Thermal Performance Investigation of a Single Pass Solar Air Heater

Ovais Gulzar, Adnan Qayoum, and Rajat Gupta

Abstract One of the most promising energy sources being utilized in much direct and indirect processes of energy conversion is solar energy, of which solar air heaters are the foremost application of direct use of solar energy. Solar air heaters use air as a medium for thermal conduction; however, air has low thermal conductivity resulting in lower heat transfer coefficient absorber plate and the medium of air. Artificial roughness induced by ribs reduces thermal resistance by breaking the viscous sublayer while promoting turbulence to increase the coefficient of heat transfer. In the present work, evaluation of the performance of conventional solar air heater with an absorber plate containing V-shaped ribs has been done. V-shaped ribs have been used on absorber plate at the relative roughness pitch of 10 and an optimum value of relative roughness height of 0.02, with 45° as angle of attack. The values for solar insolation and Reynolds number are varied from 600 to 1200 W/m^2 and 5000 to 20,000, respectively. The results show an enhancement in Nusselt number of ribbed duct from 1.9 to 2.25 times as compared to a smooth duct. The use of ribs on absorber plate has significantly increased the efficiency by about 7.75–18.33%. However, the variation in outlet temperature with increasing Reynolds number is less significant for lower values in contrast to the higher values of solar insolation. The variation of overall loss coefficient, thermal efficiency and useful heat gain is also studied for the range of operational scenarios.

Keywords Solar air heaters · Reynolds number · Solar flux · Useful heat gain · Heat transfer coefficients

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1 Introduction

The incident solar radiation at the ground surface can be thermally harvested for heat or naturally converted to biomass by photosynthesis or converted to electricity using photovoltaic materials. Wind and ocean energy are direct consequence of convention currents caused due to the solar heating. Solar energy causes the water to evaporate which subsequently produces rainfall in higher elevations leading to the potential for hydropower. With climate change happening, it is more imperative to shift toward solar-based technologies especially in developing countries [1]. Also, with the growing energy demands and the overexploitation of the nonrenewable sources of energy, the need for sustainable engineering materials and systems is increasing [2, 3]. In order to convert solar energy to thermal energy, solar air heaters are primarily and most widely systems used [4]. These find many engineering applications including heating systems, agri-drying, air preheaters, etc. A conventional solar air heater comprises transparent cover, rear bottom plate and an absorber plate. The air flows between the bottom and absorber plate. These heaters offer design simplicity with minimal maintenance. Since air possesses low thermal conductivity of about 0.0273 W/m^2 [4], it results in lower heat transfer between the air and the absorber plate [5].Thus, air heaters are subjected to many configuration changes for improving the coefficient of heat transfer. In certain cases, the intermediary fluid is changed to nanofluids which also offers a promising alternative to increase the overall thermal efficiency [6, 7]. In the present study, V-shaped ribs are used to improve surface roughness to break the viscous sublayer on the absorber plate, thereby increasing the coefficient of heat transfer between plates and air. The single pass solar air heater (SPSAH) is investigated theoretically for various operational scenarios. In doing so, the air heater is considered for two different configurations such as absorber plate without ribs and absorber plate with V-shaped ribs. The solar flux incident on the collector area is varied with constant Re and vice versa. The efficiency curves, outlet temperature, etc., are plotted using MATLAB and Origin software. The performance parameters such as instantaneous efficiency, useful heat gain, outlet temperature are investigated with the variation in Re and solar insolation. There are many other applications of solar air heaters, particularly in developing countries such as India. There are many states in India that receive very high amount of solar radiations, and these heaters can be used to tap this solar energy for useful purposes. These heaters can find special application in the states like Jammu and Kashmir, which face harsh winters but at the same time, receive enough solar energy to be used for thermal energy applications. The notion of using these heaters in remote areas and far flung areas where direct electricity cannot be delivered gains more popularity and possibility of wider applications.

2 Theoretical Analysis

The theoretical analysis of SPSAH is based on the energy balance equations and solving them analytically to investigate the behavior under certain operational scenarios. The energy balance provides an insight about the utilization of incident solar radiant energy into useful form of energy and losses that occur during the process of conversion. It quantifies the amount of losses which further can be minimized by means of various techniques. The energy balance formulations for various elements are based on below assumptions.

The energy balance formulations for various elements are based on below assumptions [8, 9]:

1. For air, the bulk mean temperature increases from T_f to $T_f + dT_f$.
2. The convective heat transfer coefficient between absorber plate and air $\left(h_{fp}\right)$ and that between bottom rear plate and air is $\left(h_{fb}\right)$ is same.
3. Loss coefficient U_b for bottom is significantly smaller than loss coefficient of the top and therefore is neglected in subsequent calculations.
4. Side losses are neglected.
5. The absorber plate and rear bottom plate have smooth surfaces.
6. The flow is turbulent and fully developed.
7. Negligible shading of collector plate.

2.1 *Specifications of SPSAH*

The overall dimensions of SPSAH are 2 m × 1 m. The SPSAH is composed of the following components as shown in Fig. 1:

1. Transparent cover or shield of glass.
2. Rear bottom plate.

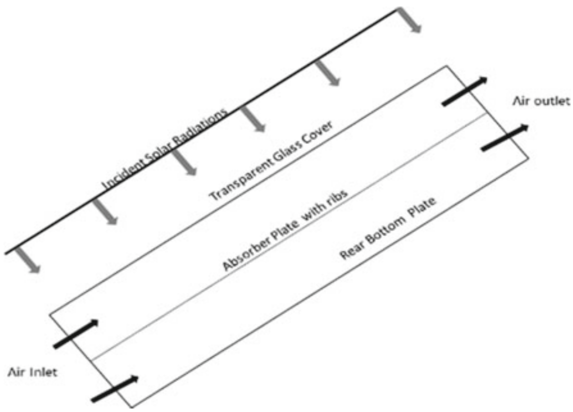

Fig.1 Schema of single pass solar air heater

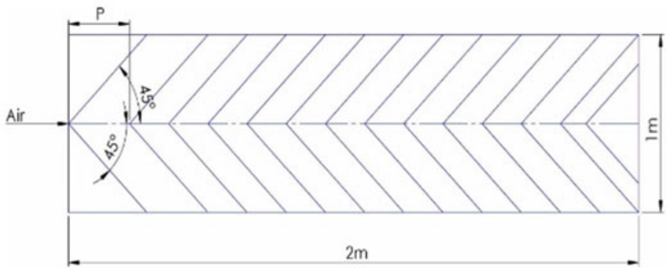

Fig. 2 V-shaped ribbed absorber Plate

3. An absorber plate.

In case of ribbed plate, the absorber plate has been given additional V-shaped ribs at the relative roughness height (e/D_h) of 0.02 with a relative roughness pitch (p/e) of 10. An incident angle of attack of 45° is taken in the present study as shown in Fig. 2.

Glass Cover

The glass shield or cover serves three main purposes. Firstly, it reduces the heat loss from the absorber, both convective and radiant. Secondly, it allows the transmission of the incoming solar radiation to the absorber plate with least loss. And thirdly, it serves as a protection or shield to the absorber plate against ambient environmental conditions [10, 11].

Transmissivity–Absorptivity Factor

The solar radiations incident on the glass cover are partly reflected, absorbed, and much of them are transmitted to the absorber plate. The absorber plate absorbs much part of radiant energy transmitted through the glass cover. The transmissivity–absorptivity product $(\tau\alpha)_{av}$ is used for the purpose of analysis. It is computed by dividing the absorbed energy flux in the absorber plate by the energy flux which is incident on the transparent glass shield of the solar air heater [6]. The greater the product of absorptivity of the absorber plate and transmissivity of glass covering, the higher is the efficiency of the collector [12]. For the purpose of analysis, average value of 0.85 is considered [8].

Absorber Plate and Bottom Rear Plate

The absorber plate is the principal element of SPSAH that absorbs the solar radiations transmitted through the glass cover. As discussed above, the absorbing capacity is defined in terms of transmissivity–absorptivity factor. The emissivity of the absorber plate and bottom rear plate is assumed to be 0.95 for analysis [8].

2.2 Properties of Air

The mean fluid temperature is assumed to be 55 °C [8], and properties are specified at mean temperature of fluid. The properties of air are listed below [4]:

$\rho = \frac{1.077\,\text{kg}}{\text{m}^3}$; $C_p = 1.005\,\text{kJ/kg} - \text{k}$; $\mu = 19.85 \times 10^{-6}\,\text{N} - \text{s/m}^2$; $K = 0.0287\,\text{W/m K}$

For the purpose of analysis, the following ambient conditions are assumed:

Air inlet temperature: 50 °C; Ambient temperature: 20 °C.

3 Calculation of Nusselt Number

Using the assumption that the surfaces are smooth for the first case and the correlation proposed by Kays [13], Nusselt number can be calculated by the following correlations:

$$\text{Nu} = 0.0158\text{Re}^{0.8} \tag{1}$$

In the second case, the absorber plate with V-shaped ribs is considered. The Nusselt number is obtained by below correlations [14]:

$$N_{ur} = 0.067 \times (R_e)^{0.888} \times \left(\frac{e}{D_h}\right)^{0.424} \times (\alpha/60°)^{-0.077} \times \exp\left[-0.782 \times (\ln\alpha/60°)^2\right] \tag{2}$$

Figures 3 and 4 show the Nusselt number variation as a function of Reynolds number for plane and rubber absorber plates, respectively. It can be seen that the Nusselt number varies from 14.38 to the maximum value of 43.59 for first case and it varies from 28.74 to 98.42 for ribbed absorber plate.

3.1 Calculation of Coefficient of Heat Transfer

For the absorber plate, the coefficient of heat transfer is assumed to be equal to coefficient of heat transfer of the rear bottom plate which is given by the following correlation [6]:

$$h_{fp} = h_{pb} = \text{Nu} \times \frac{K}{d_e} \tag{3}$$

where K represents the thermal conductivity while d_e denotes the equivalent diameter which is given by

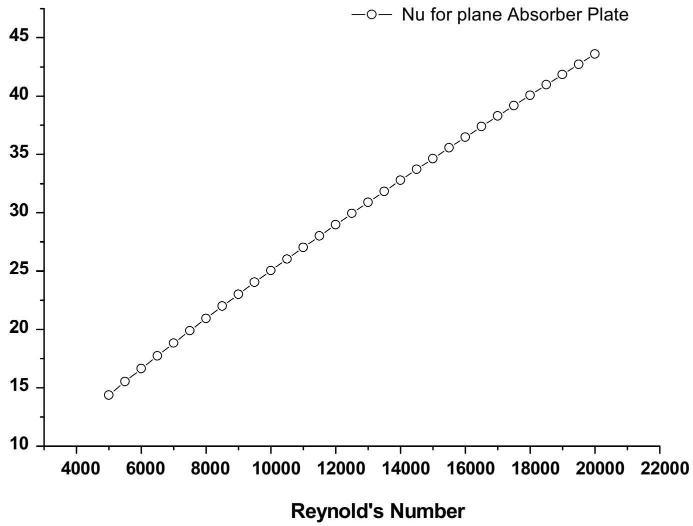

Fig. 3 Nusselt number for plane absorber plate

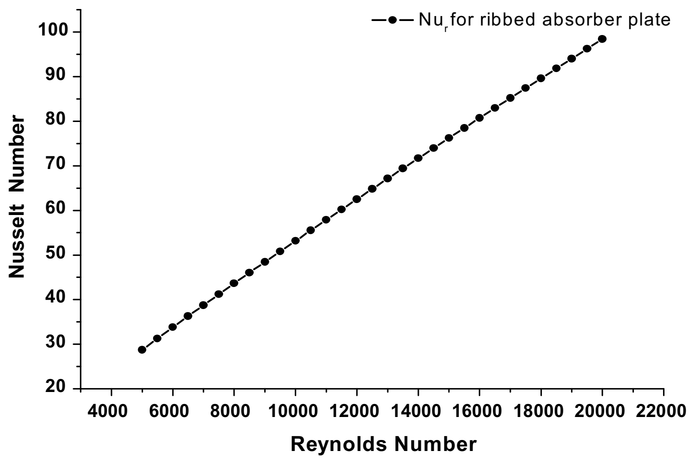

Fig. 4 Nusselt number for ribbed absorber plate

$$d_e = \frac{4 \times \text{cross sectional area of duct}}{\text{wetted perimeter}} \tag{4}$$

3.2 Calculation of Radiative Heat Transfer Coefficients

The coefficient of radiative heat transfer is determined as below [8]:

$$h_r\left(T_{pm} - T_{bm}\right) = \frac{\sigma Ldx\left({T_{pm}}^4 - {T_{bm}}^4\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1} \tag{5}$$

3.3 Determination of Coefficient of Effective Heat Transfer

The coefficient of effective heat transfer between air stream over the absorber plate is given by the below equation [5]:

$$h_e = \left[h_{fp} + \frac{h_r h_{fb}}{h_r + h_{fb}}\right] \tag{6}$$

4 Loss Coefficient of SPSAH

It is useful to express the overall loss coefficients of the air heaters defined by

$$q_l = U_l A_p\left(T_{pm} - T_a\right) \tag{7}$$

where $U_l = U_b + U_t + U_s$.

Since side losses are neglected, only top and bottom losses are considered. The top loss coefficient is calculated by taking into consideration, the reradiation losses as well as the convection losses in upward direction in the absorber plate and comes out to be 6.2 $\text{W/m}^2 - \text{K}$. Similarly, the bottom loss coefficients are calculated by taking into consideration, the convection and conduction losses in downward direction from the absorber plate, and come out to be 0.8 $\text{W/m}^2 - \text{K}$. Typical values range from 2 to 10 $\text{W/m}^2 - \text{K}$ [8]. Hence, our assumptions are correct.

5 Energy Balance for SPSAH

The total energy incident on the glass cover is transmitted to the absorber plate and subsequently to the air stream. A desirable property of the glass material is that it transmits up to 90% of the inbound short-wave rays, while almost zero percent of the returning long wave radiation from the absorber plate can transmit outwards.

The energy balance for each component is given by the equations [8].

Energy balance for absorber plate:

$$SLdx = U_t Ldx\left(T_{pm} - T_a\right) + h_{fp}Ldx\left(T_{pm} - T_f\right) + \frac{\sigma Ldx({T_{pm}}^4 - {T_{bm}}^4)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1} \quad (8)$$

Energy balance for rear bottom plate:

$$\frac{\sigma Ldx\left({T_{pm}}^4 - {T_{bm}}^4\right)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1} = U_b Ldx\left(T_{pm} - T_a\right) + h_{fb}Ldx\left(T_{pm} - T_f\right) \quad (9)$$

Energy balance for air stream:

$$\dot{m}C_p dT_f = h_{fb}Ldx\left(T_{pm} - T_f\right) + h_{fp}Ldx\left(T_{pm} - T_f\right) \quad (10)$$

6 Performance Parameters of SPSAH

6.1 Collector Efficiency Factor

The collector efficiency takes into account the various losses including the top and bottom loss coefficients. The top loss coefficient is calculated by taking into consideration, the reradiation losses as well as the convection losses in upward direction in the absorber plate. Similarly, the bottom loss coefficients are calculated by taking into consideration, the convection and conduction losses in downward direction from the absorber plate. The side losses have been neglected for the purpose of analysis. The efficiency factor of the collector is defined as the ratio of real collector output energy to the output energy when absorber plate is at the same mass flow rate and average fluid temperature. The collector efficiency factor is determined for different solar fluxes with varying Re.

6.2 Collector Heat Removal Factor

It is an important parameter for design purposes as it measures and indexes thermal resistance of solar radiation on the absorber in reaching the collector fluid and has been evaluated for the solar radiations ranging from 950 to 1650 W/m^2 for varying Re.

6.3 Useful Heat Gain Rate

The useful heat gain rate for SPSAH is the measure of net amount of energy acquired from incident solar radiations. The useful heat gain is obtained by Hottel–Whiller–Bliss equation and is given below:

$$q_u = F_R A_p\left[S - U_l\left(T_{fi} - T_a\right)\right] \tag{11}$$

7 Results and Discussions

The SPSAH is investigated theoretically for the instantaneous efficiency and temperature of air at outlet. The air heaters are influenced by various parameters including the solar insolation, mass flow rate, quality of air, ambient temperature, material of absorber plate and bottom plate transmissivity of glass cover. In the current study, SPSAH is investigated for variation of Re, and the following results have been obtained.

7.1 Effect of Variation in Re and Solar Incident Radiations on Efficiency

The most important parameter for the measure of performance of SPSAH is instantaneous efficiency. The instantaneous efficiency provides an overview about the performance of solar air heater. It takes into the consideration the overall losses and net useful gain in SPSAH. It is the ratio of useful energy gain to the incident solar radiation over an area for a unit time [9].

Figure 5 represents the effect on efficiency for different incident solar radiations with varying the Reynolds number. For lower Reynolds number, the efficiency changes rapidly as compared to higher Reynolds number. The slope of efficiency curve decreases as Reynolds number increases. Further, the efficiency curves have a common trend as Reynolds number changes from lower values to higher values. As the Reynolds number increases, the efficiency increases less rapidly as compared to the lesser Reynolds number. An increase of 7.75–18.33% in the thermal efficiency is obtained for the V-shaped ribbed solar air heater. The efficiency curves particularly for higher solar insolation 1600 and 1650 W/m^2 show slight variation in the nature of curves. The efficiency increases for increasing values of solar radiations incident on the surface for a particular Reynolds number.

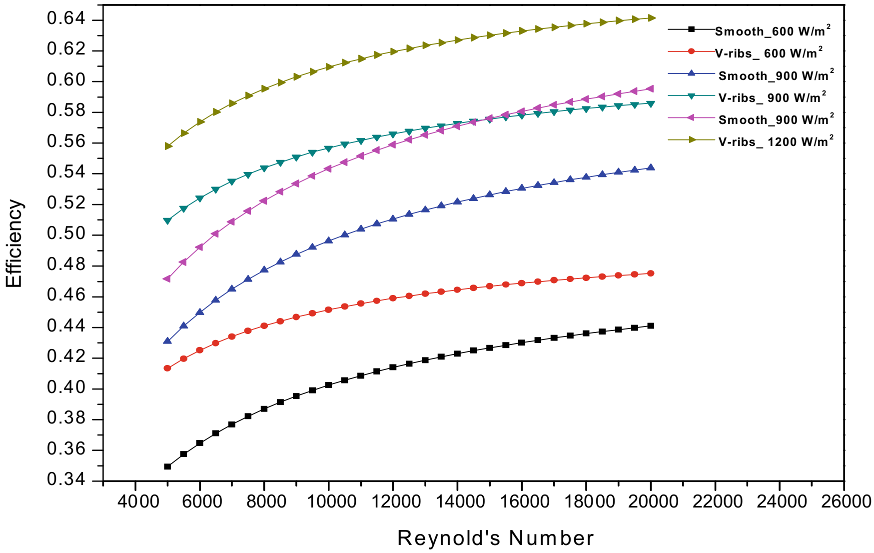

Fig. 5 Efficiency variation as a function of Reynolds number at different solar insolation

7.2 *Effect of Variation in Reynolds Number and Solar Incident Radiations on Outlet Temperature*

Figure 6 shows the trend of outlet temperature (T_{fo}) as a function of Reynolds number. At low solar fluxes, the variation in outlet temperature with increasing Reynolds number is less significant as compared to higher solar fluxes. It was established that the outlet temperature increases rapidly for lower Reynolds number. With the increase in Reynolds number, the slope of the curve shows a decreasing trend indicating fewer rise in outlet temperature. The decrease is more in case of absorber plate without ribs.

At $R_e = 5000$, the difference in outlet temperature for solar flux of 950 and 1650 W/m^2 is 1.5 °C which is less than the difference in outlet temperature 1.8 °C at $R_e = 20{,}000$, thereby indicating higher temperature differences are attained with increasing Reynolds number in both cases.

7.3 *Effect of Variation in Reynolds Number and Incident Solar Radiations on Outlet Useful Heat Gain*

Figure 7 shows the variation. The useful heat for SPSAH increases with increasing Reynolds number with more significant increase for lower values of Reynolds number over higher values of Reynolds number. For a particular solar insolation, the useful

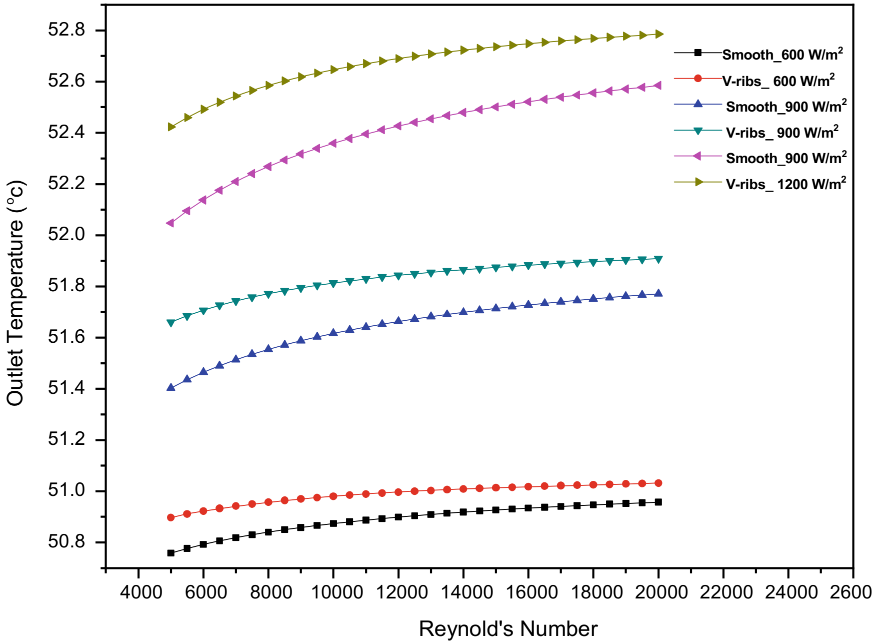

Fig. 6 Outlet temperature at different solar insolation

heat gain changes less rapidly after Reynolds number of around 12,000. The useful heat gain increases with increasing solar insolation. At higher solar insolation, the useful heat gain changes more rapidly as compared to the lower values of solar insolation which is more predominant in case of ribbed absorber plate. For lower values of solar insolation, the difference in the useful heat gain for ribbed absorber plate and plane absorber plate at lower Reynolds number is higher than the difference at higher values of solar insolation.

8 Conclusion

The SPSAH investigated theoretically in the present study has an increasing efficiency with increasing Reynolds number and solar flux over the collector. The SPSAH is the conventional design, and the use of fins and baffles can further increase the efficiency. The V-corrugated plate and double pass finned solar air heaters give higher efficiency as compared to SPSAH. More importantly, the effect of variation in Reynolds number and solar insolation on efficiency, outlet temperature and useful heat gain based on various correlations needs to be given due consideration for optimum design of SPSAH, and this study is a useful step in achieving the optimum design of SPSAH based on specific performance parameters. Based on the results

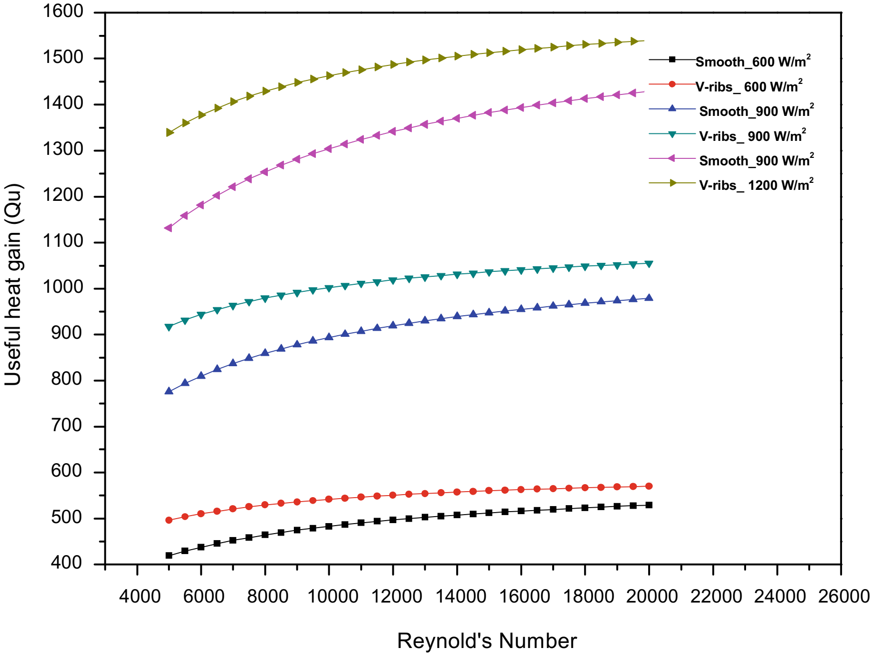

Fig. 7 Useful heat gain at different solar insolation

obtained from the theoretical analysis that the SPSAH with fins and baffles increases the efficiency, the work can be extended to the experimental analysis with different configurations and arrangements of fins. The top surface of V-shaped ribs can be modified to squared or triangular configurations leading to increase in the turbulence. To further enhance the efficiency, baffles may be introduced in the path to make efficient heat transfer. This arrangement not only increases turbulence but also increases the path such that the air remains in contact with the hot surface for longer time and is discharged at higher temperatures as compared to the other configurations.

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