Applied Energy 114 (2014) 172–178

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Experimental study on thermal performance of a solar chimney combined with PCM

Yongcai Li, Shuli Liu *

Department of the Civil Engineering, Architecture and Buildings, Faculty of Engineering and Computing, Coventry University, Coventry CV1 5FB, UK

HIGHLIGHTS

- The phase change periods are nearly 13 h 50 min for all cases investigated.
- 700 W/m^2 drives the highest air flow rate 0.04 kg/s.
- 500 W/m^2 generates the highest average outlet temperature 20.5 °C.
- All investigated cases deliver the thermal efficiency higher than 80%.
- 500 W/m^2 has the highest minimum efficiency 63%.

ARTICLE INFO

Article history:
Received 18 June 2013
Received in revised form 7 August 2013
Accepted 14 September 2013
Available online 17 October 2013

Keywords:
Solar chimney
PCM
Phase change period
Air flow rate
Thermal efficiency

ABSTRACT

The thermal performance of a PCM based solar chimney is experimentally investigated in this paper. The research is carried out within a laboratory condition with three different heat fluxes of 500 W/m^2, 600 W/m^2 and 700 W/m^2. The results show that for a same charge period of 7 h 10 min though the PCM does not fully melts in the cases of 600 W/m^2 and 500 W/m^2, the absorber surface temperature variations for the three heat fluxes are the same during the phase change transition period. Contrary to the sensible heat discharge period, during the phase change period, the surface temperatures descend very slowly till the latent heat releases completely. The phase change periods are nearly 13 h 50 min for all cases investigated. The air flow rates vary corresponding to the absorber surface temperature. The air flow rate of 0.04 kg/s for the case of 700 W/m^2 is slightly higher than 0.039 kg/s for 600 W/m^2 and followed by 0.038 kg/s for 500 W/m^2. Unlike to air flow rate, the air outlet average temperature of 19.6 °C for the case of 700 W/m^2 is the lowest amongst three cases, and then followed by 20.1 °C for 600 W/m^2 and 20.5 °C for 500 W/m^2. The peak thermal efficiencies of the solar chimney are observed to be about 80% for all cases at the early ventilation period. 500 W/m^2 however drives the highest minimum efficiency of 63%.

1. Introduction

The solar chimney as a natural draft system has been in use for centuries, and has gained more and more attentions in the last two decades, due to its potential advantages over mechanical ventilation systems in terms of energy requirement, economic and environmental benefits. Solar chimney utilizes solar radiation energy to generate air movement by stack pressure, thereby driving the heated air through the chimney channel, and then drawing cooler air through the building in continuous cycle. As a consequence, solar chimney may provide the required ventilation while simultaneously offset part of the heating and cooling requirements. The thermal performance of solar chimney has been extensively studied by theoretical, numerical and experimental methods [1–7]. The pioneering work on solar chimney was carried out by Bansal et al. [8] who developed a mathematical model to establish the stack ventilation performance of a solar chimney based on a steady state. The numerical results revealed that an induced air flow rate of 140–330 m^3/h can be achieved for a 2.25 m^2 of collector area with a 0.15 m deep air gap for solar radiation ranging from 200 to 1000 W/m^2. Arce et al. [9] experimentally investigated the thermal performance of a full-scale solar chimney under Mediterranean daylight and night time conditions. A 4.5 m high, 1.0 m wide and 0.15 m thick reinforced black concrete wall was used as the solar absorber. The air gap was 0.3 m deep and the stack height was 3.5 m. For this configuration, a maximum air temperature increment of 7.0 °C and a maximum flow rate of 370 m^3/h were obtained at a solar intensity of 604 W/m^2 occurring around

* Corresponding author. Address: JL127, Sir John Laing Building, Department of Civil Engineering, Architecture and Building, Faculty of Engineering and Computing, Coventry CV1 5FB, UK. Tel.: +44 (0) 24 7765 7822; fax: +44 (0) 24 7765 8296.
E-mail address: aa6328@coventry.ac.uk (S. Liu).

0306-2619/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.apenergy.2013.09.022

13:00 h. The obtained discharge coefficient value was about 9% less than the value generally suggested in the literature. Miyazaki et al. [10] numerically and analytically investigated the thermal performance of another solar chimney, which was integrated into a one-story office building. The solar chimney height was 3.6 m, and the chimney width was varied from 0 to 4 m in the study. A 150 mm concrete wall was used as the solar collector. The numerical results showed that the use of solar chimney could save annual energy consumption of fan shaft power by about 50%. The heating load could be reduced by 20% during the heating season, while the annual thermal load mitigation was estimated as 12% by taking the increase of the cooling load into account. Though the research results above demonstrate the potential of solar chimney in heating and cooling loads reduction as a passive heating device, it is well known that for a conventional solar chimney, concrete, brick or rock used as the thermal storage medium, which are so-called sensible heat storage. Sensible heat storage is most commonly used for solar energy applications. However, the major drawback of sensible heat storage is its low thermal energy storage density, resulting in a larger volume requirement especially for a small temperature raise. The latent heat storage is a superior way of storing thermal energy. This is because of its high storage density and isothermal nature of the storage process. A comparison of the latent and sensible heat storage indicates that 5–10 times of higher storage density can be typically reached by employing the latent heat storage [11–14].

Thus in order to effectively store the extra solar energy during the daytime and release it in particular time such as at the nighttime to achieve the aim of 'time shifting', the phase change material (PCM) as the thermal energy storage medium is applied to the solar chimney to enhance the energy storage capacity of the chimney in present study. In this case solar energy that reaches the solar absorber is absorbed and stored by the PCM. To the best of the authors' knowledge, a very few studies have reported the application of PCMs onto solar chimney pertaining to building ventilation application. In 2002, Stritih and Novak [15] designed a solar wall in which the black paraffin wax used as the PCM. The stored heat in PCM was used to heat and ventilate a house. According to the results of this study, this kind of solar wall was very promising. Amori and Mohammed [16] experimentally and numerically investigated the thermal performance of a PCM based solar chimney under Iraq weather conditions, the paraffin wax with melting temperature of 65.16 °C used as the PCM in their study. One of the experimental results was that the PCM modified the thermal performance of the chimney and extended the ventilation hours after the solar absence or night time by discharging the stored energy in PCM.

However, the previous studies just provided general information of the influence of the PCM on solar chimney. Furthermore, introducing PCM into the solar chimney would improve the solar chimney CPÖs performance, but it is still not clear that if the PCM does not change its phase completely, its effect is straight forward or not due to the PCM CPÖs complicated heat transfer performance. This information is important as the PCM is not always charged completely with the solar energy variations. No details of how the PCM performed on the solar chimney under different operating conditions (i.e., fully melting and partly melting) were found in literature so far. To gain a further insight into the PCM based solar chimney, this present work reports an experimental investigation on the influence of the PCM on thermal performance of the solar chimney. The study considers both the charging and discharging processes and the effect of heat flux on the natural ventilation performance of the solar chimney. The melting and freezing times, temperature distributions inside the PCM and inside the air channel, air flow rate and outlet air temperature are investigated.

2. Experimental set-up

2.1. Solar chimney

This solar chimney is set up inside a laboratory environment to prevent the experimental testing from the influence of variations of weather conditions. This allows the comparison of the performance of the proposed chimney for various heat fluxes under identical condition. Fig. 1 shows the schematic diagram of the experimental chimney. The experimental solar chimney has internal dimensions of 2 m high, 1 m wide and 200 mm deep, and the side walls of the chimney are constructed from timber. As the experimental rig stands on the laboratory floor, the chimney floor is fitted with a rigid polystyrene board in order to minimize the radiation and convection heat exchange with the ground. It can be seen from Fig. 1 that an opening along the top of glazing façade as the air outlet, there is also an opening along at the bottom of the absorber plate façade as the air inlet. Inlet and outlet have the same dimensions of 1000 mm wide and 200 mm high, and the openings can be closed and opened according to the experimental purposes.

2.2. Main element of the solar chimney

The macro-encapsulated paraffin wax RT42 from Rubitherm is chosen as the PCM in this study, therefore the main element of the solar chimney is the PCM container. A rectangular PCM container is constructed of stainless steel, and has the dimensions of 1000 mm wide × 1600 mm high × 40 mm deep (as shown in Fig. 2), and is filled with a total of 50 kg RT42. In order to accelerate the charging and discharging processes of PCM, 30 straight stainless steel fins are inserted and distributed as thermal conductivity enhancer with the following dimensions: 1000 mm long, 40 mm high and 1 mm thick. Each two fins are spaced evenly by 50 mm so that cut the whole PCM into 33 smaller layers. The front wall of the container is painted black as the high thermal absorptive absorber. The four lateral sides and the back side of the PCM container are well insulated by polystyrene board, in this manner, the heat loss from the side walls and back wall can be negligible.

The selected commercial paraffin RT 42 changes the phase within a temperature range around 41 °C. The relevant thermophysical properties are listed in Table 1.

Unlike to the most of solar chimney testing under laboratory conditions, a solar simulator has been designed as the heat source to reproduce solar radiation in this experiment rather than imposing a constant thermal current to the surface using thermoelectric devices and heat sources. This is because that using an artificial lighting can more accurately simulate the influence of solar energy on the thermal performance of chimney. The multiple-lamp solar simulator consists of fourteen 400-W halogen lamps. These lamps were installed in a staggered form in an area of 1.8 m by 1 m. The heat flux provided by the simulator system can vary by change the distance between the system and heat absorber.

2.3. Instrumentation

To measure the temperatures of different components of the solar chimney, a number of K-type thermocouples with the measurement range of −50 to 250 °C and accuracy of ±0.3 °C, are distributed on the glazing, absorber plate, inside the PCM and the air channel. 9 calibrated K-type thermocouples are distributed to measure the temperature profiles across the depth at the vertical centre-line of the chimney as shown in Fig. 1. Three thermocouples are evenly positioned at the vertical centre-line of the inlet. The mean temperature from the three measurements was taken as