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Thermal performance in solar air heater with perforated-winglet-type vortex generator

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ABSTRACT

An experimental and numerical study of turbulent convective heat transfer in a solar air heater duct with winglet-type vortex generators (WVGs) placed on the absorber plate is presented. Air as the test fluid enters the duct having a uniform wall heat-flux applied on the upper wall or the absorber plate with Reynolds number from 4100 to 25,500. Two types of WVGs are introduced: rectangular (RWVG) and trapezoidal (TWVG) WVGs, in order to create multiple vortex flows along the duct. The WVG parameters in the present study include two relative height ($B_R = e/H = 0.2$ and 0.48), three longitudinal pitch ratios ($P_R = P_l/H = 1$, 1.5 and 2) and a single attack angle, $\alpha = 30°$. The experimental result reveals that the RWVG with $B_R = 0.48$ and $P_R = 1$ provides the highest heat transfer and friction factor at about 7.1 and 109.5 times above the flat duct, respectively while the TWVG with $B_R = 0.2$ and $P_R = 1.5$ yields the maximum thermal performance around 1.84. Then, to improve the performance by reducing the substantial pressure loss, both the WVGs with $B_R = 0.48$ and $P_R = 1.5$ are modified to be perforated rectangular and trapezoidal winglet-type vortex generators (P-RWVG and P-TWVG) with four different punched hole/pore diameters ($d = 1$, 3, 5 and 7 mm) on their central area. The investigation indicates that among the perforated WVGs, the P-RWVG at $d = 1$ mm yields the highest heat transfer and friction factor up to 6.78 and 84.32 times higher than the smooth duct but the best thermal performance of about 2.01 is found for the P-TWVG with $d = 5$ mm. To explore the flow and heat transfer pattern, a 3D numerical flow simulation is performed and validated with available measurements where both the numerical and measured results are in good agreement.

1. Introduction

Thermal performance improvements in heating/cooling devices are needed to meet the energy saving of those thermal devices. The vortex strength and vortex-induced impinging jet phenomena are of interest in those thermal devices such as electronic devices, heat exchangers, gas turbine blades and solar collectors (Eiamsa-ard et al., 2006; Promvonge, 2008, 2010; Sriromreun et al., 2012; Promvonge et al., 2014; Skullong et al., 2017). Solar collectors are classified into two main groups: (i) photovoltaic, PV and (ii) solar air heater, SAH. The SAH is one of solar thermal systems using energy from the sun that its applications are in drying, curing, paint spraying operation and space heating processes. The SAH is widely used in today's world and plays major role in economic growth and industrialization. In general, air flowing through conventional absorber plate (flat/smooth plate) of the SAH as shown in Fig. 1, the heat transfer coefficient is quite low because of boundary layer appearance. To enhance thermal performance of the absorber plate, several vortex-flow devices are offered in the design of SAH. For decades, rib turbulators (RTs) and winglet-type vortex generators (WVGs) have been extensively introduced in high-performance SAH systems to produce strong longitudinal vortex flows inside resulting in faster rates of heat transfer. In general, the absorber plate improvement of the conventional SAH can be generally made by several enhancement techniques with emphasis on many types of augmented surfaces. The applications of the RTs and WVGs on the absorber surface of SAH have been regarded as an effective method for heat transfer augmentation in such a system (Gawande et al., 2014; Abhishek et al., 2015).

Earlier work on using RTs for increasing thermal performance was reported by Thianpong et al. (2009) who showed that the largest *e/H* rib with inline array yielded the maximum increase in both Nusselt

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Nomenclature

A_s	area of absorber plate, m^2
A_R	duct aspect ratio (= W/H)
A_h/A_w	winglet porosity ratio
B_R	winglet blockage ratio, b/H
C_p	specific heat, J/kg K
c	base of winglet, m
c_s	short side opposite base of winglet, m
D	hydraulic diameter of duct, m
d	hole/pore diameter, m
e	winglet height or leg, m
f	friction factor
f_R	friction factor ratio, f/f_0
H	duct height, m
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
L	test section/duct length, m
$\dot{m}$	rate of mass airflow, kg/s
Nu	average Nusselt number, (= hD/k)
Nu_R	Nusselt number ratio, Nu/Nu_0
P_l	length of longitudinal pitch, m
P_t	length of transverse pitch, m
ΔP	pressure drop, Pa
Pr	Prandtl number, (= $C_p \cdot \mu/k$)
Re	Reynolds number, (= UD/ν)
P_R	longitudinal pitch length ratio, (= P_l/H)
Q_{net}	rate of heat transfer, W
T	temperature, K
TEF	thermal enhancement factor, $(Nu_R)/(f_R)^{1/3}$
t	winglet thickness, m
U	average velocity, m/s
V	voltage, V
$\dot{V}$	rate of volumetric airflow, m^3/s
W	duct width, m

Greek letters

α	attack angle of winglet, (°)
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

b	bulk
0	smooth/flat duct
conv	convection
i	inlet
o	outlet
bp	blowing power
R	ratio
s	duct surface

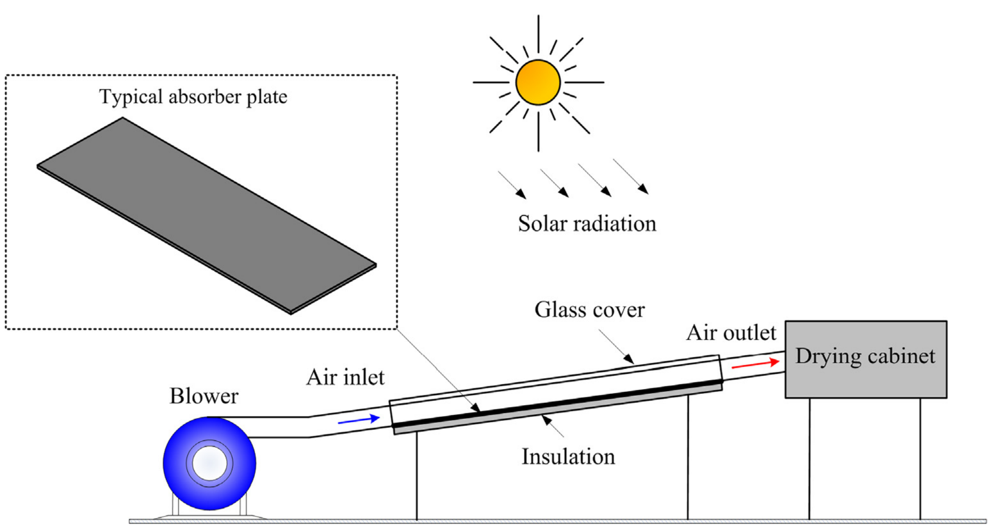

Fig. 1. Conventional solar air heater.

number (Nu) and friction factor (f) while the highest thermal enhancement factor (TEF) was at the lowest e/H rib with staggered array. Promvonge and Thianpong (2008) experimentally investigated thermal characteristics in a rectangular duct fitted with different shaped ribs. The investigation was conducted for airflow with Re ranging from 4000 to 16,000 and for four rib shapes, namely, wedges pointing upstream and downstream, triangular and rectangular ribs all mounted in in-line and staggered arrays. They reported that the highest TEF was for triangular ribs with staggered array. Tabish et al. (2014) studied thermal and friction characteristics in a SAH channel roughened by perforated holes in V-shaped blockages and suggested that the attack angle of 60° provided the highest Nu and f. Aharwal et al. (2008) examined the gap effect in inclined continuous ribs on thermal behaviors in the heated plate of a SAH duct and found that the maximum TEF was at relative gap width, g/e = 1.0 and relative gap position, d/W = 0.25. Pandey et al. (2016) experimentally investigated the effect of height, pitch, arc angle, width, gap distance and gap width for using multiple arcs with gap on Nu and f in a SAH duct and pointed that the maximum in Nu/Nu_0 and f/f_0 was about 5.85 and 4.96 times, respectively. The effect of various geometrical parameters of multiple arc shaped ribs on heat

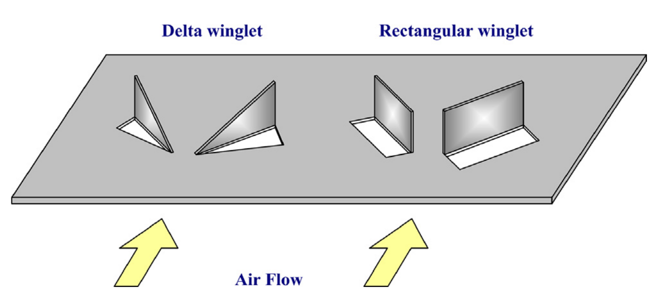

Fig. 2. Conventional winglet-type vortex generators.