Performance Evaluation of Solar Collector Having Broken Arc Ribs Of Symmetrical Gap with Staggered Elements

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Abstract: To experimentally investigate the thermal behaviour of solar collector with broken arc artificial roughness of symmetrical gap and staggered element, a study is conducted with four number of absorber surface of hot rolled steel plate of dimensions 1500 mm x 210 mm x 1.2 mm (length x width x thickness). The test dimension of plate was 1500 mm x 200 mm (LxW). The test parameters were relative roughness pitch P/e as 8-14, relative roughness height e/Dh as 0.04545, number of gaps N_g as 2, relative gap width g/e as 1, relative staggered length r/e as 4.5, relative staggered pitch p’/p as 0.4 and Reynolds number 3000-15000. The highest Nusselt number recorded at staggered length 3.5 was 5 times smooth plate. The highest thermodynamic performance was recorded 1.85 for the same value of relative staggered length.

Index Terms: Solar collector, Nusselt number, friction factor, thermodynamic performance, Heat transfer, artificial roughness.

I. INTRODUCTION:

To enhance performance of a solar collector various researchers [1-4] have thoroughly investigated various methods with reasonable success. All the passive methods pose major drawback of increased input power for fluid circulation which is due to the increased turbulence caused by augmentation methods employed. To reduce the friction and input power, the obstacle in fluid flow must be created at close proximity of absorber surface e.g. laminar boundary layer. Prasad and Mullick [5] used small diameter circular wire pasted over absorber surface of solar collector as artificial rib placed with rib side facing down in solar dryer. Prasad and Saini [6] determined the effect of various parameters which are considered as signature of any solar collection device using artificial wire rib as roughness enhancement method. These parameters such as roughness height, pitch and wire size immensely affect performance of solar collector. Sahu and Bhagoria [7] investigated broken transverse rib to investigate performance of solar collector. Aharwal et al. [8] used inclined wires with gap as ribs. They changed position of gap and gap width in the analysis of performance. Varun et al. [9] investigated mixed oblique and straight ribs across plate width, Lanjewar et al. [10] used W shape rib for upstream and downstream flow to study solar collector. Saini and Saini [11] found highest increment in Nu and f by 380% and 175% more than smooth duct for 30° arc rib. Singh et al. [12] modified single arc to multiple arc to find performance with variation in arc angle 30-75°, W/w value 1-7 and P/e value 4-16.

The authors reported approximately four times increase in heat transfer compared with smooth absorber plate. Hans et al. [13] used symmetric gap in arc roughness with P/e value 4-12, e/Dh value 0.022-0.043, α value 15-75°, g/e value 0.5-2.5, d/W value 0.2-0.8 in Reynolds number (Re) range 2000-16000. The heat transfer was observed 263% and 119% more than smooth and full arc roughness and friction was determined 2.44 and 1.14 times respectively at (P/e) as 10, (g/e) as 1, (d/W) as 0.65, α as 30° and (e/Dh) as 0.043. Gill et al [14] modified Hans [13] geometry by introducing a staggered element in arc gap. They varied relative staggered rib size (r/g) from 1 to 6 for Reynolds number (Re) 2000-16000. The values of Nu and f was 360% and 250% more than smooth duct and 260% and 227% more than broken arc geometry.

II. RIB GEOMETRY AND SELECTED TEST PARAMETERS:

To conduct desired test with rib roughness, an indoor test setup is constructed according to ASHRAE [14]. The roughness geometry selected is broken arc rib with staggered elements having two identical gaps on either side of centre of absorber surface of solar collector illustrated in Fig. 1. There are total nine parameters out of which two have been varied and rest are constants the detail of which is summed up in Table 1. Circular cross section insulated copper wire is used for ribs.

III. EXPERIMENTAL SETUP

The experimental arrangement is illustrated in Fig. 2. It consists of inlet, test area (both rectangular), converging area, iron pipe with orifice plate, hose pipe, blower and electric motor, ammeter, voltmeter, variac, thermocouple wires, electronic data logger for recording temperature, u-tube manometer and a digital micrometer.

Table 1 Study Variables

| S. No. | Selected test parameter | Value/Range |
|-------|------------------------|-------------|
| 1     | Diameter of wire (e)   | 2mm         |
| 2     | P/e                    | 8,10,12,14  |
| 3     | e/Dh                   | 0.045       |
| 4     | Re                     | 3000-15000  |
| 5     | α                      | 30°         |
| 6     | Number of gaps         | 2           |
| 7     | g/e                    | 1           |
| 8     | p’/p                   | 0.4         |
| 9     | r/e                    | 0.45        |
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Fig. 1 Rib Drawing

Fig. 2 Experiment setup

DATA REDUCTION

The temperature is measured at a constant flux and constant mass flow after attaining steady state. Nusselt number, friction factor and heat transfer are calculated using following formulae.

\[ Q = M \times C_p \times (t_o - t_i) \]  (1)
\[ h = \frac{Q}{[A_p \times (t_p - t_f)]} \]  (2)
\[ Nu = \frac{(h \times D_h)/k}{(3)} \]
\[ f = \frac{D_h \times \Delta p}{(2 \times L \times V^2 \times \rho)} \]  (4)

IV. RESULTS:

Before performing test on rough absorber surface a validity test is conducted using a smooth absorber surface to find out Nu and f and results are matched with output of modified Dittus Boelter equation and modified Blasius equations considered as standard equations.

Modified Blasius equation
\[ f_s = 0.085Re^{-0.25} \]  (1)

Modified Dittus Boelter equation
\[ Nu = 0.023Re^{0.8}Pr^{0.4} \]  (2)

Comparing Nu and f

obtained from experiment and formulae is compared in Fig. 3 and Fig. 4. The graphs are identical that confirms the validity of test procedure.

Fig. 3 Graphical representation of test and outcome of formula for Nu with smooth plate

Fig. 4 Comparison between theoretical and practical friction factor.

Fig. 5 Heat transfer variation with pitch
Fig. 6 Friction variation with pitch

A. Plot P/e Vs. Nu

The results from Fig. 5 show that the highest Nu recorded at P/e value 10 and then for value 12. For (P/e), 8 and 14, the results are almost identical. This is because for Relative roughness pitch 10, the fluid particles touch surface at a point is such that carry maximum heat from it where as for (P/e) value 8 or 10, the fluid particle touch plate either too quick or too delayed so that the heat transfer is not possible as much as with value 10. Fig. 7 shows this effect on (P/e) scale.

B. Effect of velocity on heat carried

Heat transfer increases with Reynolds number (Fig. 5), because more turbulence is created with increase in velocity which causes more molecular interaction with each other and thus heat transfer takes place from high energy molecules. Molecules not only interact with each other but also carry heat from the absorber surface by touching it more with increased Reynolds number.

C. Effect of Pitch on turbulence

In general the friction in flow reduce with increasing flow velocity because more fluid particles are carried away before they touch surface or strike the rib on the way to flow. The turbulence at rib decreases because the momentum of molecules increased. The minimum friction occurs at P/e value 10 where as for (P/e), 8 the friction is more due to dense rib position causing greater obstacle to flow and similarly friction reduces with (P/e) value 12 and 14 because of coarser rib position leading to fall in friction as less obstacle to flow (Fig. 6 and Fig. 8).

D. Effect of velocity thermal characteristics

The thermal character parameter of solar collector is measured by thermohydraulic performance. It is the ratio of ratio of Nusselt numbers of both rough and smooth plate to friction factor ratio of both the plates. Fig. 9 show that highest thermohydraulic performance is obtained at (P/e) value 10. This is because minimum friction is recorded at this pitch value and at the same time Nusselt number is highest, thus overall highest value of thermohydraulic performance is obtained. From the figure it is clear that highest thermohydraulic performance is obtained at ‘Reynolds number 8000 because at this value gain in Nusselt number is more than friction factor.
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Fig. 9 Thermal performance Vs pitch

V. CONCLUSIONS

1. The experimental result show that the highest Nu is measured at (P/e) value 10.
2. The friction is minimum at (P/e) value 10.
3. Maximum thermal characteristics performance is obtained at (P/e) 10 and Reynolds number 8000. This is because friction is minimum at Reynolds number 8000 though Nusselt number is not highest at this value.
4. The staggered element adds to the turbulence and hence there is enhanced transfer of heat from the fluid particles carrying the heat of absorber plate to the particles above laminar layer.

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| $A_p$  | Heat dissipation area of plate (m²) |
| $C_p$  | Specific heat of ambient fluid (kJ/kgK) |
| $D_h$  | Hydraulic diameter (m) |
| $i/e$  | Relative staggered rib length |
| $Re$   | Reynolds number |
| $Nu$   | Nusselt number |
| $f$    | Friction factor |
| $e/D_h$| Relative roughness height |
| $T_1$  | Air temperature (°C) |
| $T_2$  | Temperature of ambient fluid leaving (°C) |
| $T_p$  | Temperature of ambient fluid entering (°C) |
| $g/e$  | Relative gap |
| $V$    | Ambient fluid velocity (m/s) |
| $h$    | Heat transfer coefficient in convection (W/m²K) |
| $L$    | Plate length (m) |
| $m$    | Ambient fluid flow over plate (kg/s) |
| $k$    | Ambient fluid thermal conductivity (W/mK) |
| $p'/p$ | Relative staggered pitch |
| $P/e$  | Relative roughness pitch |
| $e$    | Rib height (m) |
| $\Delta P$ | Pressure drop across absorber surface length (N/m²) |
| $q$    | Heat flux (W/m²) |
| $\rho$ | Ambient fluid density (kg/m³) |

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AUTHOR PROFILE

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