Energy and Buildings 94 (2015) 218–226

Contents lists available at ScienceDirect

Energy and Buildings

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

Twenty-four hour simulation of solar chimneys

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ARTICLE INFO

Article history:
Received 29 June 2013
Received in revised form 20 February 2015
Accepted 1 March 2015
Available online 7 March 2015

Keywords:
Solar chimney
Modeling
Passive use of solar energy in buildings
Natural ventilation

ABSTRACT

A model for time dependent analysis of solar chimneys is presented. The energy balance equations for three components of solar chimneys, absorbing plate, cover glass and air-gap are discretized with respect to time using an implicit finite difference model. The discretized nonlinear energy balance equations are solved for numerous time steps over a 24-h period using the Newton–Raphson method. The time dependent solar irradiation is determined using the clear sky model. The model's performances for various parameters of solar chimney that affect the thermal mass of the absorbing plate are tested. It was determined that a solar chimney with a relatively large thermal-mass produces airflow well into night and early morning when no solar irradiance is present. Also, a high thermal mass of the absorbing plate results in smaller variations in the airflow rate. The results of the present model for a solar chimney with no thermal storage compare well with the previously published data.

1. Introduction

Solar energy is a sustainable source of energy that can be a significant source for generating electric power, hot water and ventilation in buildings. It can be an economically, and socially and environmentally sustainable passive means of ventilation for buildings. A device that uses solar energy to generate airflow is known as a solar chimney or a solar tower. The mechanism associated with a solar chimney relies on driving forces that power the air inside the chimney and causes its movement using on natural convection principles.

The need for passive ventilation systems in buildings has resulted in a large number of analytical and experimental studies on solar chimneys. Khanal and Lei [1] presented an overview of research work on solar chimney that has taken place in the last two decades. Most of these studies were performed for vertical solar chimneys, commonly known as a Trombe wall. Arce et al. [2] performed a complex conduction-convection-radiation CFD analysis to obtain a series of correlations for the wall and glass Nusselt numbers as a function of flow Reynolds number in a solar chimney. An analytical study of solar chimney used for room natural ventilation was performed by Bassiouny and Koura [3]. They concluded that the vertical chimney width has a more significant effect on ACH compare to the inlet size. Burek and Habed [4] used an experimental setup to correlate the air mass flow rate and thermal efficiency of a vertical solar chimney to the heat input and channel depth. Amori and Mohammed [5] performed experimental and numerical studies of a solar chimney with multiple entrances; bottom, side, and both side and button entrances. They also investigated the effect of using the chimney with a phase changing material (paraffin) on the thermal behavior of a solar chimney. Their experimental results show that a solar chimney with a side entrance gives a better thermal performance; also integrating a solar chimney with PCM extended the ventilation period after sunset.

Bansal et al. [6] presented a steady state model for analysis of a solar chimney. The model takes into consideration different sizes of openings of a solar chimney with varying values of the discharge coefficients. Numerical values presented in their work show that a solar chimney with area of 2.2 m^2 is able to induce an airflow between 140 and 330 m^3/h for solar irradiation of 200 W/m^2 and 1000 W/m^2, respectively. Their work simply used a fixed value of the product of the transmittance and absorptance ($\tau\alpha$) of 0.8 to calculate the solar energy reaching the inner wall, without considering the spectral characteristics of glass and the absorbing wall and energy storage in the absorbing plate of solar chimneys. In a more recent, work Basnal et al. [7] studied a window size solar chimney and have recorded an airflow velocity of up to 0.24 m/s. Ding et al. [8] used a CFD model to analyze a south facing double skin façade with a solar chimney for high-rise buildings. Lee and Strand [9] developed a model for simulation of vertical solar

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http://dx.doi.org/10.1016/j.enbuild.2015.03.001
0378-7788/

Nomenclature

A	flow area (m^2)
c	specific heat of absorbing plate (J/(kg K))
c_p	specific heat of air (J/(kg K))
d	distance between glass and absorbing plate (m)
DR	daily range temperature (°C)
E_s	solar emission or irradiation (W/m^2)
E_p	radiation emitted from the absorbing plate (W)
E_g	radiation emitted from the outer glass (W)
f	functional representation of energy balance equation
g	gravitational acceleration (9.81 m/s^2)
Gr	Grashof number
h	height of the chimney (m)
h_{go}	convection heat transfer coefficient of the glass on the outside (W/m^2 K)
h_{gi}	convection heat transfer coefficient of the glass on the inside (W/m^2 K)
h_p	convection heat transfer coefficient of the absorbing plate (W/m^2 K)
$\mathbf{J}$	Jacobian matrix
k	thermal conductivity (W/m K)
L_c	characteristic length = $h/\cos(\theta)$ for glass cover and = d for air gap (m)
Nu	Nusselt number
Pr	Prandtl number
q''	heat flux (W/m^2)
q''_s	solar heat irradiance (W/m^2)
Ra	Rayleigh number
t	thickness of the absorbing purface (m), and time (s)
Δt	time increment (s)
T_D	maximum daily range (°C)
T_a	air temperature inside the solar chimney gap (K)
T_p	temperature of the absorbing plate (K)
T_g	temperature of cover glass (K)
T_O	temperature of outside (K)
V	volume of the absorbing plate slab per unit area (m^3/m^2)
$\dot{V}$— — —	volume flow rate (m^3/s)
w	width of air layer (m)

Greek symbols

α	absorptance, and thermal diffusivity (m^2/s)
β	thermal expansion coefficient (1/K)
ε	emissivity, convergence criterion
θ	angle of the inclined plate (°)
λ	wavelength (μm)
λ_c	critical wavelength (μm)
ρ	density (kg/m^3), and reflectance
σ	Stefan–Boltzmann constant (W/m^2 K^4)
τ	cover glass transmittance
ν	kinematic viscosity (m^2/s)

Subscripts

b	beam solar irradiance
d	diffuse solar irradiance
g	corresponding to glass
gg	spectral property of glass based on glass temperature
gs	spectral property of glass based on sun temperature
gp	spectral property of glass based on the absorbing plate temperature
i	time step number
n	iteration number
r	reflected
s	corresponding to solar
t	total
p	corresponding to the absorbing plate
pg	spectral property of plate based on glass temperature
ps	spectral property of plate based on sun temperature
pp	spectral property of absorbing plate based on its temperature

chimneys for implementation in the EnergyPlus program. Tan and Wong [10] studied the use of a vertical chimney in a classroom, and concluded that the solar chimney in question would operate well in a tropic climate. The air speed in their setup reached a maximum of 0.49 m/s and the interior air temperature heated up slower and cooled down faster within 1 to 2 h.

Khedari et al. [11] used an experimental setup to study the use of a solar chimney for natural ventilation in a school building. They concluded that the use of a solar chimney creates more ventilation than if one were to, for example, leave the windows open. Their study was conducted using a single-room schoolhouse with a volume of approximately 25 m^3. The southern wall was composed of three different solar chimneys of 2 m^2 each, and the roof of the southern side included two similar units of 1.5 m^2 each. The setup was built using common construction materials. The experimental results indicated that when the solar chimney ventilation system was in use, room temperature was near that of the ambient air, indicating a good ability of the solar chimney to reduce the house's heat gain, and thereby ensuring thermal comfort. The air change rate varied between 8 and 15 times the volume of the building (1.6 to 2.5 time/hour per unit surface area of solar chimney).

Hirunlabh et al. [12] studied the effectiveness of a Metallic Solar Wall (MSW) consisting of a glass cover, air gap, black metallic plate and insulator made of microfiber and plywood. They found that the MSW with a 14.5 cm air gap and a 2 m^2 surface area ($h \times w = 2\,\text{m} \times 1\,\text{m}$) produced the highest air mass flow rate, of about 0.01 to 0.02 kg/s.

Chen et al. [13] performed an experimental investigation to study the effect of varying the gap and inclination angle of a solar chimney on its flow rate, and it was determined that the maximum flow rate was achieved at an inclination angle of around 45° for a 200 mm gap and a 1.5 m high chimney, and the airflow rate was about 45% higher than that for a vertical chimney at otherwise identical condition. Marthur et al. [14] used an analytical model to investigate the optimum absorber inclination angle for maximum solar chimney airflow rate. They found an inclination angle of 45° produces the maximum airflow rate in Jaipur India. The effect of solar chimney inclination angle on its airflow rate was later studied by Bassiouny and Korah [15], and they concluded that the maximum airflow rate was achieved when the chimney inclination is between 45° and 70° for a latitude of 28.4°. Chungloo and Limmeecokchai [16] investigated the thermal performance of a passive rooftop solar chimney cooling systems by comparing the results from a test cell and a control cell with identical walls but different roof configurations. They found that the room temperature for the configuration with a solar chimney is lower than the ambient temperature by 2.0–6.2 °C versus 1.4–3.0 °C for the control room.

None of the aforementioned works used the spectral radiative model in their analysis. They mostly used a combined $\tau\alpha$ value, described in [17], to estimate the solar energy absorbed by the solar chimney surface. However, it is well known that glasses have