INVESTIGATION OF POTENTIAL SOLAR INDUCED VENTILATION STRATEGY IN HOT AND HUMID CLIMATE

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ABSTRACT

The use of solar energy in solar induced ventilation helps to enhance the stack ventilation, which is normally less efficient in hot humid climate due to the small temperature difference between the inside and outside of naturally ventilated buildings. This paper aims to examine a potential solar induced ventilation strategy for hot humid climate. There are two methods used, which are a literature survey and a preliminary test. The literature survey was executed on the Trombe wall, solar chimney and roof solar collector. This survey resulted in the combined roof solar collector and vertical stack as the most appropriate strategy. A preliminary test using a physical model was executed in the actual environmental conditions. The findings indicate that the proposed strategy attained the air temperature difference (Ti-To) of 8.5ºC for 633 W/m² solar radiation. This air temperature difference was more than the usual air temperature difference between the inside and outside of naturally ventilated buildings in Malaysia. Hence, the paper concludes that the proposed strategy is able to enhance the stack ventilation effect in hot and humid climate.

Keywords: *Stack ventilation, solar induced ventilation, hot and humid climate*

1. INTRODUCTION

Stack ventilation is a strategy of natural ventilation. The factors influencing the airflow induced by stack ventilation are the air temperature difference between the indoor and outdoor, as well as the vertical distance between the inlet and outlet (Brown & DeKay, 2001). However, the climatic condition of Malaysia, which results in small air temperature differences between the indoor and outdoor of naturally ventilated buildings, has made the performance of stack ventilation less efficient. The air temperature difference between the indoor and outdoor is normally less than 5ºC (Rajeh, 1989). Nugroho *et al.* (2007) conducted a measurement on the indoor and outdoor air temperature of terrace houses in Johor Bharu, Malaysia. The measurement on 21st March 2006 indicated that the air temperature difference between the master bedroom and the outdoor was around 0.6ºC to 3.1ºC from 8 am to 7 pm. Meanwhile, at noon around 12 pm to 1 pm, the air temperature difference was around 1ºC only. The finding was also in accordance with Kubota *et al.*'s (2009) finding on the field measurement of terrace houses, which also resulted in 1ºC of indoor-outdoor air temperature difference at 12 pm. Consequently, solar induced ventilation is deemed as a viable alternative strategy, as higher air temperature inside the stack can be generated (Awbi, 2003).

The basic concept of solar induced ventilation is that - the absorber wall or plate is heated by the solar radiation, thus creating higher air temperature inside the stack or cavity. The decrease in the air density due to the increase in the temperature also causes the air to rise. The heated air is then replaced by the cooler air from the attached space (Awbi, 2003; Harris & Helwig, 2007). There are three distinguished solar induced ventilation strategies, namely, the Trombe wall, solar chimney and roof solar collector (Awbi, 2003), as shown in Figure 1. Although they have a similar operating concept, their configurations and locations are different. Hence, each has its own strengths and weaknesses in response to the related climate. The climatic condition is an important factor to be considered when applying solar induced ventilation (Lee & Strand, 2009).

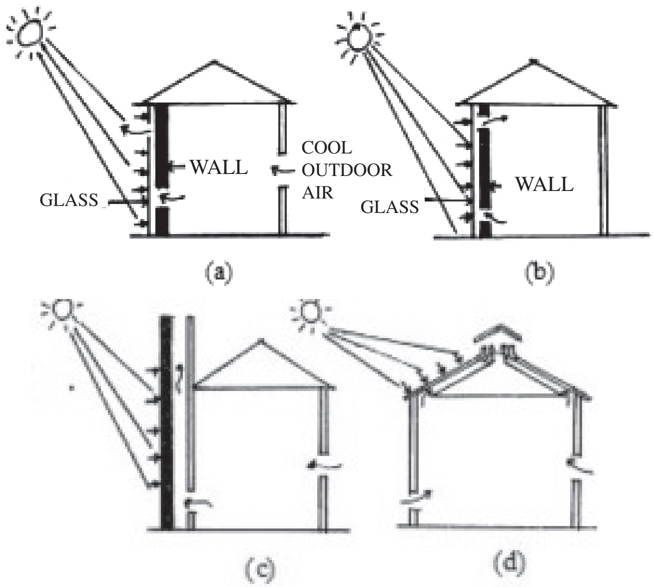

Figure 1: Solar induced ventilation strategies: (a) Trombe wall for summer ventilation, (b) Trombe wall for winter heating, (c) Solar chimney, (d) Roof solar collector (Source: Awbi, 2003).

This paper proposes a potential strategy of solar induced ventilation in hot and humid climate based on a literature survey. The proposed strategy is then examined in determining its ability to create a significant temperature difference between the air inside the stack (Ti) and the ambient air (To). This temperature difference (Ti-To) is important in creating a sufficient stack 44 pressure to induce stack ventilation. There are six sections in this paper. The first section addresses the issues relating to the stack ventilation in Malaysia, as well as the basic concept and strategies of solar induced ventilation. The second section presents the literature survey of the solar induced ventilation performances in hot and humid climate, whilst the third section describes the proposed potential strategy as a result of the literature survey. The preliminary testing executed in investigating the performance of the proposed strategy is presented in section four, whereas the results of the preliminary testing are presented and discussed in section five. The overall findings are finally concluded in section six.

2. LITERATURE SURVEY OF SOLAR INDUCED VENTILATION PERFORMANCES IN HOT AND HUMID CLIMATE

The hot and humid climate is characterized by the high temperature, humidity and rainfall. The air temperature is almost constant throughout the year, with the annual mean temperature of about 27ºC (Givoni, 1976). Malaysia's hot and humid climate is influenced by monsoon seasons, namely, southwest monsoon, northeast monsoon and two shorter periods of inter-monsoon seasons. The southwest monsoon occurs from May to September, whereas the northeast monsoon starts in November and ends in March. The inter-monsoon seasons are in April and October (Malaysian Meteorological Department, 2010). Besides that, Malaysia also receives abundant solar radiation, which makes solar energy as a potential energy resource (Sopian & Othman, 1992).

There are many previous studies executed on the performance of solar induced ventilation in hot and humid climate. These studies can be classified into four categories, which are the performance of Trombe wall, the performance of solar chimney, the performance of roof solar collector and the performance of the combined strategies. There are four variables used in measuring these performances, namely, the airflow rate, the air change per hour (ACH), the air velocity and the air temperature.

2.1 The Performance of Trombe Wall

Hirunlabh *et al.* (1999) examined the performance of Trombe wall at a house in Thailand. The studied Trombe wall had a slight modification from the conventional one, in which a metallic solar wall was applied. This metallic solar wall comprised zinc plate, micro-fibre and plywood. The highest airflow rate induced by this modified Trombe wall was about 0.01 – 0.02 kg s^{-1}. Meanwhile, the Trombe wall developed by Ong and Chow (2003) was able to induce the air velocity between 0.25 m/s to 0.39 m/s at the solar radiation intensity of 650 W/m^2. The developed Trombe wall had a cavity width between 0.1 and 0.3 m. The Trombe wall concept was also applied to window-sized solar induced ventilation. Furthermore, the development of such solar induced ventilation had been executed by Bansal *et al.* (2005), Chantawong *et al.* (2006) and Mathur *et al*. (2006a). The developed window-sized solar induced ventilation by Bansal *et al*. (2005) was able to induce the air velocity up to 0.24 m/s at 700 W/m^2 solar radiation incident, whilst the glazed solar chimney wall (GSCW) by Chantawong *et al.* (2006) was able to induce the air velocity about 0.07 to 0.14 m/s. Both of the developed solar induced ventilations had heights of less than 1 m, which enabled them to be applied to the window design. Meanwhile, the performance of Mathur *et al*.'s (2006a) window-sized solar induced ventilation was measured based on the air change per hour (ACH). For a 25 m^3 room size, it was able to induce 2 to 5.6 ACH at 300 to 700 W/m^2 solar radiation incident. Besides, for the window application, the Trombe wall concept of solar induced ventilation was also applied to the façade of multi-storey buildings in Thailand (Punyasompun *et al*. 2009). The application resulted in the reduction of room air temperature by about 4ºC to 5ºC, which was lower than the building without the solar induced ventilation.

2.2 The Performance of Solar Chimney

The solar chimney performances in hot and humid climate were examined by Nugroho (2007) and Arce *et al*. (2009). The developed solar chimney by Nugroho (2007) was applied at Malaysian single-storey terrace houses. The investigation showed that the solar chimney was able to increase the air velocity from less than 0.1 m/s to 0.7 m/s. The solar chimney performance in the hot and humid climate of south-eastern Spain was examined by Arce et al. (2009). The constructed solar chimney, which had a total height of 5.6 m, a width of 1.0 m and an air cavity of 0.3 m, was able to induce an average of 177 m^3/h airflow rate.

2.3 The Performance of Roof Solar Collector

The application of roof solar collector in hot and humid climate had been studied by Bansal et al. (1994) since 1994. In the study, a roof solar collector was combined with a wind tower. The results showed that the mass flow rate induced by the wind tower alone was 0.72 kg/s, whilst the combination of wind tower and roof solar collector resulted in higher mass flow rate, which was about 1.4 kg/s. Meanwhile, the application of roof solar collector on modern houses in Thailand was able to induce between 0.08 to 0.15 m^3 s ^{1} m ^{2} of ventilation rate (Khedari, Hirunlabh, & Bunnag, 1997). In addition, the integration of a two-unit roof solar collector, which had a total surface area of 3 m^2 on houses in Thailand was able to induce about 4 to 5 ACH (Khedari, Mansirisub, Chaima, Pratinthong, & Hirunlabh, 2000a). Due to this potential, various roof solar collector configurations were developed for residential in Thailand (Hirunlabh, Wachirapuwadon, Pratinthong, & Khedari, 2001). The highest airflow rate of 0.07 m^3/s was induced by a roof solar collector, which configuration resembled the traditional Thai roof. Meanwhile, the application of roof solar collector during the summer months in Jaipur, India, had resulted in the induced mass flow rate by about 190 kg/h (Mathur, Mathur, & Anupma, 2006b). Conversely, a roof solar collector that utilized a radiant barrier at its lower plate was examined by Puangsombut et al. (2007). The radiant barrier was able to increase the convective heat transfer and airflow rate by about 40 to 50%, as well as reducing the heat transfer through the lower plate by about 50%. Meanwhile, the application of roof solar collector with a wetted roof was able to reduce the room temperature by about 2ºC – 6.2ºC, which was more than the temperature reduction by the roof solar collector alone (Chungloo & Limmeechokchai, 2007). Besides the wetted roof, the application of roof solar collector with cool ceiling had also shown positive results. This combination was able to reduce room temperature by about 0.5ºC to 0.7ºC, which was more than the application of roof solar collector alone. There was also a reduction in the ceiling temperature by about 2ºC to 4ºC (Chungloo & Limmeechokchai, 2009).

2.4 The Performance of Combined Strategies

The performances of the combined strategies were studied by Khedari et al. (2003) and Khedari *et al*. (2000b). Khedari *et al.* (2003) examined the application of roof solar collector and Trombe wall at an air-conditioned building. These solar induced ventilation strategies were simultaneously applied in order to reduce heat transfer through the walls and roofs, thus decreasing the air-conditioner cooling load. Comparisons were made between the houses with and without the solar induced ventilation. The investigations indicated that the utilization of solar induced ventilation at the air-conditioned building was able to save about 10-20% of daily electrical consumption. Khedari *et al.* (2000) had simultaneously applied four solar induced ventilation strategies, namely, roof solar collector (RSC), modified Trombe wall (MTW), Trombe wall (TW) and metallic solar wall (MSW) at a 25 m^2 single-room school building. The reason was to enhance the ACH, as the desired ACH for thermal comfort was unable to be achieved by one strategy only. The ACH induced by one strategy was about 3 to 5, whereas the combined strategies were able to induce ACH by about 8 to 15 (Khedari, *et al.,* 2000b). However, it still did not achieve the target ACH for houses without a mechanical cooling device, which was above 20.

2.5 Research Gaps and Point of Departure

From the previous studies, it is noticed that the Trombe wall, the solar chimney and the roof solar collector are able to induce stack ventilation in hot and humid climate. Besides inducing the stack ventilation, they are also able to reduce the indoor air temperature, as well as promoting energy savings in buildings. However, there is no attempt to compare the performances of those strategies in identifying the most feasible one for hot and humid climate. Table 1 displays the summary of the solar induced ventilation studies carried out in the hot and humid climate.

Table 1: A summary of the previous solar induced ventilation studies in hot and humid climate

	Strategy			Configuration Variables					Output Performance			
Research	trombe Wall (TW)	Solar Chimney (SC)	Roof Solar Collector (RSC)	Height	Lengh	Opening	tcavity width	tilt angle	air velocity	Air flow rate	ACH	Temperature
Bansal et al. (1994)			●							●		●
Khedari et al. (1997)			●		●			●	●	●		
Hirunlabh at al. (1999)	●									●		●
Khedari et al. (2000)	●		●						●		●	●
Khedari et al. (2000)			●			●	●			●	●	
Hirunlabh at al. (2001)			●					●		●		
Khedari et al. (2003)	●		●							●		●
Ong and Chow (2003)	●						●		●	●		●
Bansal et al. (2005)	●					●	●		●			●
Mathur et al. (2006)			●					●		●		
Mathur et al. (2006)	●					●	●			●	●	
Chantawong et al. (2006)	●								●			●
Nugrobo et al. (2007)		●		●	●		●		●	●		●
Puangsombut et al. (2007)			●				●			●		
Chungloo & I.immeechokehai et al. (2007)			●							●	●	●
Aree et al. (2009)		●								●		●
Chungloo & I.immeechokehai et al. (2009)			●						●	●		●
Punyasompun et al. (2009)	●									●		●

It is apparent from Table 1 that most studies were conducted on the roof solar collectors compared to the other strategies. This is due to the fact that the roof solar collector is more effective in capturing higher amounts of solar radiation in hot and humid climate than the Trombe wall and the solar chimney because of the high solar altitude (Awbi, 2003). However, despite its potential, Khedari *et al*. (2000a) and Hirunlabh *et al*. (2001) accentuated that the induced airflow rate by the roof solar collector alone is still inadequate for the occupants' comfort. Nevertheless, there is no indication in these studies of the criteria for the evaluation of the occupants' comfort. In the study by Khedari et al. (2000a), the required ACH for occupants' comfort was up to 20 ACH, but the induced ACH by the roof solar collector was just about 4-5 ACH. On the other hand, there is no required airflow rate mentioned by Hirunlabh *et al.* (2001) for the occupants' comfort. It was just indicated that the studied roof solar collector induced a small amount of airflow rate which was insufficient. This small amount of airflow rate and ACH induced by the roof solar collector is due to the stack height limitation, as shown in Table 2.

Table 2: Strengths and weaknesses of the Trombe wall, solar chimney and roof solar collector

Strategy	Strengths	Weaknesses
Trombe Wall	- Able of collecting more solar radiation when the sun is at lower altitute (mathur, Mathur & Anupma. 2006). - Easily incorporated at any building level (mathur, et al., 2006)	-Prevent daylight and view (Harris & Helwig, 2007)
Solar Chimney	- Enable view and daylight (Harris & Helwig, 2007)	- Less architectural visual aesthetic (Harris & Helwig, 2007). - More expensive as additional structure is required for the chimney (Haris & Helwig, 2007)
Roof solar collector	- Provide minimum alteration to the existing building (harris & Helwing, 2007) - Less expensive than solar chimney (Harris & Helwing, 2007) - Able ofcollecting more solar radiation when the sun is at higher altitute (Awbi, 2003; Mathur, et al., 2006) - Able to provide large surface areas for collecting solar energy (Awbi, 2003, Harris & Helwing, 2007)	- The stack's height is restricted by the roof slope (Awbi, 2003, Harris & Helwig, 2007). - More Pressure- losses due to additional bends (Harris & Helwig, 2007). - Difficult to be incorporated at any building level (Mathur, et al., 2006).

The stack height is important in determining the stack pressure. The solar chimney is able to provide adequate height but since it has a vertical stack as the Trombe wall, the drawback is also in achieving higher solar radiation in hot and humid climate. For that reason, it is suggested in the present research that - the roof solar collector should be combined with the vertical stack for the hot and humid climate application. The purpose of the roof solar collector is to capture maximum amount of solar radiation in order to heat up the air. The heated air in the roof solar collector rises and enters the vertical stack due to the pressure difference between the two zones. Consequently, higher air temperature difference is created between the air inside the stack and the ambient air. Meanwhile, the presence of vertical stack will provide a significant height that is able to create sufficient stack pressure for the stack ventilation.

To date, there are two previous studies of solar induced ventilation which combined the roof solar collector and the vertical stack. The studies were executed by Barozzi *et al.* (1992) and Bansal *et al.* (1993), as shown in Figure 2 and Figure 3. Barozzi *et al.* (1992) focused on the airflow pattern and air velocity inside the building with the solar induced ventilation in Nigeria. Meanwhile, Bansal *et al*. (1993) developed a steady state mathematical model for solar induced ventilation.

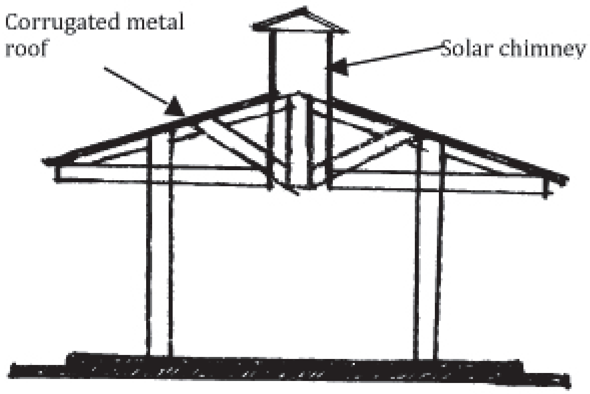

Figure 2: The solar induced ventilation by (Source: Barozzi et al, 1992)

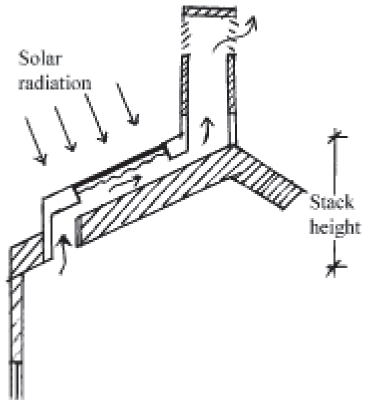

Figure 3: The solar induced ventilation by (Source: Bansal et al, 1993)

Although Bansal *et al.*'s (1993) model seems almost similar to the proposed strategy in this present research, there are differences in the location of the glass and the absorber plate in the roof solar collector. In Bansal *et al.*'s (1993) model, the glass was directly attached to the top of the absorber plate, whilst the air cavity was located beneath the absorber plate. Hence, the air was heated by the convective heat transfer from the absorber plate. However, in the proposed strategy of this present research, the air cavity is located in between the glass and the absorber plate. Therefore, the convective heat gained by the air is from both components.

3. THE PROPOSED SOLAR INDUCED VENTILATION STRATEGY

This section discusses the development of the proposed solar induced ventilation strategy for hot and humid climate based on the literature survey. From the literature survey, it can be summarized that the potential solar induced ventilation strategy for hot and humid climate is the combined roof solar collector and vertical stack, as shown in Figure 4. The proposed strategy has two parts, which are the roof solar collector and the vertical stack.

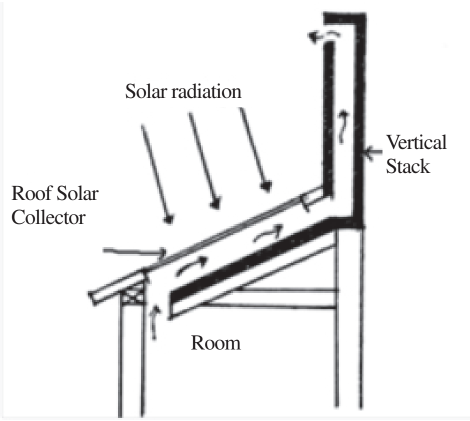

Figure 4: The combined roof solar collector and vertical stack

3.1 Roof Solar Collector

The function of the roof solar collector is to maximize the air temperature in the channel. Hence, the important configuration variables are the channel length, cavity width, inlet size and tilt angle. The channel length and the cavity width influence the creation of the thermal and velocity boundary layers inside the channel. These boundary layers are vital as they have a strong effect on the convection heat transfer (Cengel, 1997). The thickness of velocity boundary layers and thermal boundary layer grows with the distance. This is because, the increase of distance from the leading edge allows viscosity and heat transfer to enter further into the free stream (Incropera & DeWitt, 1996). The effective cavity width is also determined by the exit air temperature of the roof solar collector's channel. The friction losses dominate in the cavity width of 0.1 m. However, the friction losses decrease with the increase of cavity width (Bouchair, 1994). Although the increase of cavity width results in the increase of airflow rate due to the decrease in the friction losses, it also causes the reduction of exit air temperature (Guohui Gan, 2006). The exit air temperature of the roof solar collector channel is important in achieving higher air temperature inside the vertical stack.

The inlet size is important as it determines the amount of mass flow rate into the roof solar collector's channel. The mass flow rate of the fluid influences the magnitude of the natural convection heat transfer between the surface and the fluid (Cengel, 1997). Hence, the larger amount of mass flow rate augments the heat transfer to the air, thus enhances the thermal performance of the solar air collector (Kolb, Winter, & Viskanta, 1999). Furthermore, the tilt angle determines the amount of solar radiation captured by the roof solar collector. In maximizing the amount of solar radiation received by the collector, the tilt angle has to be altered according to the monthly-averaged optimum tilt angle (Gunerhan & Hepbasli, 2007; Yakup & Malik, 2001). However, a specific device is necessary to change the tilt angle monthly.

3.2 Vertical Stack

Stack ventilation is driven by the pressure difference, which results from the variation in the air density. This air density variation is caused by the temperature difference. The relationship between the pressure, density and temperature in gasses is explained by the ideal gas equation of state (Fox & McDonald, 1998), as follows:

P = RT

where P is the absolute pressure, is the density, R is the gas constant and T is the absolute temperature. A zone of higher temperature has higher pressure and lower density. In ensuring effective stack ventilation, it is important to have a significant temperature difference between the air inside the stack and the ambient air. In the proposed strategy, the air temperature inside the vertical stack is the result of the air that is initially heated in the roof solar collector.

Besides air temperature, other important factors that determine the performance of stack ventilation are the inlet area and the stack height. This is emphasized by the numerical equation of airflow rate caused by the stack effect (ASHRAE, 2005), as shown below:

where

Q	= airflow rate (m^3/s)
CD	= discharge coefficient for opening
HNPL	= height from the mid-point of lower opening to NPL (m)
Ti	= indoor temperature (K)
To	= outdoor temperature (K)
A	= free area of inlet openings (m^2)

In the equation above, the bigger the free area of inlet openings, the greater is the airflow rate. Greater airflow rate is also achieved when the vertical distance between the openings is higher. The pressure developed in the stack is the hydrostatic pressure. The hydrostatic pressure decreases with the increase of height. The rate of decrease is proportional to the fluid density (CIBSE, 2005). Hence, a significant height is important in achieving a high-pressure difference. It is suggested that the height of the vertical stack should be proportional to the buildings where it is applied.

4. PRELIMINARY TEST ON THE PROPOSED STRATEGY

A preliminary test using a physical model was executed in the actual environment. There are two objectives of this preliminary testing. The first objective is to investigate the potential of proposed strategy in enhancing the stack ventilation effect in hot and humid climate. This potential is measured by the temperature difference between the air inside the vertical stack (Ti) and the ambient air (To). Meanwhile, the second objective is to determine the environmental parameters that affect the air temperature difference (Ti-To) achieved by the proposed strategy. Hence, based on the laid objectives, the preliminary test is limited to the demonstrating of a proof-of-concept model – which is to develop a proposed strategy that is able to induce stack ventilation in hot and humid climate.

The test was executed at an open parking area measuring 518 m², located in Universiti Putra Malaysia, Serdang, Selangor. The selected site was surrounded by single-storey blocks of 4 m height, and a two-storey block of 8 m height, as shown in Figure 5. The physical model was placed in the middle of the site where it was exposed to the solar radiation throughout the measurements. The measurements were conducted for eight hours, from 9 am to 5 pm.

(a) (b)

Figure 5: The east (a) and west (b) views of the selected site

4.1 The Physical Model

The constructed physical model for this preliminary testing was initially derived from the literature review. The developed physical model comprised two parts, namely, a roof solar collector and a vertical stack. The roof solar collector had the dimensions of 1 m channel length, 1 m width and 0.2 m cavity width, whereas the vertical stack dimensions measured 1 m width, 1.95 m height and 0.2 m cavity width (Figure 6). All the openings had the same area, which was 0.1575 m² (0.175 m x 0.9 m). Hence, they complied with the effective ratio of 1:1 (inlet area : outlet area) as suggested by Susanti et al. (2008) and Khedari *et al*. (2000a). The 0.2 m cavity width was selected as it was the most suggested effective width according to the literature (Bouchair, 1994; G. Gan & Riffat, 1998; Miyazaki, Akisawa, & Kashiwagi, 2006), whilst the effective suggested channel length for the roof solar collector was 1 m (Khedari, *et al*., 1997; Zhai, Dai, & Wang, 2005). The roof solar collector was tilted at 10º from the horizon as it was the effective tilt angle in capturing solar radiation in Selangor (Yousef, 2007).

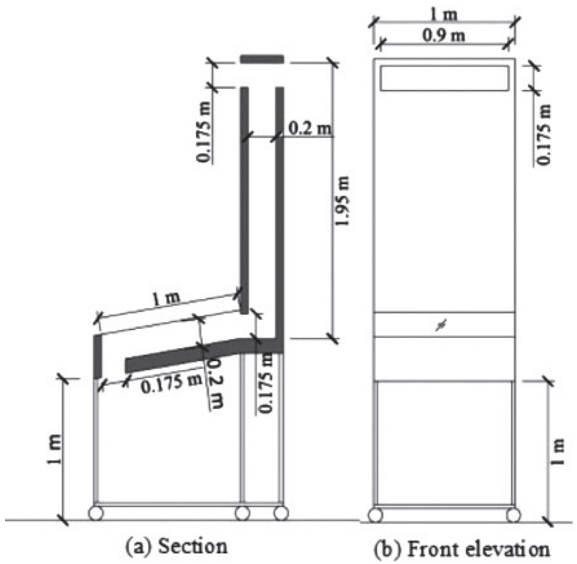

Figure 6: The dimensions of the physical model

Common materials that were used in the physical experiments of the previous studies, such as plywood (Arce, *et al*., 2009; J. Hirunlabh, *et al*., 1999; Khedari, Yimsamerjit, & Hirunlabh, 2002), glass (Arce, *et al*., 2009; Bansal, *et al*., 2005; J. Hirunlabh, *et al*., 1999; Mathur, *et al*., 2006a; Ong & Chow, 2003), micro-fibre insulation (J. Hirunlabh, *et al*., 1999) and aluminium sheet (Bansal, *et al*., 2005; Mathur, *et al*., 2006a), were also applied in constructing the physical model. However, the micro-fibre insulation and aluminium sheet were replaced by rockwool insulation and aluminium foil in the present research due to their availability and budget constraint. The walls of the roof solar collector and the vertical stack were made of 0.003 m thickness of plywood and 0.05 m thickness of rockwool insulation. The overall thermal transmittance (U-value) of the wall was 0.88 W/m² K. An aluminium foil was placed at the outer side of the walls to reduce solar radiation absorption. Meanwhile, the inner sides of the walls were also covered with the aluminium foil to reduce radioactive heat transfer between the walls. The top of the roof solar collector was covered with 0.005 m thickness of clear glass, which had a transmissivity of 0.84. The absorber was located at the bottom of the roof solar collector. It was made of a black painted aluminium foil. Hence, the solar absorptivity of the absorber was 0.95. Meanwhile, a rockwool insulation of 0.1 m thickness and a plywood of 0.003 m thickness were placed below the absorber to reduce heat loss of the space below. The space beneath the physical model was fully covered to reduce wind effects.

4.2 Measuring Instruments

The instruments used for temperature measurements were the type-K thermocouples. They were placed at 19 different locations, namely, the top and bottom surfaces of the glass cover, the top surface of the absorber, the inlet and middle of the roof solar collector's channel, the inlet, middle and outlet of the vertical stack, as well as the middle of the space beneath the physical model (Figure 7). The temperature data was recorded every 10-minute interval using the GL800 midi logger. The environmental parameters, such as the global solar radiation, the wind speed and direction, the ambient air temperature and the relative humidity, were measured and recorded using the Watchdog 2000 Series portable weather station. Meanwhile, the sky conditions were determined through observation.

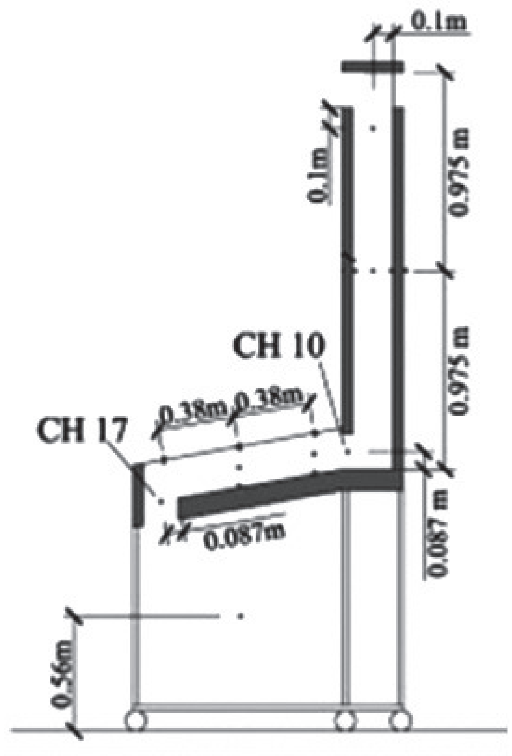

Figure 7: The locations of the thermocouples

5. RESULTS AND DISCUSSIONS

In the present paper, the focused variable is the temperature. The results are presented and discussed by comparing the air temperature difference achieved for two sky conditions, namely, the overcast sky and the semi-clear sky. These sky conditions were resulted from the observation made on the cloud cover during the measurements. In this research, the semi-clear sky condition is described as the sky that is partly clear and partly cloudy. Meanwhile, the overcast sky condition is described as a sky condition that is mostly cloudy. The environmental parameters that affect the air temperature difference are also presented.

5.1 Air Temperature Difference (Ti-To)

Figure 8 depicts the temperature difference (Ti-To) between the air inside the vertical stack of the physical model (Ti) and the ambient air (To) during the overcast sky and semi-clear sky conditions. The air temperature inside the vertical stack (Ti) was the average air temperature of three thermocouple locations, namely, at the vertical stack inlet, middle of the vertical stack and near the vertical stack outlet. The findings showed that the air temperature difference (Ti-To) was higher during the day with semi-clear sky as compared to the overcast sky due to the availability of higher solar radiation amount. The average solar radiation amount (9 am to 5 pm) for the day with semi-clear sky was 576 W/m², whereas for the overcast sky, it was 376 W/m².

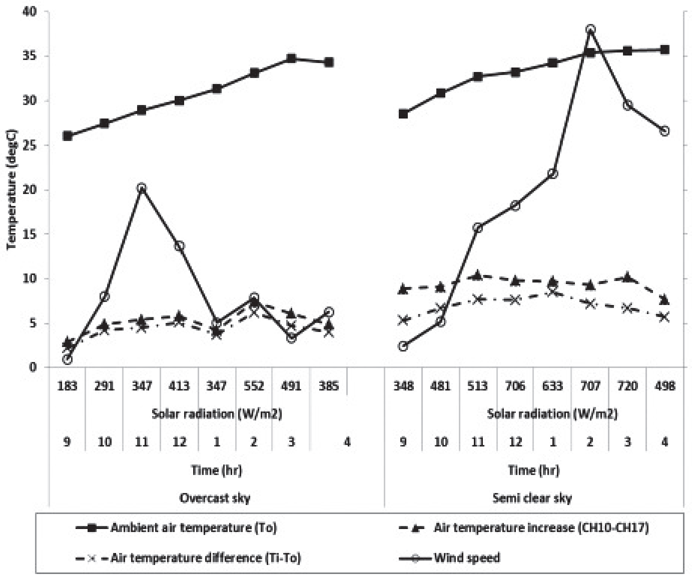

Figure 8: A comparison of the air temperature difference (Ti-To) achieved for the day using the overcast sky and semi-clear sky conditions

The highest air temperature difference (Ti-To) achieved during the day with overcast sky condition was 6.2ºC (39.3ºC – 33.1ºC) at 552 W/m² solar radiation incident, whilst the lowest was 2.2ºC (28.2ºC – 26ºC) at 183 W/m² solar radiation incident. Meanwhile, the day with semi-clear sky condition had recorded the highest air temperature difference (Ti-To) of 8.5ºC (42.7ºC – 34.2ºC) at 633 W/m² solar radiation incident, while the lowest was 5.3ºC (33.8ºC – 28.5ºC) at 348 W/m² solar radiation incident. Therefore, it shows that the proposed strategy was able to improve the stack ventilation effect due to the higher air temperature difference attained as compared to the normal air temperature difference between the inside and outside of naturally ventilated buildings in Malaysia, which is less than 5ºC (Kubota, *et al*., 2009; A. M. Nugroho, *et al*., 2007; Rajeh, 1989). The findings also show that although the solar radiation amounts at 12 pm (706 W/ m²), 2 pm (707 W/ m²) and 3 pm (720 W/ m²) were higher than that at 1 pm (633 W/ m²), the air temperature differences achieved were lower. At 1 pm, the air temperature difference attained by the proposed strategy was 8.5ºC, whereas at 12 pm, 2 pm and 3 pm, the air temperature differences achieved were 7.6ºC, 7.2ºC and 6.7 ºC, respectively. The possible explanation is due to the influence of other environmental factors, such as wind and ambient air temperature. The findings that demonstrate the influence of these factors are presented and discussed in Section 5.2.

5.2 Environmental Parameters Affecting the Air Temperature Difference (Ti-To)

It is apparent in Figure 8 that, in general, the increase and decrease of air temperature difference (Ti-To) inside the vertical stack were influenced by the air temperature increase (CH10-CH17) inside the roof solar collector. However, for the day with semi-clear sky condition, the continuous increase of ambient air temperature had resulted in the decrease of air temperature difference (Ti-To) at 3 pm (720 W/m²), although there was an increase in the solar radiation amount and air temperature inside the roof solar collector (CH10-CH17).

The findings also indicate that the air temperature increase (CH10-CH17) inside the roof solar collector was highly influenced by the solar radiation amount, as shown in Figure 8. Higher solar radiation resulted in greater air temperature increase (CH10-CH17). This profile was consistent for the day with the overcast sky condition. However, the results were otherwise at 12 pm (706 W/m2) and 2 pm (707 W/m2) for the day with semi-clear sky condition, in which the air temperature inside the roof solar collector decreased although there was an increase in the solar radiation amount. This phenomenon can be

further explained by the results of the glass temperature, absorber temperature and air temperature inside the roof solar collector for the day with overcast sky and semi-clear sky conditions, as depicted in Figure 9 and Figure 10.
In comparing the two results (Figure 9 and Figure 10), it can be seen that the increase and decrease in the temperatures of glass, absorber and air were corresponding to each other for the day with the overcast sky condition. On the other hand, for the day with the semi-clear sky condition, there were times when the results were otherwise, such as at 12 pm (706 W/m2) and 2 pm (707 W/m2). A possible explanation for these results is due to the presence of higher wind speeds during the day with the clear sky condition as compared to the overcast sky condition. The higher wind speeds increased the convective heat loss from the glass cover of the roof solar collector to ambient, thus reducing the glass temperature.

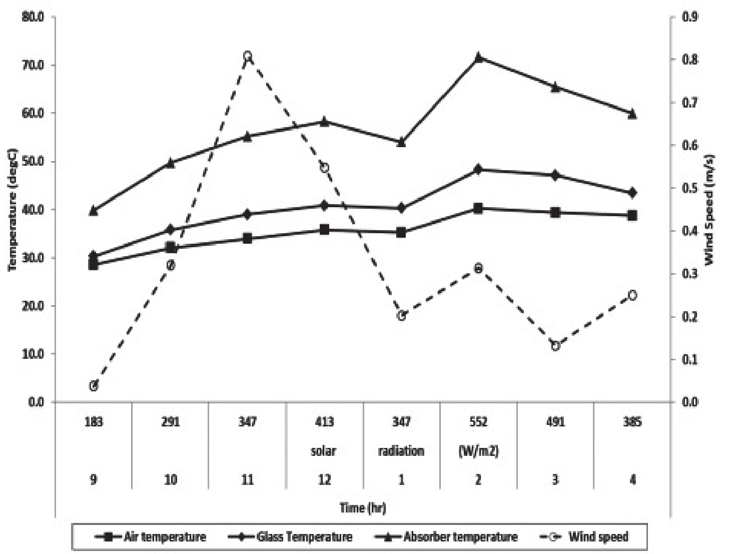

Figure 9: The glass temperature, absorber temperature and air temperature inside the roof solar collector for the day with overcast sky condition

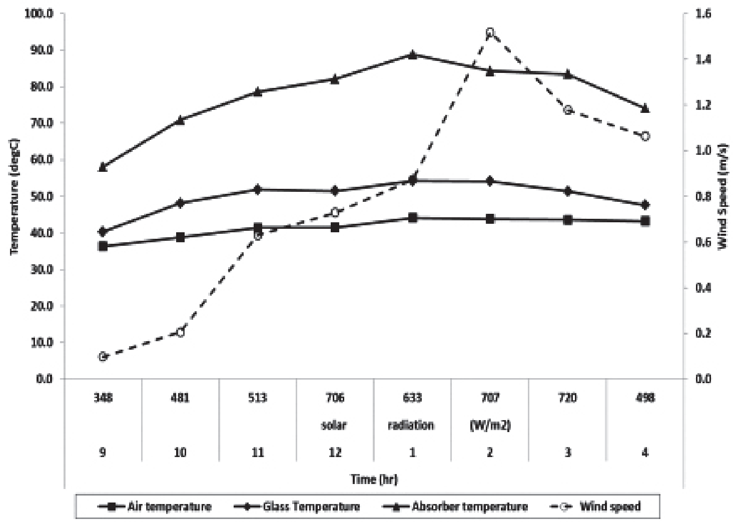

Figure 10: The glass temperature, absorber temperature and air temperature inside the roof solar collector for the day with semi-clear sky condition

The reduction in the glass temperature enhanced the radiated energy from the absorber to the glass due to the higher temperature difference between these two components. Consequently, the absorber temperature decreased though the solar radiation increased. The decrease in the absorber and glass temperature had also resulted in the decrease of air temperature due to the reduction of convective heat gain by the air. However, there was still a slight increase in the absorber temperature at 12 pm (706 W/m2), as the heat absorbed by the absorber could still compensate the losses. Moreover, the wind speed at this time was not as high as that at 2 pm (707 W/m2).

6. CONCLUSION

This paper contributes to the discussion on the investigations of solar induced ventilation strategy for hot and humid climate. The findings from the literature survey have concluded that - the combined roof solar collector and vertical stack is a potential solar induced ventilation strategy. The roof solar collector functions in maximizing the air temperature in the channel by capturing as much solar radiation as possible. Meanwhile, the vertical stack is important in providing a significant height for a sufficient stack pressure. The potential of the proposed strategy was investigated through a preliminary test using a physical model. The focused variable is the temperature difference between the air inside the vertical stack (Ti) and the ambient air (To). The findings indicate that the proposed strategy has a great potential as it is able to create the air temperature difference (Ti-To) more than the usual air temperature difference between the inside and outside of naturally ventilated buildings in Malaysia. During the day with the semi-clear sky condition, the air temperature difference (Ti-To) of 8.5ºC could be attained at 633 W/m² solar radiation incident. Meanwhile, for the day with the overcast sky condition, the air temperature difference (Ti-To) of 6.2ºC at 552 W/m² solar radiation incident was achieved. The findings also show that the environmental parameters, namely, the solar radiation, wind and ambient air temperature highly influenced the performance of the solar induced ventilation. The solar radiation and wind affected the heat transfer processes that occurred in the roof solar collector, while the ambient air temperature affected the air temperature differences (Ti-To) achieved by the proposed strategy. Hence, they have to be taken into consideration in achieving the effective performance of the solar induced ventilation. In summary, the proposed strategy has great potential to be developed for application in hot and humid climate. This is due to its ability in inducing, as well as enhancing the stack ventilation effect. Therefore, it is suggested in the future that further investigations should be undertaken on the possible development of the strategy's configuration in enhancing its performance.

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