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Passive Cooling of Building by using Solar Chimney

Insaf Mehani, N. Settou

Abstract**—**Natural ventilation is an important means to improve indoor thermal comfort and reduce the energy consumption. A solar chimney system is an enhancing natural draft device, which uses solar radiation to heat the air inside the chimney, thereby converting the thermal energy into kinetic energy. The present study considered some parameters such as chimney width and solar intensity, which were believed to have a significant effect on space ventilation. Fluent CFD software was used to predict buoyant air flow and flow rates in the cavities. The results were compared with available published experimental and theoretical data from the literature. There was an acceptable trend match between the present results and the published data for the room air change per hour, ACH. Further, it was noticed that the solar intensity has a more significant effect on ACH.

Keywords**—**Solar chimney, numerical simulation

I. Introduction

SAVING energy and sustainable development are two thems. In building constructions after the international energy crisis in 1973.

Energy required for heating and cooling of buildings in approximately 30% of the total world energy consumption. Natural ventilation and renewable energy utilization are widely used to improve the indoor air environment and reduce the energy consumption of air conditioning. The indoor environment for summer is normally obtained by air conditioning or ventilation including mechanical ventilation and natural ventilation. Natural ventilation not only can save energy and life cycle costs, but also can alleviate the environmental burden from the by-products by energy consumption.

The purpose of natural ventilation is to replace the air conditioning systems in certain regions, climates and seasons in the year. Modern society, compared with primitive society and places, is characterized by high civilization level and advanced accommodations, involving heating supply for the severe winter and air conditioning for hot summer. However, the comfort for this building fully depends on the running machines and equipments. Once the power is cut off deliberately or accidents occur, modern functions of building will totally disappear [1]. The annual summary report [2] of International Energy Agency (IEA) shows that for the well-insulated office buildings, a well-controlled and energy-efficient natural ventilation system can reduce more than 50% of energy equirement.

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Natural ventilation not only can overcome such problems as noises, sick building syndrome and complicated routine maintenance and high energy consumption, but can be easily integrated into green buildings which provide a healthier and comfortable environment.

Solar chimney as one of effective means to enhance natural ventilation has been noticed and utilized since it integrates solar energy and natural ventilation organically [3]. The solar chimney design and construction allow storing an amount of solar energy into a surface, then releasing this energy to an adjacent column of air raising its temperature, and accordingly it flows upward entraining an outdoor fresh air into the space.

This will create an air breeze inside the space. The main driving force in moving the air upward in the chimney is the buoyancy force due to the absorbed energy. Generally, solar energy with high intensity is available in the Mediterranean Sea countries. Algeria in particular, has rich sunny and clear skies. These conditions encourage adopting such a concept to enhance building natural ventilation and save energy.

II. Previous studies

The solar chimney is attractive idea for many researchers in different fields. Some previous studies have been seen in the literature that investigates the use of solar chimney, with different configurations, in ventilation improvement.

Some researchers have been interested in analyzing the vertical chimney, while others have been studying the inclined chimney. N.K Bansal, R.Mathur and M.S.Bhandari [4] were of the pioneers to study solar chimney configurations and performance. They developed a mathematical model to study the effect of using solar chimneys on thermally induced ventilation in buildings.

A Numerical solution of the proposed model revealed that the induced air flow ranged from 50-165 m^3/h for every square meter of the collector area and for solar radiation values of 100-1000 W/m^2 on the horizontal surface.

Further, that the induced air flow depends on the geometry of the air collector was found, cross-section of the duct, and the performance parameters of the air-heating solar collector such as bottom and top loss coefficients and absorptance and transmittance of the collector plate glazing. A theoretical and experimental study was carried out by J.Mathur, N.K Bansal, S.Mathur, M.Jain, and Anupma [5] to evaluate the possibility of making use of solar radiation to induce room ventilation in hot climates.

The theoretical results of the proposed model were in a good agreement with the experimental ones. It was concluded that air flow increased linearly with the increase in solar radiation or the air gap between absorber and the glass cover. Then, during night when the ambient temperature drops to about 20°C the flaps at the top were opened generating a draft through flats, cooling down the thermal masses of the ceiling and walls. J.Martri-Herreo and MR. Heras-Celemin [7] proposed a mathematical model to evaluate the energy performance of a 2 m high solar chimney with a 0.24 m concrete wall as a thermal storage. Real weather data for the Mediterranean was used as initial conditions for the model. The concrete wall reached its higher temperature 2 hours later than the ambient temperature. Also, it maintained its temperature well after the beginning of the dark, inducing night natural ventilation. They recommended further studies to be pursued on the thermal inertia of solar chimneys.

J. Mathur, S.Mathur, and Anupma [8] investigated the effect of using a solar chimney for enhancing natural ventilation. There was a trade off between the absorber inclination and stack height. Experiments showed that the optimum absorber inclination angle varies from 40° to 60°, depending on the latitude of the place. The experimental results were compared with the proposed mathematical model and a good agreement in between. An experimental investigation was carried out by S.A.M. Burek and A.Habib [9] to study the effect of varying the solar intensity, resembled by an electric heater, from 200 to 100 W/m², and the channel depth on mass flow rate through the channel. Temperatures and velocities were recorded and the mass flow rate was correlated to the heat input as $m \approx Q^{0.572}$ and to the channel depth as $m \approx S^{0.712}$. J.Mathur, Anupma, and S.Mathur [10] studied the performance of some types of solar chimneys. First an investigation of the performance a cylindrical chimney when it is covered with a transparent cover and when it is uncovered. It was found that the mass flow rate increases for the covered one. Then the effect of inclination on a solar chimney was studied, and concluded that an angle of 45° yields the highest rate of mass flow rate when compared with the vertical chimneys.

R. Bassiouny, S.Nader, and A.Koura [11] studied the effect of the chimney inlet size measured from the room floor, air gap between the glass and absorber on flow pattern and air velocity variation through the chimney. The results showed that the absorber average temperature could be correlated to the intensity as $T_W = 3.51I^{0.461}$ with an accepted range of approximation error. In addition the average air exit velocity was found to vary with the intensity as $V_{ex} = 0.013I^{0.4}$.

III. Methodology

A. Physical problem

The physical domain configuration considered in the present study is shown in Fig.1. This domain was considered a 1 m wide × 1 m height, assuming a one meter depth.

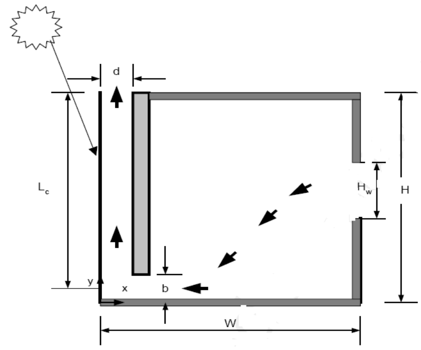

Fig. 1 A General Schematic of the Physical Domain

A solar chimney is a tall cavity, commonly positioned on the sunny side of a building. The air within the chimney is heated by solar radiation, giving rise to buoyancy forces, which drive the air upwards and out the solar chimney. The air exhausted from the chimney induces fresh outdoor air into the building, thereby providing ventilation to the building. In natural ventilation, it is much significant to know air exchange rate, the ratio of the air volume flow rate to the room volume.

This expression is known as the ACH (Air Change per Hour). This index is defined by ASHRAE as: ACH= (Q.3600)/room total volume. In this study, the room volume was considered 27 m^3 to simulate an actual room size for the purpose of reasoning values and to compare with the published data in [5]. However, it should be noted that the room model volume could be used to obtain ACH. Air inlet to the chimney was considered to have the same room air average temperature. Energy exchange between other walls in the room and the surrounding was neglected.

B. Mathematical analysis

The computational model of the wall solar chimney is a mathematical representation of the thermo-fluid phenomena governing its operation. A numerical investigation of the natural buoyancy-driven fluid flow and heat transfer in the vertical channel has been attempted. The simulations were conducted using the CFD code, Fluent.

The steady, turbulent, incompressible and two-dimensional form of the conservation equations [12] was solved for the fluid flow in the vertical channel using the Boussinesq approximation [5]. Bellow are the latter correlations that impose constant values in all thermo physical properties except for the density in the buoyancy force term of the momentum equation.

$$\beta = \frac{1}{T_m} . \quad (1)$$

$$\mu_f = [1.846 + 0.00472\,(T_m - 300)].10^{-5} \quad (2)$$

$$\rho_f = [1.1614 - 0.00353(T_m - 300)] \quad (3)$$

$$k_f = [0.0263 + 0.000074(T_m - 300)] \quad (4)$$

$$C_f = [1.007 + 0.00004\,(T_m - 300)] \times 10 \quad (5)$$

For steady flow, the equations for continuity, velocity components and temperature in Cartesian coordinates take the following form:

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Continuity equation:

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}=0 \qquad (6)$$

X momentum equation

$$\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}=\frac{\partial}{\partial x}\left(\mu\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial u}{\partial y}\right)+S_u \qquad (7)$$

Y momentum equation

$$\frac{\partial(\rho uv)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}=\frac{\partial}{\partial x}\left(\mu\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\mu\frac{\partial v}{\partial y}\right)+S_V \qquad (8)$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\frac{\partial}{\partial x}\left(\Gamma_{eff}\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma_{eff}\frac{\partial T}{\partial y}\right)+S \qquad (9)$$

C. Numerical simulation

A numerical investigation of the thermo-fluid phenomena that take place inside the wall solar chimneys is performed and the governing elliptic equations are solved in a two-dimensional domain using a control volume method. In the present study, the K-epsilon turbulence model of the fluent 6.3.26 software package, has been selected to be used in the simulations. A numerical investigation of the thermo-fluid phenomena that take place inside the wall solar chimneys is performed and the governing elliptic equations are solved in a two-dimensional domain using a control volume method. In the present study, the K-epsilon turbulence model of the fluent 6.3.26 software package has been selected to be used in the simulations.

The glass average temperature varies as ($9.15\ I^{0.199}$) how ever; wall average temperature varies as ($3.51I^{0.461}$) [11]. During the process of simulation, the density of grids has been increased until there was almost no variation between the two results (the error should be in 1%). The eventual total number of elements was 101100 cells. Fig.2 shows a zoomed in view of the computational grid used in this study.

Numbers of different configurations of solar chimney have been simulated.

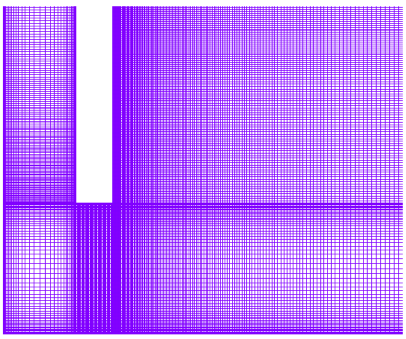

Fig. 2 The computational mesh used

IV. Results and Discussion

The solar intensity is the motive force and its natural variation in the universe is significant for the chimney performance. As shown in Fig.3, it can be seen that the ACH was increasing with the increase of solar radiation intensity.

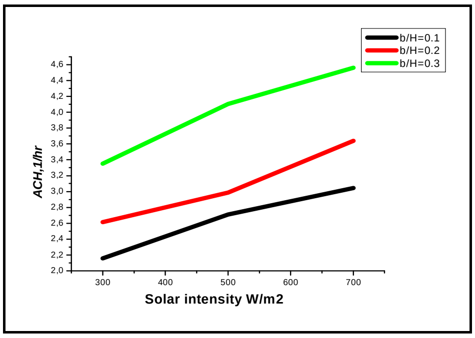

Fig. 3 The variation of ACH with solar radiation (d/ w=0.1)

As the main power for solar chimney, solar radiation was transmitted through the clear glass and then was mainly absorbed by the heat storage wall to heat the air inside. The hot air will goes up by the stack effect, which promote the indoor natural ventilation. With the increase of solar radiation intensity, the heat gain of the heat storage wall has been increased, the stack effect was more obvious and the velocity has been much increased.

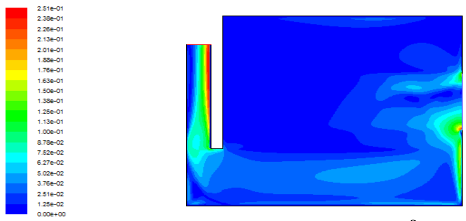

Fig. 4 Contours of velocity at 300 W/m^2

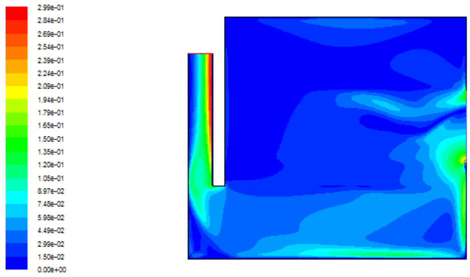

Fig. 5 Contours of velocity at 500 W/m^2

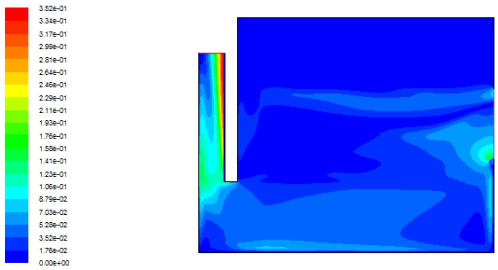

Fig. 6 Contours of velocity at 700 W/m^2

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The effect of varying the chimney width on the ACH at a selected inlet air size and at different solar intensities has been shown in Fig.7. The Fig illustrates a distinct improve in the ACH as the chimney width increases. With the increase of air gap width, the flow resistance was decreasing and the ACH was increasing. Until the air gap width was increasing to a certain value, air flow status will change from the limited space flow to unlimited space flow and backflow will occur around the outlet of solar chimney. Mass flow rate will not increase with the increase of air gap width under this condition. In contrast, the air flow rate for natural ventilation will decrease result from backflow.

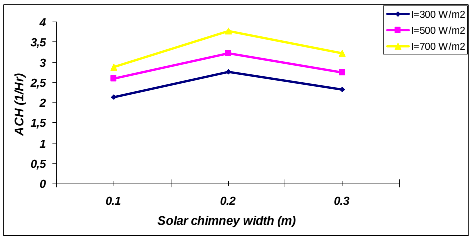

Fig. 7 The variation of ACH with different published data

Figure 8 shows the stream function through the space and chimney for 0.3 m width at 300 W/m^2.

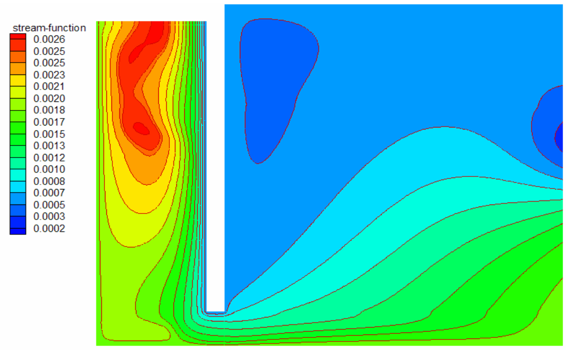

Fig. 8 The stream functions through the space and chimney at 300 W/m^2

A summary of these results for different configurations and solar intensities were listed in Table I . The quantitative comparison showed a reasonable agreement between the results obtained during this study and the published results within the operating conditions.

V. Conclusion

The present study showed that there was an optimum ratio of air gap width for solar chimney to obtain the maximum ventilation rate and ACH. The solar intensity had a very significant effect on flow rate and ACH. Furthermore, it can be seen from the results that the optimum air gap width to obtain the maximum ventilation rate was about 0.2-0.3 m. It can be concluded that increasing width by a factor of three improved the ACH by almost 25%, keeping the inlet size fixed.

TABLE I
SUMMARY OF SOME RESULTS FOR COMPARISON WITH EXPERIMENTAL AND THEORETICAL PUBLISHED DATA [5] - [11]

Chimney Height (m)	Air Inlet Size B (m)	Chimney Width (m)	ACH pour 300 W/m^2				ACH pour 700 W/m^2			
			Exp [5]	Mathur et al [5]	Bassiouny [11]	Present study	Exp [5]	Mathur et al [5]	Bassiouny [11]	Present study
0.95	0.1	0.1	2	2.497	2.249	2.1413	2.662	3.125	3.118	2.8805
	0.1	0.2	2.8	2.949	2.650	2.7618	3.73	3.879	3.671	3.7794
	0.1	0.3	2.4	2.704	2.760	2.3270	2.93	3.671	3.824	3.2117
0.9	0.2	0.1	2.66	2.608	2.535	2.62163	4	3.518	3.505	3.7670
	0.2	0.2	4.53	3.633	3.480	3.8497	3.73	4.688	4.806	4.6929
	0.2	0.3	5.33	4.054	3.891	4.18098	5.33	5.175	5.373	5.3287
0.85	0.3	0.1	3.2	2.406	2.515	3.3433	4.4	3.524	3.475	4.5895
	0.3	0.2	4	3.619	3.705	4.1651	5.2	4.942	5.112	5.5380
	0.3	0.3	4.4	4.173	4.375	4.2391	5.6	5.81	6.033	5.8012

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