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Performance Evaluation of Solar Receiver Heat Exchanger with Rectangular-Wing Vortex Generators

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***Abstract*—The paper presents an experimental investigation on heat transfer and flow resistance in a solar air heater (SAH) duct with rectangular-wing vortex generators (RWVGs) on the absorber plate to increase the SAH system performance. The experimental work is carried out in the test duct with its aspect ratio (AR) of 10 for Reynolds number (Re) based on the hydraulic duct diameter ranging from 5290 to 22,700. The RWVGs are placed on the absorber with three attack angles ($\alpha = 30°$, 45° and 60°) and three relative wing pitches ($P_R = P_l/H$ = 1.0, 1.5 and 2.0) at a single relative wing height ($B_R = b/H = 0.67$). The experimental result shows that the use of RWVGs leads to the considerable increase in Nusselt number (Nu) over the flat-plate duct (smooth duct) around 4.06–5.79 times while the increase in friction factor (f) is about 11.43–43.97 times. The Nu and f display the increasing trend with the rise of α but show the opposite trend for the increment of P_R. The highest thermal performance for using the RWVG roughness is some 1.95 at $\alpha = 30°$ and P_R = 1.5. Correlations for Nu and f have also been developed and determined as a function of RWVG parameters.**

***Index Terms*—solar air heater, vortex generators, flow resistance, thermal performance**

I. Introduction

To achieve renewable and clean energy, several solar energy/power technologies are under development and some can produce electric power by converting sunlight into thermal energy at high temperature of gas/steam to obtain the turbine work for electrical generator. However, the efficiency or performance of the current solar plants/solar thermal systems is not high. It has been suggested that the potential way to increase the thermal performance of solar thermal systems is to introduce a vortex generator (VG) device. VG devices in the form of ribs [1,2], fins [3], baffles [4], winglets [5,6] and wings [7] are passive elements widely used to enhance the rate of heat transfer in various thermal systems. VG devices provide excess heat transfer area to fluid streams which results in the rate of heat transfer. Earlier investigations have been conducted to study the effect of VG devices on heat transfer enhancement in the heat exchanger/solar air heater systems [8-11]. The effect of rib size and arrangement on turbulent heat transfer and flow friction characteristics in a solar air heater channel was experimentally investigated by Skullong et al. [12], while the thermal and flow resistance in a square duct fitted diagonally with angle-finned tapes were studied experimentally and numerically by Promvonge et al. [13,14]. Tamna et al. [15] examined thermal performance enhancement in a solar air heater (SAH) channel with multiple V-baffle vortex generators (BVG) and concluded that the single BVG with PR = 0.5 yields the highest thermal performance. Skullong et al. [16] also investigated thermal behaviors in a SAH channel using wavy grooves incorporated with pairs of trapezoidal-winglets (TW) placed on the absorber plate and found that the highest thermal performance was obtained for the wavy-groove in common with the TW at P_R = 1 and B_R = 0.24. The effect of delta-wing vortex generators located at the leading edge of a flat plate on heat transfer behaviors was reported by Gentry and Jacobi [17].

Following the above literature review, the utilization of winglets/wings has been found to give more attractive than other VG devices due to lower pressure loss. In general, winglets/wings are designed to create longitudinal vortices that can help increase turbulence levels leading to improvement of the rate of heat transfer, albeit with a minimal pressure loss penalty. However, the winglets/wings cited above, in general, have been widely used to improve the thermal performance of fin-tube heat

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exchangers due to its merit of very low friction loss and ease of installation and manufacture in comparison with other VG devices. Hence, the aim of the present work is to examine the influence of the RWVG as a longitudinal vortex generator (LVG) on enhanced heat transfer and flow characteristics in turbulent flow region.

The main purpose of the current study is to increase the rate of heat transfer as well as thermal performance of a SAH duct by using the new design absorber plate in the form of rectangular-wing VGs. Investigated parameters of the RWVG mounted on the absorber plate are three wing attack angles (α = 30°, 45° and 60°) and three relative wing-pitches ($P_R = P/H$ = 1.0, 1.5 and 2.0) at a forward arrangement.

II. Experimental Details

A. Experimental Procedure

A schematic of the experimental setup of the SAH system is displayed in Fig. 1. In the experiment, cold air at ambient condition was passed through the test duct for Reynolds number (Re) in a range of 5290 to 22,700. The volumetric airflow rate was measured by the orifice plate, built according to ASME standard [18] and calibrated by using a hot-wire/vane-type anemometer (Testo 480) for measuring the flow velocities across the tube section. The test duct was heated by an electrical heater plate attached on the absorber plate to provide a maximum uniform wall heat-flux of about 2000 W/m^2 maintained using a AC power supply (variac transformer). The outer surface of the test duct was well insulated to minimize convective heat loss to the surrounding. The SAH duct included a calm section (2.5 m), test section (0.6 m) and exit (0.4 m) was employed after the settling tank. The test duct (absorber and bottom plate) having duct height (H) of 30 mm is made of aluminum plate with 300 mm width (W) and 6 mm thickness (t). The inlet and outlet temperatures of the bulk air in the test duct were measured by RTD-type (Pt100) thermocouples positioned upstream and downstream of the test duct while the wall temperatures (T_w) were measured by 20 T-type thermocouples mounted on the upper wall of the test duct to measure the temperature variation along the absorber plate to obtain the mean wall temperature. All of the temperature readings from the measurement system were consistently recorded using data acquisition system (Fluke 2680A). Also, the pressure drops across the test duct fitted with RWVG were measured by a digital manometer. More details on the experimental setup, method and uncertainty analysis are similar as reported in an earlier paper [7].

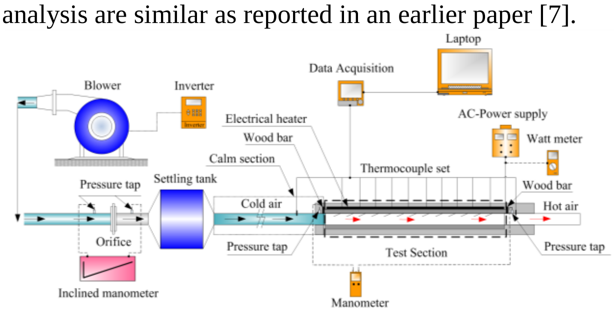


Figure 1. Schematic diagram of experimental setup for SAH system.

B. Wing Artificial Roughness

The schematic view of rectangular-wing geometry chosen for study is shown in Fig. 2. Each rectangular-wing made of 0.5 mm thick aluminum strip (δ) with 20-mm height (b) and 30-mm width (w) was placed on the absorber plate with a transverse pitch spacing (P_t) equal to duct height (=H) by using superglue, three wing attack angle (α = 30°, 45° and 60°) and three longitudinal pitch spacing (P_l = 3 mm, 4.5 mm and 6 mm) equivalent to relative wing-pitches ($P_R = P_l/H$ = 1.0, 1.5 and 2.0) at a forward arrangement.

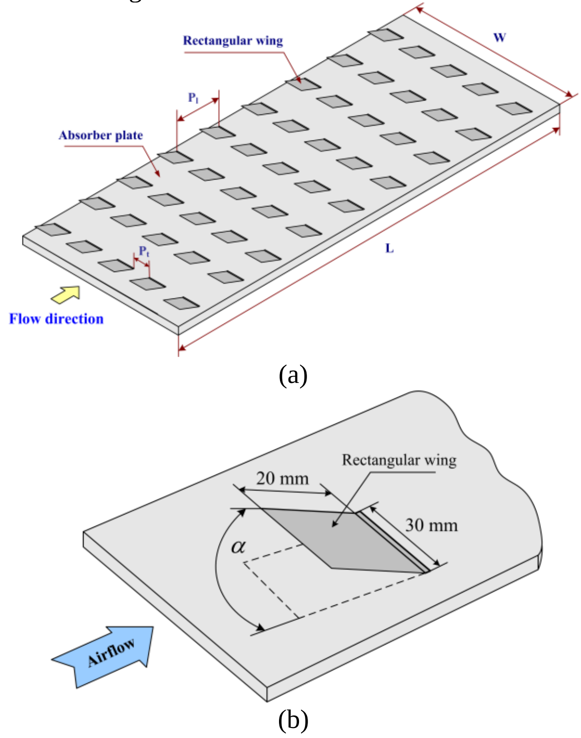


Figure 2. (a) Absorber plate with VG devices and (b) configuration of rectangular-wing.

III. Theoretical Analysis

All data were taken at a steady state condition. The steady state of each test run was assumed to have been attained when no variation of fluid and wall temperatures for twenty minutes. The experimental results are shown in dimensionless terms of Nusselt number, friction factor and thermal enhancement factor.

In the experiment, air flowed through the SAH duct under a constant surface heat-flux. The steady state of the heat transfer rate is assumed to be equal to the heat loss from the test section which can be expressed as:

$$Q_{air} = Q_{conv} \tag{1}$$

where

$$Q_{air} = \dot{m} C_{p,air} \left(T_{out} - T_{in} \right) \tag{2}$$

The convection heat transfer from the test section can be written by

$$Q_{conv} = hA\left(\tilde{T}_w - T_b \right) \tag{3}$$

in which

$$T_b = (T_{out} + T_{in}) / 2 \tag{4}$$

and

$$\tilde{T}_w = \sum T_w / 20 \tag{5}$$

where T_w is local absorber plate temperature located equally along the outer surface of the test duct. The average heat transfer coefficient (h) and Nusselt number (Nu) are estimated as follows:

$$h = \dot{m} C_{p,air} (T_{out} - T_{in}) / A(\tilde{T}_w - T_b) \tag{6}$$

The heat transfer is calculated from the average Nu which can be obtained by

$$\mathrm{Nu} = hD/k \tag{7}$$

All of thermo-physical properties of air are evaluated at overall bulk fluid temperature (T_b) from Eq. (4).

The airflow in the test duct is calculated in the form of Reynolds number (Re) as given by

$$Re = UD/\nu \tag{8}$$

The friction factor (f) computed from the pressure drop is written as

$$f = \frac{2}{(L/D)} \frac{\Delta P}{\rho U^2} \tag{9}$$

in which U is mean air velocity in the test duct.

To assess the practical use, thermal performance of the artificial roughness of the SAH duct is evaluated relatively to the smooth duct at an identical pumping power in the form of thermal enhancement factor (TEF) as suggested by Webb [19] and can be expressed by

$$\mathrm{TEF} = \left(\frac{\mathrm{Nu}}{\mathrm{Nu}_0}\right)\left(\frac{f}{f_0}\right)^{-1/3} \tag{10}$$

where Nu_0 and Nu stand for heat transfer coefficients of smooth/flat-plate duct and of absorber plate with rectangular-wing, respectively.

IV. Experimental Details

A. Validity test for flat plate duct

The experimental results are first validated by comparing the results from flat-plate duct with the equations of Dittus-Boelter and Blasius [20] for Nusselt number (Nu) and friction factor (f) which is given as below:

Dittus–Boelter equation,

$$\mathrm{Nu} = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.4} \tag{11}$$

Blasius equation,

$$f = 0.316\,\mathrm{Re}^{-0.25} \tag{12}$$

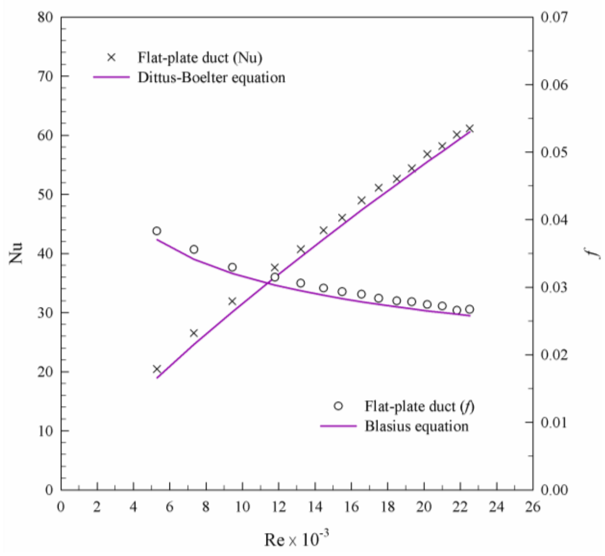


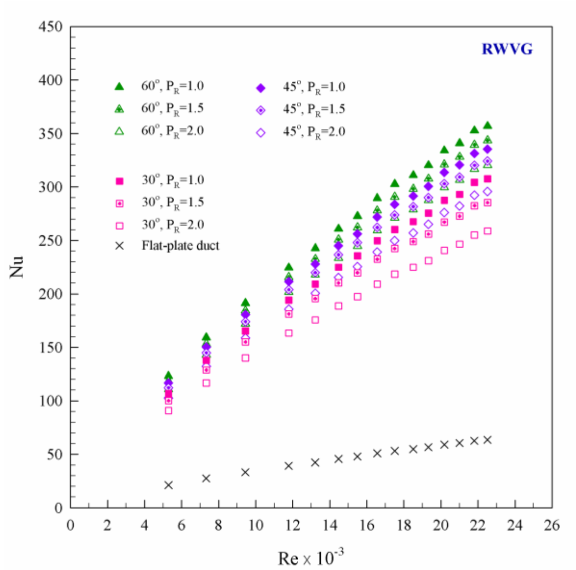
Figure 3. Confirmatory test of Nu and f of flat-plate duct.

The values of experimental and predicted data were compared and shown in Fig. 3. Manifestly, the results of the present work agree reasonably well within ±6.5% for Nu from Dittus–Boelter and ±7.4% for f from Blasius equations.

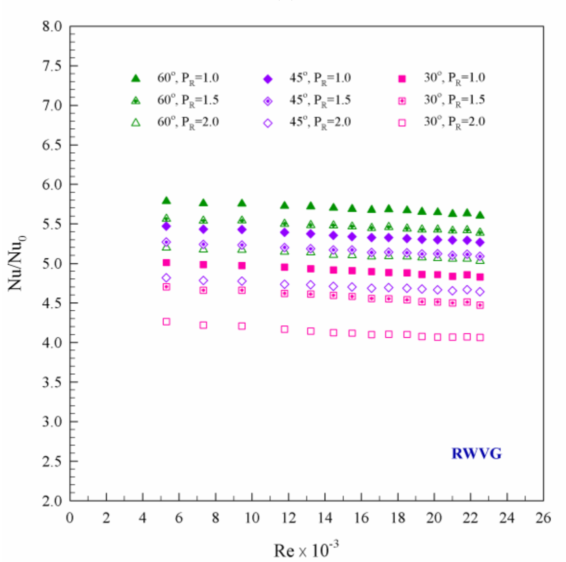
B. Heat Transfer Characteristics

Fig. 4(a) and (b) shows the variations of Nusselt number (Nu) and Nusselt number ratio ($\mathrm{Nu}/\mathrm{Nu}_0$) with Reynolds number (Re) for using RWVGs. In Fig. 5(a), it is obvious that heat transfer in the form of Nu increases with increasing Re. The SAH duct with RWVGs on the absorber shows considerably higher Nu than the flat-plate duct with no RWVG. The Nu of the RWVG duct is seen to be higher than that of the flat-plate duct around 78–83%, and the highest heat transfer is seen at $\alpha = 60°$ and P_R = 1.0. This indicates that the effect of vortex-flow from the VG device and the boundary layer disruption can help increase the convection heat transfer process.

Fig. 4(b) depicts the ratio of augmented Nu of the RWVG to Nu of the flat-plate duct, ($\mathrm{Nu}/\mathrm{Nu}_0$) with Re at various α and P_R values. In the figure, $\mathrm{Nu}/\mathrm{Nu}_0$ show the slightly decreasing tendency with the rise of Re for all cases. The smaller P_R leads to the increase in $\mathrm{Nu}/\mathrm{Nu}_0$ while the smaller α yields the reversing trend. The RWVG at $\alpha = 60°$ and P_R = 1.0 gives considerably higher $\mathrm{Nu}/\mathrm{Nu}_0$ than the others for augmenting heat transfer due to stronger vortex strength and disrupting the boundary layer at the absorber surface leading to higher rate of heat transfer between the absorber surface and air. At $\alpha = 60°$, 45° and 30°, the average $\mathrm{Nu}/\mathrm{Nu}_0$ for P_R = 1.0, 1.5 and 2.0 are, respectively, about 5.69, 5.47 and 5.11; 5.35, 5.16 and 4.71; and 4.91, 4.57 and 4.13 times, depending on Re. This implies that the RWVG with larger α and smaller P_R yields considerably higher $\mathrm{Nu}/\mathrm{Nu}_0$. However, at this condition, it comes together with extremely higher friction loss as can be seen in the next section.



(a)



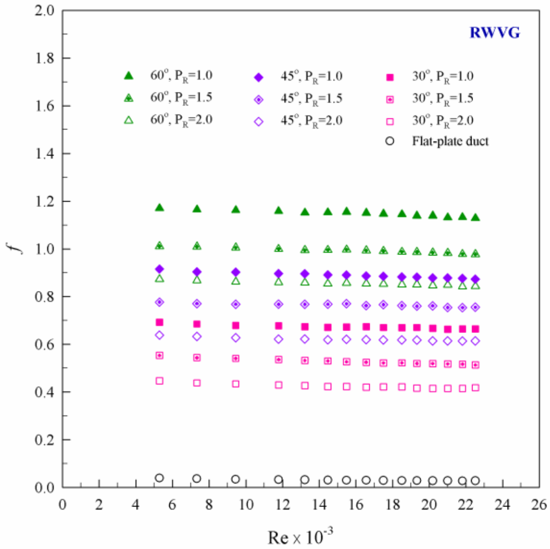
(b)

Figure 4. Variations of (a) Nu and (b) Nu/Nu_0 with Re for RWVGs.

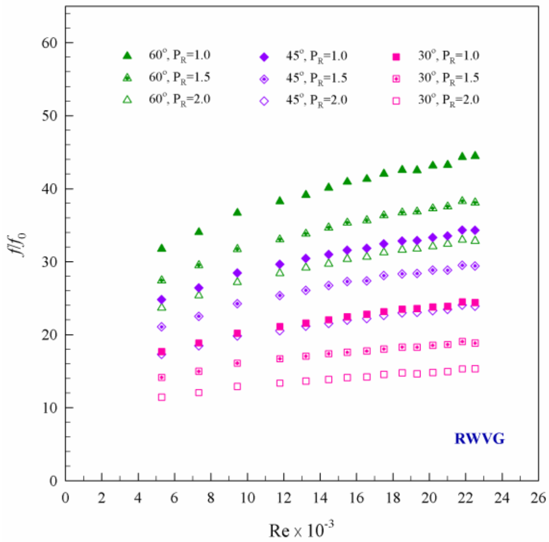
C. *Flow Friction Characteristics*

The effect of RWVG parameters on friction factor (*f*) and friction factor ratio (f/f_0) against Re is displayed in Fig. 5(a) and (b), respectively. The *f* for the absorber plate with RWVG is analysed and compared with the flat-plate duct as shown in Fig. 5(a) As expected, the RWVG can cause a significant *f* value in comparison with the flat-plate duct. *f* tends to increase with rising α but shows the downtrend with increasing P_R. This is because of higher blockage of flow especially at larger α apart from larger frontal and surface areas while the strength of longitudinal vortex is amplified as the relative height of wings is increased, which leads to larger form drag. Compared with the flat-plate duct at the Re range investigated, *f* of the RWVGs is increased around 11.43–43.97 times.

Fig. 5(b) shows the variation of f/f_0 with Re for different α and P_R values. In the figure, it is found that f/f_0 shows the uptrend with increasing α while exhibits the reversing trend with the increment of P_R. The average f/f_0 values for $\alpha = 60°$, 45° and 30° are, respectively, about 40.28, 34.83 and 29.98; 31.18, 26.82 and 21.77; and 22.24, 17.43 and 14.01 at P_R = 1.0, 1.5 and 2.0.



(a)



(b)

Figure 5. Variations of (a) *f* and (b) f/f_0 with the Re for RWVGs.

D. *Thermal Enhancement Factor*

Fig. 6 portrays the variation of thermal enhancement factor (TEF) with Re for different α and P_R values. The TEF is determined under the data of the measured Nu and *f* values for both the artificial roughness and flat-plate duct at the same pumping power as defined in Eq. (10). In the figure, TEF shows the decreasing trend with increasing Re for all cases and its maximum around 1.95 is seen at $\alpha = 30°$ and P_R = 1.5. TEF values at $\alpha = 30°$ are, respectively, found to be in the range of 1.67–1.92, 1.68–1.95 and 1.64–1.89 for P_R = 1.0, 1.5 and 2.0. Therefore, the best choice of this RWVG roughness is at $\alpha = 60°$ and P_R = 1.0 to achieve the superior thermal performance in the SAH system.

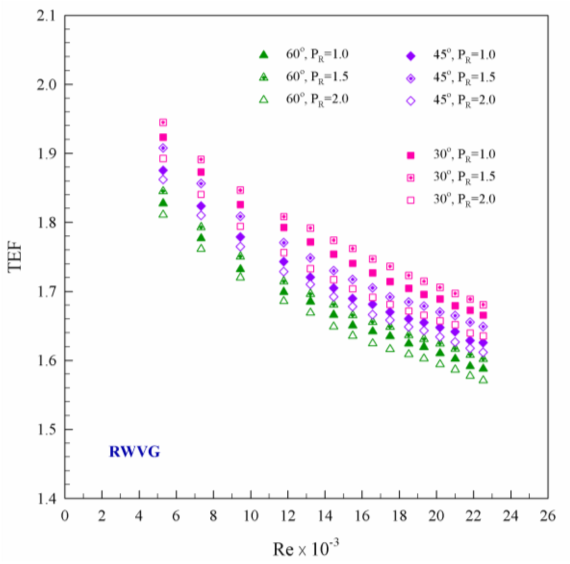


Figure 6. Variation of TEF with Re for RWVGs.

V. Empirical Correlations

In the current investigation, the Nu and f values are developed in the form of empirical correlations for the RWVGs and are correlated as given in equations (13) and (14). The Nu and f correlations are displayed as the function of α, P_R, Re and Prandtl number (Pr) whereas f is free from Pr as given below:

Nusselt number for absorber plate with RWVGs;

$$\mathrm{Nu} = 0.098\mathrm{Re}^{0.728}\mathrm{Pr}^{0.4}\alpha^{0.261}\mathrm{P}_{\mathrm{R}}^{-0.191} \tag{13}$$

Friction factor for absorber plate with RWVGs;

$$f = 0.041\mathrm{Re}^{-0.0303}\alpha^{0.895}\mathrm{P}_{\mathrm{R}}^{-0.531} \tag{14}$$

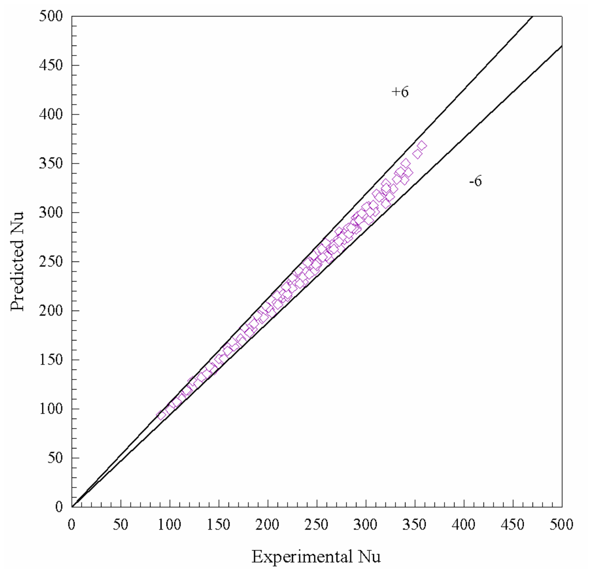


Figure 7. Comparison of experimental with predicted values for Nu.

To validate the correlation reliability, Nu and f values obtained by the prediction from the mentioned correlations were plotted against the measured data as depicted in Figs. 7 and 8, respectively. It is observed in the figure that most measured data are within ±6% and ±6.7% of the predicted Nu and f, respectively.

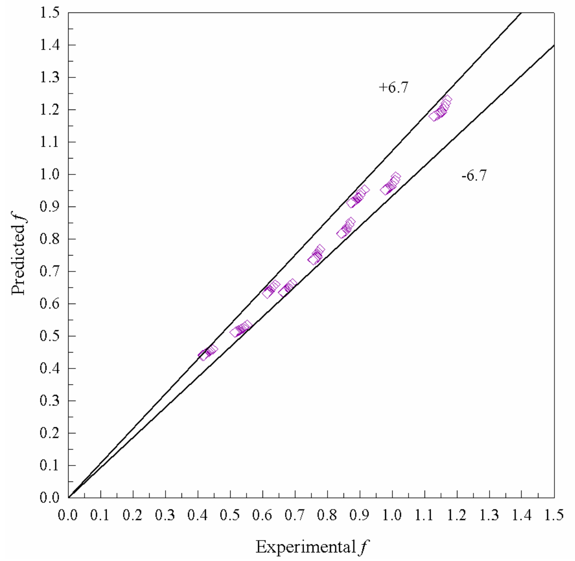


Figure 8. Comparison of experimental with predicted values for f.

VI. Conclusions

Effects of artificial roughness in the form of RWVGs placed on the absorber plate on thermal and flow resistance in a SAH duct have been experimentally studied. The effects of RWVG parameters (α, P_R and Re) on thermal performance are offered in the current study. Key findings from the study are as follows:

- The use of RWVGs yields a significant effect to vortex generators in the duct leading to enhancing Nu as well as f.
- The highest heat transfer rate for using RWVG is around 5.79 times above the flat-plate duct while the highest f is about 43.97 times at $\alpha = 60°$ and $P_R = 1.0$.
- For performance comparison, the highest TEF at about 1.95 is for $\alpha = 30°$ and $P_R = 1.5$ and Re = 5290. Thus, the RWVG artificial roughness is a promising method for performance improvement of a SAH system.
- Comparison between data of the measured and the correlations shows an excellent agreement.

Conflict of Interest

The authors declare that there are no conflicts of interest.

Author Contributions

Narin Koolnapadol: data collection and analysis.
Pongjet Promvonge: proofreading and suggestion.
Sompol Skullong: supervision in experimental work.

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