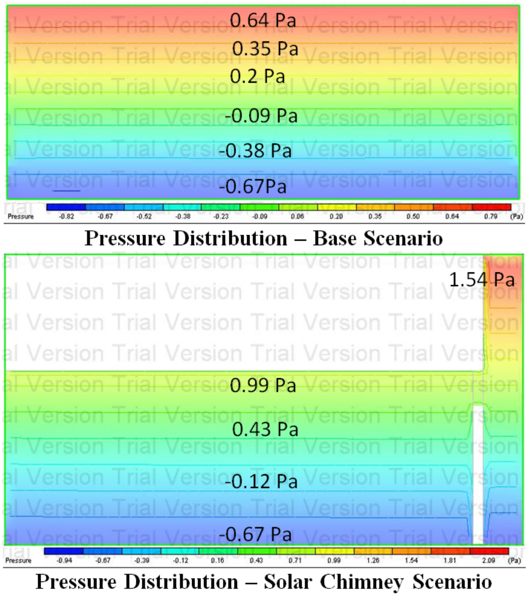

Figure 7: CFD slices (elevation) showing the pressure distribution for base and Solar Chimney scenario

Figure 8 shows the PPD and PMV distribution for base scenario. For the base case scenario the Percent of people dissatisfied with thermal condition of the zone ranges from 53-58 percent i.e. nearly more than half the number of people is dissatisfied with the comfort of the zone. The Predicted mean vote ranges from 1.5-1.6 i.e. most people feel the zone to be slightly warm to warm.

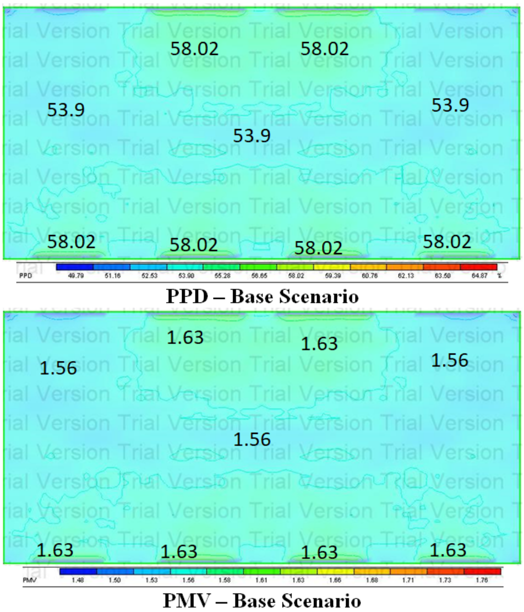

Figure 8: CFD slices (plan) showing PPD and PMV for Base Scenario

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

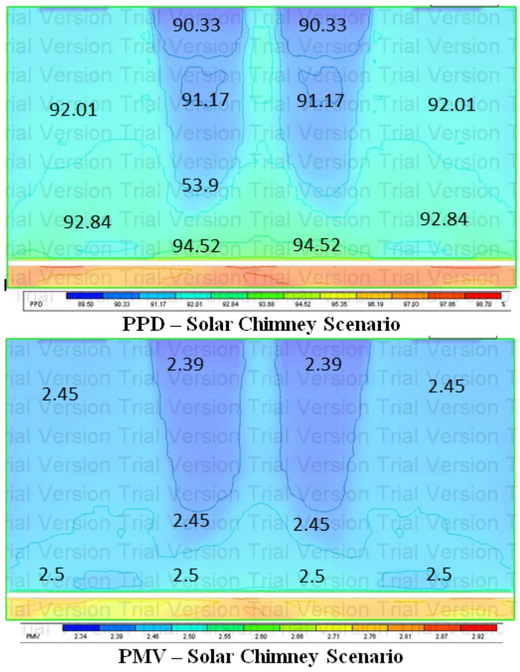

Figure 9: CFD slices (plan) showing tshowing PPD and PMV for Solar Chimney scenario

6. Conclusions

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.

The findings show that the internal air temperature in case of solar chimney scenario is slightly higher by about 1°C, than compared with base scenario. The airflow in case of base scenario is basically 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 incorporation of solar chimney as there was no stagnant air and air moved from the windows flowed through the room and escaped from vents of solar chimney.

The Thermal performance results however showed that the thermal condition deteriorated with the incorporation of solar chimney; although larger airflow occurred, the temperature of external air was above thermal comfort region causing discomfort.

In summary, although the airflow is improved with incorporation of solar chimney, the cooling aspect does not improve.

Further studies are required to determine the optimum construction details for 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 solar chimney. Paragraphs within a document can be separated just by leaving one blank line between them.

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