CFD Analysis of Passive Cooling Building by Using Solar Chimney System

Naci Kalkan, Ihsan Dagtekin

***Abstract*—**This research presents the design and analysis of solar air-conditioning systems particularly solar chimney which is a passive strategy for natural ventilation, and demonstrates the structures of these systems' using Computational Fluid Dynamic (CFD) and finally compares the results with several examples, which have been studied experimentally and carried out previously. In order to improve the performance of solar chimney system, highly efficient sub-system components are considered for the design. The general purpose of the research is to understand how efficiently solar chimney systems generate cooling, and is to improve the efficient of such systems for integration with existing and future domestic buildings.

***Keywords*—**Solar cooling system, solar chimney, active and passive solar technologies, natural ventilation, cavity depth, CFD models for solar chimney.

I. Introduction

IN the globalization world, our energy demand is produced from sources primarily from fossil fuels (coal, oil and natural gas etc.) that are non-renewable and limited in supply and sources from alternative energy that are making progress such as solar energy, wind power and moving water. Some estimates claim that our crude oil and natural gas reserves will be depleted within next 50 years [1]; however, another problematic issue is the side effects of using fossil fuels that combustion of them is considered to be the number one factor for the release of greenhouse gases. Furthermore, population growth is another very important factor as it will almost reach nine billion people over the next 50 years. The world's energy demands will increase proportionately, energy shortage associated with environmental issues will be important for replacing fossil fuel energy production with renewable clean energy supply [1].

In recent years, solar energy for environmental control has received much more attention in the engineering fields as a result of the world energy shortage [1]. Particularly, summer air conditioning solar systems have been a growing market for both residential and commercial buildings. For example, the average annual daily temperature of the UK is expected to rise between 2°C and 4 °C by 2080. This is a period that population grows with the usage of domestic air-conditioning during summer while industrial usage reduced [2]. The reports on the demand for air-condition usage in Europe showed that air-conditioned floor space had increased from 30 million m^2 to over 150 million m^2 in within last 20 years [3].

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II. Active and Passive Solar Technologies

Solar heating and cooling technologies can be driven by solar thermal that utilize passive or active solar energy to collect solar radiation and transform the energy into usable form. Many facades designs applied for solar heating and cooling mechanisms through active and passive designs. The building envelope design is used for passive solar energy whereas the use of solar collector to heat a fluid provides active solar thermal.

A. Active Solar Cooling Technologies

Cooling systems based on thermal energy generally have solar energy as the most widely available heat source for solar thermal driven cooling applications where a low temperature (below 200°C) and/or cost efficient heat source is available. Industrial processes also produce waste heat that can be an alternative to the solar energy. On the market, four major solar thermal driven cooling systems are available with absorption, desiccant, ejector, and adsorption cooling systems. Furthermore, the Rankine power cycle for refrigeration can be driven by solar thermal energy to produce work output.

B. Passive Solar Air Heating and Natural Ventilation Systems

Passive solar air natural ventilation and heating systems have similar working process. Buoyancy effect, which is occurred due to the air density difference at the inlet and outlet, is the driving force for both systems. In order to capture or store the heat or produce air movement to provide ventilation for cooling impacts, flexible options are used for the facades. Some of important passive solar systems in the market are trombe wall, unglazed transpired solar facade, solar roof, and solar chimney.

1. Solar Chimney

A solar chimney is a natural passive system, which uses solar energy to generate buoyancy effect that drives airflow through the air channel. Solar chimney technique has widely utilized in passive solar energy drying of crops, fruits, wood or grains solar heating and cooling applications [4]-[6]. There are many studies about the solar chimney system in the literature. For example; Shuli Liu has worked on thermal performance of a solar chimney without and with phase change material experimentally [7]. Mehran Rabani et al. have studied empirical investigation of the cooling performance of a new designed Trombe wall in combination with Solar Chimney and water spraying system [8].

Solar chimney provides passive cooling when the temperature outside the chimney is lower than the indoor. However, for hot weather climate countries where the sky is frequently overcast, it operates as thermal insulation to reduce heat gain of the room. These modes are demonstrated in Fig. 1 [9].

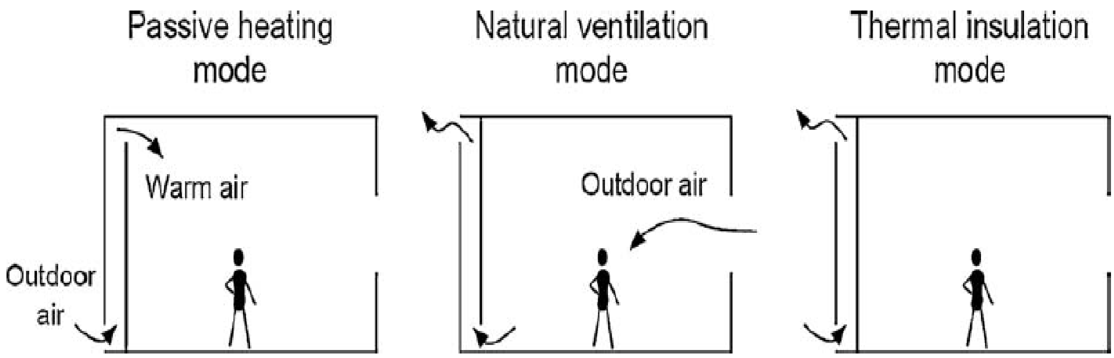

Fig. 1 Solar chimney operating modes [9]

III. Research Methods

In the tropic places, solar heat absorption for the buildings is much higher. Therefore, the high indoor air temperature causes thermal discomfort to the occupants. For this reason, the reduction of the heat transfer from roof to the occupied place is necessary to provide optimum indoor air temperature and bring thermal comfort to the occupants. In order to provide such thermal comfort to the occupants, solar chimney of passive cooling technology has been applied in this project. Basically, the solar chimney system used in this research consists of a surface (outer pane or glass cover) with glazing oriented towards the sun, a massive wall (inner wall with absorber at the inside) which may be a solid or liquid filled reservoir, an air channel (or cavity) in between, and air ventilation ports for inlet and outlet air (see Fig. 2).

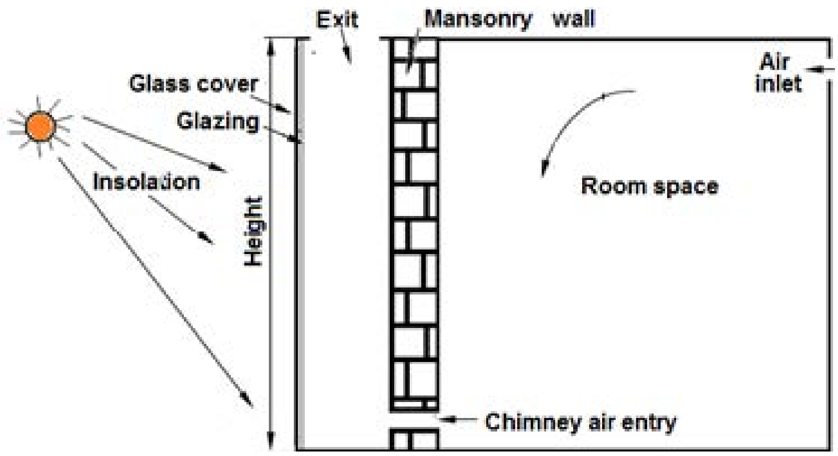

Fig. 2 Solar chimney used in building ventilation [10]

During the day time, the black-painted thermal storage wall absorbs the heat from sun radiation, to make the temperature in the chimney much higher than in other normal cavity space. The heat can strengthen the stack-effect and create an updraft of air in chimney. The updraft of air escapes from the upper chimney aperture and creates negative pressure in the shaft. That will help bottom aperture suck in inside cold air to keep convection in the chimney.

Fluid dynamics deals with the flow of fluids under various conditions governed by the physical laws. Fluid dynamics offers theoretical understanding of the wide range governing laws and the nature of fluids themselves, simulates the conditions by computational calculations. Computational Fluid Dynamics or CFD is the most popular one to solve and analyse the governing laws of fluid dynamics numerically. The complex sets of partial differential equations are solved on a mesh (or grid) which simplifies the process by dividing the geometrical domain into small volumes. CFD enables analysts to simulate and understand the world of fluid flows in new ways without the help of instruments for measuring various flow variables at desired locations.

This research determines the air-conditioning capability of the passive systems, solar chimney, and cooling cell in the hot climate places. Computational fluid dynamic (CFD) program is utilized for conventional roof solar chimney and verified the 3D numerical simulation with the transient turbulent regime because of

- CFD allows numerical simulation of fluid flows and the results are available for study even after the analysis is over.
- While conventional measuring instruments not always allow observation of flow properties without disturbing the flow itself, CFD makes it possible.
- CFD allows observation of flow properties even at non-accessible or pernicious locations (i.e. between turbine blades).
- CFD can be used numerical study of prototypes as a qualitative tool, and then Designers and analysts test experimentally.

IV. Result and Discussion

In this study, the first objective is the temperature difference (dT) average temperature of the inlet and outlet of the building (T) and outdoor temperature (To). The equation of natural ventilation shows that the larger temperature (T_1) is, the more stack vent airflow grade may be generated. On the one hand, according to the principle of stack effect ventilation, the fundamental driven force for stack effect is the temperature difference between indoor and outdoor. Therefore, when the outdoor temperature is steady, the larger the temperature difference is the stronger driven force may be generated. Here, ventilation efficiency is proportional to T or T_1.

Equation (1) - Estimated Natural Ventilation Flow Rate [11]:

$$Q_s = C_d A \sqrt{2 g H_d \frac{T_1 - T_0}{T_1}} \quad (1)$$

where: Qs = Stack vent airflow rate, m3/s; A = cross-sectional area of opening, m^2 C_d = Discharge coefficient for opening; g = gravitational acceleration, around 9.81 m/s^2 on Earth; H_d = Height from midpoint of lower opening to neutral pressure level (NPL), m; NPL = location/s is in the building envelope with no pressure difference between inside and outside [12]; T_1 = Average indoor temperature between inlet and outlet, K; T_o = Outdoor temperature, K.

According to the simulation results; from the velocity contour, in the cavity area, when cavity depth is 1', air is with relatively high velocity at the lower part of the cavity space but with low velocity at the upper part of the cavity. That means intense air movement mainly happens at the lower part of chimney skin and air cannot exhaust efficiently from top opening. An unobvious upstream air is formed during the cavity depth is 5' (Fig. 3).

When cavity depth is 3' the main upstream velocity was around 1.5 m/s that is an optimum velocity for natural ventilation. Therefore, velocity contour section further proves that best natural ventilation performance can be achieved when cavity depth is around 3'.

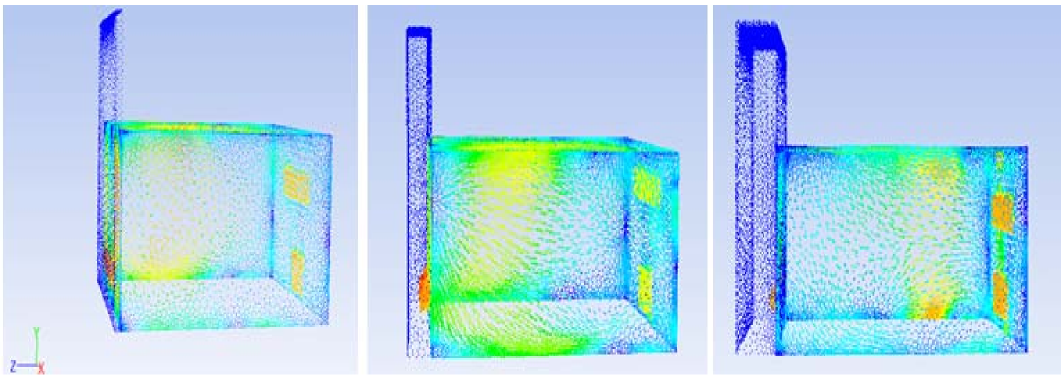

Fig. 3 Cavity depth 1 inch, 3 inch and 5 inch, respectively

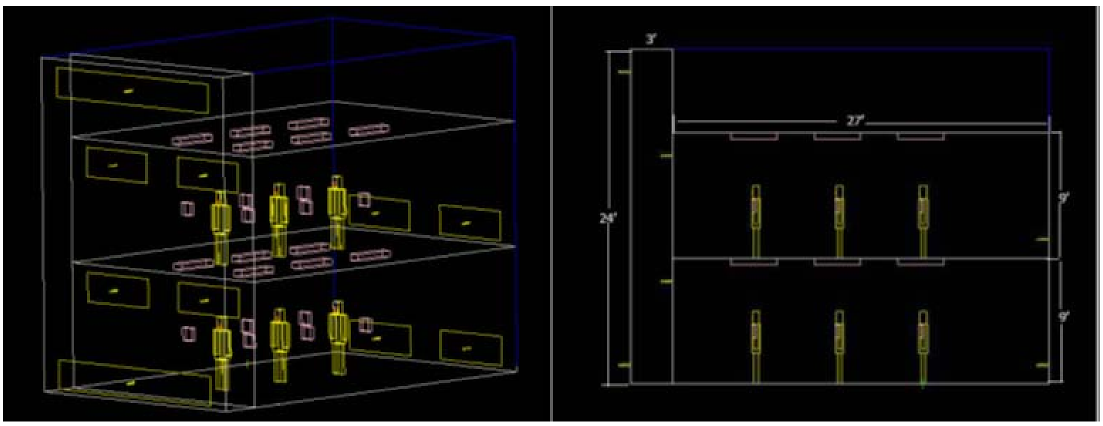

Fig. 4 Building Model in Airpak [13]

In comparison to a long-term monitoring study on natural ventilation for solar chimney building at available climate zone [13], this project has achieved nearly same results for each cavity depths. For instance, in this study average temperature for 1', 3', 4', 5' were measured 280 K, 291 K, 289 K, 285 K, respectively. The points were observed as 277 K, 290.2 K, 288 K, 285 K in validation research [13].

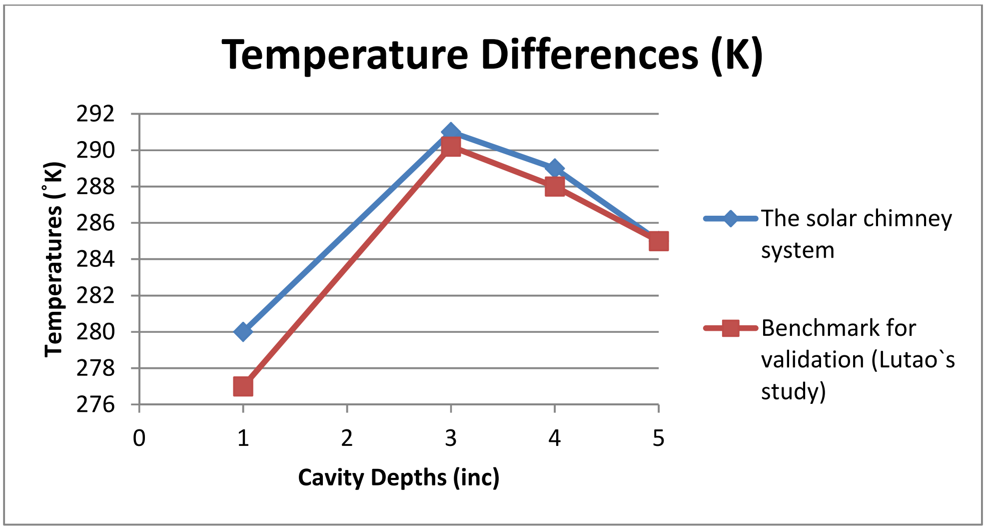

Fig. 5 Comparison of Temperature Differences for 4 different cavity depths

V. Conclusion

In general, this study figures out how a solar chimney works, solar direction and cavity depths affect the performance of solar chimney for natural ventilation and cooling of the building. Furthermore, the study provided to analyse the benefit of solar chimney application on the south facade through the numerical analysis in a building. In addition, computational fluid dynamics (CFD) simulations were conducted for the related numerical model. The 3D model was generated with CFD program which also provided to control wall temperatures in the application solar chimney as the boundary conditions.

Simulation results and validation demonstrated that main characteristics of test cases matched the basic principle of natural ventilation and proved that the building model was capable of simulating performance of the natural ventilation and cooling in solar chimney building.

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