International Journal of Heat and Mass Transfer 102 (2016) 645–656

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Numerical study of vertical solar chimneys with moist air in a hot and humid climate

Sudaporn Sudprasert [a,*], Chatchawin Chinsorranant [a], Phadungsak Rattanadecho [b]

[a] Faculty of Architecture and Planning (Building Technology), Thammasat University, 99 Mu 18 Klongluang, Patumthani, Thailand

[b] Center of Excellence in Electromagnetic Energy Utilization in Engineering (CEEE), Department of Mechanical Engineering, Thammasat University, 99 Mu 18 Klongluang, Patumthani, Thailand

A R T I C L E I N F O

Article history:
Received 24 November 2015
Received in revised form 16 June 2016
Accepted 18 June 2016

Keywords:
Solar chimney
Moist air
Natural ventilation
CFD
Hot and humid
Species transport

A B S T R A C T

The purpose of this study was to investigate numerically the effect of moist air on the performance of a vertical solar chimney. Numerical models were constructed to simulate the heat transfer and fluid flow of dry air and moist air with a relative humidity of 30–80% in a solar chimney. Computational results of air velocity and temperature distribution in the solar chimney with dry air were compared to results with moist air, under a constant chimney wall temperature. Compared to a solar chimney with dry air, the yield of ventilated air flow was 15.4–26.2% less and the overall air temperature was higher for a solar chimney with moist air. To maximize ventilation and reduce backward flow at the opening, an aspect ratio of 14:1 and a limited opening height are recommended for solar chimneys with moist air.

1. Introduction

There have been many investigations of the thermal performances of variously designed solar chimneys integrated with buildings. Although invented for use in heating and ventilation applications in a cold climate [1] the solar chimney has been studied and applied under various climatic conditions. The thermal performance, in terms of the volume flow rate, air velocity, and air temperature, depends on the chimney configuration, construction materials, and integrated renewable energy systems [2].

The amount of water vapor in the air is dissimilar in different climates. For example, one study in a hot-dry climate reported a mean ambient temperature in the summer of 30–34 °C and relative humidity (RH) of less than 20% [3]. Another study in a hot–humid climate reported an ambient summertime temperature of 33.4–37.5 °C and RH of 46.0–73.5% [4]. The water content of air was greater in the hot–humid compared to the hot-dry climate by around 10 grams of moisture per kilogram of dry air. In a hot–humid climate, high vapor content in the air will affect the thermal performance of a solar chimney and lead to specific design specifications. Specifically, air flowing inside a solar chimney in a hot–humid climate could behave like moist air, or a mixture of water vapor and dry air.

Studies have covered diverse areas related to the volume flow rate of solar chimneys of various configurations. In India, for example, experiments showed results of 2.4–5.6 air change per hour (ACH) for an absorber area of 0.7–0.9 m^2 [5]. In the hot–dry climate of Iraq, a solar chimney with an incline of 60°, aspect ratio of 13.3, and chimney length of 2 m gave 4–35 ACH for an inflow velocity of 0.3–0.8 m/s [6]. A vertical solar chimney integrated with a water spraying system in Iran [3] gave an average of 4.51–8.28 ACH for an average velocity of 0.2–0.3 m/s. The room temperature approached a comfortable temperature with an indoor RH of 10.7–34.3%. The outdoor RH did not have a significant effect on the air velocity inside the channel.

There have not been many studies of the effects of humidity on solar chimneys in hot–humid climates because the humidity is not considered to have a primary effect on the ventilation. Ventilation performance has been determined by combining the wall and the roof [7], changing the configuration [8] and [9], increasing the inclination angle [3], and increasing the temperature difference between the inlet and outlet [10] and [11] of the solar chimney. Application of direct evaporation has been avoided in hot–humid climates. Only one experiment of an inclined solar chimney with indirect evaporative cooling was found [4], which was performed in Thailand. Solar chimney is used to drive the warm air inside it to rise along the wall, which can be used for building ventilation,

* Corresponding author.
E-mail address: sudaporn@ap.tu.ac.th (S. Sudprasert).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.054
0017-9310/

Nomenclature

c_p	specific heat (J/kg·K)
$D_{i,m}$	mass diffusion coefficient for species i in the mixture (m^2/s)
$D_{i,T}$	thermal diffusion coefficient for species i in the mixture (m^2/s)
g_i	gravitational acceleration in the i direction (m/s^2)
H	height of air gap (m)
h	height of opening (m)
J_i	mass diffusion ($kg/s{\cdot}m^2$)
k	thermal conductivity (W/m·K)
L	width of air gap (m)
P	static pressure (Pa)
P_{atm}	atmospheric pressure (Pa)
Sc_t	turbulent Schmidt number
t	time (s)
T	time-mean temperature of fluid (°C)
T'	fluctuation temperature (°C)
T_0	reference temperature (=31.0 °C)
T_{w1}	temperature of air contacting the hot surface (°C)
T_{w2}	temperature of air contacting the cold surface (°C)
$T_{\alpha 1}$	ambient temperature (°C)
$T_{\alpha 2}$	air temperature at the inlet (°C)
u_i	mean velocity component corresponding to i direction (m/s)
u'_i	fluctuation velocity component in the i direction (m/s)
x_i	coordinate direction i (m)
Y_i	local mass fraction of each species

Greek symbols

β	coefficient of thermal expansion (=$1/T_0$) (1/K)
ρ	density of fluid (kg/m^3)
μ	laminar dynamic viscosity (kg/m·s)
υ	kinematic viscosity (m^2/s)
γ	diffusion coefficient

power generation, drying, etc. The solar chimney for building ventilation is similar to the solar updraft tower (also called solar chimney) for power generation [12]. In a solar updraft power plant where the buoyancy effect was applied to drive the wind turbine, under high relative humidity, the power generation became smooth, power was increased, and condensation was observed [13].

In the design of solar chimney configurations, the commercial CFD software has been widely used to determine the proper height to width ratio of the air gap [14] and the inlet positions [15] to maximize the mass flow rate. The height of the air gap (H), width of the air gap (L), and height of the opening (h) affected the ventilation rate of the solar chimney. A numerical study showed that the optimal aspect ratio varied with the Raleigh number (Ra_L) under uniform heat flux and uniform wall temperature [16]. On the basis of computational results, Gan (2006) recommended an air–gap height to width ratio (H/L) of 11.11 or 20.0. A wall solar chimney in Thailand showed the highest volume flow rate with H/L = 14 [17].

The purpose of the present study was to compare the air flow and temperature distributions within a vertical solar chimney when using moist air compared to dry air. Here, moist air refers to air with a range of RH typical of Thailand (RH = 40–80%). The air velocity and temperature distribution of moist air in the air gap were obtained simultaneously by using the computational software ANSYS Fluent 14.0. Results obtained from moist air simulated by the species transport model were compared to results from the dry-air model. Effects of moist air on the solar chimney aspect ratio and inlet height were also studied.

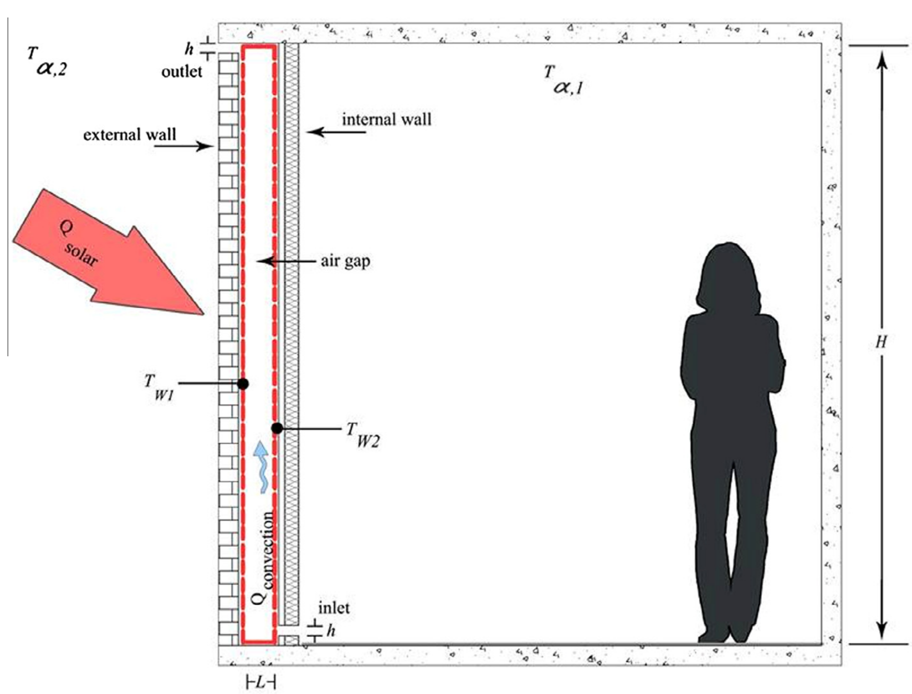

Fig. 1. Air gap of the solar chimney subjected to constant surface temperatures.