ABSTRACT

Ever-increasing gap between demand and supply of energy, growing concerns about the environmental degradation associated with the use of fossil fuels and spiraling cost of energy have forced the scientific community to find and develop alternate sources of energy. There is a need to develop self sustaining units of energy based on local inexhaustible sources of energy which are available in abundance and do not adversely affect the environment. This requires emphasis on harnessing alternate sources of energy such as solar energy, wind energy, hydropower etc. that are reliable, plentiful and environment friendly. The eco-friendly nature and free availability of solar energy in abundance are two factors that have made solar energy the most favorable among other alternate sources of energy. Among the solar collector systems, solar air heater is the cheapest and most commonly used system to convert the incoming radiations into thermal energy, which is extracted by air flowing under the absorbing surface. However, very low heat transfer coefficient between the absorber plate and air results in very poor thermal performance of solar air heaters. In order to improve heat transfer in solar air heaters, artificial roughness, in the form of repeated ribs, is generally used to disturb and produce turbulence in the laminar sub layer region. The ribs are one of the most desirable methods on account of their ability to combine heat transfer coefficient enhancement with limited increase in frictional losses.

A number of experimental investigations involving different types, shapes and orientations of ribs such as transverse, inclined, v-shaped, wire mesh, chamfered, arc shaped and rib-groove arrangements have been reported in literature for performance improvement of solar air heaters. Rib height, pitch, inclination and v-shaping of ribs are some of the important parameters that affect the thermal performance of a solar air heater having roughened absorber plate. Correlations for Nusselt number and friction factor have been developed.

Thermal performance improvement achieved by the use of artificial roughness in solar air heaters is accompanied by enhanced frictional losses resulting in an increase in pumping power requirement to overcome friction. It has been reported in literature that optimization of roughness geometry parameters of a roughened solar air heater has been carried out on the basis of thermal efficiency, effective efficiency, exergetic efficiency or thermohydraulic performance parameter.

An extensive review of the literature revealed that number of investigators had used v-ribs, having different orientations, to improve the performance of solar air heaters and observed that v-ribs outperform other rib configurations such as transverse and inclined ribs in terms of heat transfer enhancement. Other investigators who used v-ribs for heat transfer enhancement in turbines, nuclear reactors, electric and electronic equipments, also reported similar observations. However, in all the investigations involving v-ribs, a single v-rib has been used along the width of heat transferring surfaces of rectangular duct to improve heat transfer. In the present investigation, multiple v-ribs have been employed along the width of absorber plate of a solar air heater to create artificial roughness for heat transfer enhancement. This arrangement is expected to result in substantial enhancement of heat transfer coefficient due to formation of correspondingly large number of secondary flow cells.

In view of the above, the present work is proposed to include the following objectives:

i. Experimental investigation of effect of multiple v-ribs on heat transfer coefficient and friction factor in duct flow.
ii. Development of correlations for heat transfer coefficient and friction factor in terms of roughness geometry and operating parameters.
iii. Investigation of enhancement of thermal performance of solar air heater having absorber plate roughened with multiple v-ribs.

iv. Thermohydraulic optimization of roughened solar air heater to obtain optimal roughness geometry.

An experimental set up has been designed and fabricated in accordance with the guidelines suggested in ASHRAE standard 93-77 for testing of solar collectors using an open loop system. It consists of a rectangular duct having entry, test and exit sections, a centrifugal blower, two control valves, a calibrated orifice plate and other necessary instruments for measurement of temperature and pressure drop.

Extensive data has been collected on heat transfer and fluid flow characteristics of a rectangular duct roughened with multiple v-ribs. Experimental data pertaining to heat transfer coefficient and friction factor as function of geometrical parameters of roughness namely relative roughness height, e/D, relative roughness width, W/w (ratio of absorber plate width to width of single v-rib), angle of attack, α and relative roughness pitch, P/e has been recorded. The range of roughness geometry and flow parameters considered in this experimental investigation is given in Table 1.

Table 1 Range of roughness and operating parameters

S. No.	**Roughness Parameters**	**Range**
1.	Reynolds number, Re	2000 – 20000 (10 values)
2.	Relative roughness height, e/D	0.019 – 0.043 (4 values)
3.	Relative roughness Width, W/w	1 – 10 (8 values)
4.	Angle of attack, α	30^o – 75^o (4 values)
5.	Relative roughness pitch, P/e	6 – 12 (4 values)

A total of thirty-eight multiple v-rib roughened absorber plates were tested in this experimental work covering different roughness geometry parameters.

It has been found that Nusselt number and friction factor are strong functions of roughness geometry and flow parameters. Nusselt number increases with an increase in relative roughness width and attains a maximum value corresponding to relative roughness width value of 6 in the range of parameters considered. With further increase in the value of relative roughness width, Nusselt number is found to decrease. However, it has been observed that friction factor increases with increase in relative roughness width ratio and attains a maximum value corresponding to relative roughness width value of 10. Nusselt number and friction factor increase with an increase in angle of attack and attain maximum values corresponding to angle of attack value of 60^o. Nusselt number and friction factor attain maximum values corresponding to relative roughness pitch, P/e value of 8 and on either side of this value, decrease in Nusselt number and friction factor has been observed. Nusselt number and friction factor increase monotonically with an increase in relative roughness height, e/D.

The maximum uncertainties in the values of Reynolds number, Nusselt number and friction factor computed are ± 3 %, ± 6.31% and ± 5.97 % respectively.

Experimental data on heat transfer and friction factor has been utilized to develop correlations for Nusselt number and friction factor in terms of relative roughness height, e/D, relative roughness width, W/w, angle of attack, α, relative roughness pitch, P/e and Reynolds number, Re. The correlations are given below;

$$Nu = 3.35x10^{-5}\, Re^{0.92} \left(\frac{e}{D}\right)^{0.77} \left(\frac{W}{w}\right)^{0.43} \left(\frac{\alpha}{90}\right)^{-0.49} \exp\left(-0.1177(\ln(W/w))^2\right) \exp\left(-0.61(\ln(\alpha/90))^2\right) \left(\frac{P}{e}\right)^{8.54} \exp\left(-2.0407\,(\ln(P/e))^2\right) \quad (1)$$

$$f = 4.47x10^{-4}\, Re^{-0.318} \left(\frac{e}{D}\right)^{0.73} \left(\frac{W}{w}\right)^{0.22} \left(\frac{\alpha}{90}\right)^{-0.39} e\exp\left(-0.52(Ln(\alpha/90))^2\right) \left(\frac{P}{e}\right)^{8.9} \exp\left(-2.133\,(Ln(P/e))^2\right) \quad (2)$$

A comparison of experimental values of Nusselt number and friction factor and those predicted by these correlations shows that there is a good agreement between the experimental and predicted values with an average absolute deviation of 4.45% for Nusselt number and 4% for friction factor values. Hence, the designer can use the correlations with reasonably good accuracy.

A computer programme has been developed to predict the thermal performance of roughened collector in terms of plate efficiency factor, $F^{'}$, heat removal factor, F_o, and thermal efficiency, η_{Th}, on the basis of these correlations developed for Nusselt number and friction factor. The effect of roughness geometry and operating parameters on thermal performance has been investigated and thermal performance of roughened and smooth collectors was compared in order to determine the enhancement in thermal performance on account of the use of multiple v-rib type of roughness geometry.

It has been observed that thermal performance of roughened solar air heaters is a strong function of roughness geometry parameters. Enhancement in thermal efficiency has been represented in terms of enhancement factor which is defined as the ratio of thermal efficiency of roughened collector to that of conventional smooth collector for the same operating conditions. The value of enhancement factor has been found to vary in the range of 1.13 to 2.45.

As pointed out earlier, the use of artificial roughness in solar air heaters improves the thermal performance considerably; however, this improvement in thermal performance is accompanied by increased frictional losses resulting in an increase in pumping power requirement to overcome friction. It, therefore, becomes imperative to determine the values of roughness geometry parameters that result in maximum enhancement of heat transfer with minimum increase in friction. In order to determine the values of roughness geometry and flow parameters that yield the optimum performance, thermohydraulic performance of multiple v-rib roughened solar air heater has been evaluated and the following three criteria have been used for optimization of roughness geometry parameters of a multiple v-rib roughened solar air heater;.

(i) Thermal efficiency

(ii) Effective efficiency

(iii) Exergetic efficiency

For given values of operating parameters (temperature rise parameter, $\Delta T/I$ and insolation, I) optimizing parameter values were computed for all possible combinations of roughness geometry parameters. Comparison of the computed values of the optimizing parameter yielded a set of optimal values of roughness geometry parameters.

It has been observed that on the basis of thermal efficiency criterion, a single set of roughness geometry parameters yielded optimum performance for the entire range of operating parameters and is given as;

Relative roughness height, e/D : 0.043

Relative roughness width, W/w : 6.0

Angle of attack, α : 60^o

Relative roughness pitch, P/e : 8.0

No single set of roughness geometry parameters yields optimum performance on the basis of effective efficiency and exergetic efficiency criteria for the entire range of the operating parameters. The optimum values of roughness geometry parameters depend on the operating parameters (temperature rise parameter and insolation). For instance, the optimum values obtained on the basis of effective efficiency criterion are given in Table 2.

Table 2 Optimum values of roughness parameters on the basis of effective efficiency

Roughness parameter	**Temperature rise parameter range (K-m^2/W)**	**Value of Roughness parameter**
Relative roughness height, e/D	$\Delta T/I < 0.00375$	0.019
	$0.00375 < \Delta T/I < 0.006$	Function of insolation and temperature rise parameter
	$\Delta T/I > 0.006$	0.043

Relative roughness width, W/w	0.003 < ΔT/I < 0.01375	Function of insolation and temperature rise parameter
	ΔT/I > 0.01375	6.0
Angle of attack , α	ΔT/I < 0.00325	30^0
	0.00325 < ΔT/I < 0.00625	Function of insolation and temperature rise parameter
	ΔT/I > 0.00625	60^o
Relative roughness pitch, P/e	ΔT/I < 0.00575	12.0
	0.00575 < ΔT/I < 0.008	Function of insolation and temperature rise parameter
	ΔT/I > 0.008	8.0

For given values of temperature rise parameter and insolation, a set of roughness geometry parameters can be obtained from the design plots prepared for each roughness geometry parameter on the basis of effective and exergetic efficiencies. A design procedure has also been proposed to determine the optimum values of roughness geometry parameters for a multiple v-rib roughened solar air heater for given values of the temperature rise and the insolation.

Summarizing, it can be stated that the experimental investigation has revealed considerable enhancement in thermal performance of a solar air heater having a multiple v-rib roughened duct in comparison to a smooth conventional solar air heater. Empirical correlations have been developed for Nusselt number and friction factor in terms of roughness geometry and operating parameters. Optimum values of roughness parameters have been determined based on the criteria of thermal efficiency, effective efficiency and exergetic efficiency. Design plots have been prepared which can be utilized to obtain a set of optimum values of roughness geometry parameters that will result in the best thermohydraulic performance for given operating conditions. A design procedure has been proposed to arrive at the optimum roughness geometry for given set of operating parameters of a solar air heater.