

PASSIVE COOLING TECHNOLOGY BY USING SOLAR CHIMNEY FOR MILD OR WARM CLIMATES

by

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This study describes the design and analysis of solar system for mild or warm climatic conditions. In order to improve the performance of solar chimney system, well known software FLUENT is used to demonstrate the structures of these systems and finally compare the results with several examples, which have been studied 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 efficiency of such systems for integration with existing and future domestic buildings.

Key words: *active and passive solar technologies, solar cooling system, solar chimney, natural ventilation, cavity depth*

Introduction

The usage of various forms of energy is vital in human development through the ages [1]. The major energy consuming constituents of a building are heating, ventilating, and air-conditioning (HVAC). Development of solar heating and cooling technologies as renewable energy sources have been attracting the researchers. The passive solar technologies for space heating and cooling take a special consideration in this regard [2].

In need of energy for final consumption in the buildings is about 35.3% [3]. The space heating or cooling are being the dominant at total consumption of this HVAC energy in buildings, and closely related to the local climate condition. Regulating the humidity and temperature to provide thermal comfort and indoor air quality are inevitable for indoor climate controls.

In addition to this, direct solar radiation is used by both heating and cooling systems. Heating systems retain the heat within the building by collecting and storing the solar heat, whereas cooling systems improve air ventilation by providing cold or protecting the building from direct solar radiation. In cold countries, energy demand and consumption is usually for space heating. Furthermore, air conditioning has the primary contribution to energy demand in hot climate countries or during summer. For example, the service sector in the United Kingdom consumed about 50% of energy in 2004 [3-6]. In other respects, during the summer time 40% of peak load was needed for air-conditioning in Shanghai. Due to the deep impact of heating and cooling loads on CO₂ emissions, as well as on security of energy supply, renewable energy has become vital energy sources that utilise cost-free sources from the nature [3-7].

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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.

Solar chimney

A solar chimney is a natural passive technology, which utilizes solar energy to generate buoyancy effect that drives airflow through the air channel. Solar chimney system has widely used in passive solar energy drying of crops, fruits, wood or grains solar heating and cooling applications [8-10]. There are lots of studies about the solar chimney system in the literature. For example, Liu and Yongcai [11] has worked on thermal performance of a solar chimney without and with phase change material experimentally. Rabani *et al.* [12], has studied empirical investigation of the cooling performance of a new designed Trombe wall in combination with solar chimney and water spraying system.

Solar chimney acts as a thermal engine by converting thermal energy into kinetic energy of air movement. The solar chimney generates airflow through a building and the density difference of air at inlet and outlet of the chimney during the ventilation provides either cooling or heating. The heating can be supplied by use of a fan to direct the heated air into the building. Thus, the efficiency of the chimney depends on the outside temperature not the amount of the temperature rising. The working mechanism of the solar chimney is similar to Trombe wall if it is attached to wall. The heated warm air obtained from the solar collector supplies passive heating. Natural ventilation depends on the outdoor temperature as previously stated, and the 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 [13].

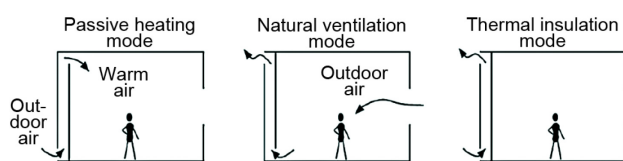


Figure 1. Solar chimney operating modes

Simple air collector architecture consist a vertical chimney that stretched horizontally above the ground with various meters height. Though, a different format as laying the collector along the roof space also possible, and they might be combined for greater efficiency

[14, 15]. Preliminary studies on the solar chimneys shown that even during cloudy days they are capable of to create cooling effect by warming the air. Nevertheless, the local climate conditions should be taken into consideration to satisfy the thermal comfort since solar chimney might need other passive or active heating/cooling systems.

In general, solar chimneys are one of the forms of solar power plants using convection of air heated by passive solar energy to improve the natural ventilation of buildings. A solar chimney consists of a glazed solar collector that the hot air generated in the collector raises by the day solar energy, and with a vertical shaft as chimney to enhance the ventilation and cooling of the building, fig. 2.

Principle of the solar chimney contains three essential elements are:

- *The solar collector.* The collector uses both direct and diffuses solar radiation. This can be located on the top part of the chimney or can include the entire shaft. The orientation, type of glazing, insulation, and thermal properties of this element are crucial for harnessing, retaining and utilizing solar gains.
- *The main ventilation shaft (chimney).* The chimney itself is the plant's actual thermal engine, and location, height, cross-section, and the thermal properties of it are also very important. There are many well-known different approaches of building a chimney and have been used in cooling towers with no needs to any special development.
- *The wind turbines (inlet and outlet air apertures).* The hot air rises up in the chimney since it is lighter than cold air. Suction from the chimney then draws in more hot air from the collector, and allows to inlet of cold air. Thus, aerodynamic aspects of these elements, sizes and location are also important for the design.

The environmental control in buildings in developed countries has been using air conditioning and mechanical ventilation as the standard method without ecological care. Development requires energy and demand on environmentally friendly energy sources increases proportionally that have led to a new environmental approach in building design. Mankind learned to make active use of clean, natural, and renewable energy sources for the innovative technological principles and design strategies to create new and potentially successful solutions. The solar chimney is one of these concepts based on the solar energy that research and experimentation are still carrying on.

A solar chimney provides the basic understanding to be able to design natural ventilation strategies rely on natural driving forces for many purposes. Natural ventilation systems are usually integrated into building where the air inside the chimney can be used to ventilate a home or an office. A solar chimney operates simply and can be designed to operate continuously 24 hours per day on pure solar energy.

The vents in upper level of a building allows rise of hot air by natural convection and evacuation to the outside. Suction of hot air from the chimney draws in more hot air from the collector, and cold air comes in from the outer perimeter; hence solar radiation causes a constant up draught in the chimney.

The chimney has to be build higher than the roof level and constructed to capture solar radiation on the wall facing the direction of the Sun to increase the heat of the air at the top and increase the difference in temperature between incoming and out-flowing air, fig. 3. Also, the air pressure differential can be increased by well-designed air passages.

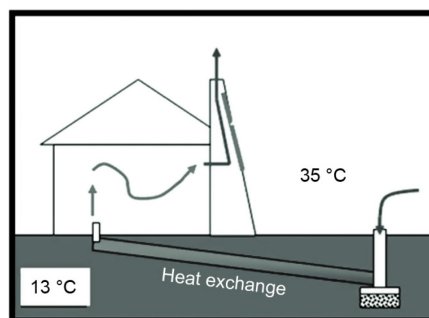


Figure 2. The solar chimney hybrid system to provide passive home cooling [16]

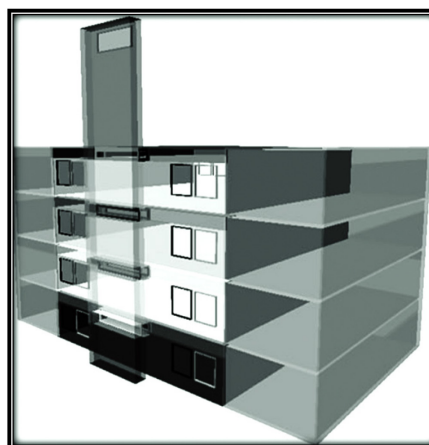


Figure 3. The CAD solar chimney model [17]

The advantages of solar chimneys use for natural ventilation could be stated:

- run continuously and provide improved ventilation rates,
- require minimum maintenance,
- reduced reliance on external elements (wind and fans for ventilation),
- increased robustness, flexibility, and consistency,
- improved control of airflow by well-designed structure,
- larger choice of air intake, and
- improved air quality and reduced noise levels.

The advantages of passive cooling may include:

- improved passive cooling during warm season,
- improved night cooling rates,
- enhancement of performance of thermal mass (cooling, cool storage), and
- improvement of control on airflow and reduction of draughts.

Solar chimney 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.

The purpose of this research is to analyse the benefit of solar chimney application on the south facade through the numerical analysis in a building. Also, CFD simulations are conducted for the related numerical model. The 3-D model is generated with CFD program which also provides to control wall temperatures in the application solar chimney as the boundary conditions.

A solar chimney on south side of building is fabricated easily by supplying an air gap between inside and outside of the building. The air gap helps to remove the hot air in the room due to the developed thermal buoyancy that happens because of the difference in indoor-to-outdoor air density resulting from moisture and temperature differences.

The modification and application of solar chimney have been examined in this research. The modifications involve using various materials for solar chimney [18, 19], changing solar direction on the solar chimney to increase temperature difference [20], increasing the amount of openings [21], and applying the different cavity depths of solar chimney.

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

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, fig. 4.

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.

This research includes four main steps:

- case setting,
- build up baseline building,
- the CFD simulation, and
- result analysis.

Case setting

Outdoor temperature, solar radiation, wind velocity, pressure, building height, cavity depth, and material of facades are possible to affect the natural ventilation and cooling. There might be more than twenty possible variables and each of them has several possible conditions.

Output: temperature, air velocity, pressure, air direction.

In order to get better analyse only one parameter is changed each time in each set of test, and benchmark for validation.

Baseline building

Values of parameters given to baseline building are set as default value for each variable (tab 1). Each default value will keep constant when testing other parameters.

Materials

Building model

Prototype model is created by CAD program Solid Works, fig. 5.

Properties of glass and construction materials of the building are given in tabs. 2 and 3, respectively [23].

In order to figure out construction material setting clearly, the explanation of tab. 3 is shown in fig. 6.

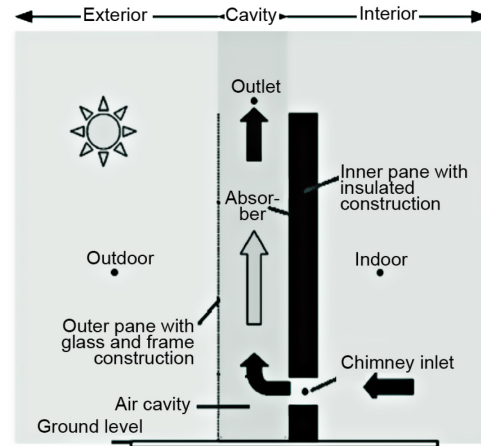


Figure 4. Vertical cross-section of a standard wall solar chimney and the boundary resolutions [22]

Table 1. General material setting of building

	Glass	Aluminum	Brick insulation (building isolation)
Density [kgm^{-3}]	2220	2719	10
Specific heat [$\text{Jkg}^{-1}\text{K}^{-1}$]	830	871	830
Thermal conductivity [$\text{Wm}^{-1}\text{K}^{-1}$]	1.15	202.4	0.1

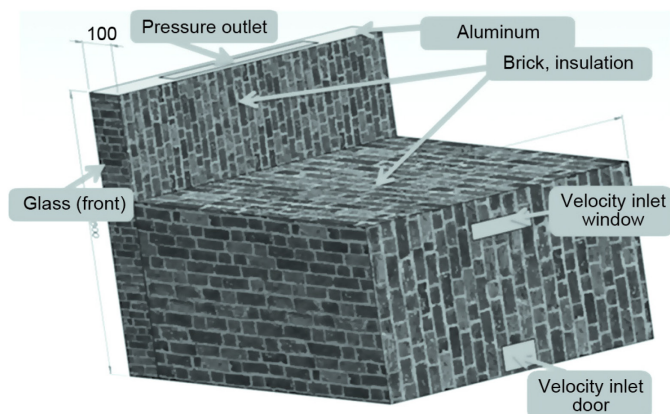


Figure 5. Section of building model: dimensions of building $0.8 \times 0.8 \times 0.5$ m (L×D×H) dimension of solar chimney $0.1 \times 0.8 \times 0.8$ m (L×D×H)

Table 2. Glass material setting of the building [23]

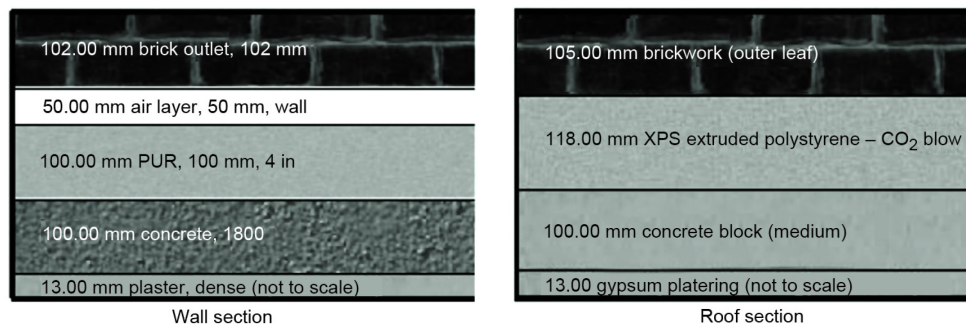
Insulated Glass			
	Window gas type and thickness	Innermost pane	SHG-C
Exterior glass (laminated)		Low-E	0.710
Interior glass	Air Space 20 mm	Low-E	0.636
	Direct solar transmission	Light transmission	U-value [$\text{Wm}^{-2}\text{K}^{-1}$]
Exterior glass (laminated)	0.680	0.811	4.233
Interior glass	0.509	0.761	2.060

Note: Low-E (low thermal emissivity) is a quality of surface which reflects low level of radiant thermal energy. Thus, low-E glass radiates more sunlight. The SHG-C is the solar heat gain coefficient that shows fraction of incident solar irradiation through a window.

Table 3. Construction material setting of the building [23]

Construction Material		
	Structure	U-value [$\text{Wm}^{-2}\text{K}^{-1}$]
Wall	102 mm Brick = 50 Air layer + 100 PUR + 100 Concrete + 13.00 Plaster	0.225
Roof	105 Brick + 118 mm XPS Extruded Polystyrene + 100 mm Concrete + + 13 mm Gypsum Plastering	0.250
Floor	100 mm Cast Concrete	4.730

Note: U-value is a measure of the heat transmission through a building part (as a wall or window).

**Figure 6. Wall and roof section of the construction material design for the building [23]**

The CFD simulation

In this research CFD simulation was used to analyse the prototype building model. 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. [24].

Turbulence modelling

The simulation of turbulent flow of low Reynolds number under the buoyancy effect in the building is an important study of airflow in the room with its solar chimney. For this purpose, the renormalisation group $k-\epsilon$ model and the Boussinesq's approximation are

carried out by the FLUENT that solves basic conservation equations continuity, momentum and energy.

The k-ε turbulence model

The k-ε turbulence model was used in this research is industry standard model and new refined model is still being developed. This regards effects like convection and diffusion of turbulent energy according to the two equation model. The energy in the turbulence and the scale of the turbulence is determined by using two transported variable as turbulent kinetic energy, k , and the turbulent dissipation, ε , respectively.

Effects of buoyancy on turbulence in the k-ε models

Buoyancy is occurred due to the difference in indoor-to-outdoor air density resulting from moisture and temperature differences. The effects of buoyancy play a key role to supply ventilation of the building because the air heated up by the wall flows upward because of the buoyancy effect. There are some following explanations for effects of buoyancy on turbulence in the k-ε models, [25]:

Once, non-zero gravity field and temperature gradient are used at the same time in the k-ε models. Generation of k because of the buoyancy can be calculated by Ansys FLUENT.

The following equation shows the generation of turbulence due to buoyancy:

$$G_b = \beta g_i \frac{\mu_t \partial T}{Pr_t \partial x_i} \quad (1)$$

where G_b is the generation of turbulence kinetic energy due to buoyancy, g_i – the component of the gravitational vector in the i^{th} direction, Pr_t – the turbulent Prandtl number for energy. The default value of Prandtl number is defined as 0.85 for the standard and realizable k-ε models and β is the coefficient of thermal expansion that is given by:

$$\beta = -\frac{1}{\rho} \left(\frac{\partial \rho}{\partial T} \right)_p \quad (2)$$

Simulation method

The simulation of cooling and natural ventilation in solar chimney is managed by CFD tools. The FLUENT CFD solver engine is used for thermal and fluid-flow calculation. The FLUENT solver can provide robust and quick calculation.

In order to study if it is appropriate to apply natural ventilation to a solar chimney building, two fundamental issues need to be known for the CFD simulation:

- how architectural features (cavity depth and width, building height, operable window size, and room height to depth ratio) affect natural ventilation, and
- which climate condition (temperature and wind speed) is available for natural ventilation in solar chimney building?

For instance: in order to determine these issues, program structure of solar chimney analyse are shown in fig. 7.

Solar load model

Radiation effects from the Sun rays may be calculated by solar load model in Ansys FLUENT. There are two alternatives for solar load model: solar ray tracing and discrete ordi-

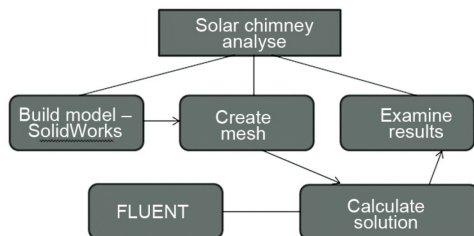


Figure 7. Program structure of solar chimney analyse

the sky depending on the input values such as time-of-day, date, and position. Solar load model works in the 3-D solver only and may be utilized to steady and unsteady flows.

Solar calculator in Ansys FLUENT provides to calculate solar beam irradiation and direction for given inputs such as time, date, and position. These values might be utilized as inputs to the solar ray tracing model. All these inputs are specified in the solar calculator dialog box that is inside the radiation model dialog box, fig. 8.

rates irradiation. In this research, solar tracing approach is used because such option can be utilized standalone solar loading model or it can be applied with one of the radiation models of the Ansys FLUENT. Solar ray tracing model is practical and highly efficient of solar load and is used as heat sources in the energy equations.

Solar calculator

Solar calculator program in the solar load model provides to build Sun location in

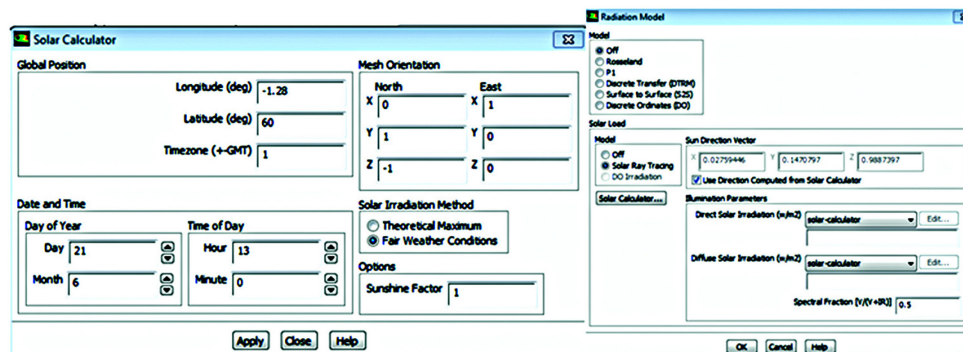


Figure 8. Solar calculator and radiation model

Theory

There are two alternatives for the calculation solar load in Ansys FLUENT: fair weather conditions method and theoretical maximum method. Although, both of such options are same methods, there is a key difference. The fair weather conditions method, that represents the atmospheric conditions, forces higher attenuation on the solar load.

The following equation shows direct normal irradiation for fair weather conditions method [26].

$$E_{dn} = \frac{A}{B \cdot e^{\sin(\beta)}} \quad (3)$$

where E_{dn} is the direct normal irradiation at the earth's surface on a clear day, A and B – the apparent solar irradiation at air mass $m = 0$, and atmospheric extinction coefficient respectively, and β – the solar altitude above the horizontal.

Simulation inputs

According to fig. 8, some values were calculated by FLUENT solar loading radiation model:

- Sun direction vector: X: 0.0275968, Y: 0.14708, and Z: 0.98874,
- sunshine fraction: 1,
- direct normal solar irradiation (at Earth's surface) [Wm^{-2}]: 842.901,
- diffuse solar irradiation – vertical surface [Wm^{-2}]: 104.078,
- diffuse solar irradiation – horizontal surface [Wm^{-2}]: 112.949, and
- ground reflected solar irradiation – vertical surface [Wm^{-2}]: 78.9921.

Result and discussion

Cavity depth

One of the most important solar chimney characteristic for ventilation is cavity depth. That is because the depth of cavity may highly affect the efficiency of natural ventilation by forcing the air movement and turbulence in the building and solar chimney.

The study will focus on analysing temperature and pressure differences in the building with different cavity depths of the solar chimney system. Those are the most important parameters that may describe the capability of ventilation.

Simulation results

Temperature differences

When cavity depth is 7.6 cm, the temperature difference, ΔT , between average temperature of the inlet and outlet achieves the maximum value, 18 °C. The highest T happens when cavity depth is 7.6 cm, and it decreases when cavity depth either gets higher or lower than 7.6 cm. The decreasing gradient is sharper when cavity is lower than 7.6 cm. The smallest temperature difference, ΔT , appears when cavity depth is 2.54 cm, which is only 7 °C. These temperature differences are presented in fig. 9.

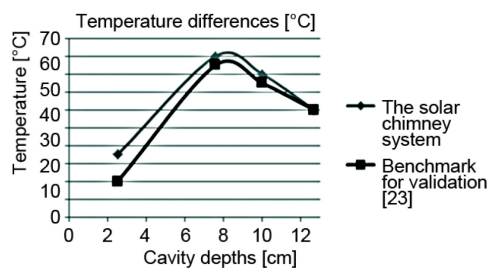


Figure 9. Comparison of temperature differences for four different cavity depths

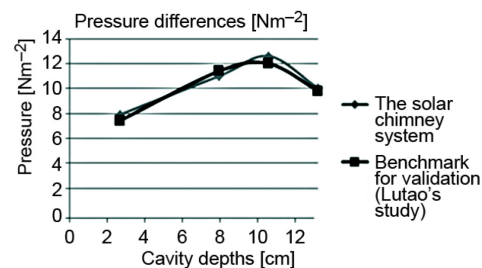


Figure 10. Comparison of pressure differences for four different cavity depths

Pressure differences

The second study objective is pressure difference, ΔP , between the top and bottom openings that is the direct driven force for ventilation and should be related to temperature difference theoretically. Larger pressure difference supplies stronger driven force for stack-effect ventilation.

When cavity depth is 10 cm, pressure differences arrives at the highest value which is 12.6 N/m^2 , reduces pressure difference value when cavity depth either increases or decreases.

The minimum pressure difference, 7.9 N/m^2 also appears when cavity depth is 2.54 cm, fig. 10. The minimum pressure difference is.

According to the simulation results of three parameters and the previous analysis, between the range of 2.54 cm and 12.7 cm, optimum ventilation might be succeed when cavity depth is around 7.6 cm to 10 cm. Furthermore, when cavity depth is too wide, 12.7 cm, and too narrows, 2.54 cm, natural ventilation can not have reasonable performance. Once cavity depth is 2.54 cm, the air velocity is remarkably high at the bottom of the chimney but at the same time, low speed air is at the upper part of the chimney. That means, relatively high air movement mainly occurs at the bottom part of the chimney, so air can not flow efficiently to upstream in the chimney. On the other hand, an unobvious upstream air is happened when the cavity depth is 12.7 cm.

From the velocity contour, in the cavity area, when cavity depth is 2.54 cm, air is with relatively high speed at the lower part of the cavity space but with low speed at the upper part of the cavity, fig. 11(a). That means intense air movement mainly happens at the lower part of chimney skin and air can not exhaust efficiently from top opening. When the cavity depth is 12.7 cm, an unobvious upstream air is formed according to fig. 11(c).

When cavity depth is 7.6 cm obvious upstream is presented on fig. 11(b). when compare Lutao's study, the main upstream speeds was around 1.5 m/s that is an optimum speed for natural ventilation. Therefore, speed contour section further proves that best natural ventilation performance can be achieved when cavity depth is around 7.6 cm.

Benchmark for validation

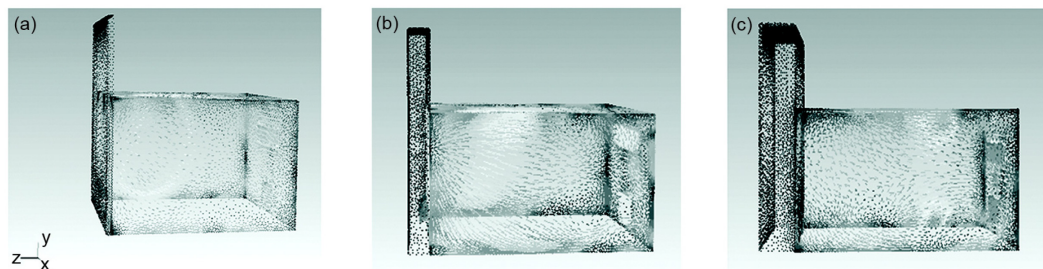


Figure 11. (a) Cavity depth 2.54 cm, (b) cavity depth 7.6 cm, and (c) cavity depth 12.7 cm

In comparison to a long-term monitoring study on natural ventilation for solar chimney building at available climate zone [23], this project has achieved nearly same results for each cavity depths. At the end of the calculation, simulation results proved that outputs were approximately same when compare Lutao's study.

Conclusions

In general, this study shows how solar chimney works, solar direction, and cavity depths affects the performance of solar chimney for natural ventilation and cooling of the building. Moreover, the research provided to analyse the benefit of solar chimney application on the south facade through the numerical analysis in a building. Also, CFD simulations were conducted for the related numerical model. The 3-D model was generated with CFD program

which also provided to control wall temperatures in the application solar chimney as the boundary conditions.

In the study, in order to analyse temperature differences resulting from various solar directions, only solar parameters were changed for each simulation. At the end of these simulations, temperature differences were observed and recorded. These results proved that different solar directions resulted in different temperature variations on building.

Furthermore, in comparison to long term monitoring study of ventilation for solar chimney building [23], this study has succeeded similar results for each cavity depths. Both resources prove that best natural ventilation performance can be achieved when cavity depth is around 7.6 cm.

Simulation results and validation demonstrated that main characteristics of test cases in mild or warm climates 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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