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# Effective efficiency prediction for discrete type of ribs used in solar air heaters

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**Abstract**
The use of an artificial roughness on a surface is an effective technique to enhance the heat transfer from the collector plate to the air in a solar air heater duct. However, artificial roughness leads to even more fluid pressure thereby increasing the pumping power. Number of geometries of roughness elements has been investigated on the heat transfer and friction characteristics of solar air heater ducts. This paper presents a comparison of effective efficiency of solar air heaters having different types of geometry of roughness elements (discrete ribs) 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:** Artificial roughness, Discrete ribs, Effective efficiency, Heat transfer, Solar air heater.

## 1. Introduction

Solar energy is very large, inexhaustible source of energy. The power from the sun intercepted by the earth is approximately 1.8 x $10^{11}$ MW, which is many thousands of times larger than the present consumption rate on the earth of all commercial energy sources. Thus, in principle, solar energy could supply all the present and future energy needs of the world on a continuing basis and makes it one of the most promising of the unconventional energy sources [1]. The simplest and the most efficient way to utilize solar energy is to convert it into thermal energy for heating applications by using solar collectors. Solar air heaters, because of their simplicity are cheap and most widely used collection devices. The thermal efficiency of solar air heaters has been found to be generally poor because of low heat transfer capability between the absorber plate and air flowing through duct. Use of an artificial roughness on the underside of absorber plate is an effective technique to enhance the rate of heat transfer [2]. However, it would result in an increase in frictional losses leading to more power required by fan or blower. In order to keep the friction losses at a minimum level, the turbulence must be created only in the region very close to the duct surface i.e., in laminar sub-layer. The surface roughness can be produced by several methods, such as sand blasting, machining, casting, forming, welding or providing ribs of small diameter wires. Nikuradse [3] investigated the effect of roughness on the friction factor and velocity distribution in pipes roughened by sand blasting. Dippery and Sabersky [4] developed a friction similarity law and a heat momentum transfer analogy for flow in sand grain roughened tubes. In case of solar air heaters, artificial roughness in the form of ribs has been investigated mostly. The ribs can be discrete (broken) or full (continuous) depending on whether ribs in pieces or one complete rib is placed on the absorber plate.

The orientation of the ribs can be as transverse, inclined and v-shaped. Varun et al. and Hans et al. [5, 6] presented a review of various types of roughness geometries used in solar air heaters. The effect of artificial roughness on the performance of the heat transfer surface has been studied extensively. Webb et al. [7] developed heat transfer and friction factor correlations for turbulent flow in tubes having repeated rib roughness. Prasad and Saini [8] investigated the effect of relative roughness height and relative roughness pitch on heat transfer and friction factor. They developed the relations to calculate the average friction factor and Stanton number for artificial roughness of absorber plate by small diameter protrusion wire. Han and Zhang [9] found that ribs inclined at an angle of attack of 45º results in better heat transfer performance when compared to transverse ribs. Lau et al. [10] and Taslim et al. [11] investigated the effect of v-shaped ribs and found that v-shaped ribs result in better enhancement in heat transfer in comparison of inclined and transverse ribs. Gupta et al. [12] investigated the thermo-hydraulic performance in terms of effective efficiency of solar air heater with rib roughened surface by using heat transfer and friction factor correlation developed by them. Muluwork et al. [13] compared the thermal performance of v-shaped staggered discrete ribs with transverse staggered discrete ribs. Momin et al. [14] experimentally investigated the effect of geometrical parameters of v-shaped ribs on heat transfer and fluid flow characteristics of rectangular duct of a solar air heater. Karmare and Tikekar [15] experimentally investigated heat transfer and friction characteristics of a rectangular duct having absorber plate roughened with a defined grid of metal ribs of circular cross-section. Saini and Verma [16] studied the effect of roughness and operating parameters on heat transfer and friction factor in a roughened duct provided with dimple-shape roughness geometry. Varun et al. [17] carried out an experimental study on heat transfer and friction characteristics by using a combination of inclined and transverse ribs on the absorber plate of a solar air heater and developed the correlation of Nusselt number and friction factor. Kumar et al. [18] carried out an experimental investigation to determine the heat transfer distributions in solar air heater having its absorber plate roughened with discrete w-shaped ribs. Similar investigations for heat transfer and fluid flow characteristics have been carried out by Saini and Saini [19] for expanded metal mesh; Bhagoria et al. [2] for wedge shaped rib; Jaurker et al. [20] for rib-grooved; Saini and Saini [21] for arc shaped wire type roughness on the absorber plate. It is evident that various investigators have developed correlations for heat transfer and friction factor for solar air heater ducts having artificial roughness of different geometries. Several researchers have carried out the detailed experimental investigation for various types of ribs on the absorber plate, but none of study has been reported for their respective comparison. Hence, an attempt has been done to carry out the thermo-hydraulic performance evaluation in terms of effective efficiency of solar air heaters having discrete ribs as a roughness element on the absorber plate.

## 2. Effective efficiency of solar air heater

Providing artificial roughness on the underside of the absorber plate of solar air heater enhances the thermal performance. However, this improvement is accompanied by substantial pumping power. The roughness geometry should be selected for maximum thermal gain with minimal frictional losses. Thus, selection of roughness geometry has to be based on the parameter that takes into account both the thermal and hydraulic performance. Cortes and Piacentini [22] evaluated the thermo-hydraulic performance of unglazed solar air heaters having artificial roughness on the absorber plates. They defined the term "effective efficiency" which includes the friction penalty due to rib roughness along with the useful energy collection rate. The effective efficiency has been computed for different selected geometries investigated by different investigators [14-16, 18]. The effective efficiency $\eta_{eff}$ of solar air heater is computed from the relation:

$$\eta_{eff} = (Q_u - P_m / C) / IA_p \tag{1}$$

where $Q_u$ is the useful heat gain ($W$), $I$ is the irradiance (W.m$^{-2}$), $A_p$ is the area of absorber plate (m$^2$), $C$ is the conversion efficiency (mechanical power, $P_m$ 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 rate of useful thermal energy may be obtained from the equation [12]:

$$Q_u = F'[I(\tau\alpha) - U_L(T_o - T_i)/2]A_p \quad (2)$$

where $F'$ is the collector efficiency factor, $(\tau\alpha)$ is the transmittance-absorptance product for absorber cover combination, $U_L$ is the total loss coefficient ($W.m^{-2}.K^{-1}$), $T$ is the temperature (K) and the subscripts ($i$) and ($o$) are the inlet and outlet respectively.

$$F' = [h/(h + U_L)] \quad (3)$$

where $h$ is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$).

The rate of useful thermal energy gain roughened solar air heater may also be calculated from the following equation:

$$Q_u = mc_p(T_o - T_i) \quad (4)$$

where $m$ is the mass flow rate ($kg.s^{-1}$), $c_p$ is the heat capacity of the fluid ($kJ.kg^{-1}.K^{-1}$).

The mechanical power consumed is given by the expression;

$$P_m = VA\Delta p \quad (5)$$

where $P_m$ is the mechanical energy consumed for propelling air through collector (W), $V$ is the velocity of air in solar air heater duct ($m.s^{-1}$), $A$ is the area of cross-section ($m^2$), and $\Delta p$ is the pressure drop across collector length ($N.m^{-2}$)

$$\Delta p = (2fLV^2\rho)/d \quad (6)$$

$$d = 2WH/(W + H) \quad (7)$$

where $f$ is the friction factor, $L$ is the collector length (m), $\rho$ is the density of air ($kg.m^{-3}$), $d$ is the equivalent diameter of air passage (m), $W$ is the collector width (m), and $H$ is the solar air heater duct depth (m).

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 system and operating parameters considered under the present investigation are as given in Table 2.

## 3. Results and discussions

The thermo-hydraulic performance in terms of effective efficiency of solar air heaters for different discrete roughness elements has been evaluated and compared for various relative roughness height (e/d), irradiance (I), total loss coefficient ($U_L$) and temperature rise parameter ($(T_o-T_i)/I$). Figures 1-8 shows the variation of effective efficiency with temperature rise parameter ($(T_o-T_i)/I$). These figures can be used for selecting optimum roughness geometry of discrete type on the underside of the absorber plate of a solar air heater. Out of these geometries used in this investigation, dimple-shaped roughness geometry gives the best performance. The corresponding mass flow rate for a desired temperature rise parameter needed for a particular application at any location can be estimated as the intensity of solar radiation is known. Effective efficiency is strongly a function of Reynolds number, as Reynolds number increases the value of effective efficiency increases say up to 10,000-14,000. After that it starts decreasing and after value of 22,000 it shows negative value due to increase in friction losses. It is also highly dependent upon relative roughness height (e/d). As the value of e/d increases heat transfer increases but friction losses also increases. For a low Reynolds number, performance is higher for higher e/d but as Reynolds number increases the performance starts decreasing for higher e/d as compared to lower e/d.

Table 1. Correlations developed for heat transfer coefficient and friction factor for different roughness geometries used in solar air heater duct

Table 1. Correlations developed for heat transfer coefficient and friction factor for different roughness geometries used in solar air heater duct

| Authors | Type of roughness | Range of parameters | Correlations: Heat transfer coefficient | Correlations: Friction factor |
|---|---|---|---|---|
| Momin et al. [14] | V-shaped ribs | e/d: 0.02-0.034<br>p/e: 10<br>α: 30°-90°<br>Re: 2500-18,000 | $Nu_r = 0.067\,\mathrm{Re}^{0.888}(e/d)^{0.424}(\alpha/60)^{-0.077}$ $\exp[-0.782\{\ln(\alpha/60)\}^2]$ | $f_r = 6.266\,\mathrm{Re}^{-0.425}(e/d)^{0.565}(\alpha/60)^{-0.093}$ $\exp[-0.719\{\ln(\alpha/60)\}^2]$ |
| Karmare and Tikekar [15] | Metal rib grits | e/d: 0.035-0.044<br>p/e: 12.5-36<br>l/s: 1.72-1<br>Re: 4000-17,000 | $Nu_r = 2.4\times10^{-3}(\mathrm{Re})^{1.3}(e/d)^{0.42}(l/s)^{-0.146}(p/e)^{-0.27}$ | $f_r = 15.55\times(\mathrm{Re})^{-0.26}(e/d)^{0.91}(l/s)^{-0.27}(p/e)^{-0.51}$ |
| Saini and Verma [16] | Dimple-shape | e/d: 0.018-0.037<br>p/e: 8-12<br>Re: 2000-12,000 | $Nu_r = 5.2\times10^{-4}\,\mathrm{Re}^{1.27}(p/e)^{3.15}\times\exp[(-2.12)(\log(p/e))^2]$ $(e/d)^{0.033}\times\exp[(-1.30)(\log(e/d))^2]$ | $f_r = 0.642\,\mathrm{Re}^{-0.423}(p/e)^{-0.465}\times\exp[(0.054)(\log(p/e))^2]$ $(e/d)^{-0.0214}\times\exp[(0.840)(\log(e/d))^2]$ |
| Kumar et al. [18] | W-shaped ribs | e/d: 0.0168-0.0338<br>p/e: 10<br>α: 30°-75°<br>Re: 3000-15,000 | $Nu_r = 0.105\,\mathrm{Re}^{0.873}(e/d)^{0.453}(\alpha/60)^{-0.0081}$ $\exp[-0.59\times(\ln(\alpha/60))^2]$ | $f_r = 5.68(\mathrm{Re})^{-0.40}(e/d)^{0.59}(\alpha/60)^{-0.081}$ $\exp[-0.579\times(\ln(\alpha/60))^2]$ |
| Dittus-Boetler and Blasius | Smooth duct | – | $h_s = 0.024(k/d)\times\mathrm{Re}^{0.8}\times\mathrm{Pr}^{0.4}$ | $f_s = 0.085\times\mathrm{Re}^{-0.25}$ |

where (e/d) is the relative roughness height, (p/e) is the relative roughness pitch, (l/s) is the relative length of metal grit, (Re) is the reynolds number, (α) is the angle of attack of roughness elements (°), (Nu) is the Nusselt number, (f) is the friction factor, (h) is the convective heat transfer coefficient ($W.m^{-2}.K^{-1}$), (Pr) is the Prandtl Number, (k) is the thermal conductivity of air ($W.m^{-1}.K^{-1}$), (d) is the equivalent diameter of air passage (m). The subscripts (r) and (s) are the rough and smooth respectively.

Table 2. Typical values of system and operating parameters

| Collector parameters | Values |
|---|---|
| Length , L (mm) | 1000 |
| Width , W (mm) | 200 |
| Height , H (mm) | 20 |
| Irradiance , I ($W.m^{-2}$) | 800-1200 |
| Overall loss coefficient , $U_L$ ($W.m^{-2}.K^{-1}$) | 5-10 |
| Transmittance-absorbtance , ($\tau\alpha$) | 0.85 |
| Average inlet temperature of air , $T_i$ (K) | 298 |
| Relative roughness height , e/d | 0.02-0.04 |
| Relative roughness pitch, p/e | 10 |
| Reynolds number , Re | 2000-30,000 |

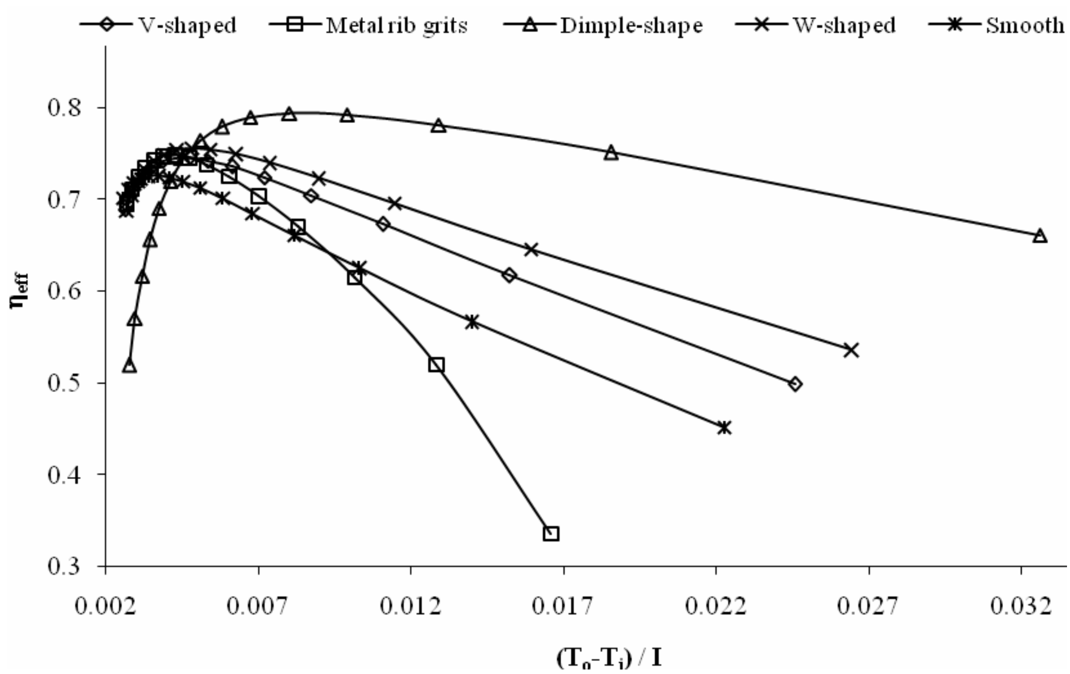


Figure 1. Variation of effective efficiency with temperature rise parameter for various roughness geometries (at *e/d* = 0.025, *I* = 1200 W/m$^2$ and $U_L$= 5 W/m$^{-2}$K)

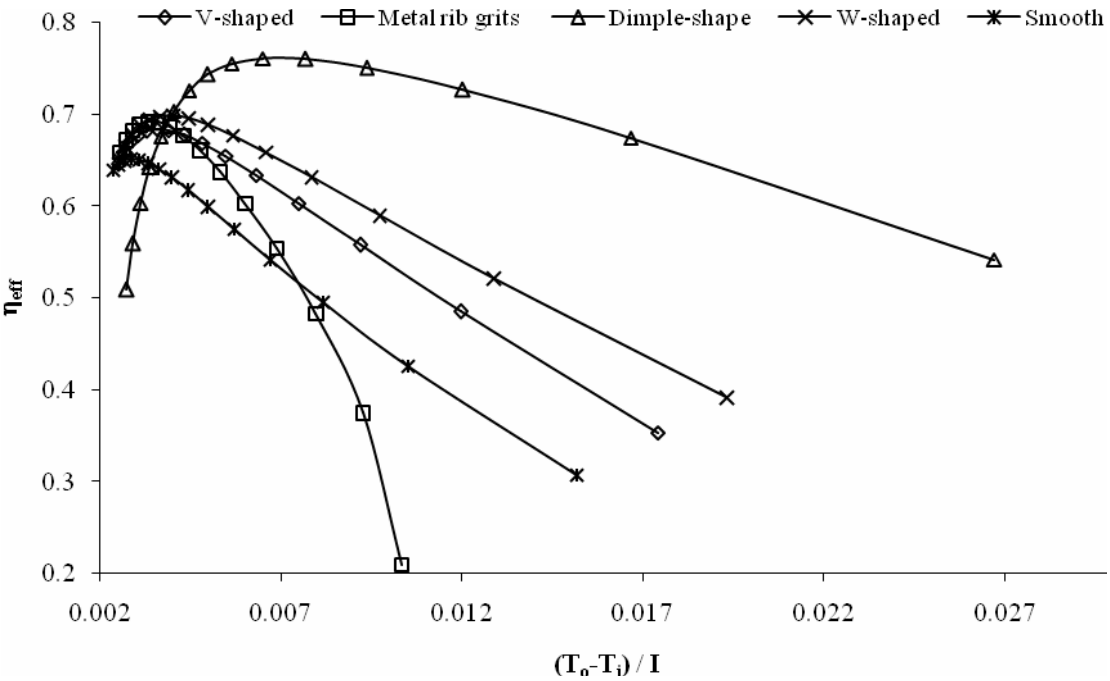


Figure 2. Variation of effective efficiency with temperature rise parameter for various roughness geometries (at $e/d$ = 0.025, $I$ = 1200 W/m$^2$ and $U_L$ = 10 W/m$^{-2}$K)

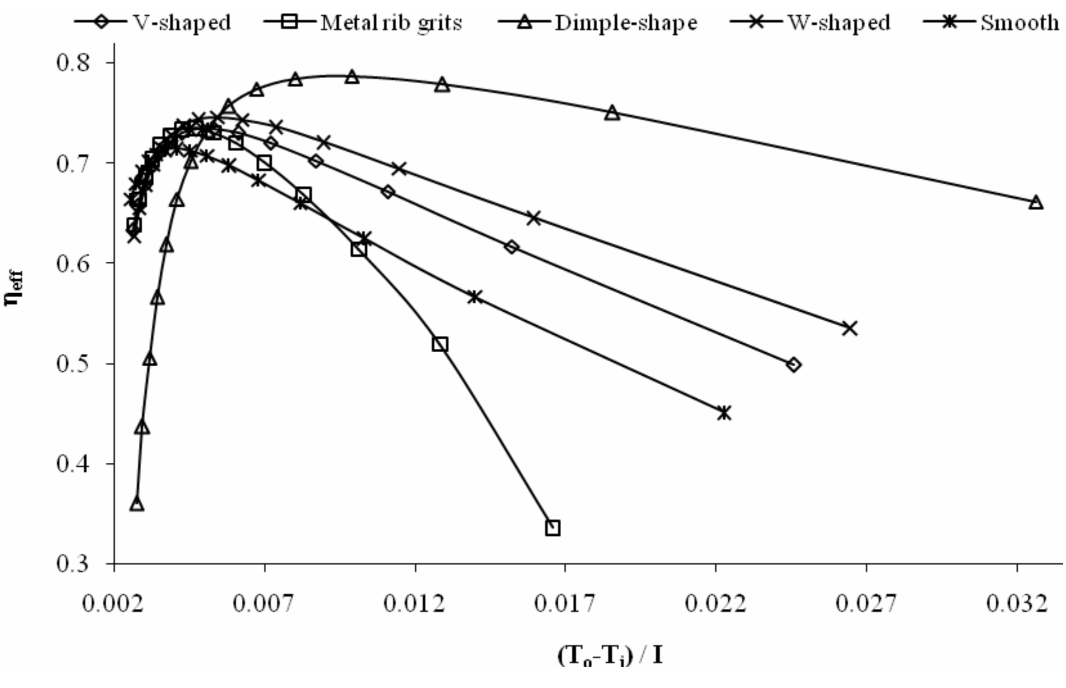


Figure 3. Variation of effective efficiency with temperature rise parameter for various roughness geometries (at $e/d$ = 0.025, $I$ = 800 W/m$^2$ and $U_L$ = 5 W/m$^{-2}$K)

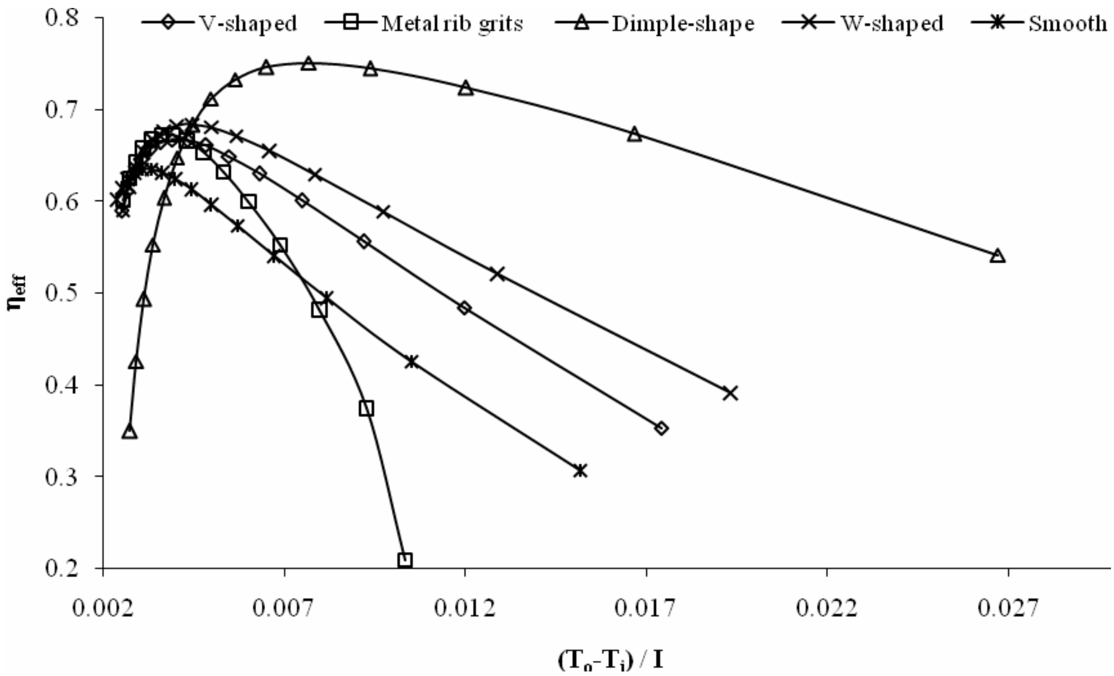


Figure 4. Variation of effective efficiency with temperature rise parameter for various roughness geometries (at *e/d* = 0.025, *I* = 800 W/m$^2$ and $U_L$ = 10 W/m$^{-2}$K)

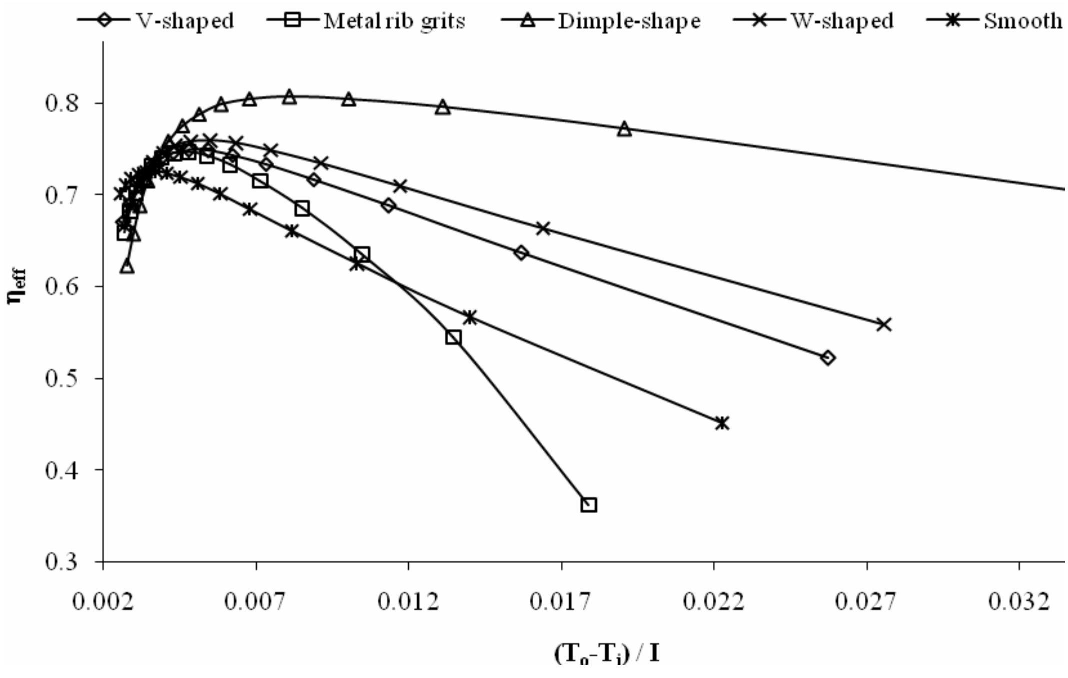


Figure 5. Variation of effective efficiency with temperature rise parameter for various roughness geometries (at *e/d* = 0.035, *I* = 1200 W/m$^2$ and $U_L$ = 5 W/m$^{-2}$K)

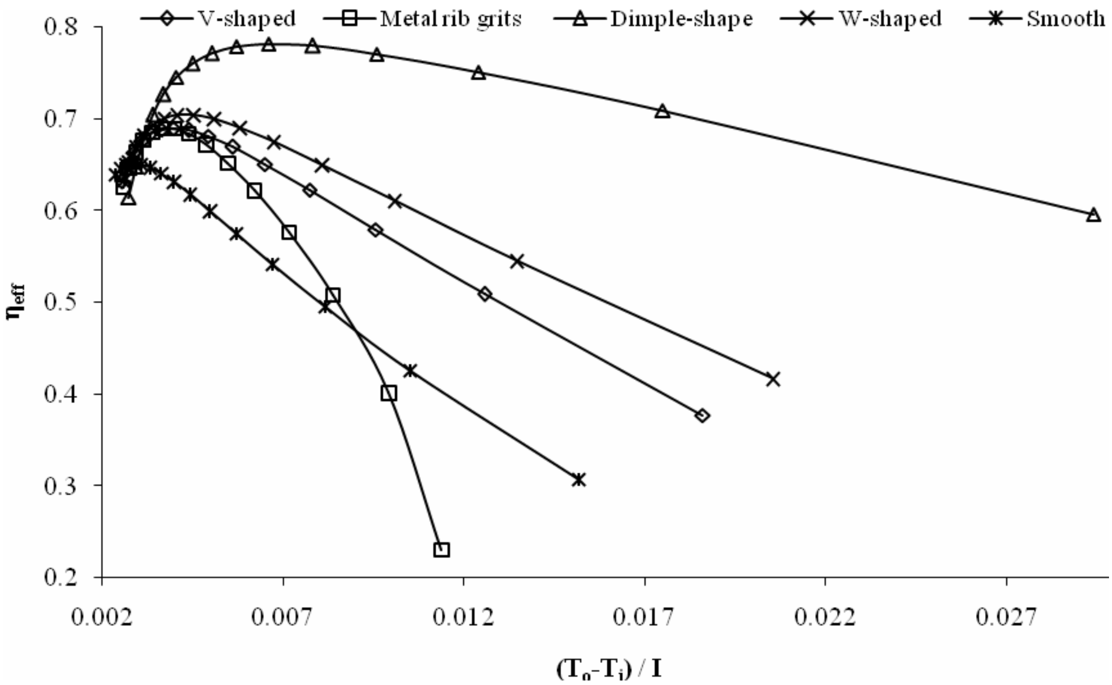


Figure 6. Variation of effective efficiency with temperature rise parameter for various roughness geometries (at *e/d* = 0.035, $I$ = 1200 W/m$^2$ and $U_L$ = 10 W/m$^{-2}$K)

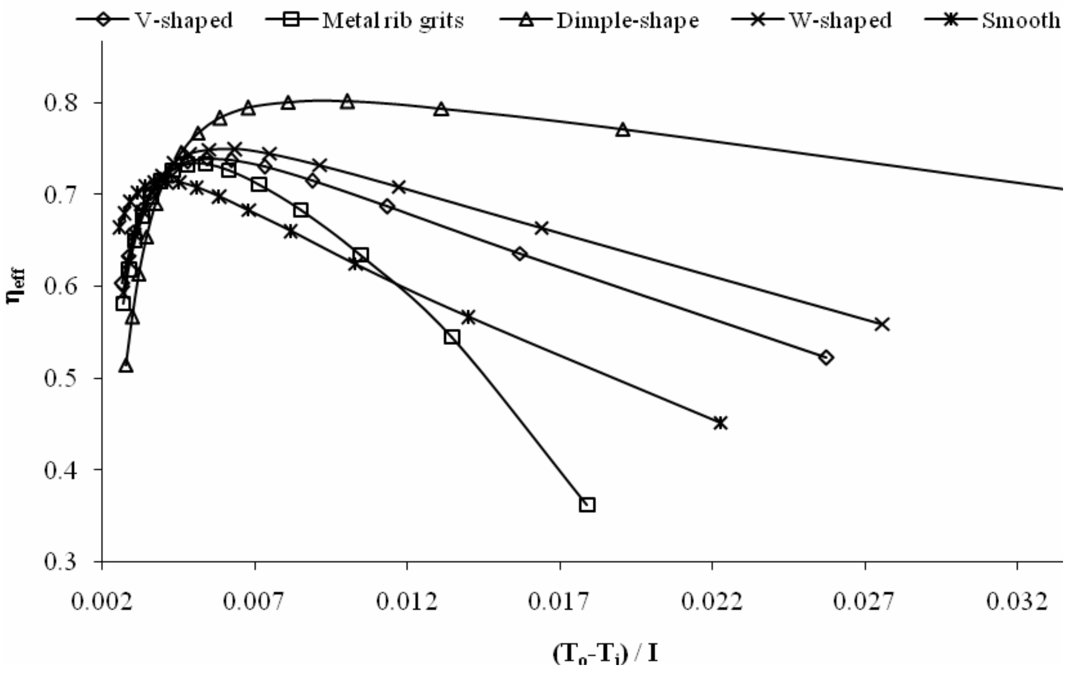


Figure 7. Variation of effective efficiency with temperature rise parameter for various roughness geometries (at *e/d* = 0.035, $I$ = 800 W/m$^2$ and $U_L$ = 5 W/m$^{-2}$K)

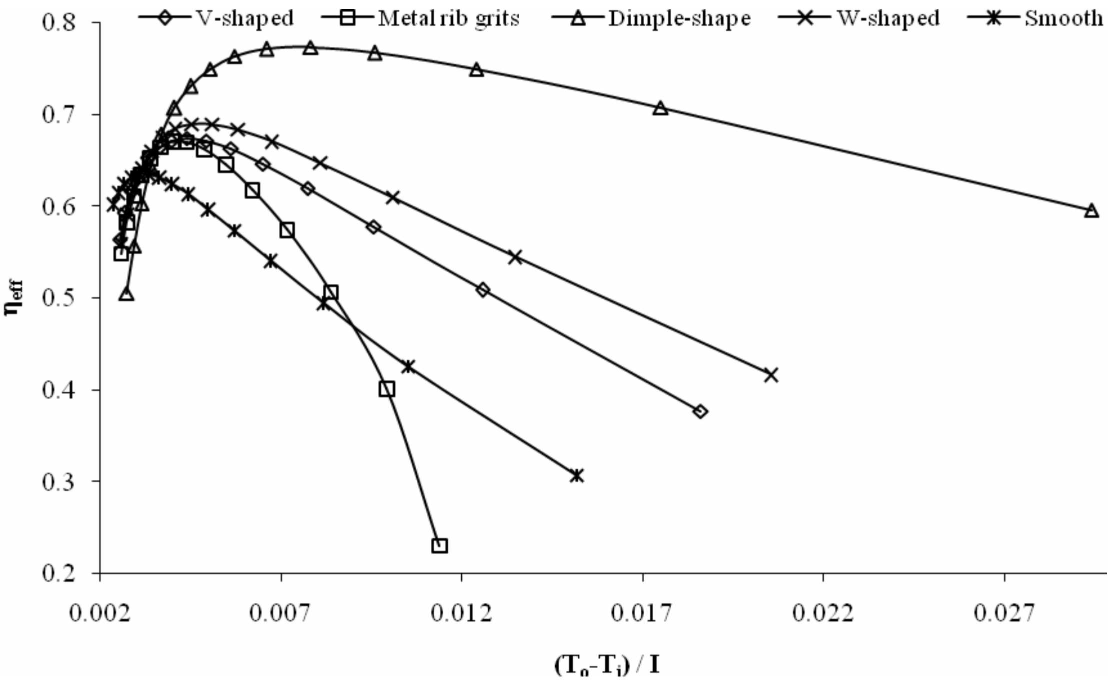


Figure 8. Variation of effective efficiency with temperature rise parameter for various roughness geometries (at $e/d$ = 0.035, $I$ = 800 W/m$^2$ and $U_L$ = 10 W/m$^{-2}$K)

## 4. Conclusions

It is concluded that the presence of roughness on the absorber plate yields considerable enhancement of heat transfer. This enhancement in heat transfer is always along with the additional friction losses as compared to smooth surface. The selection of roughness geometry should be such that the heat transfer increases significantly but the increase in friction is to be very less.

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