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Improving Performance Driven Air Ventilation Through Solar Chimney: An Investigation of Various Room Layouts to Achieve Cooling in Hot Semi-Arid Climate

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Abstract- Solar Chimneys attached to walls with a certain volume of space behave as a ventilation tool and increase the comfortable conditions of the adjacent rooms. The airflow rate increases with the increased internal air buoyancy force inside the Solar Chimney. The studies done so far evaluated the configuration of Solar Chimneys but ignored the impact of the layout of the room including sizes of openings, their placement in walls, etc. on the working of Solar Chimney to improve ventilation rate. In this study, the impact of room layout (with the windows in the room) on the performance of solar chimneys is studied. This study seeks to investigate the effect of sizes and placement of windows rather than the dimensions of a room on the performance of a Solar Chimney. The research is carried out using the dynamic method of calculation to study the air flow rate. The model of a single-story room of 28 cubic meters in volume is analyzed using computer simulations. The tool used is the CFD-based computer software ANSYS FLUENT to enhance natural ventilation through window size and location modification and to predict the significant flow pattern in the space connected to the solar chimney. Room size (e.g. length, width, height, etc.) is noted to impact very little the airflow of the inlet. The results showed the best optimization of the solar chimney by achieving a rate of airflow of 0.25 m/s as per ASHRAE Standard 55 specifications.

Keywords- Air Flow, Air Ventilation, Computational Fluid Dynamics (CFD), Environmental Sustainability, Room Fenestration, Solar Chimney,

I. INTRODUCTION

Climate Change is the phenomenon that is the most talked about topic in this century. [1]. The basis of this climate change can be linked to the excessive use of energy in all sectors of life. Energy is significant as it is important to perform daily activities on Earth. This use of energy is exacerbated when it causes the depletion of valuable natural resources along with environmental degradation. [2]. All the above factors contributed to the rising temperature of our planet. The building sector contributes to 42% of yearly energy consumption at a global level. This energy is being utilized in buildings for heating, cooling, lighting, etc. [1]. In the building sector, high-rise buildings, specifically have evolved with entirely glazed facades and deeper plans with the advancement of technology. This has led to increased reliance on conventional HVAC systems which causes adverse impacts on the environment including Urban Heat Island Effect. The ultimate solution is to incorporate efficient design strategies that can naturally provide heating, cooling, and light to buildings and can reduce the reliance on conventional HVAC systems. [3-4]. The researchers have also emphasized the use of renewable energy resources in the second half of the 20^{th} century. In hot climates, buildings need energy for cooling to create a comfortable environment inside. As energy is expensive, Architects and Designers as well as researchers are seeking ways to cool the buildings in natural ways. [5]. So passive cooling is the need of the time.

Passive cooling is the second tier according to a 3-tier approach to cooling buildings. (See Figure 1)

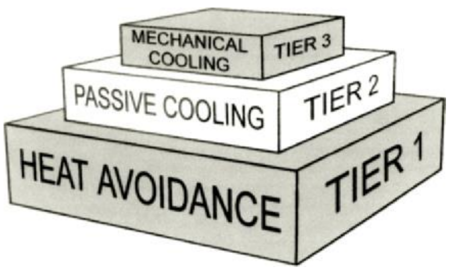

Figure 1: Sustainable cooling is achieved by the three-tier design approach Source: [6]

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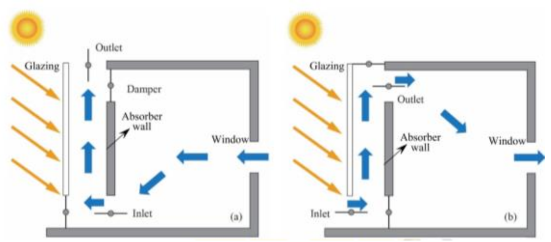
Passive cooling utilizes either air motion to raise the comfort zone or lower the temperatures inside the spaces. [6] In this context, buildings have utilized solar chimneys at a large scale as an effective passive renewable energy system to address serious environmental constraints and issues like global warming, energy crisis, etc. [7].

1.1 Solar Chimney

A Solar Chimney attached to a room acts as a solar air heater which can be installed with a wall or a roof. A typical Solar Chimney consists of an absorption wall attached to the space and a glazing wall with a cavity in between. The absorption wall is for heat absorption and glazing is for solar penetration. The working principle of Solar Chimney depends on the thermal buoyancy effect of air. This causes the air entering the chimney to rise because of the hot glazed wall of the chimney due to incident solar radiation. The natural ventilation inside a space is improved in this way either by removing excess heated air (cooling mode) or carrying in hot air (heating mode). In this way, the installation of a Solar chimney with a space or room lowers the amount of conventional energy required and associated greenhouse gas emissions, making the Solar chimney a passive strategy. The dampers control the heating and cooling modes. (See Figure-2)[8]



(a) (b)

Figure 2: Typical Solar Chimney attached with wall (a) Cooling mode (b) Heating Mode

1.2 Literature Review

Various research has been done so far to study the effect of solar chimneys on enhancing air ventilation under heating and cooling modes.

Khanal & Lei reviewed the literature to investigate the improvement of natural ventilation inside the space due to the application of Solar chimneys. The research drew the inference that the potential of solar chimneys as a passive cooling system for cooling over mechanical systems of cooling is not fully understood yet. [9]

Hweij inquired about the effectiveness of a solar chimney in a novel-designed system in the Arid climate of Riyadh. The novel system i.e. evaporatively cooled window comprised of an air cooler, window, and solar chimney stacked on one another and is closed to enhance the buoyancy effect of air to promote ventilation. This novel system is attached to external facades in an office space to promote thermal comfort at lower energy consumption. Results reported 10% energy savings at readings taken at 2 representative hours. [10]

Shi investigated the factors that determine the efficacy of a solar chimney to its fullest potential. The objective of the study is to generate the guidelines for design and construction of solar chimneys as a passive strategy attached directly to the space. The study reviewed the existing literature and research on solar chimneys and highlighted the fundamental concepts of the designing of solar chimneys. The study provided optimum values for modeling a solar chimney. The review provided 13 key factors that influence the performance of solar chimneys, categorized into 4 groups, which include configuration, installation, material, and external environment. The analyzed literature was concluded to have an ideal chimney with a gap as a cavity of 0.2–0.3 m, an inlet and outlet of equal size, a ratio of height/gap of about 10, an inclination angle of 45–60° (for a roof solar chimney considering latitude), an optimized opening with double or triple glazing in a room, a 5 cm thick insulation wall, and a solar absorber with larger absorptivity and emissivity. [7]

Hong studied the impact of a solar chimney in a double-storey detached house with an area of 220m2 in the hot and cold climate of China using the dynamic method of calculation. The study used Energy Plus as a tool to carry out simulations. The study evaluates a comparison of heating and cooling loads generated during 2 scenarios, a base case without the application of a solar chimney and a scenario with the installation of a solar chimney. The results indicated a higher ventilation rate with solar chimney application as compared to the base case. It is also concluded that the higher ventilation rates need to be controlled at some times of the year with the application of base case. [11]

Salehi, found that climate is an important factor that determines the most desirable period for the working of a Solar Chimney. The suitability of 4 different climates for the Solar Chimney to function to create thermal comfort is investigated. A thermosyphon model was established and then further substantiated contrary to published and experimental measurements from previous works. Thermal simulations of a residential building are carried out using the EnergyPlus software. The study inferred that Solar chimneys show different airflow characteristics and temperature distributions according to the climatic conditions.[12]

Fang investigated the sizes of the openings of Solar Chimney (air inlet and outlet) installed with a wall. The study was carried out intending to determine the optimized sizes of air inlet and outlet to make the solar chimney work to its full potential. Different S values (ratio of the inlet and outlet cross-sectional area) were used to develop six physical models of solar chimneys. These models are then analyzed concerning internal air velocity and temperature distribution. Ansys Fluent software is used as a simulation tool. The study concluded that the formation of a local vortex occurred in the airflow of a solar chimney if the value of S> 100% and also caused the secondary return flow of air. However, the airflow of wall wall-mounted chimney did not form vortices if S <80%. [13]

Wang investigated the performance of solar chimneys under the influence on external environment factors like solar radiation and wind velocity by studying the fluid characteristics using numerical equations. The numerical findings are validated, then through experimental testing and results have been generated. The findings proved that performance of the solar chimneys was not affected noticeably under the influence of strong solar incident radiation and showed a noticeable change under the external wind speed. The performance enhanced with low external speed and decreased due to high external wind speed. High external wind speed is concluded to dominate the performance of solar chimney negatively. [14]

The research conducted so far tends to focus more on the geometric configuration of solar chimneys including height of shaft, height-to-gap ratio, cavity width, inclination angle of glazing, installation with wall or roof and materials, etc. The potential of a solar chimney concerning space configuration including sizes of inlets in the room as well as their positions and number of openings is not understood till now.

This research is focused on exploring the sizes of openings (inlets), number of inlets (one, two), and their position in the wall to have an impact on enhancing the natural ventilation using the buoyancy effect of air. The effectiveness of a chimney is measured in terms of speed and temperature of air..

The study will explore the potential months of the year with their specific air velocities to induce during which the chimney will perform at its peak.

II. METHODOLOGY

This research is based on quantitative analysis and is framed under the applied research. The specific objectives are achieved using the dynamic method of calculation employing computer simulation. The tool used to carry out the research is software used for conducting CFD analysis to study the airflow named Ansys Fluent. The tool is suitable for studying fluid flow in all aspects. A framework of research is presented in Figure 1. The CFD simulation is based on four steps: geometry development, mesh generation, putting boundary conditions, and simulation in Ansys Fluent software till convergence. A brief detail of the model developed in software is given below.

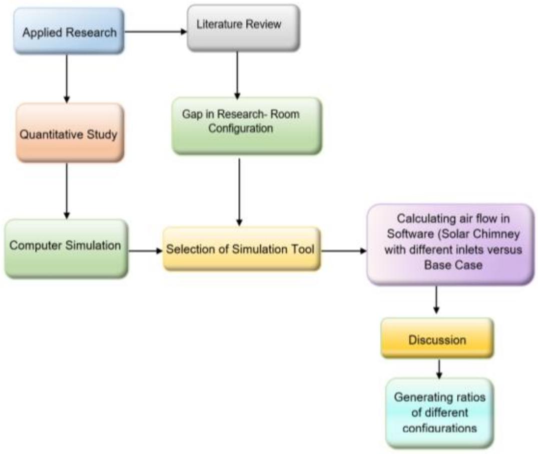


Figure 3: Framework of Study

2.1 Study Region

The geographical region selected for conducting this research is the city of Lahore, Pakistan, whose geographical coordinates are between 31°-15′ and 31°-43′ north latitude and between 74°-10′ and 74°-39′ east longitude. The extremely hot months are May, June & July with a mean maximum temperature of up to 40ºC and extreme cold months are December, January, and February with a mean minimum temperature of up to 5ºC.[15].

Figure 2 shows the monthly diurnal ranges of Lahore. This shows that the months suitable for natural ventilation are March, April, September, and October respectively.

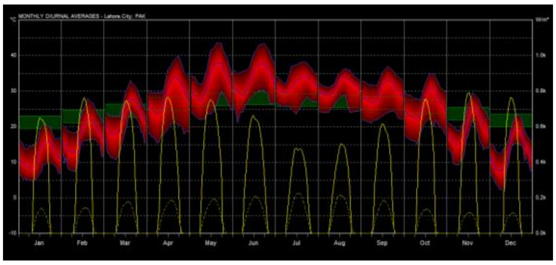


Figure 4: Monthly Diurnal Ranges of Lahore
Source: Authors

2.2 Study Model

A two-dimensional model is created with different window configurations to study the efficacy of Solar Chimneys in the specific climate conditions mentioned in section 2.1. The physical model consists of a single-room structure with dimensions of 3 meter by 3 meter with a solar chimney attached to the wall. The height of the room is 3 meter. One room has a solar chimney of 3 meter height and one room has a solar chimney with a greater height than the room i.e 4.2 meter. Furthermore, the exposed side of the Solar Chimney is of glass cover which consists of double-glazed glass type (due to its high performance characteristics). The Location is in Defence, city of Lahore Pakistan. The height above sea level is 236 m. The room structure consists of, 9 inches thick brick walls with no insulation. The direct solar radiation incident on the solar chimney was evaluated for 15th April at a time between 14.00h and 16.00h. The room has no furniture to ensure a minimal thermal exchange between objects. The windows of the room face towards the East and the chimney towards the west.

Small-scale rooms are attached to two different chimney models as shown in Figure 5. Other than that 3 physical models of different aperture heights and widths were developed to study the velocity at the outlet of the solar chimney. In order to assess thoroughly the impact of different parameters on thermal comfort indicators, a comparison is made between the airflow rate (m/s 2) of different configurations. Integration of solar chimney with the single room structure in the following two ways are modeled for simulations.

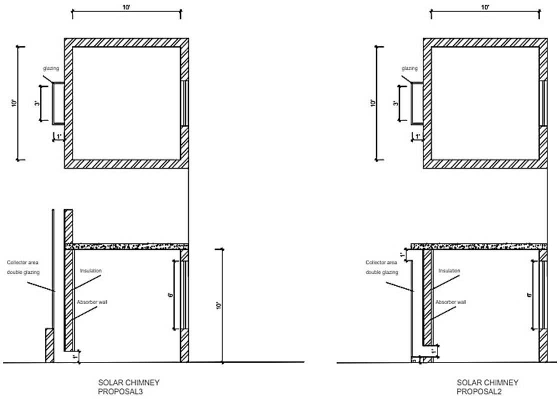
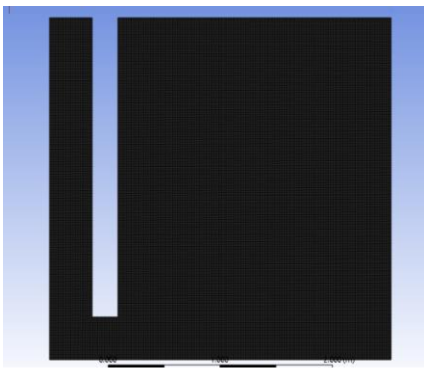


Figure 5: Model Design of 2 different chimneys attached to a wall of small scaled room

2.3 Meshing of the Physical Model

The standard and authenticity of analysis and results are highly dependent upon the characteristic features of the mesh created in the software. In this context the flow solver is inconsiderate. The body-fitted technique is most suitable and is applied by stretching and twisting the block to create the mesh. First mesh is generated then it is refined by the mesh control option to refine the simulated results. The mesh is well-defined and uniform throughout the surface. Mesh size is taken as 0.002 millimeters in this model to achieve the highest precision in simulation. (See Figure 6)



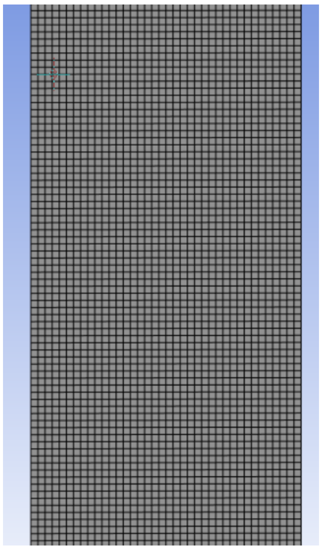


Figure 6: Mesh Sizing

2.4 Boundary Conditions

For this project, boundary conditions are as follows:

a. The turbulence model was selected in the software Ansys Fluent 2024 R1 to carry out the numerical simulation to achieve desirable objectives. In this domain, a realizable K-Epsilon model was used as a turbulence model in the software.

b. The gas in the solar chimney installed in the model with the wall is set to air.

c. The steady state is set for airflow, subjected to a gravity of 9.8 m/s2. The Boussinesq approximation is used to model the buoyancy of air in the software. It is due to the reason that natural convection occurs during a slight change in air temperature under the stack effect of Solar Chimney.

d. The simple geometry is employed by using the SIMPLE pressure-velocity coupling method to establish a computational model. Computational inlet and outlet are set as “pressure inlet and pressure outlet” respectively in the software. In this way computational model is created in the software.

e. Except for pressure inlet and outlet, the remaining surface boundaries act as fixed walls under no-slip conditions.

f. The walls of the interior are outside the computational model so to ignore the outer wall’s radiant heat loss consider them as adiabatic.

g. The absorber surface of the solar chimney is included by giving it a thermal Flux value.

h. It also ignores the viscous dissipation of air in the flow channel.

III. RESULTS & DISCUSSION

3.1 Influence of Height of Solar Chimney

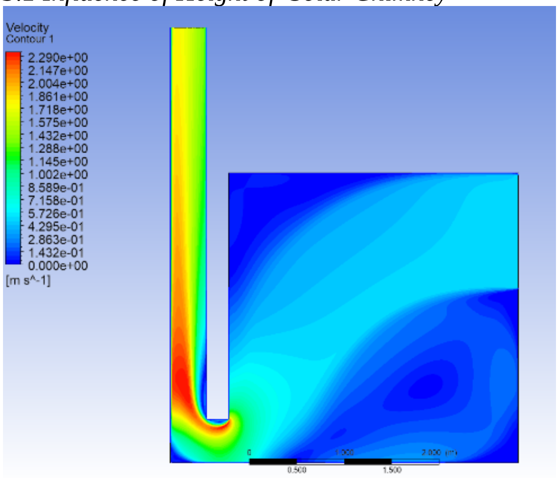


Figure 7. Model A1

The vertical height of the cavity of the Solar Chimney is referred to as the height of the Solar Chimney installed with the wall. The findings indicate that efficiency is improved by greater height of the Solar Chimney (4.2 meter). Various logics explain the phenomenon. The first reason is the difference in pressure which is created due to the height of the cavity of the Solar Chimney resulted in improving the rate of air ventilation. Excessive heat gain is the second reason.[9]. The velocity of air increases from 0.9 m/s to 2.3m/s when height is increased from 10ft to 15 ft. It is advisable to select the longest vertical length possible within the limits of building codes in the city of Lahore. The best performance of Solar Chimney is ensured in this way. Increased air speed is achieved in both the Solar Chimney as well as the interior of the room as shown in Figure 7.

3.2. Influence of configuration of windows

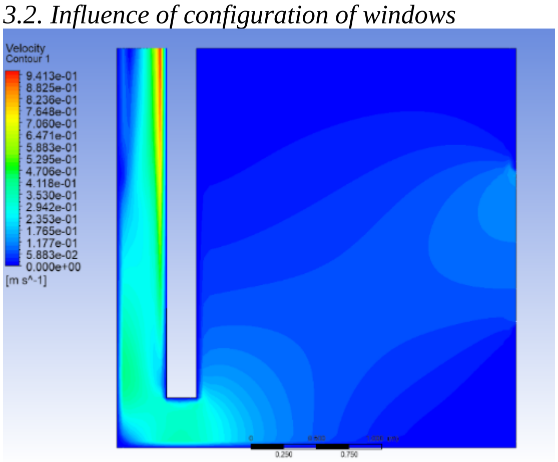


Figure 8. Model A2

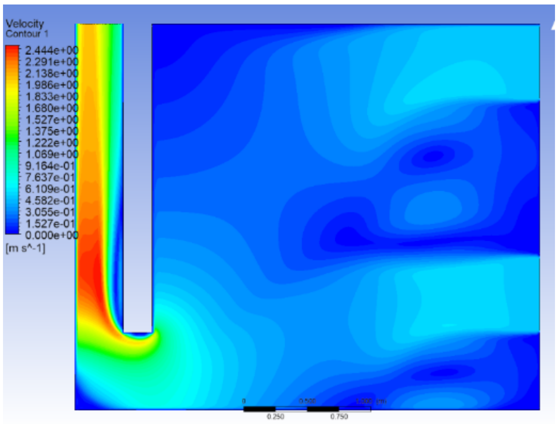


Figure 9. Model A3

To determine the influences of the placement and sizes of windows, maximum air velocities gained on 15th April at 12:00 pm are examined and compared at the ambient temperature. From the above simulations, it is seen that a maximum air speed of 2.444m/sec is achieved in model A 3, where the window area is split into two levels.

As the ideal range for most comfort scenarios is between 0.1 and 0.3 m/s according to ASHRE.[16]. The adjacent room in Model A3 receives the value of 0.3 m/s and airflow is distributed uniformly no voritces are formed in the room as in Model A1 and Model A2. (see Figures 8 & 9).

The aforementioned findings are based on the computer simulations of a single room with a Solar Chimney attached to a wall, which had a limited range of application. The configuration of the solar chimney's stack height is bounded by the height of the building (including the height of the roof), ranging from two stories to four stories giving a stack height of 10 ft to 40 ft.

The solar chimney's depth is bounded by 0.10 m and 0.90 m as depths lower than 0.1 meter give fairly low air speed according to published literature while depths higher than 0.90 m will be physically too large relative to the building so the depth is fixed as 3ft in all simulations.

Similarly width of the solar chimney is fixed as 1 foot in all computational models which is the ideal value taken from the previous literature. Several researchers note that the width will directly affect the volume flow rate and the interior airspeed.

The ideal inlet size should be the same as the width of the solar chimney so it is also taken as 1 feet obtained from published literature.

Double glazing is used in the solar chimney model as it can prevent downdraught (and thus reverse flow) and has also been found to increase the induced airflow rates up to 17%.

3.3. Limitation of Study

The behavior of solar chimneys for nocturnal ventilation in the climate of Lahore under the transitional season is not in the scope of this paper.

IV. CONCLUSION

Some background information on the many factors influencing the performance of SC systems as well as the physical mechanisms involved has been acquired thus far. Numerous research have examined the ability of SC systems to propel airflow and accomplish adequate passive ventilation in buildings, with positive results. However, the majority of this research presumed steady-state circumstances and involved single-room or single-zone buildings.This study targets the gap in current research regarding the best performance of Solar Chimneys and seeks to explore various possibilities. It focuses on the impact of shaft height and building opening positions on natural ventilation and flow rate (m/s). Since the climate is a determining factor in promoting natural ventilation, the climatic conditions of Lahore are first analyzed completely then comparisons of different models are studied for the better performance of solar chimneys simultaneously. That is how to improve its efficacy to cope with certain climatic conditions of Lahore.

Hot air rises under buoyancy, which causes the pressure inside the cavity to drop. According to the ideal gas law, the shaft's internal pressure drop is caused by the high temperature. Air from inside the room then enters the cavity through the intake due to the pressure differential. Concurrently, air from outside the room comes through the window, slowing the flow channel down a little bit. This whole phenomenon is simulated with the help of ANSYS Fluent Benchmark which helps find the options to improve ventilation rate and thermal Regulation through solar chimney. It has been studied by various models and was observed that a stand-alone solar chimney used in a single room and ideal climatic conditions could effectively provide indoor thermal regulation and enhanced ventilation rate. Some keyfindings are:

a) Solar Chimney is an efficient passive strategy for improving natural ventilation and ensuring thermal comfort in March, April & September, and October in the hot semi-arid climate of Lahore as explained in section 2.1.
b) Windows placement and its surface areas will impact the airflow. The area of the chimney's opening relative to the window opening is important for achieving ideal air exchange as shown in Model A2 and A3.

A well-designed solar chimney specially with suitable shaft height help speed up ventilation. Since the room is 3m high, a chimney that rises above the roofline (e.g., 4m to 6m) would create a temperature gradient sufficient to draw hot air upwards. Reference to Model A1 and A2.

There are several possible directions for future research on solar chimneys; like its effectiveness in various building types and climate particularly its ability to induce natural ventilation. Or work on ideal window-to-room size ratio for maximizing airflow in rooms using solar chimneys. Or further study an effective window size that is minimum or maximum for a certain temperature range.

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