Solar Air Heater Thermal Performance Enhancement using V-Up Continuous Ribs

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Abstract. The viability of renewable energy sources (emphasizing solar energy) helps reduce the barrier of fossil energy depletion. Despite the issue of low thermal performance, different techniques are projected to gain high energy to boost the heat transfer for the solar energy system. This experimental work evaluates the thermal performance enhancement of two designed solar air heaters with and without V-rib (smooth plate). Using V-up continuous ribs, the impact of various attack angles (α) at 30°, 45°, and 60° on the thermal-hydraulic performance of artificially roughened solar air heater duct is investigated. Thermal performance consideration involves the intensification of heat transfer (Nusselt Number, Nu) and diminution of friction factor (f). The tests were performed as an indoor experiment where the intensity of solar energy was simulated by heating the absorber plate using the electric heater to gain 1000 W/m² of constant heat flux. Furthermore, adjusting the air-flow rates provides the Reynolds number (Re) values between 3480 – 9980. The results showed that the solar air heater with V-up continuous ribs experienced the maximum thermal performance when α reached 60° then gradually decreased with increasing of α. Compared with the smooth plate, the presence of V-ribs in solar air heaters gained a higher value of Nu, f, and thermal-hydraulic performance. Adjusting the α at 30°, 45°, and 60° of V-up continuous ribs improves the Nu in the maximum value of 123% for α of 60° as compared to those of the smooth tube. Besides, it also occurs that the maximum increment of f and thermal performance factor was 2.85 times and 1.26 for α of 60°. Moreover, empirical correlations developed from current results can predict the Nu and f with a reasonable agreement between the experimental predicted values.

1 Introduction

Solar energy tends to be the most attractive development to help reduce fossil energy use. Yet, it is known that it can be freely utilized as clean and eco-friendly energy [1]. The solar air collector is possibly the simplest way to convert solar energy. However, the main drawback of this collector is that the air convective heat transfer is relatively small [2]. The researcher proposes many methods to gain convective heat transfer. The following literature shows that the absorber plate modification has a significant effect on the improved performance of the solar air heater. Singh et al. [3] used the serpentine wavy channel for the solar air heater. The combination of the geometrical parameters was investigated to optimize the performance of the solar air heater. The system thermal performance increased by a maximum value of 66% due to the presence of a wavy channel. A new hybrid duct was developed by Sivakandhan et al. [4]. They used the roughened absorber plate, which was modified by inclined ribs. They found that the newly developed system increased performance by around 22.4%. The heat transfer is enhanced because the ribs break the laminar sublayer's creation while boosting the vicinity of the reattachment points. Wang et al. [5] improved the performance of the solar air heater by ribs, which were formed as “S” shape. They added the gap on the ribs to reduce the flow resistance. Their results revealed that such a configuration could improve efficiency by up to 48%. The evaluation of the thermal performance of solar air heaters was also conducted by Kashyap et al. [6]. Using multiple V-ribs with symmetric multi-gaps offers the maximum thermal-hydraulic performance by 4.24. Using computational fluid dynamics software, Saurabh et al. [7] evaluated the artificially roughened solar air heater's heat transfer and fluid flow analysis. They found that the parameters studied, relative roughness height, relative roughness pitch, and relative arc radius, give different behavior to the thermal performance. Kumar et al. [8] modified the roughness pattern using dimple and protrusion elements to improve the conventional solar air heater. They found that the proposed roughness enhanced the thermal and overall performance by 2.1 and 1.95 times, respectively, compared to the conventional one. Many configurations of the ribs (known as artificial roughness) can be adjusted to increase heat transfer. However, since many effects contribute to thermal performance, their influence is still significant to be studied. Therefore, the current work

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provides an experimental effort to modify the plate absorber by adding the ribs with the V-up continuous ribs configuration. Their effect is investigated to find the solar air heater’s heat transfer and friction factor characteristics. We also proposed the empirical correlation for predicting the heat transfer and friction factor based on our experimental data.

2 Methodology

2.1 Experimental Setup

The experimental setup for evaluating the thermal hydraulic performance of the solar air heater is presented as an actual photograph in Fig. 1, while it is schematically provided in Fig. 2.

Fig. 1. Actual photograph of the experimental setup.

Fig. 2. Schematic diagram of experimental setup (1) entrance section, (2) test section, (3) outlet section, (4) plenum, (5) duct, (6) pitot tube, (7) exit pipe, (8) variable speed blower, (9) control valve, (10) thermocouple reader.

As shown in Figs. 1 and 2, the solar air heater system comprises entrance and outlet sections, test sections, and measurement devices. The entrance section was a duct with a dimension of 0.9 m in length, while the test section length had a dimension of 1 m. In the exit section and plenum, the lengths were 0.5 m for the exit section and 0.4 m for the plenum. The total length of the duct was 2.4 m. The experimental study was studied for the indoor experiment, yet we adopted the standard for measuring the performance of solar collectors by ASHRAE Standard 93-97 [9]. The solar radiation was generated by the electrical heater, which produces a constant heat flux of 1000 W/m². To avoid the heat loss to the surrounding, the duct was well insulated using a combination of glass wool and thick wooden panels.

The measurement devices measured the temperature, air flow rate, and pressure drop. K-type thermocouples with an accuracy of 2.2°C were employed to measure the temperature where 15 points were attached to the surface of the absorber plate, 5 points were placed in the outlet section, and 1 point was connected in the entrance section. The Pitot tube manometer, with an accuracy of ±0.3% of full scale, was used to measure the air flow rate. In order to measure the pressure drop within the system, a micromanometer with an accuracy of ± 1 % of ± 1 Pa was connected just before and after the test section.

The test section was the absorber plate made of galvanized iron (GI), which later will be called the smooth plate. Then, the enhanced plate used in the study was the modification of a smooth plate called the V-up continuous ribs, as shown in Fig.3.

Fig. 3. Schematic view of roughened plate with V-up continuous ribs.

Fig. 3 shows the schematic view of the roughened plate with V-up continuous ribs. The angle of attack (α) was adjusted in the value of 30°, 45°, and 60°. The relative roughness height (e/Dh), which is defined as the ratio between the height of the artificial roughness, e, (wire diameter), and hydraulic diameter (Dh), was set as a constant value of 0.0325. Since the pitch (p) value was kept constant, the relative roughness pitch (p/e) was 10.

2.2 Data Processing

The heat transfer rate and friction factor calculations are based on the temperature and pressure drop data under steady-state conditions.

The air mass flow rate is given by:

$$\dot{m}_a = \rho_a V_a A_p$$  \hspace{1cm} (1)

where $\dot{m}_a$, $\rho_a$, $V_a$, and $A_p$ represent mass flow rate (kg/s), density (kg/m³), velocity (m/s), and cross-section area (m²), respectively. Subscripts $a$ and $p$ denote the air and pipe. The mass flow rate was calculated in the exit pipe.

The heat transfer rate is expressed as:

$$Q = \dot{m}_a c_{pa} (T_o - T_i)$$  \hspace{1cm} (2)

where Q is the heat transfer rate (W), $c_{pa}$ is the specific heat of the air (J/kgK), and $T$ is the temperature (K), while the subscripts o and i represent outlet and inlet, respectively.
Then, the heat transfer coefficient is evaluated as:

\[
h = \frac{Q}{A_c (T_{pm} - T_{fm})}
\]  

(3)

where \( h \) and \( A_c \) denote the heat transfer coefficient (W/m\(^2\)K) and the heat transfer area (m\(^2\)), subscripts \( pm \) and \( fm \) represent the mean plate and average fluid. Since the heat transfer coefficient is known from the (3), the Nusselt number can be defined as:

\[
u = \frac{hD_h}{k}
\]  

(4)

where \( \nu \) is the Nusselt number, \( D_h \) is the hydraulic diameter of the duct (m), and \( k \) is the air thermal conductivity (W/mK). The friction factor characteristic is calculated by using the following equation:

\[
f = \frac{2\Delta p_d D_h}{\rho_d L_f V_d^2}
\]  

(5)

where \( \Delta P \) and \( L_f \) represent the pressure drop (Pa) and test section length (m), while the subscript \( d \) denotes duct. The friction factor is calculated based on the pressure drop of the test section measured by the micromanometer.

Analogous to the friction factor calculation, the Reynolds number \((Re)\) is also measured based on the air properties inside the duct. The calculation of the \( Re \) is as follows:

\[
Re = \frac{\rho_d V_d D_h}{\mu}
\]  

(6)

### 3 Result and Discussions

#### 3.1 The Effect of the Attack Angle on Heat Transfer Characteristics

Fig. 4 depicts the effect of the variation of attack of angle on the heat transfer characteristics expressed by the Nusselt number \((\nu)\).

![Fig. 4. Variation of Nusselt number with adjusted attack angle values.](image)

By adding the V-up continuous ribs as the artificial roughened to the smooth plate, we observed that the \( \nu \) is more likely to reveal high values than the smooth one. The artificial roughened pretends to increase the heat transfer rate by the flow separation effect, flowing through the V-up continuous ribs. Besides, the secondary flow, which occurs within the Vup continuous rib length, can be a reason for this behavior. The attack angle's change has a more significant effect on the \( \nu \), where it is increased with the rise of the attack angle. It is found that the highest \( \nu \) was for an angle of attack of 60° with a maximum increment value of 123% compared with the smooth tube.

#### 3.2 The Effect of the Attack Angle on Friction Factor Characteristics

The friction factor characteristics of the solar air heater with the V-up continuous ribs can be seen in Fig. 5.

![Fig. 5. Variation of friction factor with adjusted attack angle values.](image)

Increasing the attack angle value affects an ascending trend to the friction factor. The transformation of the flow characteristics due to the presence of V-up continuous ribs tends to make the friction factor of the solar air heater with an artificially roughened solar heater higher than the smooth plate. Its flow characteristics changed because of the combination of flow separation, flow reattachment, and flow regeneration of the secondary flow, which intensified the magnitude of the friction factor for V-up continuous ribs. The highest friction factor was found to be 2.85 higher than the smooth tube for an attack angle of 60°.

#### 3.3 The Effect of the Angle on Thermal-Hydraulic Performance

The thermal performance factor \((\eta)\) of the solar air heater artificially roughened with V-up continuous ribs is evaluated by:

\[
\eta = \frac{(\nu_r/\nu_s)}{(f_r/f_s)^{3/2}}
\]  

(7)

Equation (7) explained that the thermal performance of the solar air heater was the ratio between the increment of the \( \nu \) value as well as \( f \). The increase of the \( \nu \) and \( f \) was evaluated based on the rate of the \( \nu \) and \( f \) values for the enhanced and smooth absorber. Through the experimental data, we obtained the \( \eta \) value provided in Fig. 6. As expected, the highest angle of the attack revealed the upper \( \eta \) with a value of 1.26.
Evaluation of the results from Figs. 7 and 8, it can be seen that the predicted data follow the experimental results quite well, with the differences of about 9%. Therefore, the proposed correlations can be used to predict the enhanced characteristics of the solar air heater's heat and friction factors. Yet, it carries the limitation of the range of the Reynolds number.

### 4 Conclusion

The experimental work on the thermal-hydraulic performance of artificially roughened solar air heater ducts with V-up continuous ribs was conducted in the current study to evaluate their heat transfer and friction factor characteristics. The modified ribs were done by adjusting the angle of attack to 30°, 45°, and 60°. The following conclusion can be drawn. The heat transfer and friction characteristics expressed by the \( \text{Nu} \) dan \( f \) are increased with the increased attack angle. The V-up continuous ribs performed higher \( \text{Nu} \) and \( f \) than the smooth absorber plate. For the highest angle of attack of 60°, it can boost the \( \text{Nu} \) as high as 123% than the smooth absorber, while it gained 2.85 times the friction factor for the same cases. The highest thermal performance factor was also found at the highest angle of attack of 60° with a value of 1.26. Lastly, the proposed correlation is possible for predicting the heat transfer and friction factor characteristics as they show minor discrepancies between the predicted values and experimental data. It was less than 10%.

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### Nomenclature

\[
\begin{align*}
A & : \text{area, m}^2 \\
\alpha & : \text{angle of attack, } ^\circ \\
c_{p,\text{a}} & : \text{specific heat of the air, } \text{J/kg}^\circ\text{C} \\
D_h & : \text{hydraulic diameter of the duct, m} \\
e & : \text{height of the artificial roughness, m} \\
f & : \text{friction factor} \\
h & : \text{heat transfer coefficient, } \text{W/m}^2\text{°C} \\
k & : \text{air thermal conductivity, } \text{W/m}^\circ\text{C} \\
m & : \text{mass flow rate, } \text{kg/s} \\
Q & : \text{heat transfer rate, } \text{W} \\
T & : \text{temperature, } \text{°C} \\
Re & : \text{Reynolds number} \\
\rho & : \text{density, } \text{kg/m}^3 \\
V & : \text{velocity, m/s} \\
\end{align*}
\]

Subscripts

\( a \) air
\( d \) duct
\( i \) inlet
\( o \) outlet

\[
\text{Nu}=0.027\text{Re}^{0.832}(\alpha/90)^{1.022}\exp[-1.03(\ln^2/90)^2] \tag{8}
\]

\[
f=30.57\text{Re}^{-0.731}(\alpha/90)^{1.215}\exp[-1.144(\ln^2/90)^2] \tag{9}
\]
References


