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Experimental investigation on convection heat transfer in solar air heater with perforated-winglet vortex generators

Narin Koolnapadol[1)], Sombat Tamna[2)], Witoon Chingtuaythong[3)], Sompol Skullong[4)] and Pongjet Promvonge*[5)]

[1)]Department of Automotive Mechanical Engineering, Faculty of Industrial Technology
Rajabhat Rajanagarindra University, Chachoengsao 24000, Thailand.
[2)]Applied Mathematics and Mechanics Research Laboratory (AMM), Faculty of Engineering,
Thai-Nichi Institute of Technology, Bangkok 10250, Thailand
[3)]Department of Mechanical Technology, Faculty of Industrial Technology, Thepsatri Rajabhat University,
321 Naraimaharat Road, Talaychubsorn, Lopburi 15000, Thailand.
[4)]Department of Mechanical Engineering, Faculty of Engineering at Sriracha, Kasetsart University Sriracha Campus,
199 M.6, Sukhumvit Rd., Sriracha, Chonburi 20230, Thailand.
[5)]Department of Mechanical Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang,
Bangkok 10520, Thailand.

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Abstract

An experimental investigation on thermal and flow friction characteristics of turbulent flow in a solar air heater duct with perforated rectangular winglet (PRW) vortex generators placed repeatedly on the absorber plate has been carried out. The experimental work is performed by varying the airflow rate in the form of Reynolds number from 5300 to 23,000. The PRW elements are mounted repeatedly with four perforated-winglets having punched hole diameters, (d=1.5, 3, 5 and 8 mm) at a single attack angle (α=45°), pitch ratio (PR=2) and blockage ratio (BR=0.4). Influences of the PRW parameters on heat transfer characteristics in terms of Nusselt number (Nu) and friction factor (f) are investigated. The obtained result reveals that the employ of PRW elements provides much higher heat transfer and friction loss than using the duct alone. Although the non-perforated rectangular winglet, RW (without holes) gives the maximum heat transfer and friction loss but the highest thermal performance is found for the PRW with punched hole diameter of 5 mm.

Keywords: Solar air heater, Absorber plate, Vortex generator, Thermal performance

1. Introduction

The utilization of solar energy has been widely needed in several solar thermal systems such as photovoltaic (PV) and solar air heater (SAH) due to available freely and unlimited. The SAH is one of the solar thermal systems which is extensively used for heating purposes, namely, drying of agricultural, curing of fruit, space heating and so on. In general, the flat plate absorber plate is used in many SAH systems, the heat transfer between the airflow and the heated absorber is relatively low due to the development of thermal boundary layer. The higher thermal performance of the SAH system can be achieved when the artificial roughness in the form of a vortex-flow device is fitted on the absorber plate. Artificial roughness used for the heating duct/channel SAH such as ribs [1-2], rib-grooves [3] and baffles [4-5] are often encountered in order to increase the convective heat transfer coefficients leading to the compact heat exchanger and increasing the efficiency. In the present study, the heat transfer and friction loss behaviors for turbulent flow over the perforated rectangular winglet (PRW) vortex generators mounted periodically on the absorber of the SAH are examined. The main purpose is to investigate the heat transfer performance in the SAH duct fitted with the PRW for turbulent duct flow in the range of Re from 5300 to 23,000.

2. Experimental setup

In the experiment, the test duct was made of aluminum with 30 mm in height (H), 420 mm in length (L), 300 mm in width (W) and 8 mm in thickness (t). The perforation of the artificial roughness (PRW) was described by the values of the punched hole diameter on the winglet (d = 1.5, 3, 5 and 8 mm) while the PRW parameters were at a single winglet height, b (or in the terms of blockage ratio, b/H=BR=0.4), winglet pitch, P (or in the terms of pitch ratio, P/H=PR=2.0) and winglet attack angle, α = 45° as shown in Figure 1a. The experimental work was conducted in an open-loop experimental facility as shown in Figure 1b. The tested duct was heated by an electrical heater plate placed on the upper wall (or the absorber plate) with the power source from the

*Corresponding author.
Email address: kpongjet@gmail.com
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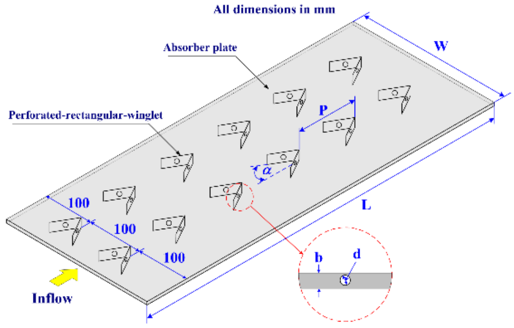
AC power supply to yield a uniform wall heat-flux. The temperatures of the bulk air at the inlet and outlet were measured at certain points using a data logger in common with two thermocouples, RTD-type. Twelve thermocouples of T-type were placed on the duct top-wall to measure temperature distributions along the duct surface to get the average wall temperature. The duct geometry and position of the thermocouples on the absorber plate is depicted in Figure 2. The bulk airflow rate was varied in terms of Reynolds number from 5300 to 23,000 and the pressure drop across the test duct was measured with a pressure transmitter or a digital manometer.



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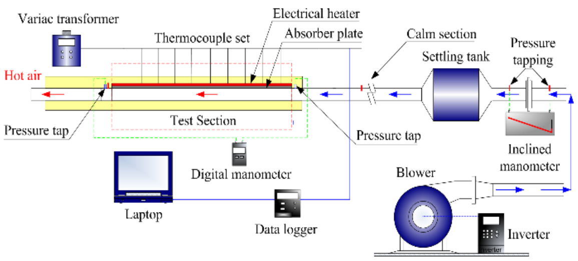

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Figure 1 (a) Test section with PRW and (b) schematic diagram of experimental setup

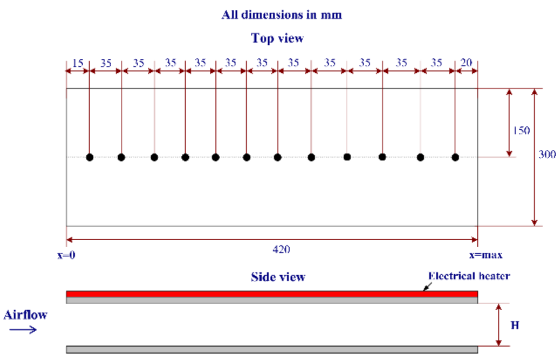


Figure 2 Duct geometry and position of the thermocouples on the absorber plate

3. Data reduction

In the present work, air used as the working fluid was flowed through an insulated tested duct having a uniform wall heat-flux on the absorber plate. The steady heat transfer rate assumed to be equal to the convection heat loss from the test duct can be expressed as

$$Q_{\mathrm{air}} = Q_{\mathrm{conv}} \quad \Rightarrow \quad \dot{m}C_{\mathrm{p,a}}(T_{\mathrm{o}} - T_{\mathrm{i}}) = hA(\tilde{T}_{\mathrm{w}} - T_{\mathrm{b}}) \qquad (1)$$

where $C_{p,a}$, T_w and T_b are specific heat of fluid, local wall temperature and bulk temperature, respectively.
The mean heat transfer coefficient (h) is calculated by:

$$h = \dot{m}C_{\mathrm{p,a}}(T_{\mathrm{o}} - T_{\mathrm{i}})/A(\tilde{T}_{\mathrm{w}} - T_{\mathrm{b}}) \qquad (2)$$

where T_i and T_o is the inlet and outlet fluid temperature, respectively.
The mean Nusselt number, Nu, are estimated as follows:

$$\mathrm{Nu} = hD/k$$

The friction factor, f, can be written as

$$f = 2\Delta P/((L/D)\rho U^2) \qquad (3)$$

The Reynolds number, Re, is given by

$$\mathrm{Re} = UD/\nu \qquad (4)$$

where U and ν is mean velocity of working fluid and kinematic viscosity, respectively.

The thermal enhancement factor, TEF, at a constant pumping power defined as the ratio of the heat transfer coefficient of artificial roughness to that of the smooth duct can be written as:

$$\mathrm{TEF} = h/h_0\big|_{pp} = \mathrm{Nu}/\mathrm{Nu}_0\big|_{pp} = (\mathrm{Nu}/\mathrm{Nu}_0)(f/f_0)^{-1/3} \qquad (5)$$

4. Results and discussion

4.1 Validity test for smooth duct

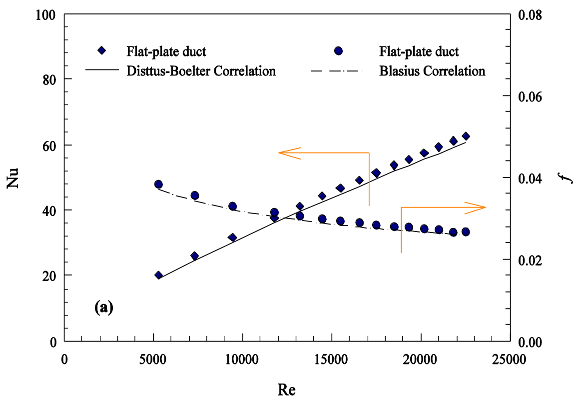
The experimental results for the flat-plate duct (smooth duct) in the terms of Nu and f are compared with the Dittus-Boelter and Blasius correlations [6] as depicted in Figure 3a. Manifestly, present data of the smooth duct are in good agreement with those calculated by the mentioned correlations within ±5% for Nu and ±6% for f.

4.2 Wall temperature profile

Figure 3b displays the axial wall temperature distribution for the d=1.5 mm PRW at Re=9733 including the non-perforated RW. The temperature distribution shows the linearly increasing trend along the duct length while the RW gives slightly lower temperature than the PRW because of larger quantity of heat removal from the absorber. The temperature drop near the exit ($x/H \approx 12$ and 13) is due to the exit effect.

4.3 Heat transfer results

The variation of Nu and $\mathrm{Nu}/\mathrm{Nu}_0$ with Re for all winglets is, respectively, depicted in Figure 4a and b. It is seen that Nu increases with the decrease in d and attains a maximum value for the non-perforated winglet, RW due to stronger longitudinal vortex flows along the SAH duct and higher level of mixing between the hot and cold fluids (cold fluid flow through the absorber plate). The $\mathrm{Nu}/\mathrm{Nu}_0$ of the RW is about 2.9–3.1 times and is around 1.1–12.7% higher than the PRW for all d values while that of the PRW with d = 1.5 mm



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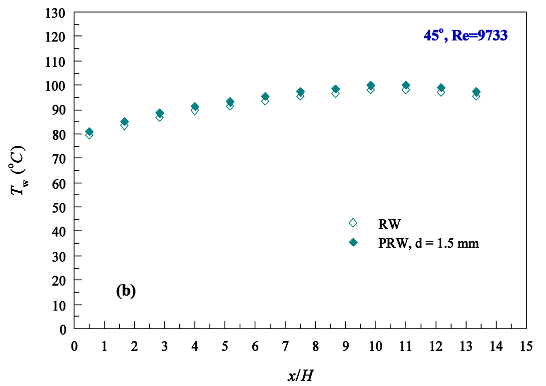

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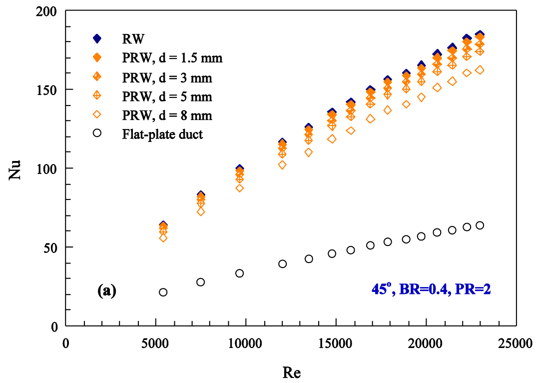
Figure 3 (a) Verification of Nu and *f* for smooth duct and (b) Axial wall-temperature profile.



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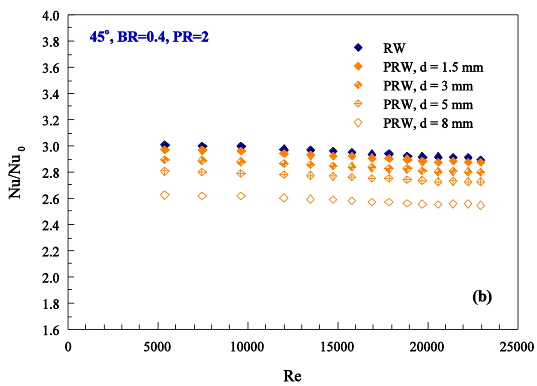


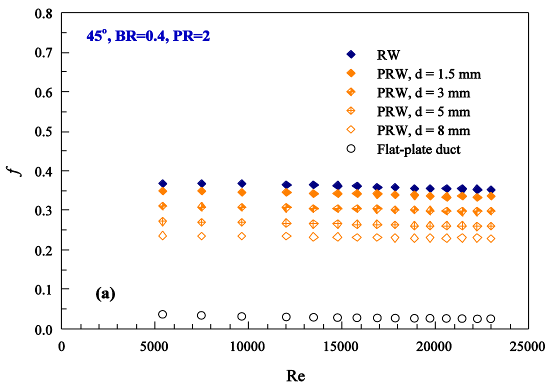
(b)

Figure 4 (a) Nu and (b) Nu/Nu_0 versus Re

is around 2.88–2.97 times and is 2.4–2.8%, 5.2–5.8% and 11.1–11.8% higher than the one with *d* = 3, 5 and 8 mm, respectively. This is because the smaller hole diameter of winglet (*d*=1.5) can create stronger vortex-flow induced in the main flow than the larger one.

4.4 Friction factor results

The friction factor (*f*) and the friction factor ratio (f/f_0) are demonstrated in Figure 5a ad b, respectively. In Figure 5a, it is apparent that the use of all the winglets leads to a substantial increase in *f* over the flat-plate duct alone. It can be seen that the RW yields higher *f* than the PRW. As expected, the obtained *f* for the *d*=8 mm PRW is substantially lower than that for the smaller *d* ones. In Figure 5b, it is noted that the f/f_0 shows the increasing trend with the rise of Re but with reducing *d*. The f/f_0 of the RW is 10–13.7 times and is around 4.6–36.1% higher than that of the PRW for all *d* values. The PRW with *d*=1.5 gives the f/f_0 of 9.5–13.1 times and about 10.6–14.4%, 21.7–22.8% and 30.9–32.5% above the one with *d*=3, 5 and 8 mm, respectively. The PRW can reduce the recirculation zone behind the winglet, leading to the reduction of pressure drop across the duct, especially for larger hole diameter (*d*=8 mm).



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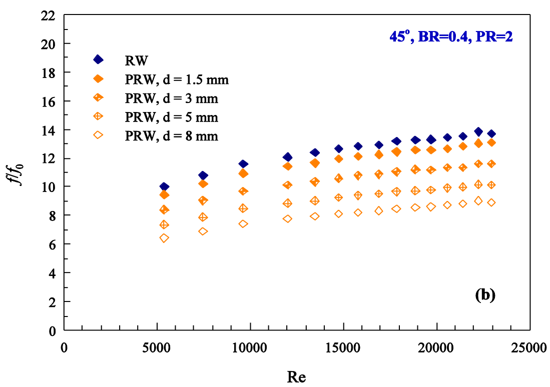

(b)

Figure 5 (a) *f* and (b) f/f_0 against Re

4.5 Thermal performance

The variation of the thermal enhancement factor (TEF) with Re values for the PRW and the RW is displayed in Figure 6. The optimum TEF is around 1.44 for the PRW with *d*=5 mm at lower Re because at this point, the Nu/Nu_0 is still high while lower f/f_0 value is achieved. Depending upon the punched hole diameter, the use of PRW may lead to approximately 1.6% improvement in TEF in comparison to that of the RW.

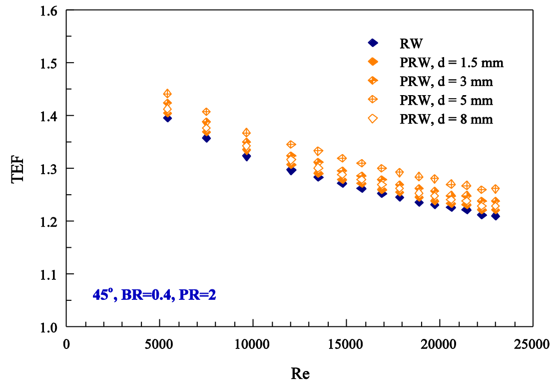

Figure 6 Variation of TEF with Re.

5. Conclusion

Thermal characteristics for turbulent flow in a SAH duct with perforated rectangular winglet (PRW) placed repeatedly on the absorber are investigated experimentally. The Nu in the PRW duct is found to be about 2.55–3.1 times higher than the flat-plate duct with no winglet. However, the heat transfer enhancement is related to the enlarged *f* ranging from about 6.4 to 13.7 times above the flat-plate duct. The TEF for the PRW is much higher than unity and its maximum value is about 1.44 at *d*=5 mm and Re=5300. In comparison with the non-perforated RW, the PRW with *d*=5 mm provides higher thermal performance at about 3.6%.

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