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## Thermo-hydraulic Performance of Artificially Roughned Solar Air Heaters - A Review

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**ABSTRACT:** The use of an artificial roughness on a surface is an effective technique to enhance the rate of heat transfer to fluid flow in the duct of a solar air heater. This paper presents a comparison of thermo-hydraulic performance of solar air heaters having different types of geometry of roughness elements (continuous ribs) on the absorber plate. Analysis shows that solar energy can be efficiently used for process heating in industries, drying agriculture products etc. The poor thermal efficiency of solar air heaters is generally due to the low heat transfer coefficient between absorber plate and fluid flowing through the duct. The low heat transfer coefficient is due to existence of thin boundary layer known as the viscous sub-layer which cause to make the insulate situation between heated surface and heat convecting fluid. In the last few years, there has been a growing interest in use of roughness underside the absorber plate which is a very effective method for improving the heat transfer coefficient. In particular, using the roughness causes to break the viscous sub-layer which results into the high thermal performance of the solar air heaters. However, the major drawback of this approach is accompanied by higher friction factor that causes excessive pumping power for propelling the forced air through the duct. In view a designer needs to carefully examine shape and orientation of roughness elements in order to choose the best fit roughness geometry for intended application. Different roughness geometries have been compared on the basis of heat transfer enrichment and thermo-hydraulic performance to draw attention towards their usefulness. Thus there is scope of further enhancement of thermo-hydraulic performance.

**KEYWORDS:** Thermo-hydraulic performance, Nusselt's number, Friction factor, Relative roughness height, Relative roughness pitch.

### I. INTRODUCTION

With the recent trend of providing both heating and cooling with solar energy, solar water heaters have gained more popularity. As far as the ultimate application of heating air to maintain a comfortable environment is concerned, the solar air heater is the most logical choice. Heating a fluid by the sun, then transferring heat from fluid to the air results in loss of temperature potential available. If the limitations of solar energy applications in terms of attainable temperatures and related efficiencies as well as the low cost requirement are considered, it would be wiser to eliminate any heat transfer operation. Direct use of the air circulated through the solar air heater as the working substance also reduces the number of components required in the system. Solar heated air has also been used more effectively for drying under controlled conditions. Solar air heater supplying hot air to a conventional drier or special designs combining the air heater and the drying cabinet in one package have cost and efficiency advantages for drying applications.

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## 1.1 Artificial Roughness

Artificial roughness is basically a heat transfer enhancement technique by which thermo hydraulic performance of a solar air heater can be improved. Artificial roughness may be in the form of continuous ribs, baffles, dimple shape or protrusions etc. Energy for creating turbulence in flow passage has to come from the fan or blower and the excessive power is required to flow air through the duct. Therefore, it is desirable that the turbulence must be created only in the region very close to the heat transferring surface, so that power requirement may be reduced.

## 1.2 Thermohydraulic optimization of roughened solar air heater

Since the enhancement in heat transfer(Nusselt Number) as well as friction factor are strong function of roughness parameters, it is essential that optimum values of these parameters are found that result into best thermohydraulic performance of solar air heater i.e. result in maximum possible enhancement in thermal efficiency with minimum possible increase in pumping power requirements. The following criteria have been proposed to be considered for the optimization of roughness parameters of artificial roughness:

1. Effective efficiency
2. Thermo-hydraulic performance

### 1.2.1 Effective efficiency

Cortes and Piacentini [1990] defined effective efficiency on the basis of net thermal gain which is obtained by subtracting the equivalent thermal energy that will be required to produce friction power from collector gain and is written as:

$$\eta_{\text{eff.}} = (Q_U - P_M/C) / A I$$

Gupta et al. [1997] also used the criterion of thermohydraulic performance for optimization of wire roughened solar air heater. Thermal and effective efficiencies of a collector are shown as function of Reynolds number in Fig.1.1 which shows that the thermal efficiency increases monotonously with Reynolds number.

### 1.2.2 Thermohydraulic performance parameter ( $\epsilon$ )

Lewis [1975] proposed that the enhancement in thermal performance can be evaluated on the basis of thermohydraulic performance parameter which incorporate both the thermal as well as hydraulic considerations and can be expressed as:

$$\eta = (S_r/S_{ts})^3 / (f/f_s)$$

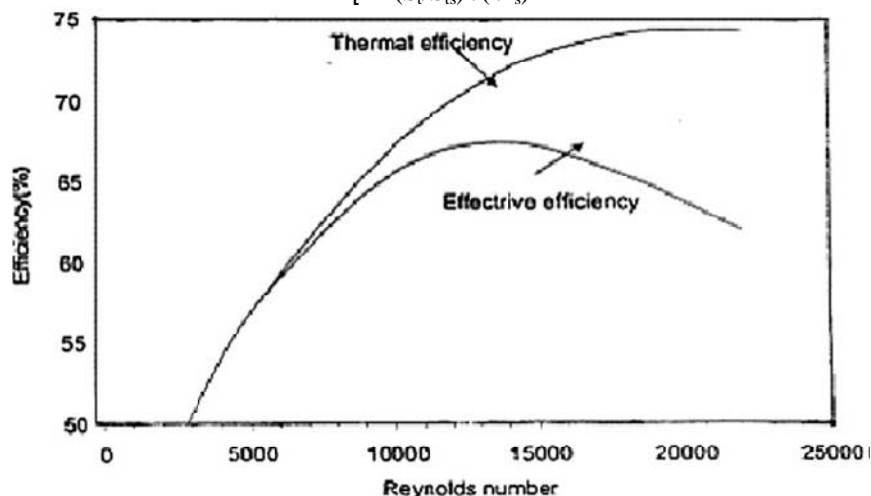


Figure 1.1: A plot of Efficiency vs. Reynolds number [Kumar et al, 2012]

## 1.3 Comparison thermohydraulic performance of roughened solar air heater duct

The study of heat and fluid flow characteristics of the roughened solar air heater ducts and the literature reveals that an enhancement in heat transfer is always accompanied with increased pumping power penalty due to corresponding

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increase in the friction factor. Therefore, it is essential to determine the geometry that will results in the maximum enhancement in heat transfer and minimum increase in friction factor, thereby lower power penalty. In order to achieve this objective of simultaneous consideration of thermal as well as hydraulic performance, Lewis [1975] proposed a thermohydraulic performance parameter known as efficiency parameter  $h$ , which evaluates the enhancement of heat transfer for same pumping power requirement and is defined as,

$$h = (St/St_s)/(f/f_s)^{1/3}$$

Thermohydraulic performance has been compared using the correlations of heat transfer and friction factor for different roughness geometries. Comparison thermohydraulic performance of different roughness geometries has been shown in Figure 1.3. Figure 1.3 shows the variation of Reynolds number used in solar air heaters ducts. Figure 1.2 Energy flow diagram of a solar air heater. Amongst the entire solar air heater ducts roughness geometries considered, Multi v-shaped rib geometry has the best thermohydraulic performance as compare to other roughness geometries as described by Kumar et al., 2012.

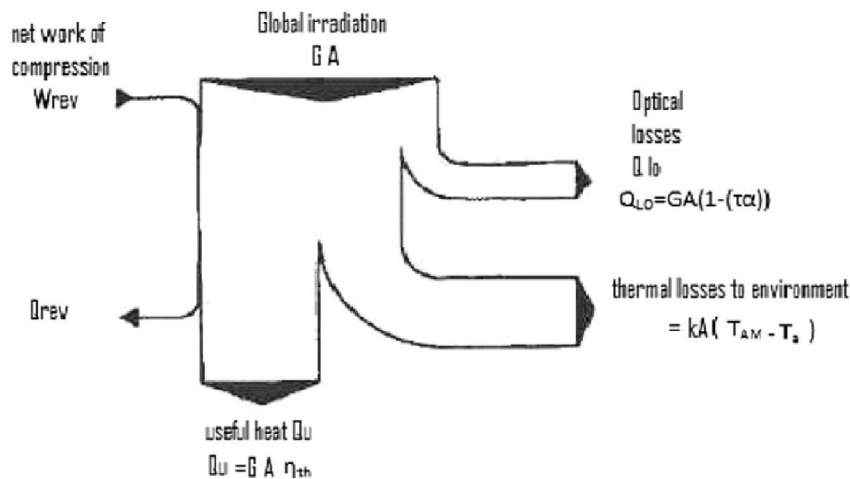


Figure 1.2 Energy flow diagram of a solar air heater [Kumar, et al. 2012]

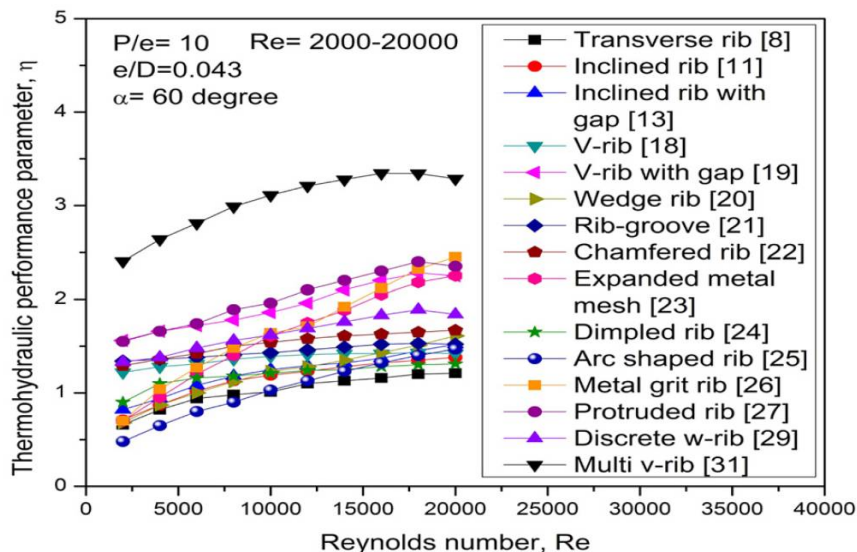


Figure 1.3: Comparison of thermohydraulic performance [Kumar et al. 2012]

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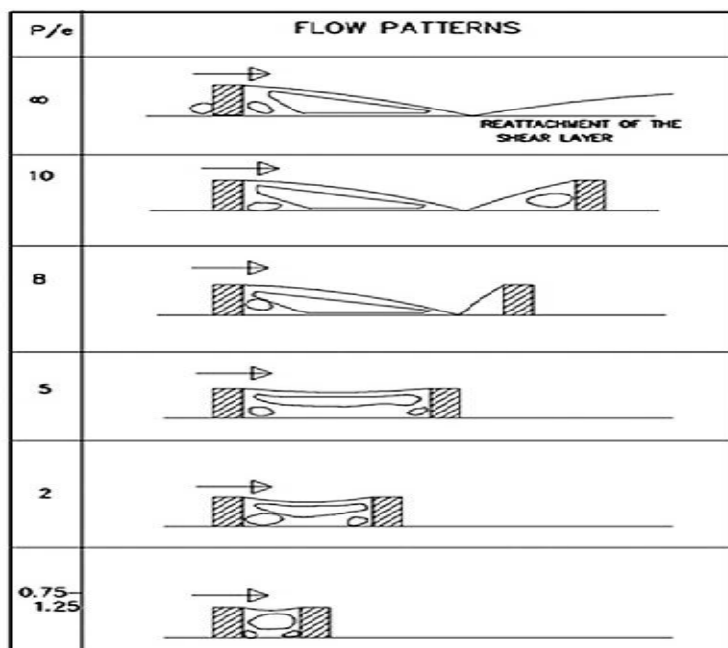
Vol. 6, Issue 10, October 2017

### 1.3 Relative roughness pitch (P/e)

Table 1.1 shows the value of relative roughness pitch for a maximum value of a heat transfer coefficient for different types of artificial roughness geometries. Figure 1.4 shows the flow patterns downstream of a rib with variation in rib pitch. The flow separation occurs downstream of a rib and reattachment does not occur, if relative roughness pitch is less than about 8-10. Hence optimum value of relative roughness pitch is between 8-10 for maximum value of heat transfer rate in solar air heaters other than transverse ribs.

**Table 1.1 Values of relative roughness pitch at which maximum value of heat transfer rate for different artificial roughness geometries used in solar air heater duct.[Saini et al. 2012]**

S. No.	Investigators	Rib geometry	Value of relative roughness pitch (P/e)
1.	Prasad and Saini	Transverse continuous rib	P/e = 10
2.	Sahu and Bhagoria	Transverse broken rib	P/e = 13.33
3.	Aharwal et al.	Inclined rib with gap	P/e = 10
4.	Varun et al.	Combination of inclined and transverse rib	P/e = 8
5.	Momin et al.	V-shaped rib	P/e = 10
6.	Singh et al.	Discrete v-rib	P/e = 8
7.	Bhagoria et al.	Wedge Shaped rib	P/e = 7.57
8.	Jaurker et al.	Rib-groove	P/e = 6
9.	Karwa et al.	Chamfered rib	P/e = 7.09
10.	Saini and Verma	Dimpled Shaped rib	P/e = 10
11.	Karmare and Tikekar	Metal grit rib	P/e = 17.5
12.	Lanjeware et al.	W-shaped rib	P/e = 10
13.	Kumar et al.	Discrete w-shaped rib	P/e = 10
14.	Bopche and Tandale	U-shaped rib	P/e = 10
15.	Hans et al.	Multi v-shaped	P/e = 8



**Figure 1.4: Effect of pitch on flow transverse continuous ribs [Prasad et al., 1988].**

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Vol. 6, Issue 10, October 2017

### 1.4 Effect of relative roughness height (e/D)

Table 1.2 shows the value of relative roughness height for a maximum value of a heat transfer coefficient for different types of artificial roughness geometries. Figure 1.5 shows the flow pattern downstream of a rib and effect on the laminar sub-layer as the rib height is changed respectively. Breakage of the viscous sub-layer due to repeated ribs increases the rate of heat transfer by creating local wall turbulence. (D=Hydraulic Diameter of Duct and e = height of roughness element) as described by Kumar et al. (2012).

**Table 1.2 Values of relative roughness height at which maximum value of heat transfer rate for different artificial roughness geometries used in solar air heater duct [Kumar et al. 2012]**

S. No.	Investigators	Rib geometry	Parameters (e/D)
1.	Prasad and Saini	Transverse continuous rib	e/D = 0.033
2.	Sahu and Bhagoria	Transverse broken rib	e/D = 0.0338
3.	Gupta et al.	Inclined continuous rib	e/D = 0.023
4.	Aharwal et al.	Inclined rib with gap	e/D = 0.0377
5.	Varun et al.	Combination of inclined and transverse rib	e/D = 0.030
6.	Momin et al.	V-shaped rib	e/D = 0.034
7.	Singh et al.	Discrete v-rib	e/D = 0.043
8.	Bhagoria et al.	Wedge Shaped rib	e/D = 0.033
9.	Jaurker et al.	Rib-groove	e/D = 0.0363
10.	Karwa et al.	Chamfered rib	e/D = 0.0328
11.	Saini and Saini	Expanded rib	e/D = 0.039
12.	Saini and Verma	Dimpled Shaped rib	e/D = 0.0379
13.	Saini and Saini	Arc shaped rib	e/D = 0.0422
14.	Karmare and Tikekar	Metal grit rib	e/D = 0.044
15.	Lanjeware et al.	W-shaped rib	e/D = 0.0337
16.	Kumar et al.	Discrete w-shaped rib	e/D = 0.0338
17.	Bopche and Tandale	U-shaped rib	e/D = 0.0398
18.	Hans et al.	Multi v-shaped	e/D = 0.043

Momin et al. (2002) described the effects of relative roughness height on Nusselt number and friction factor as depicted in Figures 1.6 and 1.7 respectively. It can be observed that the increase in relative roughness height results in an increase in heat transfer coefficient and the friction factor. It is seen that the rate of increase of Nusselt number is lower than that of the friction factor. This appears due to the fact that at relatively higher values of relative roughness height, the re-attachment of free shear layer might not occur and the rate of increment heat transfer enhancement will be less and increase in friction factor is more rapid, so a value of e/D = 0.033 to 0.043 is desired for optimum increase in Nusselt number (heat transfer enhancement) and friction factor does not increase too much.

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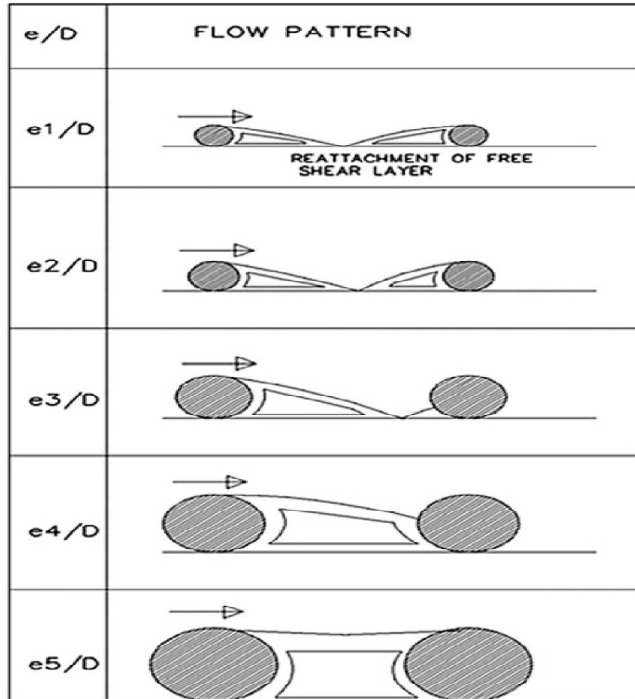


Figure 1.5: Effect of rib height on flow [Kumar et al. 2012]

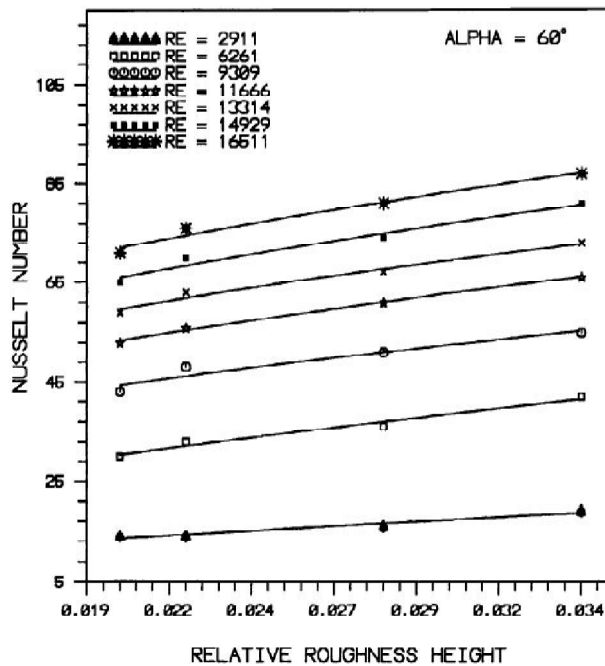


Figure 1.6: Effect of relative roughness height on Nusselt number for given Reynolds number and for an angle of attack of flow of 60°. [Momin et al. 2002]



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Vol. 6, Issue 10, October 2017

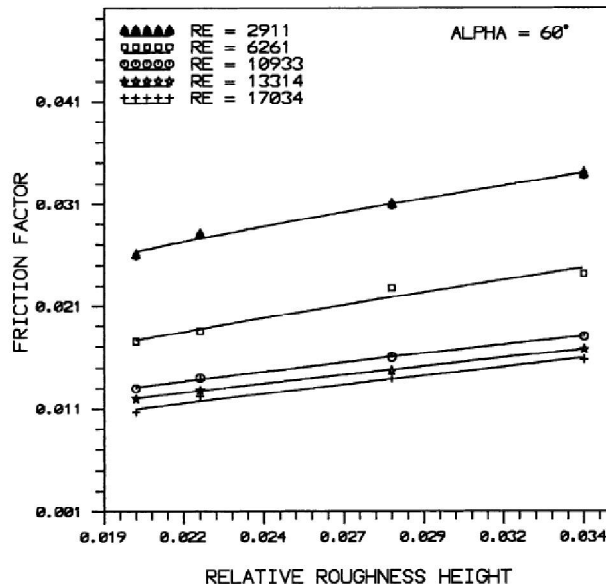


Figure 1.7: Effect of relative roughness height on friction factor for given Reynolds number and for an angle of attack of flow of  $60^\circ$  [Momin et al. 2002]

## II. CONCLUSION

This paper reported review on thermo-hydraulic performance (THP) of different artificially roughened surface with different geometries of different shapes, sizes and orientation by various investigators. Use of artificial roughened surface is found to be the good technique to enhance the heat transfer rate with little penalty. Maximum increment in Nusselt number and Friction Factor due to various roughened surfaces over smooth duct have been summarized and listed in Table. The least and maximum values of THP are found to be 1.2 and 2.9 respectively. Multi-V rib and V-rib with gap shows the highest THP (Kumar et al. 2012). Thus there is scope of further enhancement of THP by increase in Nusselt number with less penalty of friction factor. For that optimum shape, size and orientations of roughness element need to be done.

1) Roughened solar air heaters are thermohydraulically advantageous for lower Reynolds numbers, whereas a smooth solar air heater will perform better thermohydraulically, although the thermal efficiency of a roughened solar air heater may be more than that of a smooth heater, beyond a certain limiting value of Reynolds number; this limiting Reynolds number has been found to lie in the range of 13000-19000, the actual value depending upon the actual relative roughness height and insolation. [Gupta and Saini 1997]

2) At low air mass flow rates corresponding to high values of temperature rise parameter  $\Delta T/I$ , solar air heaters with smaller duct depth or high L/H values give better thermo-hydraulic performance while at high flow rates (corresponding to the low temperature rise parameter), the pumping power requirements are significant and solar air heaters with large duct depth or low L/H values are better from the thermo-hydraulic performance consideration. [Karwa, 1999]

3) The effective efficiency of a roughened solar air heater increases as the insolation increases for Reynolds numbers higher than 10,000. However, at lower Reynolds numbers (i.e. below 10,000) the thermohydraulic efficiency decreases with increasing insolation. An optimum operating condition exists for a given insolation and this optimum condition shifts to a higher value of Reynolds number as insolation increases. [Gupta and Saini 1997]

4) It can be concluded that an increase in roughness height ( $e$ ) will result in the shift of the point of maximum effective efficiency towards lower Reynolds number, whereas Nusselt number ( $Nu$ ) and friction factor ( $f$ ) both increase with increase in relative roughness height. [Gupta and Saini 1997]

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Vol. 6, Issue 10, October 2017

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