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Enhancement of stack ventilation in hot and humid climate using a combination of roof solar collector and vertical stack

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In the hot and humid climate, stack ventilation is inefficient due to small temperature difference between the inside and outside of naturally ventilated buildings. Hence, solar induced ventilation is a feasible alternative in enhancing the stack ventilation. This paper aims to investigate the effectiveness of a proposed solar induced ventilation strategy, which combines a roof solar collector and a vertical stack, in enhancing the stack ventilation performance in the hot and humid climate. The methodology selected for the investigation is physical experimental modelling which was carried out in the actual environment. The results are presented and discussed in terms of two performance variables: air temperature and air velocity. The findings indicate that the proposed strategy is able to enhance the stack ventilation, both in semi-clear sky and overcast sky conditions. The highest air temperature difference between the air inside the stack and the ambient air (T_i–T_o) is achieved in the semi-clear sky condition, which is about 9.9 °C (45.8 °C–35.9 °C). Meanwhile, in the overcast sky condition, the highest air temperature difference (T_i–T_o) is 6.2 °C (39.3 °C–33.1 °C). The experimental results also indicate good agreement with the theoretical results for the glass temperature, the air temperature in the roof solar collector's channel and the absorber temperature. The findings also show that wind has significant effect to the induced air velocity by the proposed strategy.

1. Introduction

In recent years, there has been an increasing interest in promoting the energy savings in buildings. Natural ventilation is one of the passive means for energy savings. It can be achieved by two strategies; cross ventilation and stack ventilation. Cross ventilation is wind-induced ventilation, resulting from different pressure distribution around buildings due to wind effect. Meanwhile stack ventilation is a result of air density variations due to the air temperature differences [1]. The hot and humid climatic condition in Malaysia has made the stack ventilation inefficient due to the lower air temperature difference between the inside and outside of naturally ventilated buildings. The air temperature difference is normally less than 5 °C [2]. In addition, the study by Nugroho et al. [3] on the indoor and outdoor air temperature of terrace houses in Malaysia indicated that the air temperature difference was around 0.6 °C–3.1 °C during the day. Hence, in enhancing the stack ventilation, a solar induced ventilation is a viable alternative [1].

Due to the potential of solar induced ventilation, studies on that strategy had been executed in the hot and humid climate [4–14]. Hirunlabh et al. [4] investigated the potential of a metallic solar wall in removing heat from a house in Thailand. The proposed solar wall was able to induce air flow rate of about 0.01–0.02 kg s^{-1}. Meanwhile, a house ventilation rate of about 0.08–0.15 $m^3\ s^{-1}\ m^{-2}$ was able to be induced by roof solar collector in Thailand.[7] Due to this potential, various configurations of roof solar collector had been developed by Hirunlabh et al. [8] in achieving more ventilation rate. Among the developed configurations, the highest air flow rate of about 0.04 m^3/s was achieved by roof solar collector tilted at 60°. Meanwhile, the application of four configurations of solar induced ventilations (the roof solar collector, the modified Trombe wall, the Trombe wall and the metallic solar wall) at a school building resulted in the increasing of ACH between 8 and 15, and the reduction of room overheating by about 50% [10]. In Malaysia, the

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application of solar chimney at a single storey terrace house was able to increase the indoor air velocity up to 0.58 m/s higher than the air velocity of a house without solar chimney [5]. Whilst, in Jaipur, India, the roof solar collector tilted at 45° was able to induce about 190 kg/h air flow rate during the summer months [9]. The potential of solar chimney in the hot and humid climate of South-eastern Spain had been investigated by Acre et al. [11]. The constructed solar chimney (5.6 m total height, 1.0 m wide and 0.3 m air gap width) was able to induce volumetric air flow rate in the range of 50–374 m^3/h within 24 h (0:00 h–24:00 h). The potential of solar induced ventilation application at multi-storey buildings in Thailand was investigated by Punyasompun et al. [12]. The investigation resulted in good potential which the room temperature of the building model with solar induced ventilation was lower by about 4–5 °C than the building model without it. Comparison was also made on two configurations of solar induced ventilation; the separated (inlet and outlet openings at each floor) and the combined solar induced ventilation (inlet opening at each floor and one outlet opening at the top floor). It was found that the combined solar induced ventilation was able to reduce room temperature by about 4–5 °C lower than the other configuration. The application of solar induced ventilation with other passive cooling strategies in the hot and humid climate was examined by [6,13] and [14]. Bansal et al. [6] developed a combination of roof solar collector and wind tower. The combination was able to increase the air flow rate up to 1.4 kg/s, which was double from the air flow rate induced by a wind tower alone. Chungloo and Limmeechokchai [13] applied a roof solar collector with a wetted roof in reducing the room temperature. The room temperature was reduced by about 1–3.5 °C with the application of roof solar collector alone. However, the combination of both system (roof solar collector and wetted roof) was able to reduce more room temperature, which was about 2–6.2 °C. Due to this potential, Chungloo and Limmeechokchai [14] had investigated the utilization of other passive design strategy, which was cool ceiling, with the roof solar collector. The utilization of both systems had also resulted in the reduction of more room temperature than the application of roof solar collector alone.

Those studies have proven the potential of solar induced ventilation in inducing the stack ventilation in the hot and humid climate. However, most of the studies were conducted on the potential of roof solar collector [6–10,13,14], as its inclination configuration has enabled the capturing of more solar radiation compared to the vertical solar induced ventilation, namely the Trombe wall and the solar chimney. This is due to the higher sun altitude in the hot and humid climate [1]. Nevertheless, the roof solar collector has a drawback in which the stack height is restricted by the roof slope [1,15]. There are also studies executed on the potential of Trombe wall [4,10] and solar chimney [5,11] in the hot and humid climate. Although these two vertical solar induced ventilation configurations have the advantage in providing higher stack than roof solar collector, but they are able to capture more solar radiation when the sun is at lower altitude [9]. For that reason, the proposed solar induced ventilation strategy in the present research has a combination of roof solar collector and vertical stack.

In the proposed strategy, solar radiation is solely collected in the roof solar collector, whereas the vertical stack functions like a conventional chimney, with no collection of solar radiation. Detail description of the proposed solar induced ventilation strategy is discussed in Section 2. To date, there are two previous studies which have similar combination strategy to the present research. They are the studies by Barozzi et al. [16] and Bansal et al. [17]. Barozzi et al. [16] investigated the effects of having solar induced ventilation to the air flow inside a building prototype in Nigeria. The differences between that study and the present research are in terms of the investigation method and the solar induced ventilation configuration. In the former study, small-scaled physical experimental method was executed in a sealed laboratory chamber. The building's roof which was made of corrugated metal had been utilized as the solar induced ventilation whereas in the present research the proposed solar induced ventilation strategy is equipped with top glass cover and an absorber. Meanwhile, Bansal et al. [17] developed a steady state mathematical model in calculating the air flow induced by the solar induced ventilation strategy. Although the proposed solar induced ventilation strategy in the present research is almost similar to Bansal et al.'s [17] model, there is a slight difference in the position of glass and absorber plate at the roof solar collector. In Bansal et al.'s [17] model, the glass was placed directly on top of the absorber plate, while the air cavity was at the bottom of the plate. Thus, the air was heated by the convective heat transfer from the absorber plate. Whereas, in the present strategy, the air cavity is located in between the glass cover and the absorber plate. Hence, the heat is transferred to the air by convection from the glass cover and the absorber plate. Besides that, the method of investigation is also different. In the present research, the proposed strategy's performance is investigated in the actual environmental condition.

This paper has been divided into six sections. The first section addresses the issues relating to the stack ventilation as well as previous studies of solar induced ventilation in the hot and humid climate. In the second section, the proposed strategy is described, while the third section discusses on the physical experimental modelling which is executed in the actual environmental conditions. The mathematical model adopted for the proposed strategy is described in section four. Meanwhile, the results are presented in section five. They are analyzed and discussed based on two performance variables, which are temperature and air velocity. Finally, the overall findings are concluded in section six.

2. The strategy description

The proposed solar induced ventilation strategy consists of two parts, namely a roof solar collector (RSC) and a vertical stack. The purpose of the roof solar collector is to capture as much solar radiation as possible, thus maximizing the air temperature inside the roof solar collector's channel. The heated air inside the channel rises and flows into the vertical stack due to the pressure difference between the two zones. Meanwhile, the vertical stack is important in providing significant height for sufficient stack pressure. Significant height is essential as the pressure developed in the stack is hydrostatic pressure. The hydrostatic pressure decreases with the increasing of height [18]. The vertical stack's walls are insulated in minimizing the heat loss to the environment. In the proposed strategy, the vertical stack functions solely as a conventional chimney with no collection of solar radiation.

3. Physical experimental modelling

The methodology opted for the study was a physical experimental modelling, which was executed under the actual environment. The experiment was conducted under three different prototype device conditions, namely device A, device B and device C. Detail descriptions on these prototype devices are explained in Section 3.1. The experiment was carried out in an open parking area in Universiti Putra Malaysia, Serdang, Selangor. The north and south locations of the site are surrounded by single storey blocks, with an average height of 4 m. Meanwhile, there is an 8 m high 2-storey block on the east side. The prototype device was placed in the middle of the site where it was exposed to the sun throughout the measurements. As the experiment was conducted in the actual