Energy and Buildings 68 (2014) 305–311

Contents lists available at ScienceDirect

Energy and Buildings

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

# Mathematical analysis of the influence of the chimney height and collector area on the performance of a roof top solar chimney

Hussain H. Al-Kayiem*, Sreejaya K.V., Syed Ihtsham Ul-Haq Gilani

*Mechanical Engineering Department, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Malaysia*

ARTICLE INFO

*Article history:*
Received 12 May 2013
Received in revised form 8 September 2013
Accepted 15 September 2013

*Keywords:*
Mathematical modelling
Renewable energy
Roof top solar chimney
Solar chimney
Solar updraft
Thermal solar system

ABSTRACT

Determination of the roof top solar chimney behaviour during the day time is essential for the proper designing and sizing. This paper presents a mathematical model and analysis of an inclined type roof top solar chimney. The thermal energy and fluid flow processes were simulated mathematically based on the energy and mass balances. The model was converted to a MATLAB computer program and solved by iteration method. The analysis was carried out at various collector areas (15, 150, and 600 $m^2$) and various chimney heights (5, 10, and 15 m). The model was validated by comparing the results with the experimental measurements. The developed mathematical model was able to predict the dynamic behaviour of the system. The results demonstrated that the performance of the system is highly influenced by the solar intensity. The system becomes functional for space ventilation when the solar intensity is higher than 400 $W/m^2$ with a 15 $m^2$ collector area and 5 m chimney height, under Malaysia and similar weather conditions. As the wind speed increases from 1.5 to 6 m/s, it contributes to reduce the system performance by 25% at solar intensity of 900 $W/m^2$.



## 1. Introduction

Renewable energy technologies are essential contributors to the future of the energy supply portfolio, as they contribute to reduce the dependency on the main fossil energy resources and provide opportunities for mitigating greenhouse gases. One of the renewable energy technologies is the solar chimney. It has been investigated for power generation and the experimental prototype build in Spain proved the concept, Schlaich [1]. The roof top solar chimney operates based on the same principles of traditional solar chimney power plants but for ventilation applications. It utilises the house roof as the solar absorber, and a translucent cover which is designed to cover the collector which allows the penetration of the solar radiation. The absorbed radiation is converted to thermal energy to heat up the air by energy transfer. This air gains kinetic energy and flows to the top of the roof where a chimney is installed to create buoyancy for the moving air to exit.

Numerous investigations have been reported including experimental and mathematical analysis. A few articles have reported results from numerical simulation.

Aboulnaga [2] performed an analytical study on a 15 $m^2$ roof solar chimney assisted by a cooling cavity for natural ventilation in buildings in hot arid climates, particularly in Al-ain city. The separation between the roof solar chimneys walls was varied from 0.08 to 0.25 m. The maximum air velocity derived in the chimney is about 1.1 m/s.

Ong [3] proposed a mathematical model of heat transfer in a steady state for a solar chimney, and contrasted the model with a real solar chimney. Chen et al. [4] carried out an experimental study on a solar chimney model with a uniform heat flux on one chimney wall with a variable chimney gap-to-height ratio between 1:15 and 2:5, and a different heat flux and inclination angles. Results showed that the air flow rate reached a maximum at a chimney inclination angle of around 45° for a 200 mm gap and 1.5 m high chimney.

Bassiouny and Koura [5] carried out an analytical and numerical study on a solar chimney of 1 m wide × 1 m height × 1 m depth for the room ventilation. The study concluded that by increasing the chimney width from 0.1 to 0.3 m improved the air change per hour by 25%, keeping the chimney inlet size fixed. In addition, they found that the chimney width has a more significant effect on the space flow pattern than the chimney inlet size.

The most common design of the solar chimney for ventilation application is the vertical configuration utilising the side wall, or vertical construction on the roof. Bassiouny and Korah [6] continued the study on the effect of the solar chimney inclination angle on the space flow pattern and ventilation rate, analytically and numerically. The analytical results showed that an optimum air flow rate value was achieved when the chimney inclination was between 45° and 70° for latitude of 28.48°.

* Corresponding author. Tel.: +60 53687008; fax: +60 5365 6461.
*E-mail addresses:* hussain_kayiem@petronas.com.my, hussain_faten@yahoo.com (H.H. Al-Kayiem).

0378-7788/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.enbuild.2013.09.021

**Nomenclature**

| | |
|---|---|
| $A_c$ and $A_{ap}$ | area of transparent cover and absorber plate ($m^2$) |
| $A_o$ and $A_i$ | outlet and inlet areas ($m^2$) |
| $C_{air}$ | specific heat of air (J/kg K) |
| $C_d$ | coefficient of discharge |
| $g$ | gravitational constant |
| $h_{c,ap-air}$ | coefficient of convective heat transfer from absorber plate to collector air ($W/m^2$ K) |
| $h_{c,air-c}$ | coefficient of convective heat transfer from transparent cover to collector air ($W/m^2$ K) |
| $h_{r,ap-c}$ | radiated heat transfer coefficient from the absorber plate to cover ($W/m^2$ K) |
| $I$ | intensity of solar radiation ($W/m^2$) |
| $m_{air}$ | air mass flow rate (kg/s) |
| $v_w$ | wind speed (m/s) |
| $T_{ap}$, $T_{air}$ and $T_c$ (K) | mean temperature of the absorber plate, air and cover respectively (K) |
| $T_{amb}$ | ambient temperature (K) |

*Greek letters*

| | |
|---|---|
| $\nu$ | kinematic viscosity |
| $\alpha$ | thermal diffusivity |
| $\tau_c$ | transitivity of the cover |
| $\alpha_{ap}$ | absorptivity of the plate |
| $\sigma$ | Stephan–Boltzman constant |
| $\varepsilon$ | emissivity of the cover |
| $\alpha_c$ | absorptivity of the absorber plate |

Punyasompun et al. [7] have experimentally investigated the application of the solar chimney for natural ventilation in multi-storey buildings. Two different vertical chimney arrangements were investigated. The first was continuous and had one opening at the top, while the second was non-continuous and had three openings, each at the same level of the roof of each storey. They also modelled the chimney, mathematically. The analysis showed that the chimney with one opening at the top provided a better ventilation option, and it was suitable for Thailand's weather conditions.

Arce et al. [8] carried out experimental measurement on vertical prototype of RTSC having vertical wall and cover configuration. He achieved 7 °C raise in the air temperature at the highest solar intensity of 604 W/$m^2$.

A study by Mathor [9] showed that the optimum inclination is within 40° to 60° depending on the location latitude. His analysis has shown that at 45° inclination, the mass flow rate is about 10% higher than the flow rates at 30° and 60° inclinations.

It can be concluded that the performance of solar chimney for ventilation purpose is investigated with focus on the air gap influence (Aboulnaga [2], Ong [3], Chen et al. [4], and Bassiouny and Koura [5]) and the inclination angle influence (Bassiouny and Korah [6], Punyasompun et al. [7], and Mathor [9]).

The objective of the present work has been to mathematically model the RTSC to investigate the influence of the chimney height and the chimney area on the system performance. The model simulates and analyse the behaviour of the system during the day time. The mathematical model was established from the mass and energy balance principles within the different parts of the RTSC. The simulation was solved computationally at 5, 10, and 15 m chimney heights and 15, 150, and 600 $m^2$ absorber areas under various solar intensities. After validation, the results are presented in the form of the air flow velocity, mass flow rate and performance indictor as the multiplication of the temperature rise and mass flow rate. Also, the wind speed effect on the performance has been investigated and discussed.

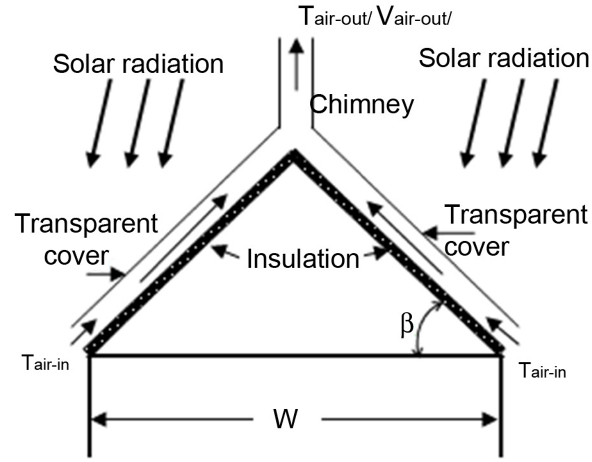


**Fig. 1.** Schematic view of roof top solar chimney.

## 2. Theory and principles

The RTSC adopted in this simulation is double sided inclined absorbers, with circular cross section chimney pipe, as outlined in Fig. 1. The main components of the RTSC system are the transparent cover, solar absorber, and chimney. The cover and collector are inclined at an angle, $\beta$ and separated at a perpendicular distance, $L_{ap-c}$ apart. Due to the distance between the cover and the collector, a pathway is created for air flow. During sunny days, the solar radiation would penetrate the transparent cover and heat up the absorber.

The thermal energy is transferred to the air in the pathway causing an increase in the air temperature. The hot air raises and exits at the top of the chimney with velocity, $V_{air,o}$ and temperature, $T_{air,o}$ while the cooler air is drawn in from the bottom at the inlet of the collector, providing a continuous air flow. Air at ambient temperature, $T_{amb}$ enters the pathway and flows upward to the top. In this manner, the air stream is flowing continuously through the system. If the system is intended to be used for ventilation, holes should be opened in the absorber to allow the accumulated warm air in the room to merge with the collector air stream, and the cooler air would enter from the opening at the base of the room. If the system is intended to be used for electricity generation, a wind rotor linked to the generator is installed in the chimney to convert the kinetic energy of the air flow to electric power.

## 3. Mathematical modelling

Fig. 2 shows the thermal network of the solar energy conversion in the RTSC components, cover and absorber plate.

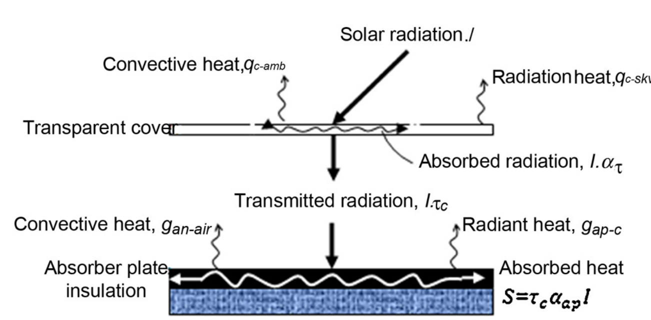


**Fig. 2.** Solar energy conversion network in the roof top solar chimney.