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Effective efficiency of solar air heaters having different types of roughness elements on the absorber plate

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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 effective efficiency of solar air heaters having different types of geometry of roughness elements on the absorber plate. The effective efficiency has been computed by using the correlations for heat transfer and friction factor developed by various investigators within the investigated range of operating and system parameters.

Keywords: Solar air heater; Artificial roughness; Effective efficiency; Heat transfer; Friction factor

1. Introduction

Solar air heaters, because of their simplicity, are cheap and most widely used collection devices of solar energy. The thermal efficiency of solar air heaters has been found to be generally poor because of their inherently low heat transfer capability between the absorber plate and air flowing in the duct. By providing artificial roughness on the underside of absorber plate the heat transfer coefficient can be enhanced. However, the energy for creating such turbulence has to come from the fan or blower. It is therefore; the turbulence must be created only in the region very close to the heat transfer surface, i.e. in the laminar sublayer only. Several investigators have attempted to design a roughness element, which can enhance convective heat transfer with minimum increase in friction losses. Zhang et al. [1] and Han et al. [2] investigated the effect of artificial roughness on heat transfer and friction factor for two opposite roughened surface. However, in case of solar air heaters, the roughness elements have to be considered only underside of one wall of duct, which receives the solar radiation. Therefore, the solar air heaters are modeled as a rectangular channel having one rough wall and three smooth walls. Based on the literature review, it is found that most of the investigations have been concentrated on high Reynolds number in the range of $10^5 < Re < 10^6$ for gas turbines and other heat exchanger applications. However, the flow Reynolds number in solar air heaters ranges as $2000 < Re < 15\,000$.

2. Types of artificial roughness

Nikuradse [3] investigated the effect of roughness on the friction factor and velocity distribution in pipes roughened by sand blasting. Nunner [4] and Dippery and Sebersky [5] developed a friction similarity law and a heat momentum transfer analogy for flow in sand grain roughened tubes. In case of solar air heaters, rib type roughness has been investigated mostly. The ribs can be full (continuous) or discrete (broken) depending on whether one complete rib or the ribs in pieces are placed on the absorber plate. The orientation of the ribs can be as transverse, inclined and V-shaped. Han and Zhang [6] found that ribs inclined at an angle of attack of 45° results in better heat transfer performance when compared to transverse ribs. Lau et al. [7], and Taslim et al. [8] investigated the effect of V-shaped ribs and found that V-shaped ribs result in better enhancement in heat transfer in comparison to inclined ribs and transverse ribs. Ichimiya et al. [9] experimentally

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Table 1
Correlations used for heat transfer coefficient and friction factor for different roughness geometries

Author	Type of roughness	Range of parameters	Correlations	
			Heat transfer coefficient	Friction factor
Momin et al. [16]	V-shaped rib	e/D: 0.02–0.034 p/e: 10 α: 30–90 Re: 2500–18 000	$Nu_r = 0.067Re^{0.888}(e/D)^{0.424}(\alpha/60)^{-0.077} \times \exp\left[-0.782\{\ln(\alpha/60)\}^2\right]$	$f_r = 6.266Re^{-0.425}(e/D)^{0.565}(\alpha/60) - 0.093 \times \exp\left[-.719\{\ln(\alpha/60)\}^2\right]$
Bhagoria et al. [15]	Wedge-shaped rib	e/D: 0.015–0.033 p/e: $60.17\ \phi^{-1.0264}$ $<p/e<12.12$ ϕ: 8, 10, 12, 15 Re: 3000–18 000	$Nu_r = 1.89 \times 10^{-4}Re^{1.21}(e/D)^{0.426}(p/e)^{2.94} \times \exp\left[-0.71\{\ln(p/e)\}^2\right](\phi/10)^{-0.018} \times \exp\left[-1.5\{\ln(\phi/10)\}^2\right]$	$f_r = 12.44Re^{-0.18}(e/D)^{0.99}(p/e)^{-0.52}(\phi/10)^{0.49}$
Saini and Saini [14]	Expanded metal mesh	e/D: 0.012–0.039 L/e: 25.00–71.87 S/e: 15.62–46.87 Re: 1900–13 000	$Nu_r = 4.0 \times 10^{-4}Re^{1.22}(e/D)^{0.625}(s/10e)^{2.22} \times \exp\left[-1.25\{\ln(s/10e)\}^2\right](l/10e)^{2.66} \times \exp\left[-0.824\{\ln(l/10e)\}^2\right]$	$f_r = 0.815Re^{-0.361}(l/e)^{0.266}(s/10e)^{-0.19}(10e/D)^{0.591}$
Gupta et al. [13]	Angled circular rib	e/D: 0.020–0.053 p/e: 7.5 & 10	$Nu_r = 0.0024(e/D)^{0.001}(W/H)^{-0.06}Re^{1.084} \times \exp\left[-0.04(1-\alpha/60)^2\right] \quad \text{for } e^+ < 35$	$f_r = 0.1911(e/D)^{0.196}(W/H)^{-0.093}Re^{-0.165} \times \exp\left[-0.993(1-\alpha/70)^2\right]$
		α: 30°–90° Re: 5000–30 000	$Nu_r = 0.0071(e/D)^{-024}(W/H)^{-0.028}Re^{0.88} \times \exp\left[-0.475(1-\alpha/60)^2\right] \quad \text{for } e^+ > 35$	
Prasad and Saini [12]	Small diameter protrusion wire	e/D: 0.020–0.033 p/e: 10–20	$\bar{S}t = \dfrac{\bar{f}/2}{1 + \sqrt{\bar{f}/2}\left\{4.5(e^+)^{0.28}Pr^{0.57} - 0.95(p/e)^{0.53}\right\}}$	$\bar{f} = \dfrac{(W+2B)f_s + Wf_r}{2(W+B)}$
		Re: 5000–50 000		Where
				$f_r = \dfrac{2}{\left[0.95(p/e)^{0.53} + 2.5\ln(D/2e) - 3.75\right]^2}$
Dittus-Boetler and Blasius [12]	Smooth duct	—	$h_s = 0.024(k/D)\ Re^{0.8}Pr^{0.4}$	$f_s = 0.085\ Re^{-0.25}$

investigated the effect of porous type roughness on the heat transfer and friction characteristics in parallel plate duct. The rib roughness can also be recognized in accordance with the shape of cross section of ribs such as square, rectangular, triangular, circular, semicircular and trapezoidal ribs. Ravigururanjan and Bergles [10] used four types of roughness, namely semicircular, circular, rectangular and triangular ribs to develop the general statistical correlations for heat transfer and pressure drop for single phase turbulent flow in internally ribbed surface. Liou and Hwang [11] tested three shapes of rib roughness, namely square, triangular and semicircular ribs to study the effect of rib shapes on turbulent heat transfer and friction in a rectangular channel with two opposite ribbed walls.

3. Effect of roughness parameters on heat transfer and friction factor in solar air heaters

A number of investigators investigated heat transfer and friction for roughened duct of solar air heaters. Prasad and Saini [12] investigated the effect of relative roughness height and relative roughness pitch on heat transfer and friction factor in transverse ribs. Gupta et al. [13] investigated the effect of relative roughness height, angle of attack on heat transfer and friction factor in rectangular duct having circular wire ribs on the absorber plate. Saini and Saini [14] investigated the effect of expanded metal mesh geometry [i.e. relative long way length of mesh (l/e) and relative short way length of mesh (s/e)] on heat transfer and friction factor. Bhagoria et al. [15] performed experiments to determine the effect of relative roughness pitch, relative roughness height and wedge angle on the heat transfer and friction factor. Momin et al. [16] experimentally investigated the effect of geometrical parameters of V-shaped ribs on heat transfer and fluid flow characteristics of rectangular duct. The investigation covered a Reynolds number range of 2500–18 000, relative roughness height of 0.02–0.034 and angle of attack of flow (α) of 30–90° for a fixed relative pitch of 10. The correlations for heat transfer and friction factor developed by these investigators for different geometries of roughness element are given in Table 1.

Table 2
Typical values of system and operating parameters

Parameters	Values
Length, L (mm)	1000
Width, W (mm)	200
Height, H (mm)	20
Insolation, I (W/m^2)	1000
Overall loss coefficient, U_l (W/m^2 °C)	5
Transmittance–absorbtance, ($\tau\alpha$)	0.85
Relative roughness height, e/D	0.02–0.04
Relative roughness pitch, p/e	10
Reynolds number, Re	2000–24 000

4. Effective efficiency of solar air heater

The use of artificial roughness on the absorber plate of solar air heater enhances the thermal performance however; this is accompanied by a substantial pumping power penalty. The roughness geometry should be selected for maximum thermal gain with minimum friction losses. Therefore, the selection of roughness geometry has to be based on the parameter that takes into account both the

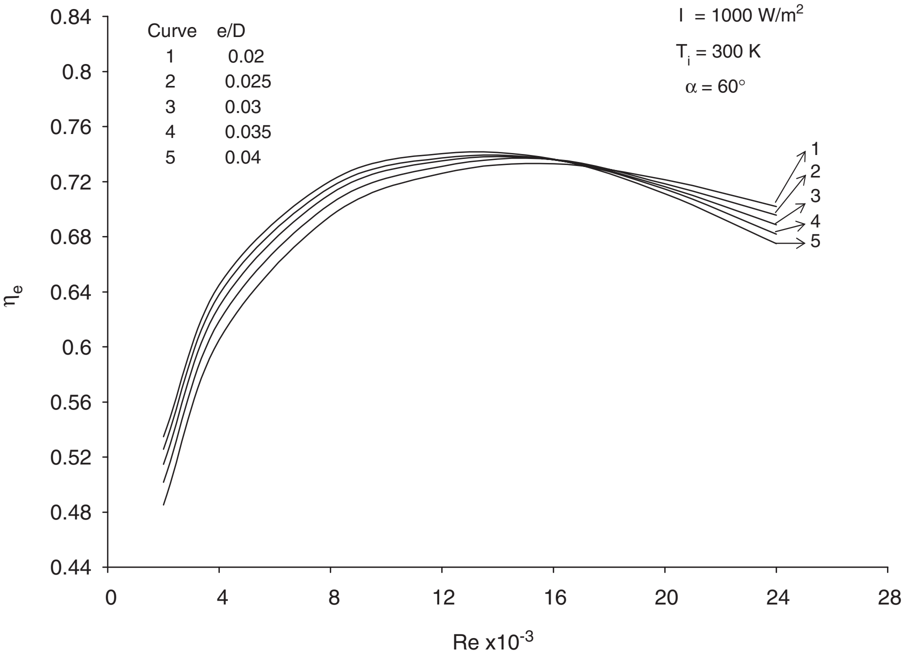

Fig. 1. Effective efficiency vs. Reynolds number for the roughness geometry used by Momin et al. [16].

thermal and hydraulic (friction) performance. Cortes and Piacentini [17] defined an effective efficiency of solar air heater on the basis of net thermal energy gain obtained by subtracting the equivalent thermal energy that will be required to overcome the friction power, from the collector useful gain. The effective efficiency is expressed as follows:

$$\eta_e = \frac{q_u - P/C}{IA_c}, \tag{1}$$

where C is the conversion efficiency (mechanical power, P to thermal), considering that mechanical power is obtained from a typical thermal power plant. The value of C is taken by considering typical values of various efficiencies as 0.2 [= thermal power plant efficiency (0.34) × transmission efficiency (0.90) × motor efficiency (0.90) × efficiency of the pump (0.75)].

The effective efficiency has been computed for different five geometries investigated by different investigators

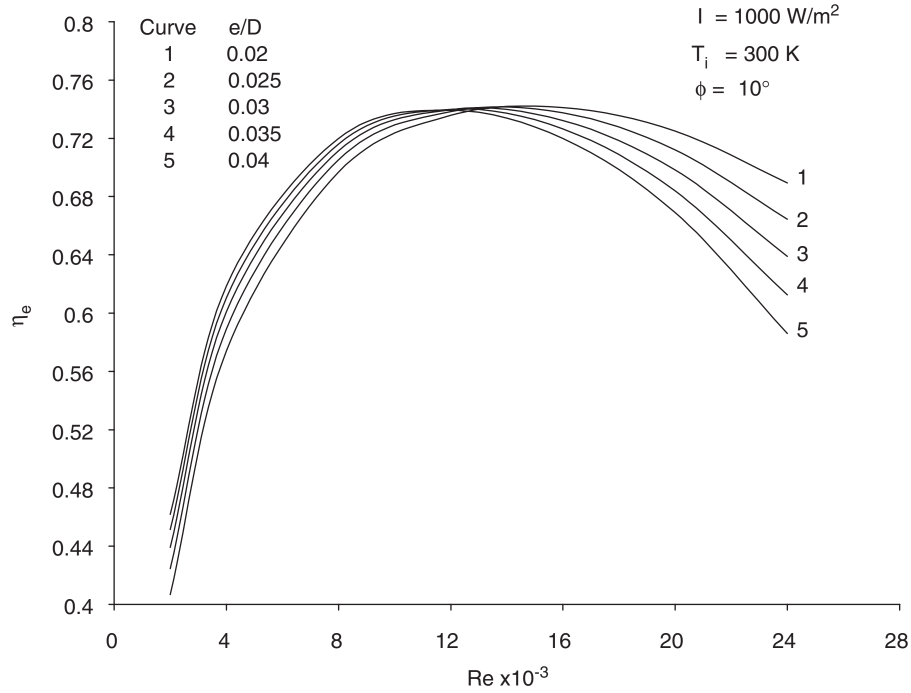

Fig. 2. Effective efficiency vs. Reynolds number for the roughness geometry used by Bhagoria et al. [15].

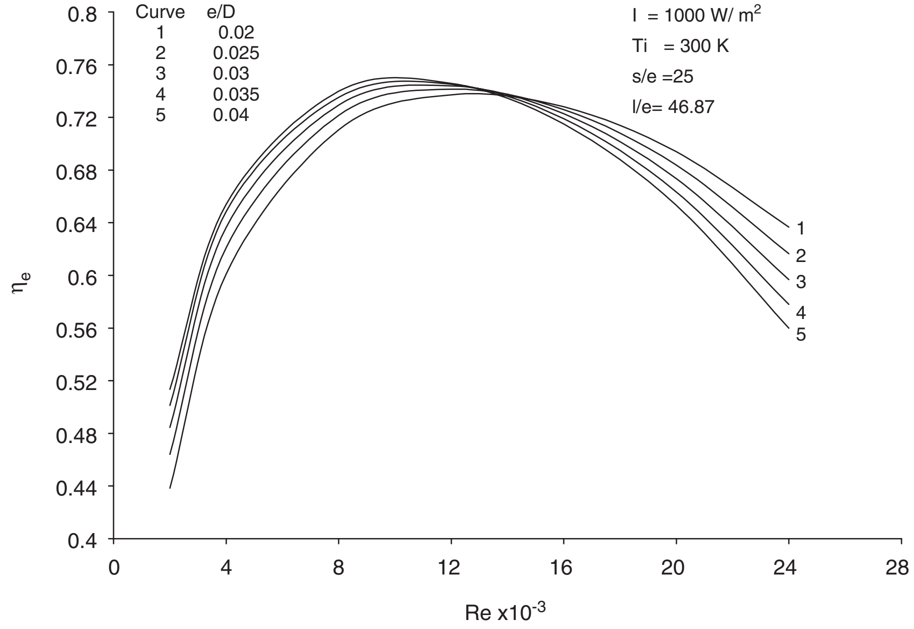

Fig. 3. Effective efficiency vs. Reynolds number for the roughness geometry used by Saini and Saini [14].

[12–16]. The rate of useful thermal energy gain (q_u) and mechanical power (P) consumed, has been obtained by using the following[13]:

$$q_u = F'\left[I(\tau\alpha) - U_L(t_o - t_i)/2\right]A_c, \tag{2}$$

where

$$F' = h/(h + U_L) \tag{3}$$

and,

$$P = VA\,\Delta P. \tag{4}$$

The term ($\tau\alpha$) represents transmittance–absorptance product, which accounts for the complex interaction of optical properties of the glass cover and absorber plate, (t_o–t_i) is the fluid temperature rise and F' is the collector efficiency factor.

The value of pressure drop (ΔP) across the collector having length as 'L' flow velocity 'V' and hydraulic diameter 'D' is determined by using friction factor 'f' as follows:

$$\Delta P = (2f\,LV^2\rho)/D. \tag{5}$$

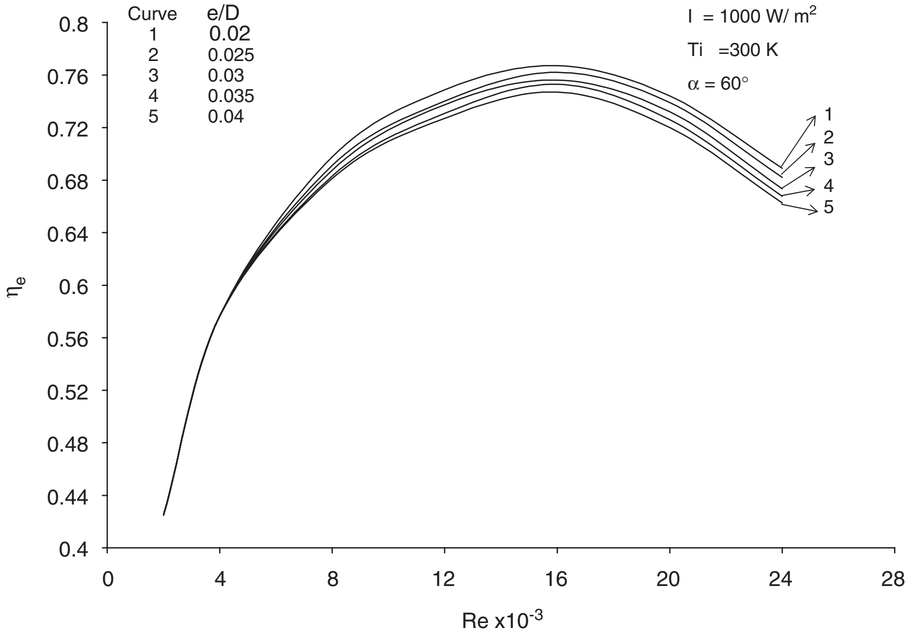

Fig. 4. Effective efficiency vs. Reynolds number for the roughness geometry used by Gupta et al. [13].

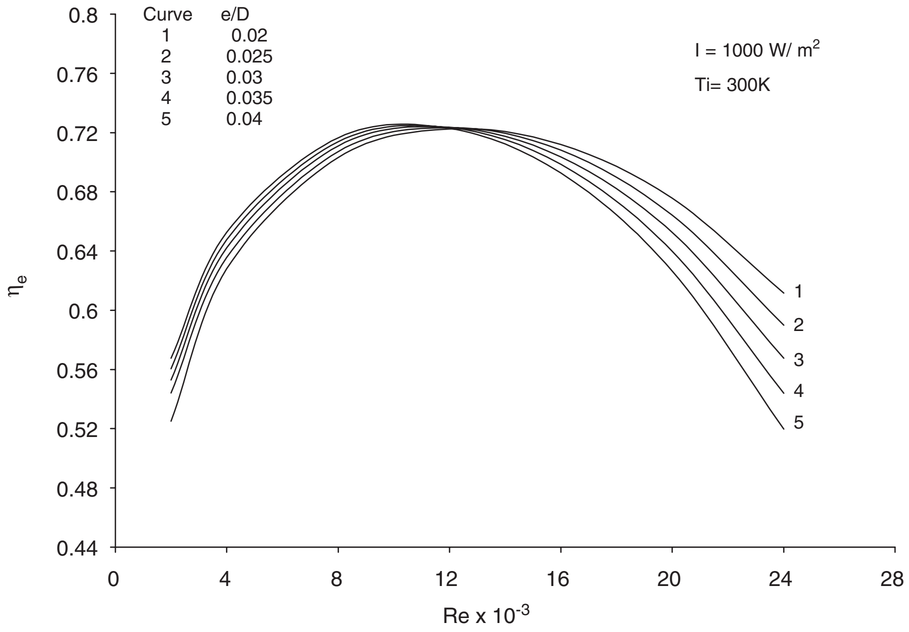

Fig. 5. Effective efficiency vs. Reynolds number for the roughness geometry used by Prasad and Saini [12].

The values of heat transfer coefficient, *h* and friction factor, *f* for roughened and smooth solar air heaters have been determined from the correlations developed for heat transfer and friction factor by several investigators as given in Table 1. The typical values of other parameters considered under the present investigation are as given in Table 2.

5. Results and discussions

The Effective efficiency of roughened as well as smooth absorber plate solar air heaters has been computed on the basis of method proposed by Cortes and Piacentini [17]. For effective efficiency of solar air heater, the relative roughness height (e/D) is considered as strong parameter of roughness element. Figs. 1–5 have been prepared to show the effect of relative roughness height on the effective efficiency for the optimal values of other parameters, suggested by various investigators. It can be observed from these figures that for given values of roughness parameters, similar trend in variation of effective efficiency is obtained with Reynolds number. Initially effective efficiency increases with the increase of Reynolds number, attains maxima and thereafter it starts decreasing. The reason may be due to dominance of mechanical power, which is required to overcome the frictional forces in the duct. It is also observed that the effective efficiency corresponding to the higher values of roughness height is better in the lower range of Reynolds number, however the value of effective efficiency is reversed in the higher range of Reynolds number. This effect can be attributed to the fact that at lower Reynolds number, the increase in the friction losses in the duct is insignificant with increase in relative roughness height, while the increase in heat transfer from roughened surface is quite substantial due to increase of turbulence in the vicinity of roughened surface.

Fig. 6 has been prepared to compare the effective efficiency of solar air heaters having different roughness geometries. It can be observed that among all the roughness elements investigated, the inclined ribs having low values of roughness height (e/D) resulted in better effective efficiency in higher range of Reynolds number (more than 12 000). However, in lower range of Reynolds number (less than 12 000) the better effective efficiency is observed for the solar air heater having expanded metal mesh as artificial roughness element. Further it is also observed that the Effective efficiency of smooth solar air heater is better than the roughened solar air heaters in the range of very high Reynolds number. In order to determine the uncertainty in the results computed for these two cases a sensitivity analysis has been carried out. The values of effective efficiency have been determined for smaller range of parameters and marked over respective curves of effective efficiency as shown in Fig. 6. It has been observed that in the lower range of Reynolds number the maximum value of uncertainty is about 2.5% for the expanded metal mesh geometry and 0.8% for inclined ribs. However, in the higher range of Reynolds numbers, the maximum uncertainty has been found as 0.5% and 0.4% for expanded metal mesh and inclined ribs respectively.

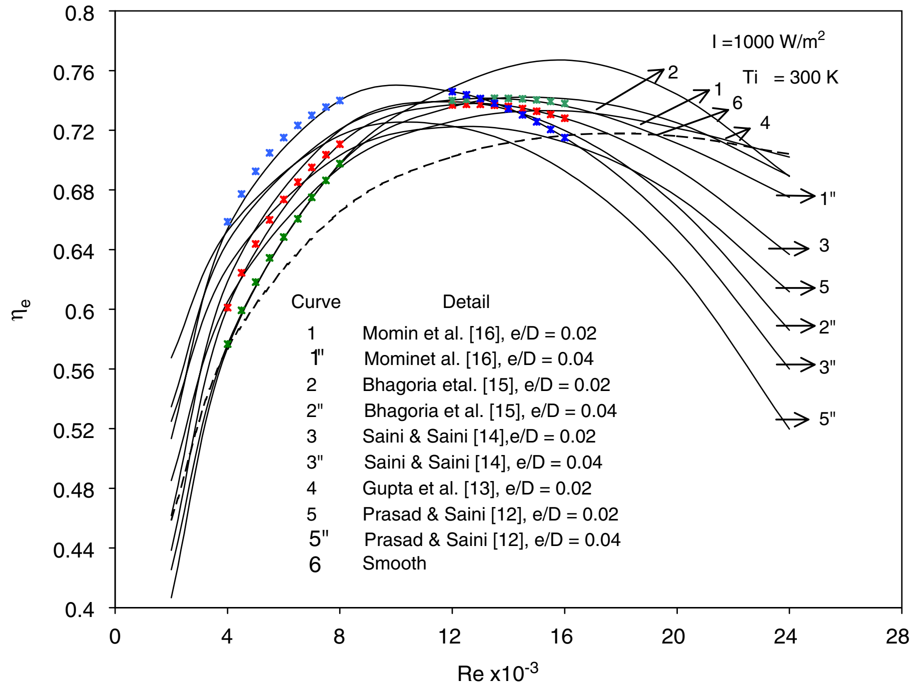

Fig. 6. Effective efficiency vs. Reynolds number for roughened and smooth solar air heaters.

6. Conclusions

There is a considerable enhancement in the effective efficiency of solar air heaters having roughened duct provided with different types of roughness elements. Solar air heater having inclined ribs as roughness elements is found to have better effective efficiency in the higher range of Reynolds number. However, expanded metal mesh is found suitable roughness element in the lower range of Reynolds number.

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