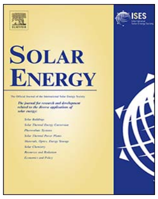
Solar Energy 159 (2018) 966–983

Contents lists available at ScienceDirect

Solar Energy

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



Thermal performance improvement of a solar air heater fitted with winglet vortex generators

Sunil Chamoli[a,b], Ruixin Lu[a], Dehao Xu[a], Peng Yu[a,*]

[a] Department of Mechanics and Aerospace Engineering, Southern University of Science and Technology, Guangdong 518055, China
[b] Department of Mechanical Engineering, DIT University, Dehradun 248009, India

ARTICLE INFO

Keywords:
Heat transfer
Friction factor
Winglet vortex generator
Solar air heater
Numerical simulation

ABSTRACT

Numerical simulations are carried out to investigate the thermal and flow characteristics of a solar air heater (SAH) embedded with winglet vortex generator (WVG) for the Reynolds number (Re) ranging from 3500 to 16,000. The geometrical parameters of WVG considered are the tip edge ratio (c/a) from 0 to 1 and the angle of attack (α) from 30° to 90°, respectively. Computations are based on the finite volume method coupled with the SIMPLE algorithm. The effects of WVG on the dimensionless parameters, Nusselt number (Nu), friction factor (f), Nusselt number ratio (Nu/Nu_s), friction factor ratio (f/f_s), and thermal enhancement factor (TEF) are discussed. Nu and f increase with the initial increase of α from 30° to 60° and then decrease with a further increase in α. The maximum values of Nu and f appears at $\alpha = 60^\circ$ and $c/a = 1$. The results show that the WVG with $c/a = 0$ and $\alpha = 30^\circ$ provides the best TEF in the range from 1.72 to 2.20. The internal flow behavior along with the distribution of the temperature field and streamlines is explored to explain the effect of WVG configurations on heat transfer and friction factor, respectively. The modified WVG affects the flow and temperature fields, which leads to a significant enhancement in the convective heat transfer rate.

1. Introduction

The abundant and renewable nature of solar energy makes it suitable to be harnessed using solar thermal systems. The solar air heater (SAH) is a popular device for collecting solar energy because of its outstanding qualities such as a simple design, low cost, and low maintenance requirement. However, it exhibits a low thermal efficiency in comparison to solar water heater, because of the low rate of convective heat transfer between the absorber plate and flowing air and also due to the low heat capacity of air. This results in a high absorber-plate temperature and significant thermal losses into the environment. The economic viability of SAHs can be improved by improving their thermal efficiency. This can be accomplished by creating a fully turbulent flow in these systems and minimizing the heat loss with appropriate pressure drop.

Researchers employed different techniques to improve the SAH performance and there is a drastic change observed in the research trend of SAH. Significant numbers of research papers were published in last five years with the different methodology of thermal performance improvement of SAH. The effect of collector material on solar collector performance is explored in O'Hegarty et al. (2017) and Zukowski and Woroniak (2017). The performance improvement using nanofluid as a working medium was found in Iranmanesh et al. (2017), Rose et al. (2017) and (Verma et al. 2017). The recent studies on the integrated solar collector with phase change material (PCM) for heat storage were carried by Navarro et al. (2016), Serale et al. (2016), and (Kabeel et al. 2017). The thermal efficiency improvement of coaxial evacuated tube solar collector by reducing the heat losses was carried by Zhang et al. (2014). However, the high heat transfer rate can be achieved by other methodologies including the heat pipes and passive heat transfer techniques. Moreover, these two techniques showed remarkable thermal performance and employed in many industrial processes. The heat pipe technology takes an advantage of high heat transfer efficiency and employed in industrial applications such as aerospace engineering Park et al. (2010), electronic cooling Li et al. (2013), and waste heat recovery (Brito et al. (2015) and (Remeli et al. 2015)). The implementation of heat pipes in solar collectors was successfully rendered by Azad (2008) and Jalilian et al. (2016). Sivakumar et al. (2012) and Wei et al. (2013) integrated the heat pipes in the solar collector and reported the significant performance improvement of the system. Zhu et al. (2015, 2016) investigates the effect of air flow rates and season tendency on thermal performance of solar collector that uses flat micro-heat pipe arrays (FMHPA) as the central transporting component. The integration of phase change material with micro heat pipe array as core

---

[*] Corresponding author.
E-mail address: yup6@sustc.edu.cn (P. Yu).

https://doi.org/10.1016/j.solener.2017.11.046
Received 13 July 2017; Received in revised form 11 October 2017; Accepted 18 November 2017

Nomenclature

A	absorber plate surface area, m^2
a	height of WVG, m
b	length of WVG, m
$C_{1\varepsilon}$	constant, 1.44
$C_{2\varepsilon}$	constant, 1.92
c/a	tip edge ratio
C_p	specific heat of fluid, $J\,kg^{-1}\,K^{-1}$
D	duct hydraulic diameter, m
e	base of obstacles, rib height, m
e/H	relative roughness height
f	friction factor
$\frac{f}{f_s}$	friction factor ratio
G_k	generation of turbulence kinetic energy due to the mean velocity gradients
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
$h_{\times}$	local heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
H	duct height, m
k	turbulent kinetic energy, $m^2\,s^{-2}$
L	length of test section, m
Nu	Nusselt number
$Nu_{\times}$	local Nusselt number
$\frac{Nu}{Nu_s}$	Nusselt number ratio
p	fluid pressure, Pa
ΔP	pressure drop across duct, Pa
P_L/a	relative longitudinal pitch
P_T/b	relative transverse pitch
P/e	relative roughness pitch
Pr	Prandlt number
q	heat flux, W/m^2
Re	Reynolds number
SAH	solar air heater
T	fluid temperature, K
T_w	mean wall temperature, K
T_f	mean fluid temperature, K
TEF	thermal enhancement factor
u	fluid velocity in the duct, $m\,s^{-1}$
u_i	velocity component in x_i-direction, m/s
WVG	winglet vortex generator

Greek letters

α	flow angle of attack, deg
β	open area ratio (%)
δ	leading edge tip spacing between WVG pair, m
ε	dissipation rate, $m^2\,s^{-3}$
σ	winglet aspect ratio
σ_k	turbulent Prandtl number for k
σ_ε	turbulent Prandtl number for ε
λ	thermal conductivity of fluid, $W\,m^{-1}\,K^{-1}$
μ	dynamic viscosity, $kg\,s^{-1}\,m^{-1}$
μ_t	turbulent viscosity, $kg\,s^{-1}\,m^{-1}$
ρ	density of fluid, $kg\,m^{-3}$

Subscripts

m	mean
pp	pumping power
s	smooth channel
i, j	Cartesian coordinates in x and y direction

heat transfer element in solar air collector was explored by Zhu et al. (2016). They marked the high thermal efficiencies for large volume air flow rates. Zhu et al. (2017) experimentally evaluated the thermal performance of a new designed micro heat pipe array (MHPA) integrated vacuum tube solar air collector. The study revealed that the MHPA-based vacuum tube solar air collector have the enough potential to fulfill the energy needs of commercialized applications of farmhouse heating, agricultural drying, and building heating etc. Zhu et al. (2016) proposed a new novel design of compound parabolic concentrator solar air collector with micro heat pipe. They analyzed experimentally and numerically the thermal performance of the new designed solar collector and reported an average efficiency of 61% for the flow rate of $320\,m^3/h$ at the radiation value of $799\,W/m^2$. In addition to the introduction of heat pipe in solar air collector for improving the thermal performance, passive methodology of heat transfer enhancement also employed in solar collector for improving the thermal performance. The passive methodology has the advantages of the ease of fabrication and the low cost of installation. Turbulence promoters in the form of ribs, baffles, vortex generators (VGs), obstacles, and winglets are often used to improve the thermal performance of SAH. They destroy or produce a thin thermal boundary layer on the absorber plate, augment the turbulence intensity, and induce appropriate fluid mixing, which enhance heat transfer. However, they also yield a considerable increase in pressure drop due to the high flow blockage.

Several experimental and numerical studies have been conducted to investigate the thermal and fluid flow behavior of a SAH integrated with different geometrical inserts and reviewed by Chamoli et al. (2012), Alam et al. (2014), Patil (2015) and Gawande et al. (2016a, 2016b). The small height ribs attached to the absorber plate into different shapes, and orientations were investigated and the substantial enhancement in the heat transfer and pumping power requirements was reported (e.g. V shape ribs with gap by Singh et al. (2011), multi V ribs with gap by Kumar et al. (2013), multiple arc ribs by Singh et al. (2014), multiple arc shaped ribs with gap by Pandey et al. (2016), dimple ribs in arc arrangement by Sethi et al. (2012), reversed L shaped ribs by Gawande et al. (2016a, 2016b)). The turbulence promoters in the form of baffles/obstacles/winglets produced the more significant effects on heat transfer. However, the enhanced heat transfer also accompanied with a serious pressure drop. Among these elements, vortex generators (VGs) especially obstacles/winglets, have received the majority of attention. Obstacles and winglets have been successfully used in the modern thermal systems because they can induce a high heat transfer by producing intensive longitudinal vortices, and the associated pressure drop can be controlled by modifying their shapes Abene et al. (2004). Researchers have focused on identifying the best shape of VGs that induce the maximum heat transfer with minimum pressure drop. Romdhane (2007) found the 60% efficiency improvement of a SAH embedded with baffles. Ozgen et al. (2009) used aluminum cans in the single and double pass arrangements of a SAH. The study revealed that the double pass SAH with obstacles on both sides produces higher thermal efficiency than the single-pass SAH. Performance of a SAH with three different types of obstacles (Types I, II and III) was experimentally investigated by Akpinar and Kocyigit (2010). The study showed that the channel with Type II obstacles exhibited the best performance over the complete range of flow and operating conditions. Bekele et al. (2013) investigated the effect of delta shape obstacles on the performance of a SAH. They reported the enhancement of around 3.5 times in Nusselt number (Nu) for $P_l/e = 3/2$ and $e/H = 0.75$ at Reynolds number $Re = 10{,}000$. Karwa and Maheshwari (2009) explored the effect of half (26% open area ratio) and fully (46.8% open area ratio) perforated baffles in a SAH duct. The 76–169% enhancement in Nu was reported with half perforated baffles.

Alam and Kim (2016) investigated the effect of semi elliptical obstacle on the SAH performance. The study showed the maximum Nu