Jurnal Alam Bina, Jilid 8, No.1, 2006.

Possibility to Use Solar Chimney to Improve Stack Ventilation in Tropical Climate

Agung Murti Nugroho [1], **Mohd Hamdan Ahmad** [2]

1. PhD Candidate, Lecturer, University of Brawijaya, Malang, Indonesia
2. Associate Professor, Department of Architecture, Faculty of Built Environment,
Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia

ABSTRACT: *The climatic conditions of the tropical regions are characterized by high air temperatures, high relative humidity and very low wind speeds, which make the environmental conditions uncomfortable. A good dwelling design can keep the indoor environment favorable and comfortable during most of the year without the use of any mechanical devices. Depending on ambient conditions, natural ventilation may lead to indoor thermal comfort without mechanical cooling. However, in cases where the wind effect is not well captured or outdoor wind speed is very low, then stack ventilation may be a viable alternative. Stack ventilation standing involved temperature difference experiments which can be done using both experimental and numerical study. This paper evaluates the possibilities of use of solar chimney to improve stack ventilation in Malaysia's climatic conditions. The use of solar chimneys as stack ventilation in buildings is one way to increase natural ventilation and, as a consequence, improve indoor air quality. The discussion of previous researches indicated that application of solar chimney strategy can increase ventilation performance in the room with optimize configuration variable. Based on the above results a next strategy will be developed to improve stack ventilation.*

Keywords: Stack ventilation, Solar Chimney.

Introduction

In tropical climatic regions passive cooling is one of the most difficult problems to solve. The simplest and the most effective solution for active cooling are to introduce air conditioning. However, such equipment involves high initial and operational costs for installation, energy and maintenance. Therefore air conditioners are unlikely to be applied widely, in particular, for residential building. Thus, a passive cooling system is more desirable. Although in Malaysia, passive cooling method is a popular cooling strategy adopted in residential building, researches (Pan, 1997; Tan, 1997; Jones, 1993; Zulkifli, 1991; Hui, 1998; Sapian, 2004) have shown that its natural ventilation performance could not provide internal thermal comfort. Climate conscious design in the equatorial tropic assumes that air movement is one of the main cures for thermal comfort ills. According to Hui (1998), the indoor air velocity is about 0.04m/s – 0.47 m/s in low rise building under Malaysian climate condition. The reasons may be due to inappropriate design solutions for indoor air movement or low outdoor air velocity remains to be determined. However, recent data from the Malaysian Metrological Service Department showed that mean outdoor air velocity is between 1 m/s to 1.5 m/s and less in suburban terrain roughness (Majid, 1996).

Natural ventilation may result from air penetration through a variety of unintentional openings in the building envelope, but it also occurs as a result of manual control of building’s openings doors and windows. Air is driven in and out of the building as a result of pressure differences across the openings, which are due to the combined action of wind and buoyancy-driven forces. Today, natural ventilation is not only regarded as a simple measure to provide fresh air for the occupants, necessary to maintain acceptable air-quality levels, but also as an excellent energy-saving way to reduce the internal cooling load of housing located in the tropics. Depending on ambient conditions, natural ventilation may lead to indoor thermal comfort without mechanical cooling being required.

Natural Stack Ventilation

In theory, there are two natural ventilation mechanisms (ASHRAE, 1997). First is by wind pressure and the second is by temperature difference or stack effect. Both mechanisms have the same aim, which is to act as an aid to create air movement and consequently control the indoor air temperature (Sapian, 2004). Air flow through a building is created by a pressure difference between two opposing sides. The pressure difference between any two points on the building envelope determines the potential driving force for ventilation where openings are provided at these points, when wind blows and impinges on a building, a distribution of static pressure is developed over the building's exterior surface that is determined by the wind direction. Temperature difference between the indoors and outdoors of a building creates a difference between outdoor and indoor air densities. Openings at different levels cause the resulting pressure differences to generate air flow. The warmer indoor air that is less dense rises and flows out of the building through the top openings, and colder air enters the building through lower openings near its base (Majid, 1996). The same principle can be applied for opening at differences height, the different in pressure between them is due to the vertical gradient (Awbi, 2004).

As applied to a hot humid condition with open windows, the temperature differences between inside and outside is unlikely to exceed 5º C; the maximum height difference between inlet and outlet in a single storey building is less than 1.5m (for a total ceiling height of 3m and an inlet with a sill height of 0.6 m and an outlet with a sill height at 1.8m), the wind speed in the opening would be just over 0.3m/s, but with an average internal wind speed considerably lower and certainly less than 0.25m/s. Following this, Evans (1980) stated that the stack effect cannot be relied on to provide cooling using air movement over the skin under hot humid condition. It utilizes solar radiation, which is abundant in these regions, to generate the buoyant flow. However, as currently applied, the induced air movement is insufficient to create physiological cooling. Velocities associated with natural convection are relatively small, usually not more than 2 m/s (Mills, 1992). Air movement created by the stack effect is usually too weak to achieve physiological cooling. It is less than the recommended air speed range for cooling of 0.15 to 1.5m/s in tropical condition (Satwiko, 1994). More studies are needed to improve the ventilation performance of this cooling method. It can be seen that two means are available for improving air movement: firstly, by increasing the air volume (stack height) and secondly, by increasing the air temperature difference. Meanwhile, the indoor air temperature has to be kept low. All the above designs involve stack effect.

Solar Induced Ventilation

Stack induced ventilation can be improve by solar induced ventilation. However, in cases where the wind effect is not well captured then solar–induced ventilation may be a viable alternative. This strategy relies upon the heating of the building fabric by solar radiation resulting into a greater temperature difference. There are three building element commonly for this purpose: Trombe Wall, Solar Chimney, and Solar roof (Awbi, 2004).

The first type incorporates glazed element in the wall to absorb solar irradiation into the wall structure. The building has double walls which are combined into a shaft at their upper end. The south facing shaft wall was made from glass. The solar radiation that penetrates the glass heats the inner wall. Eventually, this inner wall heats the air which will rise and induce a flow of fresh air from the openings below (Watson, 1979). Two examples of stack induced ventilation concepts is solar collector and stack height. The former shows one way to amplify stack effect by utilizing solar collectors and increasing the height of the hot air column (stack height). Critical parameters of this design are the stack height and cross sectional area of its inlet and outlet. A massive and high version of this type is needed to generate indoor air velocity as high as 1.0 to 2.0 m/s, which can be achieved easily in an ordinary shallow buildings (with no obstruction at all).

The second, form is the solar chimney which has long been known, and applied in vernacular architectural designs. In general, the induced air movement is not used directly to suck indoor air. Instead, it is used for ventilating the building (such as in the double skin building). A stack chimney is usually designed in combination with a wind tower in hot arid climatic regions. In many types of ventilated building, winds are considered to be more important than buoyancy. This is because wind induced ventilation flow is commonly stronger than stack induced flow, in particular, in low rise buildings. A milk house that was built in 1800s is a historical example of a stack chimney application (Satwiko, 1993).

The last, solar roof is used in areas with large solar altitude. In this case a large sloping roof is used effectively to collect the solar energy (Awbi, 2004). A solar roof design called *the Nigerian Solar* Roof was studied by Barozzi et. al. (1992), using physical and numerical (Computational Fluid Dynamics Codes) modeling and data from Ife, Nigeria. Two findings were noticeable from this experiment. Firstly, both physical and numerical experiments gave almost identical results. Thus, it showed the potential of CFD Codes to simulate air flow. Secondly, both types of modeling indicated the presence of buoyancy driven ventilation within the model. However, the air speed within the occupant's zone was too low to create physiological cooling. The term s*olar chimney* is used extensively in Barozzi's experiment as the *chimney* shape is quite obvious. In his study the term *Solar chimney* seems to be more suitable as the chimney takes the form of a roof (Barozzi, 1992).

Research of Solar Chimney Ventilation

In the past decade, solar chimneys have attracted much attention in various investigations. Barrozi et al (1992) modeled a solar chimney-based ventilation system for buildings. The roof of a building performed as a solar chimney to generate air flow and provide cooling for the living room. Experimental tests were carried out on a 1:12 small-scale model of the prototype. Bouchair (1994) showed that for his 1.95m high and variable width chimney which was electrically heated, the optimum ratio of chimney width/high is 1/10 for maximum air flow rate. If the chimney was too big reverse circulation occurred whereby there was a down-ward flow. Hirunlabh et al. (1999) studied the performance of a metallic solar wall for natural ventilation of building in Thailand. Theoretical and experimental studies on the natural ventilation of buildings were also carried out by him for four different combinations of height and air gap. Alfonso and Oliveira (2000) compared the behaviour of a solar chimney with a conventional one. They presented a thermal model and transient simulation of a solar chimney by applying a finite difference model to the chimney brick wall assuming unsteady state one-dimensional heat transfer in the direction of the brick wall and not along the flow. Khedari et al (2000) studied the feasibility of using roof and wall to induce ventilation. They showed a significant potential of passive solar ventilation of houses. The Roof Solar Collector (RSC) could be formed below a heated roof to draw air from the inner spaces of a building. Waewsak et al (2003) carried out another field measurement for the same kind of roof solar collector that outer side of the RSC is replaced by glazing. Ong (2003) has presented a mathematic model and experimental result on a 2m high solar chimney. He used the matrix method for solving simultaneous equations for heat transfer. Drori (2003) studied the induced ventilation on a real-size house based on continuous temperature measurement performed inside and outside the building in summer. Satwiko (2005) found a Solar Wind Generated Roof Ventilation System for low cost dwellings located in high building density urban area. The roof prototype can generate evenly distributed vertical cross ventilation within the occupant’s zone.

Bansal (2005) developed a steady sate mathematical model for solar chimney system consisting of solar air heater connected to a conventional solar chimney. The estimated effect of the solar chimney was shown to be substantial in promoting natural ventilation for low wind speeds. Table 1 gives the summary of the review on researches on solar chimney ventilation.

Table 1 Summary of previous research related to solar chimney

	Climate			**Applied**			**Configuration**						**Performance**					**Tool**			
Research	**Hot Humid**	**Hot Arid**	**Temperate**	**Wall**	**Roof**	**Top of roof**	**Height**	**Width**	**Length**	**Thickness**	**Material**	**Opening**	**Air velocity**	**Air Mass flow rate**	**ACH**	**Temperature**	**temp Difference**	**Full scale**	**Scale**	**Simple method**	**simulation**
Barrozi, 1992	*					*					*	*	*						*		*
Bouchair, 1994			*	*				*				*		*							*
Hirunlabh, 1999	*			*	*		*	*			*			*					*	*	
Alfonso, 2000		*			*	*	*	*		*	*			*				*			*
Khedari, 2000	*				*			*	*			*	*		*		*	*			
Waewsak, 2003	*				*										*		*	*			
KS Ong, 2003	*			*				*			*		*			*			*	*	
U Drori, 2004		*			*											*		*			*
Satwiko, 2005	*				*								*								*
Bansal, 2005	*			*				*			*		*			*				*	

Many researches and experiments on solar chimney have been carried out under different conditions and utilizing different building element. From review it is found that researches on solar chimney ventilation can be categorize into:

a. Solar chimney strategy and application

Studies on solar chimney strategies and application have been expressed in terms of conventional solar chimney, roof solar chimney, wall solar chimney and combine solar chimney. Barrozi (1992) and Alfonso (2003) developed solar chimney built on the top of building that can be used to determine the conventional solar chimney. Barrozi (1992) experimented the building prototype in Nigeria consisted of a single chamber. The dimensions were approximately 5.5m (length) x 3.5m (width) x 3.0m (height), with a corrugated metal roof and fiberboard ceiling. The experiment was performed with a 1:12 scale model of the prototype, constructed with the same materials where possible. A solar chimney was built into the roof to provide ventilation and cooling. Air flowed through the windows and was exhausted out through the top of the solar chimney. Alfonso (2000) indicated the use of solar chimneys in buildings is one way to increment natural ventilation and, as a consequence, to improve indoor air quality. In order to evaluate the contribution of solar chimneys to the natural ventilation of buildings, two chimneys were built, one solar and the other one conventional, each one installed in one compartment of a test cell located in Porto, Portugal.

Khedari (2000), Waewsak (2003), Drori (2004) and Satwiko (2005) developed a roof solar collector that can be used to determine the roof solar chimney. Khedari’s roof solar collector can reduce the mechanical cooling energy cost of new housing built in a hot and humid region, with maximize the natural ventilation and minimize the fraction of sun energy absorbed by a dwelling. The roof solar collector “RSC” used CPAC Monier concrete tiles and gypsum board. Two units of RSC were integrated in the roof structure of the school solar house. The effects of air gap and openings of RSC on the induced air flow rate and thermal comfort were experimented. Waewsak (2003) investigated the performance of a new multi-purpose bio-climatic roof (BCR) developed by The Building Scientific Research Center, Thailand. The innovative functions of this BSRC-BCR are to decrease daily heat gain through the roof fabrics, to induce significant air ventilation rate, which improves the thermal comfort of residents, to ensure appropriate day lighting without any overheating and to act as a roof radiator during nighttime. Drori (2004) presented a research experimental induced ventilation of a one-story detached real-size building. The building is a small well-insulated manufactured home. It is located at the Northern edge of the Negev desert in Israel. The flow of air inside the building is induced by a hot element heated by solar radiation. This element is a horizontal metal sheet mounted above the roof of the building and forming a duct connected to the inner space of the building. Heated air flows out of the duct while fresh air is sucked into the manufactured home from the surroundings. Satwiko (2005) developed of the prototype roof chimney which takes advantages of the abundant solar radiation of hot humid climatic regions to create buoyancy driven ventilation. This research grows out of a desire to find a Solar-Wind Generated Roof Ventilation System for low-cost dwellings located in high building density urban areas where horizontal air movement is restricted. Solar-Wind Generated Roof Ventilation System was developed as a technique to improve indoor air velocity. It utilizes the available solar radiation and wind to maximize air temperature and wind pressure differences, respectively. A simple residential building type T21 (3x7 m^2) located in a high building density area was taken as the case study.

Bouchair (1994), Gan (1997), Hirunlabh (1999), Ong (2003), and Bansal (2005) developed a tromble wall modification to solar collector that can be used to determine the wall solar chimney ventilation. Bouchair (1994) conducted a solar chimney for the use in hot arid climates. In this case, the solar chimney walls are made from a high thermal capacity material, allowing a nighttime ventilation strategy to cool occupants within the building. During the daytime, dampers at the entrance and exit of the chimney are closed, allowing the chimney walls to store heat. At night, when the outdoor air is cool, the dampers are opened, and the store heat in the walls is transferred to the air within the chimney, thereby creating a temperature difference between the chimney air and the out doors, and consequent movement of cool air through the building. Hirunlabh (1999) proposed to utilize a passive system, namely, produced ventilation by a metallic solar wall "MSW” with room side insulation was constructed to investigate heat removal of houses in Bangkok. Room air is removed by ventilation produced by the MSW through openings at the bottom and the top of MSW. The air flow is determined by the inlet area and the square root of the height times the average temperature difference. Ong (2003) showed solar induced air ventilation to be provided by incorporating solar chimneys in building. The solar chimney is designed with one or more walls of a vertical chimney which are made transparent by providing glazed wall. Solar energy heats up the air inside the chimney. The solar chimney is similar to the Trombe wall except that the wall is assumed to have negligible mass. Bansal's (2005) studies are based upon the theoretical modeling and experimental validation studies conducted for a small-sized solar chimney, specially having absorber length less than 1m. The additional purpose of conducting this study for small-sized absorber length was to explore the possibility of using small-size window openings as solar chimneys in hot and arid climatic conditions.

b. Solar chimney and configuration variable

Studies on impact of configuration variable on solar chimney have been expressed in terms of height, length, width, thickness, material and opening. Several studies were concerned with height variable of solar chimney design ventilation. Hirunlabh (1999) found the temperatures increased with increased Metal Solar Wall (MSW) heights. In addition, temperature along the metallic wall height is at a maximum at the middle of the MSW and at minimum near the opening due to the incoming room air at the bottom of the MSW and to the contact with ambient air a the top. Experimental investigations of the performance of the MSW showed that with 1m height and 03.4 cm gap the MSW would produce optimum natural ventilation. Alfonso (2000) evaluated height parameters of solar chimney for satisfying the needed average flow rate. To evaluate the effect of chimney height on ventilation flow rate, several dimensions of chimney height between 0.5 and 3m were simulated. Air flow rate increases for higher values of height (H). The Amplitude in air flow rate (differences with between daily maximum and minimum) increases with chimney height.

Khedari (1998) showed the impact of length variable for solar chimney ventilation. This air velocity could be increased by increasing the surface area of solar chimney or the number of units of solar chimneys on roof, eastern and western walls.

Several works (Bouchair, 1994; Hirunlabh, 1999; Alfonso, 2000; Khedari, 2000 and Ong, 2003) considered the width of solar chimney as main variable. Bouchair (1994) completed an important study of a solar chimney for cooling ventilation. The chimney had a fixed height of 2m with both walls maintained at the same temperature. The influence of the chimney width was investigated. The effect of chimney width on the mass flow rate for inlet heights of 0.1m and 0.4m with the chimney wall temperature in the range of 30^{oC} to 60^{oC}. The ambient air temperature was maintained constant at 20^{oC}. It was found that in the chimney width range 0.1m – 1m, there was an optimum chimney width between 0.2 and 0.3m, which gives maximum ventilation rate. It was also found that this optimum chimney gap is essentially independent on the chimney wall temperature. However, it may be seen that the optimum gap is slightly wider when the chimney inlet becomes higher from 0.1m to 0.4m. The optimum chimney width was approximately one-tenth of the chimney height, or an aspect ratio (H/w) of 10. Hirunlabh (1999) investigated the relation between air gap and air mass rate in metallic solar wall. The hourly variations of the experimental air mass flow rate produces by the MSW for two different gaps (10-14.5 cm). It can be seen that the mass flow rate increased with increased gap. The maximum average of air mass flow rate during the hot period (10:00-16:00 h) was about 0.015 kg/s. Alfonso (2000) changed the width of solar chimney to evaluate the effect for air flow rate in the room. The variations of the study are as follows; chimney width (W) between 1m and 5m, which correspond to chimney sections between 0.2 and $1m^2$. Airflow rate increases linearly with the increase in W. Also, the amplitude in air flow rate increases with chimney width. One can also conclude that the increase in chimney width is more effective than the increase in chimney height, when one seeks to increase solar collection area in order to favour air flow rate. Khedari (2000) developed two units of Roof Solar Collector, tilted at 25°, and were integrated into the south-facing roof of the single side room solar house model. Their design allows us to test different air gaps, 8 and 14 cm. The variation of induced air flow rate by RSC with two different air gap spacing. It was found that with 14 cm air gap RSC1, the air flow rate is higher than that induced with 8 cm air gap RSC4. Therefore, large air gap is recommended. Ong (2003) investigated the effects of air gap and solar radiation intensity on the performance of different chimneys. In order to verify the theoretical model, experiments were conducted on a 2m high physical model with air gaps of 0.1, 0.2 and 0.3m. A solar chimney with a 0.3 m air gap was able to provide 56% more ventilation than one with a 0.1 m air gap. Bansal (2005) investigated the impact of air gap for entry of air in the chimney. An experimental setup was developed as a cubical wooden chamber having a size of 1m x 1m x 1m was made. One of its vertical sides was made like a sliding shutter. This shutter when lifted made opening for the exit of air from the room for its entry into the solar chimney.

In another study by Alfonso (2000) analyzed the effect of the thickness variable of solar chimney by performing simulations for thicknesses of 5, 10, 15 and 20 cm. Thickness does not change significantly the average flow rates, the maximum being obtained for 10cm. However, air flow distribution along time has some differences. A higher thickness allows more energy storage in the wall, decreasing the flow rate during sunshine hours and increasing it during the night period. However, thicknesses above 10cm do not produce a significant difference in the flow rate time distribution. To investigate the effect of insulation thickness on ventilation flow rate, new simulations for a thickness of 0 and 5 cm were performed. The use of insulation increases both daily and night flow rates. A thickness of 5cm gives results that are similar to the ones of an ideal insulation. Therefore, there is no need of a much higher thickness, for the climatic conditions considered.

The impact of material variable for solar chimney was done by Barrozi (1992), Hirunlabh (1999), Alfonso (2000), Ong (2003) and Bansal (2005). In Barrozi studies (1992), the solar chimney is made of corrugated metal, which has low thermal storage capacity, allowing ventilation to begin as soon as the sun adequately heats the metal. Therefore, this system is best suited to daytime ventilation, it having inadequate thermal capacity to maintain ventilation night. Hirunlabh (1999) developed the Metallic Solar Wall consists of a glass cover, air gap, black metallic plate and insulator made of micro fiber and plywood. The MSW was integrated to the south wall of the house. The MSW was 1m wide and 1m high, which is obvious as more radiation was absorbed by MSW. Alfonso (2000) compared between a conventional chimney and a modification of solar chimney. The modification of solar chimney is similar to conventional chimneys except that the south wall is replaced by a glazing. In order to perform experimental tests, an existing test cell was modified. The walls, ceiling and slab are made of concrete, with outside insulation. It is fundamental to use outside insulation in the brick wall, to take advantage of solar gains; if outside insulation is not used, solar assistance efficiency reduces by more than 60%; a thickness of 5cm is sufficient. Studies under Ong (2003) one side of the chimney is provided with a glass cover which wit the other three walls of the chimney form a channel through which the heated air could rise by natural convection. An opening at the bottom of the wall allows room air to enter the channel. The exposed surface of the heat absorbing wall is painted black to increase solar radiation absorption. The heat absorbing wall was made of pre-laminated polyurethane sheet, similar to the other solid walls. A 50 mm thick polystyrene sheet was attached to the back of the heat absorbing wall to provide additional heat insulation. The glass cover and the heat absorbing wall provided an air gap through which air could flow. Bansal (2005) used on the exposed side of the shutter of wall solar chimney with a 1mm thick aluminum sheet was attached with the help of glue and nails to act as a solar radiation absorber for the setup. Aluminum sheet was painted black with ordinary paint. On the same side, a telescopic frame of matching size was made with a provision of sliding on rollers. The face of this parallel to the sliding shutter was made with float glass. The vertical side of this telescopic part (parallel to the shutter) was made of 4 mm thick float glass. On the vertical face opposite the absorber, an opening was provided for suction of air from the surroundings. All the sides, exposed to ambient, were insulated using 2.5-cm-thick thermocol (EPS) sheets, for prevention of heat transfer. Similarly, on the backside of the absorber that faces inside of the chamber, 5 cm insulation was provided for prevention of flow of heat in this direction. It can be concluded that in hot climatic conditions, when windows are kept closed/ covered for preventing the entry of solar heat, the concept of solar chimney can be utilized by making minor modifications in the existing window design.

Studies about solar chimney opening variables are done by several researchers (Barrozi, 1992; Bouchair, 1994; Khedari, 2000). Barrozi (1992) used different window arrangements were obtained by maneuvering the light wooden wall panels, thus allowing the effect of different geometries on the airflow to be examined. A chimney vent is provided at the side of the solar chimney, allowing the exhaust of air. Bouchair (1994) concluded the impact of chimney inlet height (and thus inlet area) for solar chimney performances. The effect of the inlet height on the mass flow rate at two inlet height: 0.1m and 0.4 m for chimney width in the range of 0.1m to 0.5 m, that at a chimney width of 0.1 m, the mass flow rates were similar at both inlet heights. This suggests that the inlet height at this chimney width had little influence on the ventilation flow rate and the friction loss in the chimney dominated the total pressure loss in the system. However, it can be seen that with an increase in width, friction loss in the chimney was reduced and the influence of the chimney inlet height became more and more significant. Consequently, the friction loss at the inlet became the major contribution to the total pressure loss and determined the mass flow rate through the whole system at the large chimney widths. Khedari (2000) investigated different free opening vents. Its dimensions are as follows: 2.68 m height, 3.35m width and 3.45m length. The solar house has a window and a door with a grill on the northern side. The variation of induced air flow rate by Roof Solar Collector for the different opening vents RSC1, RSC2 and RSC3. It was found that with equal and larger size of free inlet–outlet openings, configuration RSC1, the induced air flow rate was the highest one. Therefore, opening vents have to be of equal size and as large as possible. A higher number of Air Change Rate (ACH) could be done by increasing the surface area of RSC, i.e., increasing the number of RSC units and making use of walls to act similarly. Opening the window and door is less efficient than using solar chimneys, as temperature difference between the rooms and ambient was higher than that obtained with solar chimneys.

c. Solar chimney strategy and performances parameters

The relation between solar chimney and air velocity performance carried out by Barrozi (1992), Khedari (2000), Ong (2003), Satwiko (2005) and Bansal (2005). Barrozi (1992) illustrated the air velocities inside the building were found to be generally very low suggesting that the cooling effect may be less than required. Large flow velocities were predicted along the inclined roof surfaces due to high buoyancy forces. The results showed that the flow pattern in the room was very sensitive to the window geometry, the air flowed indirectly along a path from the window inlet to the ceiling opening; while for window geometry increased, the air flowed from the inlet almost vertically along the wall to the ceiling and then through the ceiling opening. Khedari (2000) indicated that the average air velocity along horizontal planes increased with increasing vertical height. Thus, at the living level, about 1m above floor, there is continuous air motion induced by the buoyancy driven force resulting from the four solar chimney ventilators used here. Regarding thermal comfort, the induced air motion of about 0.04 m/s cannot satisfy occupants as with temperature of about 35°C–37°C, a higher air velocity is needed. This air motion could be increased by increasing the number of units of solar chimneys on roof, eastern and western walls and by installing several free openings at the northern facade of room. Ong (2003) showed the higher air velocity through the large air gap of solar chimney, causing greater cooling effects on the heat absorbing wall and glass which then tended to be lower. Air velocity increased with solar radiation and larger air gaps. Air velocities between 0.25 m/s and 0.39 m/s for radiation intensity up to 650 W m were obtained. No reverse air flow circulation was observed even at the large gap of 0.3m. It could be seen that the solar chimney induced air flow rates of between 0.25m/s and 0.39m/s at air gaps between 0.1m and 0.3m, respectively at 650 W/m. Satwiko (2005) found, ‘The Solar Wind Generated Roof Ventilation System’ could generate an indoor air speed range from 0.15 to 0.7m/s, with all windows closed, and applying the wind speed of 3.53m/s at 10m above the ground, combined with solar radiation of 540 W/m^2. When the wind was calm (0 m/s), the heat from absorbed solar radiation can create an indoor air velocity of 0.4m/s. Obtains thermal comfort through physiological cooling. Increasing air movement is the most logical way to passively achieve thermal comfort in a hot humid climate. Bansal (2005) analyzed the small size solar chimney has opened possibilities of utilizing windows as solar chimneys since the flow velocity up to 0.24m/s has been experimentally recorded. For the three combinations that were experimentally investigated, the highest flow velocity in the chimney was found to be 0.24m/s.

Several studies have been looked about the air mass flow rate performance in solar chimney (Bouchair, 1994; Hirunlabh, 1999 and Alfonso, 2000). In Bouchair’s experiments (1994), a mass balance investigation was also carried out for the mass flow rate through the window (room, inlet), the chimney inlet and the chimney outlet. However, at a chimney width of 0.5m, the measured mass flow rate at the chimney outlet was higher than that through the window and the chimney inlet. Hirunlabh (1999) found that the Metalic Solar Wall with 14.5 cm air gap and 2 m^2 of surface area (HxW: 2x1m) produced the highest air mass flow rate of about 0.01-0.02 kg/s. Alfonso (2000) concluded that a significant increase in ventilation rate can be achieved with solar chimney. Average flow rates for a solar chimney are always higher than the ones for a conventional chimney.

Studies on air change rate performance were carried out by Khedari (2000) and Waewsak (2003). Khedari (2000) illustrated the units of Roof Solar Collector produce the average number of induced air change is about 4–5 ACH, which is not sufficient to satisfy complete resident thermal comfort. A higher number of ACH, depending on season, up to 20 is required for houses without any mechanical cooling device. Waewsak (2003) complete a field measurements of the thermal and lighting performance of the BSRC-BCR demonstrated that this innovative bio-climatic roof could reduce heat gain significantly and induce significant air change. With these characteristics, it is expected that the bio-climatic roof can achieve thermal comfort without any mechanical devices during a long period annually where outdoor temperature is not excessive. The rate of induced air change depends mainly on the intensity of solar radiation. The corresponding induced ACH by BSRC-BCR was quite high during the day varying between 10–15 in summer and 5– 8 in winter. Obviously, this high air change rate induced by BSRC-BCR is due to the fact that more heat is admitted through the transparent tiles. Therefore, the BSRC-BCR can improve indoor thermal comfort considerably. To satisfy resident comfort for different activities and non-air conditioned spaces, a higher ACH is required (about 20–25 ACH). This could be achieved easily by increasing the number of units of BSRC-BCR.

Studies on the temperature parameters on solar chimney performance were carried out by Hirunlabh (1999), Ong (2003), Drori (2004) and Bansal (2005). Hirunlabh (1999) illustrated the room temperature during tests was near to ambient air, ensuring human comfort resulting from ventilation produced by Metallic Solar Wall. The MSW can reduce significant heat gain in experimented house. Ong (2003) evaluated the prediction of the temperatures of the glass glazing and the heat-absorbing wall and also the temperature and velocity of the induced air flow in the chimney. Mean wall temperatures were always higher than mean glass or mean air temperatures. Mean air temperatures were always lower than mean glass temperatures for the range of incident solar radiations encountered. Mean air temperatures and temperature rise increased with solar radiation. It was also found that mean temperatures and temperature rise decreased with air gap depth. Drori (2004) showed the experimental and numerical results that the air temperature inside the structure typically followed the ambient temperature, indicating that effective induced ventilation has been achieved in the modified structure, while in the closed manufactured home the air temperature was considerably higher than the ambient, especially during the afternoon hours. The results show that effective induced ventilation has been achieved, and the air temperature inside the structure typically followed the ambient temperature. In contrast, when the manufactured home had no openings, the temperature inside it was considerably higher than the ambient, especially during the afternoon hours. Bansal (2005) indicated the calculated temperature of glass and air in the flow channel tends to be lower than their respective measured values of the small size solar chimney. It has been found that the developed theoretical model slightly under-predicts the temperatures of glass and air in the flow channel. Nevertheless, it can be concluded that the model can predict the performance of such systems well and this approach is even applicable to small-sized solar chimneys. More heat loss from the absorber reduces its temperature and increases the temperature of air. Due to this increase, the temperature difference between glass and air is reducing; hence the heat transfer from glass to air also gets reduced.

Studies on solar chimney and temperature differences carried out by Khedari (2000) and Waewsak (2003). Khedari (2000) showed the use of Roof Solar Collector to reduce the rate of heat transferred through a ceiling by inducing natural ventilation. The temperature of CPAC Monier, air and gypsum board is changing along with the intensity of solar radiation. When the solar chimney ventilation system was in use, room temperature was near that of the ambient air, indicating a good ability of the solar chimney to reduce house’s heat gain and ensuring thermal comfort. Waewsak (2003) showed the variations of the temperature differences (TD) index for different days in summer and winter, respectively. It can be seen that the TD index of Bio Climatic Roof (BCR) was almost always below or close to neutral (zero) particularly during the hottest midday period (10:00 a.m.–3:00 p.m.). This means that indoor air temperature is distinctly lower than outdoor and BCR has good potential for decreasing heat accumulation and inducing a high ventilation rate. When compared to RSC, BCR performs much better as the daytime index is smaller than that of RSC. It should be pointed out that the TD index is higher than zero in the afternoon (after 4 p.m.) due to the heat gain through the non-insulated west wall (common masonry wall). During night time, both BCR and RSC perform similarly as good radiative coolers. From these results, it can be concluded that the BCR roof design could decrease heat accumulation efficiently year round.

d. Solar chimney and research tool

Alfonso (2000) showed the use of thermal model can predicts with good accuracy measurements. Originally, it was a one-zone test cell, with a floor area of 12 m^2 (4x3m). The experiment used full scale two rooms were equipped with a heating facility, with a precise control of the inside temperature. The exhaust chimneys were fully instrumented with anemometers, thermocouples and flux meters. In his work, results of air flow rate measurements in both compartments with a tracer gas technique are shown, as well as their comparison with theoretical values obtained with a simulation program specially developed for this purpose. A tracer gas technique was used for measurement of air flow rates of both compartments of the test cell, because it enables the evaluation of air exchange rates of buildings in real time. Khedari (2000) introduced a full scale experimental method to measure the air temperature and the air velocity at different points on the Roof Solar Collector units and in the room. The study was conducted using a single-room house of approximately 25m^3 volume. The roof was made by using CPAC Monier concrete tile dark red color. The floor was plywood on grade. The surface area of the RSC unit is considered equal to 1.5 m^2 (*LxW*: 1.5x1 m^2). The outer side was made by CPAC Monier concrete tiles (33x42x1.5 cm^3; 4.4 kg/piece; dark red color while the inner one was made of gypsum board 100x150x0.9 cm^3; 1.7 kg). Experimentation started at 8:00 a.m. and ended at 5:00 p.m. by recording data at 30 min intervals. Waewsak (2003) compared a conventional Khedari's Roof Solar Collector (RSC) with Bio Climatic Roof (BCR). The RSC is composed of CPAC Monier tiles at the outer side, 0.14 m air gap and gypsum board at the inner one. Both units of 1.5 m^2 surface area each were integrated into the south facing roof of a single-room solar house of 25 m^3 volume. White plywood boards were used to separate the interior space under the two units (BCR and RSC) to make two separate compartments "rooms". Data were recorded every 30 min during 24 h. The experiments were carried out during different days in winter (December 1999) and summer (March–April 2000). Drori (2004) experimented with a manufactured home a one-story detached real-size building has been studied experimentally and numerically. An extensive experimental study was based on continuous temperature monitoring performed inside and outside the building in summer. Velocity measurements inside the building were performed, as well. Typical experimental runs took from 12 h to a few days. An extensive experimental study included temperature and velocity measurements both in the modified open and the original closed structure, with typical experimental runs from at least one full day to several days long.

Barrozi (1992) developed solar chimney ventilation using a scale model and the result were used to validate a two dimensional, CFD simulation model. The experiment was performed in a sealed laboratory chamber for the conditions of overhead sun and no wind, the scenario placing highest demand upon the ventilation system. Climatic parameters were limited to the ambient outdoor temperature and solar radiation. Relative humidity was assumed to be constant. Several series of tests were taken to asses the reliability and repeatability of their experimental data. A simple solar simulator consisting of four Osram Ultra Vitalux lamps was places above the model to heat its room, until steady state conditions were achieved. A PC (computer) data acquisition system recorded converted data from temperature and velocity sensors. Velocity measurements were limited to the solar chimney outlet region as velocities at other sections were too low to allow accurate measurement. Flow visualization was achieved by injecting smoke near the inlet (window) and recording the smoke trails on film. Hirunlabh (1999) used a small model of a solar house with 1.57 m height and base area of 2.24x2.34 m^2. It had one window and a door with an air grille on the north side. A set of type-K thermocouples were used to measure the temperature at several points of the Metallic Solar Wall and at six points inside the room. A hot wire anemometer was used to measure the air velocity at the outlet and inlet vents at several points and an average was calculated. Campbell, portable hybrid and data logger recorder were used to record temperatures. A propeller type anemometer was used to measure the velocity and temperature of ambient air. Studies by Ong (2003) with scale experimental models were carried out outdoors on the roof and the experimental model exposed to both direct and diffuse solar radiation. The solar chimney was oriented facing south and exposed to solar radiation.

Mathematic studies on wall solar chimney use were investigated by using Metal Solar Wall “MSW” by Hirunlabh (2001). Comparison between numerical study and experimental results showed a good agreement. Therefore the numerical model is validated. Thus, it can be used to evaluate the long term reduction of heat transfer into the habitation. Ong (2003) used a mathematical model to simulate the thermal performance of a solar chimney by predicting the surface temperatures of the wall and glass cover and the temperature and induced natural convection flow rate of the air stream in the chimney. More satisfactory qualitative agreement was obtained between experimental and theoretical results. The difference between experimental and predicted instantaneous efficiency values was about 10% in all cases. Bansal (2005) developed a mathematical model for predicting airflow velocity in a solar chimney, through predicting temperature of the absorber, air in flow channel and glass cover. Experimental validation of the model has been done using a solar chimney having less than a 1-m-high absorber. Good agreement between observed and calculated results has been obtained. A mathematical model of the experimental setup was developed for estimating the performance of the solar chimney under different ambient conditions. Validation of the theoretical model with the experimental results was carried out in two steps. The first step was the validation of temperatures at various points and the second one was the validation of the airflow rate.

Barrozi (1992) completed an experimental research with numerical study of a building with a solar chimney. For the numerical simulation, the following simplifications were made in their work: the problem was two dimensional, radiation inside the building was negligible, flow was steady and laminar. Alfonso (2000) tried to obtain Computational Fluid Dynamic (CFD) based models predict accurately air velocity distribution in the solar chimney, but assuming very simple wall surface conditions: typically, a constant surface temperature and a constant air heat transfer coefficient. The model combines the equations for heat transfer processes in the solar chimney with the equations for natural ventilation flow. However, a constant value leads to calculated flow rates that are within 10% of the measured values. Therefore, the model offers enough confidence to allow its use for different situations and geometries. In another study by Drori (2004) with numerical studies were performed using the Fluent 4.52 CFD software. Their purpose was to exemplify the flow field typical to the system investigated during the day hours. The temperatures of the heated metal sheet and the ambient air were almost constant for 4–5h about noon. Since these temperatures determine the system performance, it was assumed that steady ventilation of the structure could be achieved. For this reason, steady-state simulations were performed at this stage. Transient simulations would have required much more computing resources, and will be performed in the future. The research by Satwiko (2005) used computer simulation techniques to calculate and analyze the aerodynamic and thermal performances of SiVATAS. This included the aerodynamics and thermal consequences for any changes in its form and material. A general purpose computational fluid dynamics (CFD-ACE+) program was utilised to explore, analyse and develop a roof model based on its aerodynamics and thermal performance to obtain optimum wind pressure and temperature differences. Comparisons were made with physical scale models. The CFD program requires inputs representing problem type, flow domain (material, type of flow, etc.), boundary conditions (walls, inlet, outlet, symmetric wall), and calculation method. The problem type is used to activate calculation modules; in this case, Flow, Heat Transfer, and Turbulence modules.

Conclusion

Previous sections reviewed the literature about solar chimney in order to get a clear understanding of the state-of–art knowledge in the field and identify the areas which had not been covered in the past. The review revealed that research on solar chimney had been focused mainly on four issues: solar chimney strategy and application, impact configuration variable, impact performance parameters, and solar chimney research tool. Many studies in hot humid tropical climate suggested that possibility the use of solar chimney to increase stack ventilation in the building but still not enough for thermal ventilation requirement. Also, little studies are applied of combination of solar chimney type in the building to increase thermal ventilation performance.

Though it was mentioned in many research works and publication that solar chimney configuration variable to increase solar chimney performance, there many research done was only little research done on related solar chimney configuration with room configuration. Review also suggests that solar chimney have a significant impact on the thermal ventilation specially for psychological cooling. Few studies have looked into this aspect under different thermal comfort ventilation standard, and with different solar chimney strategies. Further they do not produce holistic performance result for any particular climate and thermal comfort standard. Generally, research tool in solar chimney studies used experiment model, but many numeric and computational method was validation. Validation result shows good agreement with real measurement. However, little research done by computational tool and was validations with many experimental model.

Thus, the above reviews suggest that solar chimney strategy on increase air velocity and decrease air temperature has been dealt as separate issues. There is no specific research done to study the relationship between optimal solar chimney configuration and psychological cooling performance. Therefore this next research attempts to focus on the solar chimney configuration to improve stack ventilation for thermal ventilation in tropical condition.

References

Abdul Majid Ismail, 1996, Wind Driven Natural Ventilation in High-Rise Office Building With Special Reference To The Hot-Humid Climate of Malaysia, University of Wales College of Cardiff, PhD, Thesis,

Alfonso, Clito.2000. Solar Chimneys: Simulation and Experiment, Energy and Buildings, Vol. 32, Pergamon Press., pp. 71–79.
ASHRAE Handbook Fundamentals, 1989. American Society of Heating and Air Conditioning Engineers, Inc. Atlanta.

Awbi, Hazim B., 2003. Ventilation of Building, Spon Press, London.

Bansal, N.K, R. Mathur, M.S. Bhandari, 1994. A Study of Solar Chimney Assisted Wind Tower System for Natural Ventilation in Buildings, Building and Environment, Vol. 29, 4, Pergamon Press., pp. 495-500.

Barozzi G.S., Imbabi M.S.-E., Nobile E., Sousa A.C.M. 1992. Physical and Numerical delling of a Solar Chimney-based Ventilation System for Buildings. Building and Environment, Vol.27, No.4, Oxford: Pergamon Press, pp.433-45.

Bouchair. 1994. Solar Chimney for Promoting Cooling Ventilation in Southern Algeria, Building Services Engineering Research and Technology, Vol.15, pp.81-93.

Drori, U, G.Zizkind, Induced ventilation of a one-story real size building, Energy and Building. Vol 36, 2004

Evans M, Housing Climate and Comfort, The Architectural Press Ltd., London, 1980

Flomerics Limited. 2000. “Flo Vent User’s Guide”

Gan, G, A. 1998. Numerical Study of Solar Chimney for Natural Ventilation of Buildings with Heat Recovery, Applied Thermal Engineering, Vol. 18, Oxford: Pergamon Press , p 1171-1187

Hui Seng Kin, 1998. Natural Ventilation of Low Cost Dwellings in The Hot Humid Tropics Malaysia, Master Thesis

Hunt, G.R., Linden, P.F., 1999. The Fluid Mechanics of Natural Ventilation—Displacement Ventilation by Buoyancy-Driven Flows Assisted by Wind. Energy Environ. Vol. 34, pp. 707–720

Khedari J, Weerapong Mansirisub, Sompong Chaima, Naris Pratinthong, Jongjit Hirunlabh. 2000. Field Measurements of Performance of Roof Solar Collector, Energy and Buildings, Elsevier Science Ltd. ,Vol 31, pp 171–178.

Khedari J. 2000. Field Measurements of Performance of Roof Solar Collector, Energy and Buildings, Elsevier Science Ltd. ,Vol 31, pp 171–178.

K.S. Ong, C.C. Chow. 2003. Performance of a Solar Chimney, Solar Energy, Elsevier Science Ltd., Vol. 74, pp 1–17.

Mills A.F.1992. Heat Trans Boston: Irwin. p.293.

M Rajeh. 1989. Natural Ventilation in Terrace Housing of Malaysia: Effect of Air Well on Air Flow and Air Velocity, University of Queensland, Master Thesis.
Sapian Abdul Razak. 2004. Possibilities of using Void to Improve Natural Cross Ventilation in High-rise Low Cost Residential Building, Thesis.

Satwiko, Prasasto.1994. The Development and Modelling of a Natural Ventilation System for Indonesian Conditions, Thesis Master of Building Science, Victoria University of Wellington.

Satwiko, Prasasto.2005. Solar-Wind Generated Roof Ventilation System (SiVATAS) for a Warm-Humid Climate, International Journal of Veentilation, Vol 3 No 3, 2005

Waewsak. J, Hirunlabh, Khedari, U.C.Shin, Performance Evaluation of the BSRC multi purpose Bio-Climatic Roof, Building and Environment, Vol 38, 2003

Watson D., ed. 1979. Energy Conservation through Building Design. An Architectural Record Book, New York: McGraw Hill Book Company., p.34.