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Numerical Analysis of a Solar Chimney

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Abstract— Passive ventilation is among the widely used means of reducing power consumption in residential as well as commercial establishments because of its cost and energy effectiveness. One method of passive cooling that has been around for many years is the use of solar chimneys. Solar chimney is essentially a thermosyphon utilizing the energy from the sun. The energy coming from the sun heats up the air occupying the chimney cavity to create stack effect that in turn provides natural ventilation. In this study, two-dimensional numerical analysis of a vertical solar chimney is performed to determine the effect of air gap on air flow rate at a given range of solar radiation intensity of 200W/m^2 to 400 W/m^2. RNG k-epsilon turbulence model used was validated by comparing the results to experimental data, and is found to have good agreement with experiment data for air gap of 0.4. Equivalent air changes per hour (ACH) is then computed for a 59.27 m^3 container house to be 5.4 for the vertical solar chimney model, with a chimney gap of 0.4 m at solar radiation intensity of 400 W/m^2.

Keywords— Numerical Analysis, Solar Chimney, thermosyphon

1. INTRODUCTION

Solar chimneys, like Trombe walls, are essentially open cavities designed to take advantage of solar energy for natural ventilation. Various studies have been done to determine the effect of solar chimney geometry in achieving adequate air flow rate and thermal comfort inside the building. Factors such as location, climate, orientation, and size and heat gain of space to be ventilated dictate the appropriate design of specific solar chimney. Regardless of these factors, the basic elements of a solar chimney are solar collector/absorber, transparent cover or glazing, and chimney inlet and outlet. The geometry of the channel is described by the height (height between inlet and outlet of chimney), length, cavity width or depth. The common goal of solar chimney studies is to determine optimum chimney design for enhanced passive ventilation suited for a particular climate and location. Design parameters such as chimney aspect ratio (height/width), ventilation height, inlet and outlet areas, and chimney inclination angle have been shown to have significant effects on solar chimney performance in terms of volume flow rate or air changes per hour (Xu Jianliu, Liu Weihua 2013) (Karima E. Amori, Saif Watheq Mohammed 2012).

The simplicity of the features of solar chimney and its salient ventilation effect have attracted researchers to explore the influence of the different design parameters on chimney performance. Among these is the study conducted by Bassiouny et al. (Ramadan Bassiouny, Nader S.A. Koura 2008) where

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they reported that increasing the chimney width from 0.1 m to 0.3 m improved the ACH by almost 25% while keeping the chimney inlet size fixed. From their analytical and numerical study, they also concluded that the chimney width has a more significant effect on the space flow pattern than the chimney inlet size. Their results showed that the absorber average temperature could be correlated to the intensity as $T_w = 3.51I^{0.461}$ and that the average exit velocity varies with intensity as $v_{ex} = 0.013I^{0.4}$. Siva et al. (V. Siva Reddy, M. Premalatha, K.R. Ranjan 2012) conducted experimental studies on performance of solar chimneys at different inclination angles and for various gaps between glass and absorber plate. They found out that an inclination angle of 50^o from the horizontal was optimum for the location Tiruchirappalli (longitude+78° 69'E and latitude+10° 81'N), giving efficiency greater than that of the vertical chimney, using a black coated aluminum wall surface. From the measured result of the chimney, it was also found that the highest rate of ventilation was found experimentally to be 0.32 m^3, at a solar radiation intensity of 1000 W/m^2. Mathur et al (Jyotirmay Mathur, N.K. Bansal, Sanjay Mathur, Meenakshi Jain, Anumpa 2006) conducted an experiment on small scale solar chimney to determine the effect of absorber height and gap between glass and absorber on the ventilation rate induced with the help of solar chimney. From nine different combinations of air gap and stack height, their study showed that air flow increases linearly with increase in solar radiation and that airflow also increases with increase in the gap between absorber and glass cover. They were also able to show that ventilation rate is a function of the ratio of inlet and outlet area and stack height-air gap ratio. Zamora et al (B. Zamora, A.S. Kaiser 2009) conducted a numerical study on both laminar and turbulent flows induced by natural convection in channels with solar chimney configuration for a wide range of Rayleigh numbers. Turbulence was modelled using low-Reynolds k-ω for the turbulent cases. They were able to obtain a correlation for the air gap to height ratio that maximizes the local Nusselt number. However, for the purpose of determining optimum air gap, they concluded that it is not feasible to simultaneously maximize thermal and dynamic performance (mass flow rate). Jing et al (Haiwei Jing, Zhengdong Chen, Angui Li 2015) performed laboratory experiments of a solar chimney with height and width of 2m and 1m respectively. The absorber was modelled as a wall with uniform heat flux while all the other walls are insulated. They studied the effect of air gap and heat flux by varying the air gap from 0.4m to 1.2m, and the uniform heat flux as 200, 300, and 400 W/m^2. They then proposed an improved equation for the prediction of air flow rate that incorporated pressure loss coefficients for the inlet and outlet, as well as buoyancy effects and occurrence of reverse flows.

A significant advantage of the solar chimney for ventilation purpose is that the demand for cooling is in phase with the supply of solar radiation. The primary motivation of this study is to explore the possibility of applying solar chimney technique in the design of social housing in a tropical country such as the Philippines. A two-dimensional numerical model of a vertical solar chimney is employed to determine the effect of varying air gap on chimney performance in terms of volume flow rate which is proportional to air changes per hour.

2. METHODOLOGY

The goal of this study is to determine the effect of chimney air gap on the ventilation performance of a vertical solar chimney at solar radiation intensity of 200 W/m^2 to 400 W/m^2. Ventilation performance is measured in terms of volume flow rate of the solar chimney and air changes per hour when the model is incorporated in a living space. Air changes per hour (ACH) is one measure of solar chimney performance and has been shown to be dependent on solar chimney geometry as well as other external factors. Air changes per hour is the ratio of the air volume flow rate (Q) to the total volume of the room (V) where the solar chimney is installed, and is calculated using the expression defined by ASHRAE

$$ACH = \frac{Q \times 3600}{V} \tag{1}$$

where the units of Q and V are m^3/s and m^3, respectively. Various studies have shown that certain combinations of design parameters lead to improvements in ACH.

The solar chimney being considered, shown schematically in Figure 1, is basically a vertical channel bounded on one side by the absorber and on the opposite side by the glazing. For this model, the absorber is always parallel to the glazing and inclination relative to the horizontal is zero.

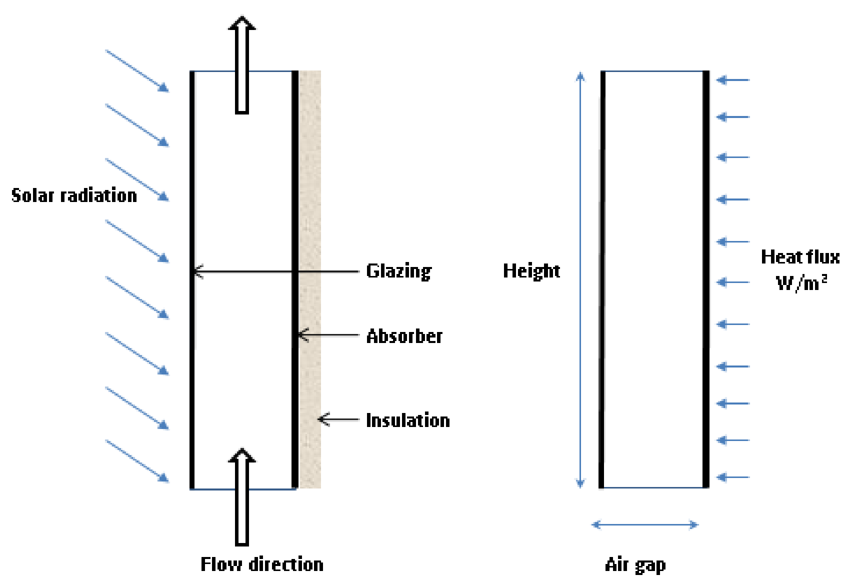

Figure 1. Schematic diagram of a solar chimney

2.1 Computational Model

The fluid domain is modelled as a two-dimensional model using ANSYS Design Modeler with chimney height of 2m and air gap varying from 0.4m to 1.2 m. The mesh model is created using ANSYS Meshing Tool using quadrilateral elements. Mesh is refined in regions where significant temperature gradient is expected. The CFD simulation is carried out using commercial package

FLUENT v15.0. The following assumptions were used to simplify the problem without sacrificing the accuracy of the solution:

a. Steady incompressible three-dimensional air flow exists in the chimney
b. Conduction heat transfer in the absorber wall and glazing is neglected
c. Radiation heat transfer is not considered in the model

RNG k-e model with enhanced wall function is used to model turbulence in the flow. This turbulence model has also been used in other solar chimney studies because of its better performance in modelling buoyant plume over the standard k epsilon turbulence model (Ji 2014) (Cook MJ, Ji Y, Hunt GR 2003).

Pressure inlet and pressure outlet boundary conditions are assigned to the inlet and outlet of the solar chimney respectively with zero ambient air velocity. The inlet temperature is set to room temperature which is 300K, with total gauge pressure equal to zero. Gauge pressure at outlet is also equal to zero with exit air temperature of 300K. The side adjacent to the glazing is assigned as a no slip wall with zero heat flux, representing adiabatic surface. The side of the fluid domain adjacent to the absorber plate is assigned as a no slip wall with constant heat flux from 200 W/m^2 to 400 W/m^2. Boussinesq approximation is employed in modeling the working fluid which is air. This model treats density as a constant value in all solved equations, except for the buoyancy term in the momentum equation. This approximation assumes that changes in air density is proportional to temperature change, and that changes in density is small compared to the density itself (i.e. $\frac{\Delta\rho}{\rho} \approx \beta(T - T_\infty) \ll 1$). For many natural convection problems, this approximation provides faster convergence. Previous studies have shown that temperature difference can range from 5 to 15 degrees Celsius, and the value for $\beta(T - T_\infty)$ can be between 0.017 to 0.05.

2.2 Numerical Procedure

The governing equations are solved using a commercial finite volume solver. SIMPLE scheme is used for pressure and velocity coupling as the model is under steady state condition with fairly simple geometry. Second-order upwind discretization scheme is used for the advection terms of the momentum, energy, and turbulence transport equations. Simulations are carried out on a structured, non-uniform mesh with fine mesh distributed in the areas near the absorber and glazing to better capture the dynamics of flow behavior in areas where the boundary layers are expected to develop. PRESTO is used as the pressure interpolation scheme for the natural convection in the solar chimney where the computed Rayleigh number is of the order of 10^{13}.

Mesh independence study is also conducted to ensure a grid-independent solution. This was performed on three meshes with 16,640 elements, 51,000 elements, and 63,395 elements. The volume flow rate at the outlet is measured since it gives a direct measure of the dynamic performance of the solar chimney. The finest mesh with 63,395 elements is chosen since the difference in volume flow rate between this mesh size and the intermediate is only 1.6% and also for better spatial resolution. Convergence is ensured by monitoring residuals and making sure that scaled energy residuals have reduced to 10^{-6}, while scaled residuals for continuity and momentum variables have reduced to 10^{-4}.

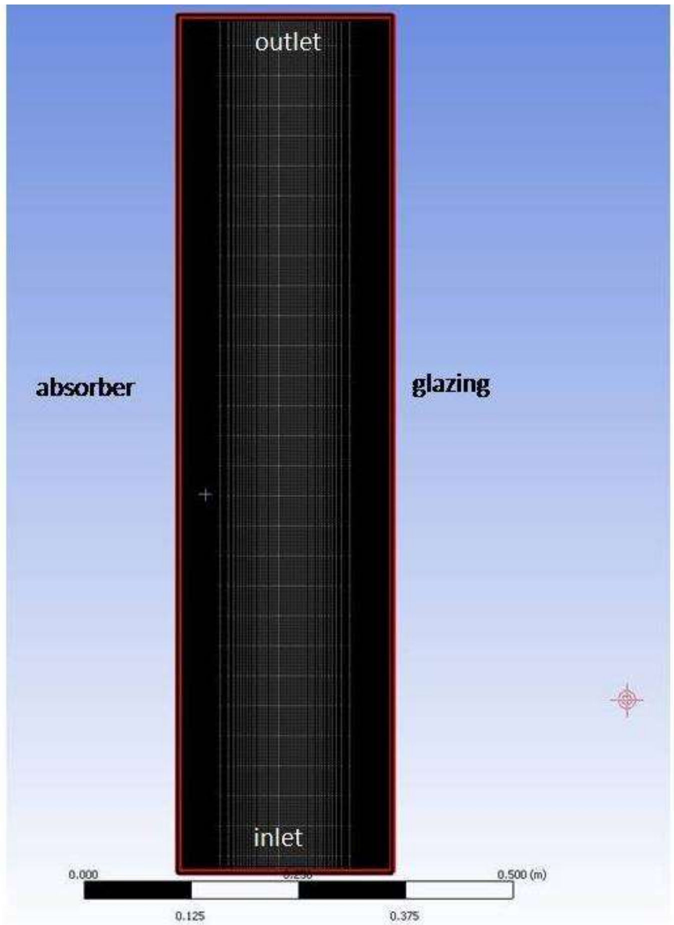

Figure 2. Mesh of fluid domain

3. RESULTS AND DISCUSSION

3.1 Validation of 2D Model

Solar energy transmission through the chimney has been shown to create a stack effect that induces natural ventilation in a space. The glazing temperature is considerably low and close to ambient temperature as is expected since a large portion of the incident radiation is transmitted through it. The absorber wall temperature, on the other hand, has been shown by experiment results of Siva et al to be much higher due to the high absorptivity of wall material. This significant temperature difference between the absorber wall and the air in the chimney cavity, which is initially at ambient or room temperature, is the driving force for natural convection in the solar chimney cavity. For the purpose of validating the numerical model, the results are compared against the experimental results of Jing et al.

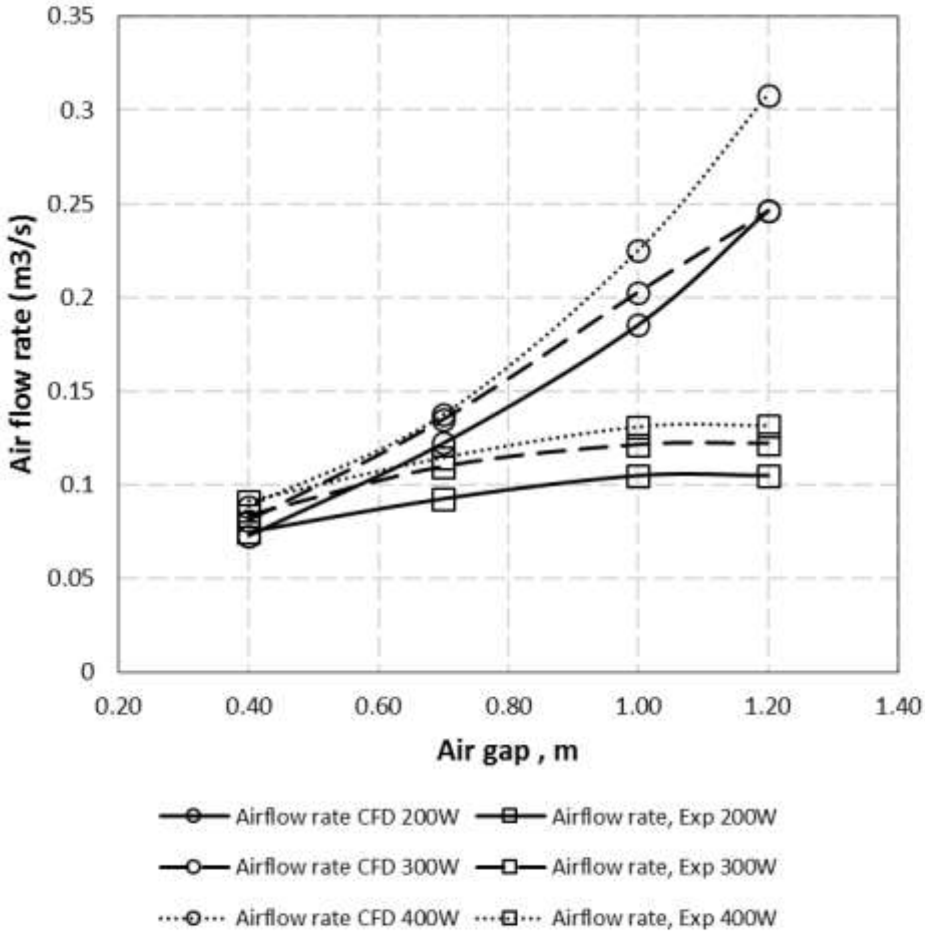

Figure 3. Plot of air flow rate

The plot of the airflow rate shows that the model is able to predict volume flow rate at an air gap of 0.4 m, and over predicts values as the air gap is increased. Figure 4 shows a comparison of air flow rate at an air gap of 0.4m. For the specified heat flux, the result of the numerical model compares well with the experimental data of (Haiwei Jing, Zhengdong Chen, Angui Li 2015) with an average difference of 4%.

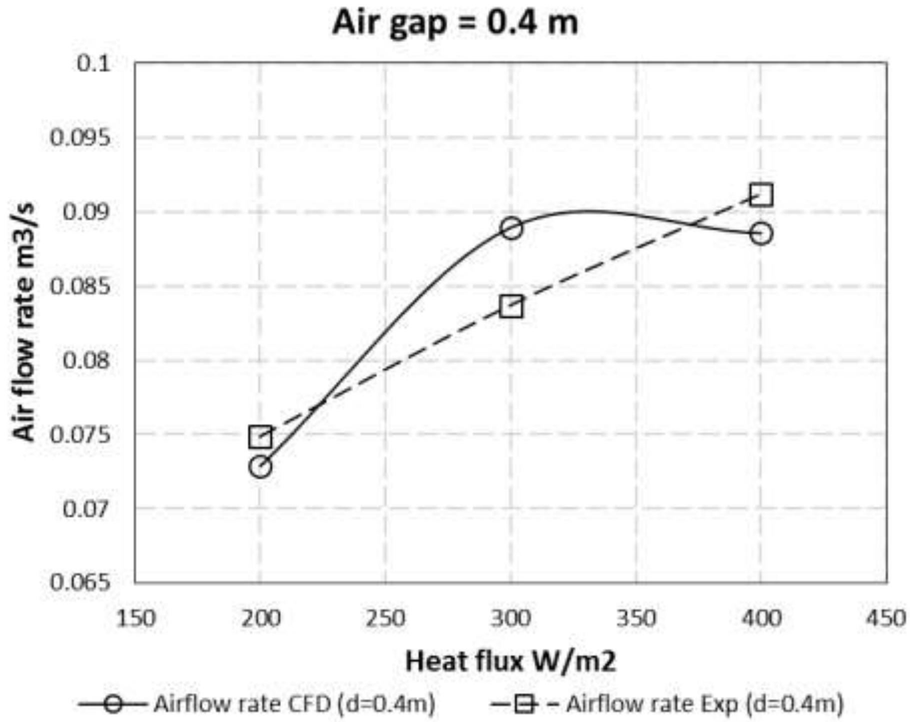

Figure 4. Air flow rate at air gap of 0.4m

Referring to Figure 5, the thermal boundary layer develops in the absorber side of the chimney which is due to the transfer of heat from the hot absorber side to the fluid layer adjacent to it. The thickness of this boundary layer is dependent on the flow characteristic which is mainly driven by the temperature difference between the fluid and the absorber plate.

Figure 6 and Figure 7 show the variation of velocity in the flow direction. High velocity is observed in the region near the absorber, as is expected, for all four air gaps studied. It is observed that as the air gap is increased, regions where flow reversal occurs also increases as indicated by regions of low velocity. Also, flow in the direction that contributes to the induced stack effect is confined in a smaller region near the absorber relative to the region of flow reversal. This observation is in agreement with the results obtained by (B. Zamora, A.S. Kaiser 2009) (Rakesh Khanal, Chengwang Lei 2015) (Haiwei Jing, Zhengdong Chen, Angui Li 2015) where generally, the phenomena of reversed flow at chimney outlet occurs for wide chimney air gap. The over prediction of the volume flow rate could be due to this reversed flow that the solver incorporates in the computation of volume flow rate. With an increase in air gap, regions of flow reversal is also increased, and volume flow rate is over predicted by as much as 128% at a fixed value of heat transmission.

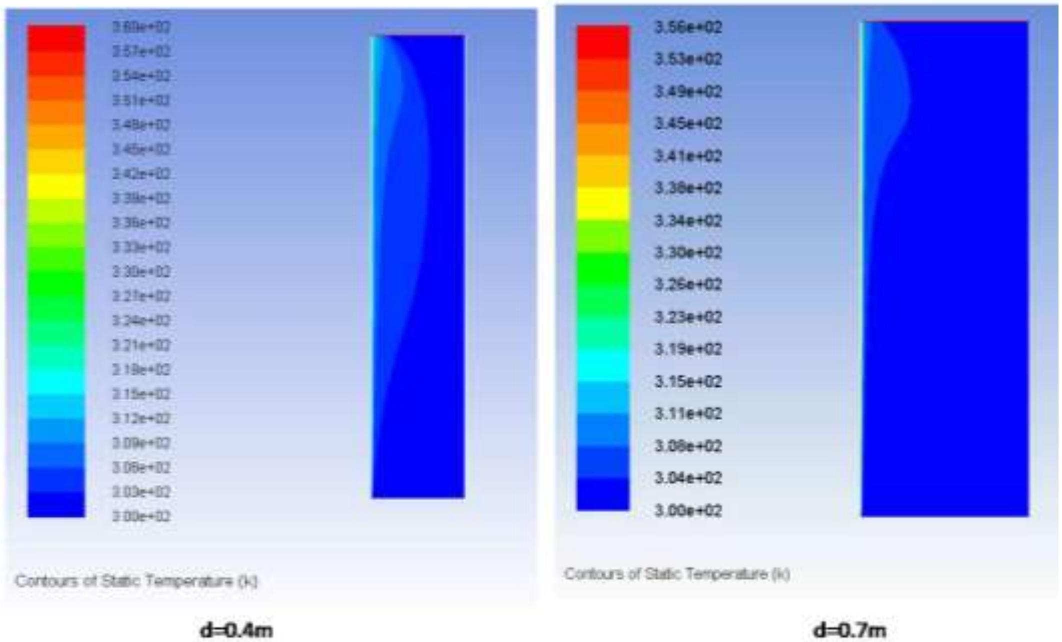

Figure 5. Temperature contour for d=0.4m and d=0.7m at 200 W/m^2

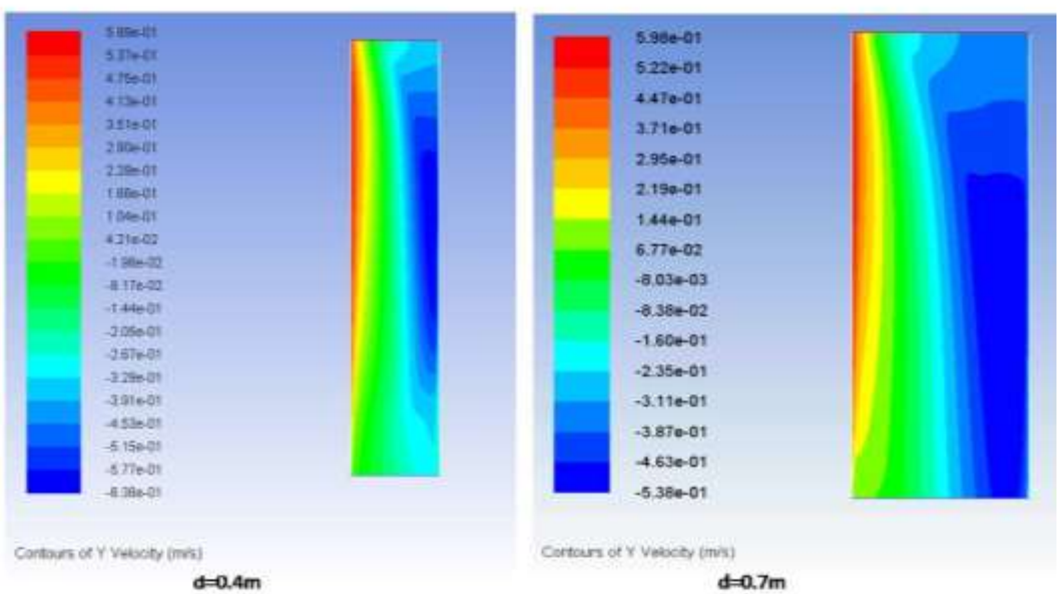

Figure 6. Velocity contour at 200 W/m2 heat flux

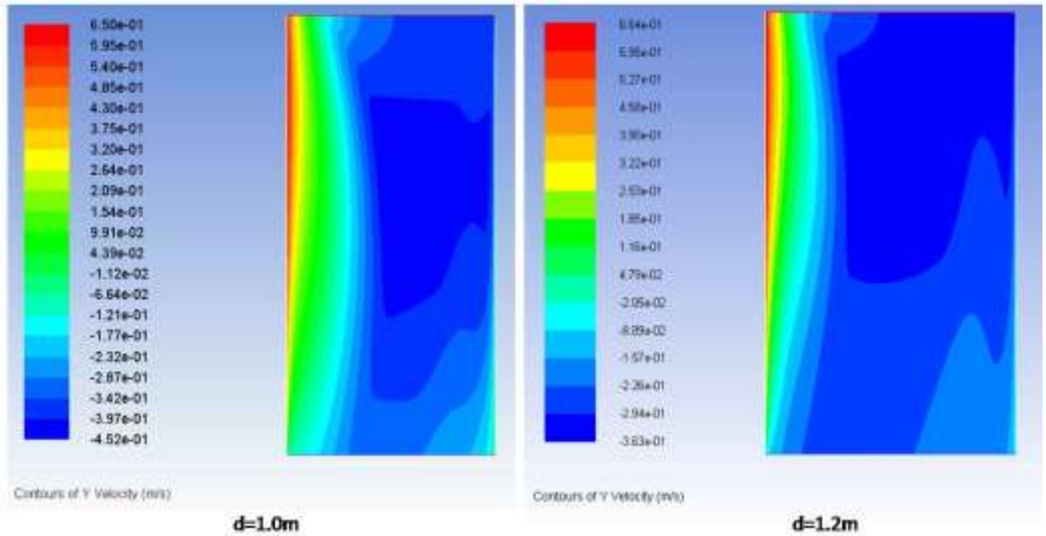

Figure 7. Velocity contour at 200 W/m2 heat flux

3.2 Air changes per hour for a model container house

Having validated the 2D numerical model against existing experiment data, the next step is evaluating the natural ventilation effect of the chimney when it is incorporated in a given occupied space. One such living space is the container house intended for low cost socialized housing. A study by De Asis (Asis n.d.) explored the feasibility of repurposing container vans as a solution to the housing needs of the urban poor in the Philippines. It was pointed out that while it may be economical, the hot and humid climate in the country may prove to be a challenge in ensuring thermal comfort of the occupants. One of the existing container houses in the country that were cited in the study used double walls with fiber glass insulation, while another used double walls with foam insulation. The study highlighted that natural ventilation should be well incorporated in this type of housing as the target occupants are expected to rely mostly on this for thermal comfort with occasional use of electric fans. This is where a solar chimney becomes a valuable passive ventilation system.

Air changes per hour is used as a measure of the ventilation effect induced by the solar chimney. It is essentially the rate at which air in a given space is replaced. The ACH computed are based only on the range of solar heat flux for which the 2D model has been validated, which is 200 – 400 W/m^2. The occupied space used in the computation of ACH is based on the dimensions of the proposed container housing in the study by De Asis which is constructed out of 2 units of 20’ container vans placed side by side. Figure 8 presents a comparison of ACH with increasing heat flux at different air gaps. However, due to possible constraints in land area for the possible location of the container house, the chosen air gap for the solar chimney is 0.4 m. It is also this air gap that provided a good agreement in the estimation of volume flow rate in the 2D model validation.

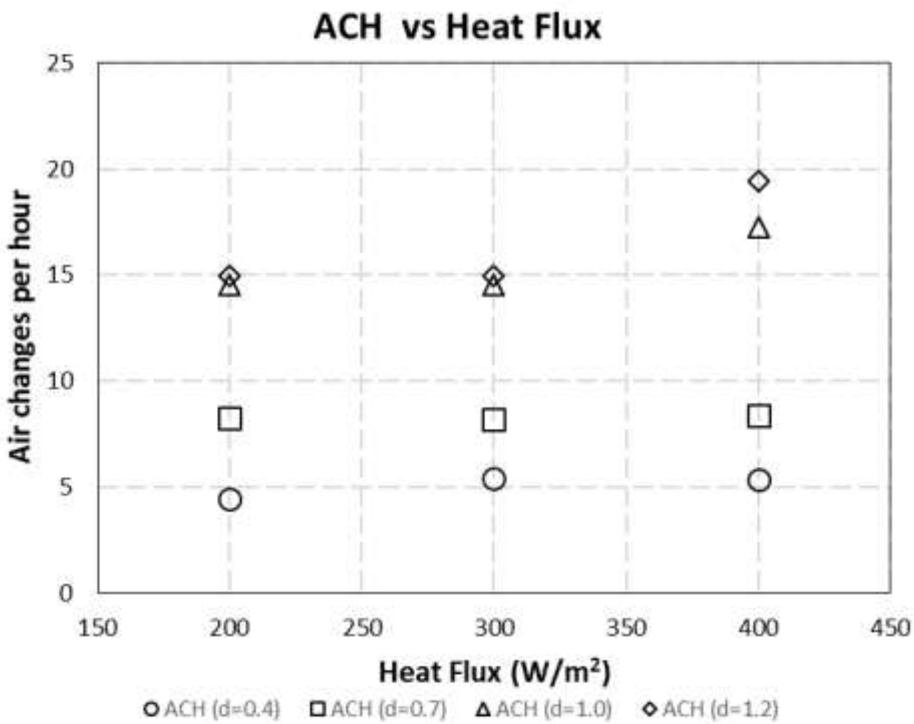

Figure 8. Air change rate vs heat flux for different air gaps studied

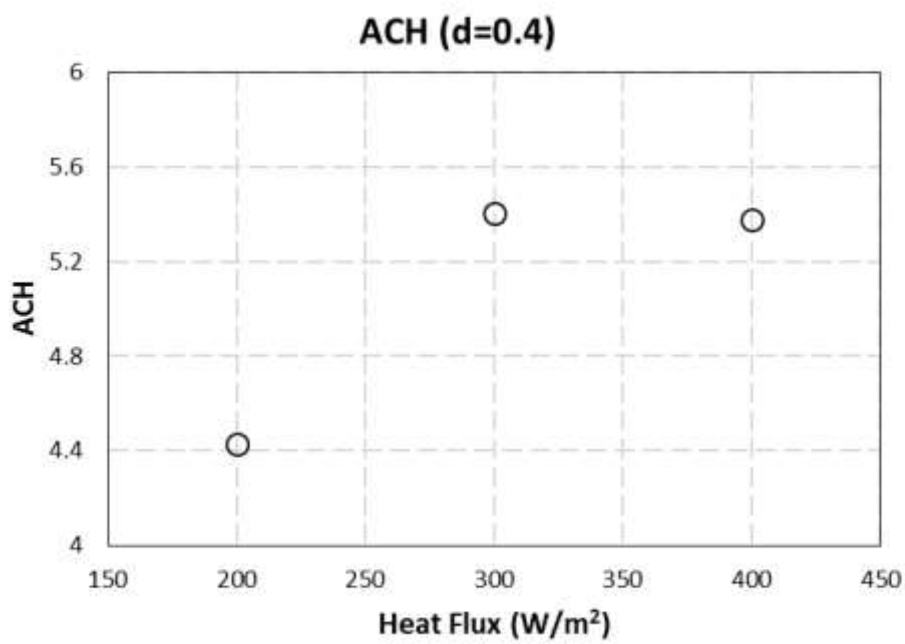

Figure 9. Air change rate for the proposed container housing @ 59.27 cu meter.

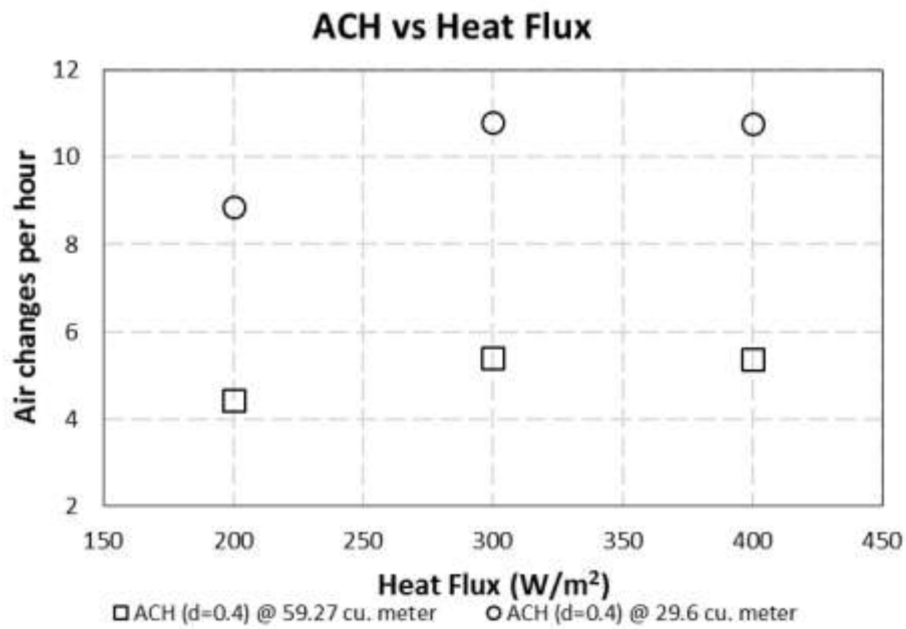

Figure 10. Air change rate comparison (2 units vs 1 unit of 20').

For the proposed container housing in the study by De Asis, a solar chimney with an air gap of 0.4m can provide ACH of 5.4 at a heat flux of 400 W/m^2. This heat flux is representative of the solar irradiance reaching the absorber of the solar chimney. This may be considered relatively low because at certain locations solar irradiance vary according to location and time of the day. Specifically, in Quezon City solar irradiance may be as low as 100 W/m^2 to as high as 1000 W/m^2 at certain times of the day. According to NREL solar data, Quezon City has an annual average insolation of 5.05 kWh/m^2 per day or roughly 200 W/m^2. A heat flux of 400 W/m^2 may then be considered as an approximate solar irradiance for a day - higher than the annual value but less than the daily average which varies over a wide range of values in a day.

For a container house consisting of a single unit of 20’ container van, ACH is doubled. This suggests that there is a prescribed number of solar chimney to be installed for a given room size to achieve the recommended ACH. It should be noted that the number of occupants will ultimately dictate the desired ACH as well as external factors like ambient temperature and weather condition. The computed ACH values do not account for the ventilation effect due to occupant behaviors such as opening of windows and doors. Nevertheless, it has been shown that the solar chimney can provide a significant amount of air movement to provide natural ventilation in a container house. This can be equated to savings in energy that would otherwise be used to power an electric fan for ventilation.

4. CONCLUSION AND RECOMMENDATIONS

The present study shows that the two-dimensional numerical modelling of solar chimney is able to predict flow behavior for air gap of 0.4m at the given range of heat flux with an average of 4% difference. For all air gap studied, the flow velocity in the chimney is shown to be highly non uniform at the specified heat flux of 200, 300, and 400 W/m^2. Flow reversal at the outlet and within the chimney is intensified as the air gap is increased. The practical applicability of the numerical model is that since it is able to predict flow behavior at an air gap of 0.4m, the result can then be used for computing for the natural ventilation induced when the chimney is attached to a room. The equivalent air changes per hour, when used in a 59.27 m^3 container house is 5.4, which provides supplemental ventilation to ASHRAE prescribed ACH in a living space of 7.5 L/s per person.

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