Solar Energy 135 (2016) 130–153

Contents lists available at ScienceDirect

Solar Energy

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

Role of distributed/discrete solar heaters during natural convection in the square and triangular cavities: CFD and heatline simulations

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ARTICLE INFO

Article history:
Received 28 December 2015
Received in revised form 25 April 2016
Accepted 29 April 2016

Keywords:
Solar heating
Convection
Discrete heaters
Triangular enclosures

ABSTRACT

Solar heating has gained significant attention for various material processing applications and the current work focuses on the discrete solar heating of fluids involving natural convection heat transfer. Five different cases based on the heater location on the side walls of the square, triangular-type 1 and triangular-type 2 (inverted triangle) enclosures are studied. The mathematical tool of 'heatlines', which represents the trajectories of flow of heat is used to visualize the total energy flow in the domain. Galerkin finite element method with adaptive grids has been implemented for solving the governing equations of heat and fluid flow and Poisson-type of equations for solving the streamfunction and heatfunction. The local and average Nusselt numbers vs. average or cup mixing temperature have been evaluated. Based on the optimum thermal mixing and high temperature uniformity, the discrete solar heating strategy involving the positioning of the heaters near the bottom portion of the side walls and heaters along the central portion of the side walls were found to be energy efficient irrespective of any enclosure. The asymmetrically distributed heating strategy was also found to be suitable for the systems leading to the significant temperature uniformity over a larger region. Overall, the results displayed an increase in the mixing efficiency index for the square and triangular-type 2 (inverted triangle) enclosures in the presence of discrete solar heaters.

1. Introduction

The world in the present age is facing major challenges on energy consumption as the stocks of the non-renewable energy sources are gradually depleting (Kayal and Chanda, 2015). In addition, the 21st century is facing tough challenges against the global warming and the oil price is anticipated to be higher in the coming days (Gebreslassie et al., 2012). As a result, scientists and researchers are primarily focusing on the renewable energy resources such as solar energy, as it is readily available and also cost effective (Monreal et al., 2015; Khalid et al., 2015). Due to the promising economic and environmental benefits, the renewable energy resources are expected to play a pivotal role in the energy-planning endeavor. In the recent past, the renewable heating technologies such as solar heating has gained the wide attention as it plays a leading role in the substantial renewable contribution to minimize the energy consumption (Vaziri et al., 2015; Kooli et al., 2015; Kulkarni et al., 2015). The solar heating technique involves the absorption of the irradiation by a solar collector to heat the working or processing fluid (Cheng et al., 2012; Anderson, 2013). It may be noted that the solar heaters play an important role in many engineering applications such as solar drying devices (Duran et al., 2015) and building heating systems (Li et al., 2015; Good et al., 2015).

The processing with natural convection, or buoyancy, has often been proposed for the use in solar applications. The important role of natural convection in solar applications has resulted in impressive amount of heat transfer research aimed at understanding and controlling natural convection in different enclosures. The natural convection heat transfer coefficient in a vertical flat-plate solar air heater was experimentally evaluated by Hatami and Bahadorinejad (2008). Wu et al. (2010) comprehensively reviewed the natural convection heat loss from a cavity receiver in the parabolic dish solar thermal power system. In addition, Tao and He (2010) numerically studied the fluid flow and heat transfer process during natural convection in a parabolic trough solar collector tube. Wilson and Paul (2011) numerically modeled the experimental data corresponding to convection occurring under a photovoltaic (PV) panel. Later, Al-Ansary and Zeitoun (2011) numerically studied the conduction and convection heat losses from a half-insulated air-filled annulus of the receiver of a parabolic trough collector. Sanchez et al. (2013) studied the thermal

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http://dx.doi.org/10.1016/j.solener.2016.04.045
0038-092X/

Nomenclature

g	acceleration due to gravity, m s^{-2}
L	height of the enclosure, m
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
Ra	Rayleigh number
$RMSD$	Root mean square deviation
T	temperature, K
T_h	temperature of hot wall, K
T_c	temperature of cold wall, K
u	x component of velocity, m s^{-1}
U	x component of dimensionless velocity
v	y component of velocity, m s^{-1}
V	y component of dimensionless velocity
x	distance along x coordinate, m
X	dimensionless distance along x coordinate
y	distance along y coordinate, m
Y	dimensionless distance along y coordinate

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	volume expansion coefficient, K^{-1}
γ	penalty parameter
θ	dimensionless temperature
ν	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
Θ_{cup}	cup mixing temperature, K
Θ_{avg}	area average temperature, K
φ	angle with positive X-axis
ψ	dimensionless streamfunction
Π	dimensionless heatfunction

Subscripts

l_i	length along the left wall
r_i	length along the right wall
k	global node number

and fluid dynamic behavior of an open joint ventilated façade (OJVF) with buoyancy driven fluid flow. Reichl et al. (2013) compared the particle image velocimetry and local temperature measurements with the CFD simulations during the natural convection heat transfer process within the compound parabolic concentrator. Bottillo et al. (2014a,b) carried out a thermo-fluid dynamic analysis of natural convection effects on the heat transfer coefficient and turbulent kinetic energy in an urban canyon. Zhang et al. (2014) carried out an experimental study on the solar thermal convection based on supercritical natural convection. Al-Kayiem and Yassen (2015) studied the natural convection heat transfer in a rectangular passage air heater. Sultana et al. (2015) studied natural convection within a rooftop concentrating collector. Rahbar et al. (2015) investigated the heat and mass transfer behavior within the tubular solar still during natural convection using 2D-CFD simulations. Li et al. (2015) carried out the field synergy principle analysis in order to reduce the natural convection heat loss from a solar cavity receiver. Ngo et al. (2015) studied the numerical modeling and optimization of natural convection heat loss suppression in a solar cavity receiver with plate fins. Bahrehmand and Ameri (2015) used various mathematical models in order to study the energy and exergy analysis within various solar air collector systems with natural convection.

Over the years, scientists have implemented the solar heating strategy at a particular location via solar collectors which essentially denotes the side wall or differential heating. This type of differential system may lead to the local overheating or cold pockets and that may further lead to poor thermal mixing and management. In the recent past, a number of experimental and numerical studies within the differential heated systems (Merrygold and Osman, 1998; Hua and Lu, 2001; Daniels and Punpocha, 2004) also demonstrated large zones of temperature stratification near the core of the enclosure and consequently, the temperature uniformity was found to be poor. This may finally lead to a thermally inefficient system as the energy consumption in such systems is high. The method of discrete/distributed heating may be an efficient technique in order to maintain the uniform temperature and high thermal mixing throughout the enclosure. The distributed heat sources induce the local buoyancy flow which may result in the enhanced thermal mixing within the enclosure. Consequently, the process is expected to be more energy efficient. A considerable number of experimental and numerical studies on natural convection in the various discretely heated enclosures are reported in the literature (Sarris et al., 2004; Aydin and Pop, 2005; Koca et al., 2007; Varol et al., 2007, 2006). However, a few works are available in the literature based on the discrete solar heating. Souza et al. (2014) experimentally studied the convective phenomenon within an inclined discretely heated cavity of an integrated collector storage water heater (ICSSWH). It was found that the discrete solar heating from the lower half of the inclined wall resulted in the lower stratification of temperature in the cavity and consequently, a low temperature difference was found to exist between the upper and lower half of the cavity. It was also observed that the heat losses are lesser due to the enhancement in the overall surface area of the solar heat sources. Thus, it may be inferred that the discrete solar heating would immensely help in designing systems with high energy efficiency and the overall cost of the system will be largely reduced. It may be noted that the discrete solar heaters can be used in various solar thermal applications such as refrigerators (Islam and Morimoto, 2014; Brites et al., 2016), radiators (Kim et al., 2015), windows (Vossen et al., 2016), heat sink (Alvarado et al., 2011).

In order to maintain the constant temperature along the heaters, the mushy PCM (Phase Change Materials) salt hydrates such as sodium sulphate (melting point = 32.4 °C, heat of fusion = 252 kJ/kg), sodium silicate (melting point = 72.2 °C, heat of fusion = 267 kJ/kg), etc. may be considered and these materials are assumed to circulate along the solar heater panel. The use of PCM stems from the applications of PCM for its unique property, as elaborated in the earlier research works (Farid et al., 2004; Sharma et al., 2009). Note that, the PCM limits excessive temperatures by storing the excess heat during the day, and releasing it during the night (Farid et al., 2004). The PCM salt hydrates have larger energy storage density and higher thermal conductivity compared to the organic PCM compounds (such as Paraffin wax) (Farid et al., 2004). It may be noted that the PCM circulation along the heaters depend on the daylight. During the sunshine hours (day time), the PCM can be circulated intermittently along the heaters to control the enormous energy storage of PCM in order to maintain the constant temperature. In the absence of the solar irradiations (night time), the uniform temperature is maintained across the solar heater panels by increasing the circulation of the PCM along the heaters. Hence, these discrete solar heaters infused with PCM, are useful at both the day and night hours for the effective heating of the fluid (Sharma et al., 2009). Note that, the current simulation studies have been carried out at the steady state