Experimental investigation of thermal efficiency of solar air heater duct with different spacing ribs as artificial roughness

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Abstract:*Experimental work is performed to investigate the thermal efficiency of solar air heater ducts with varying pitch. It involves the design and manufacturing of solar air heater as per the guide linesof ASHRAE. The roughened absorber plate is developed by applying discrete ribs on the absorber plate in the form of staggered manner to investigate the enhancement of heat transfer and thermal performance of solar air heater duct with respect to smooth solar heater. The roughness parameters for experimental investigation are as Reynolds number 2000 to 14000, relative roughness pitch 6 to 21 for constant relative roughness height of 0.036. The result shows that the heat transfer and thermal performance of solar air heater duct have higher values than that of the smooth solar heater.Hence artificial ribs in discrete form are recommended for all industrial purposes.*

Keywords: artificial roughness, solar air heater, thermal efficiency, nusselt number

1.Introduction: The rapid depletion of fossil fuel resources has necessitated an urgent search for alternative sources of energy to meet energy demand for the immediate future and for generations to come. As can be seen, the reserves and resource base of fossil fuels are limited and exhaustible. The awareness of an impending shortage or non-supply thought in distant future dawn in early 70's which resulted is an abnormally sharp increase in oil prices, has come to be known as "Energy Crisis". This was not, in reality, an availability crisis but only an awareness of exhaustible nature. This was a shock to predominantly oil based economies in the form of 8 to 10 times increase in oil prices in a short span of 2 to 3 years. This affected both developed and developing nations, rich and poor, urban and rural people. Since 1973, in the wake of "energy crisis", scientists started looking for renewable energy sources, especially the solar energy.Solar energy is the most popular resource of non-conventional energy. It is superior in quality, quantitatively abundant, available every-where, inexhaustible for all practical purposes, and has

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no polluting effect on the environment when converted in useful forms and utilized. However, its availability is intermittent, i.e. only available during the day. It is also dependent on the climatic and weather conditions. Some of the important applications of solar energy are solar cooking Solar water heating,solar space heating and cooling, solar crop drying, solar power generation. In order to make the solar energy utilization economically viable, one of the important requirements is its efficient collection. Flat plate collector is the most important type of solar collector because it is simple in design, cheap in construction, easy in operation and little maintenance cost. It is designed for a variety of applications in which temperature ranging from ambient to 100ºC. [7]The principle usually followed is to expose a dark surface to solar radiation so that radiation is absorbed. Apart of the absorbed radiation is then transferred to fluid like air or water. But the efficiency of solar air heater is usually low due to lower value of heat transfer coefficient. Thus artificial roughness is provided on lower side of absorber plate to increase the value of heat transfer coefficient by creating turbulence in rectangular duct.

2 Artificial Roughness on Heat Transferring Surface

The artificial roughness has been used extensively for the enhancement of heat transfer and thermal efficiency of solar air heater. The use of artificial roughness in solar air heaters owes its origin to several investigations carried-out in connection with the enhancement of heat transfer in nuclear reactors cooling of turbine blades and electronic components. For basic type of roughness geometry, the key dimensionless variables are as follows:

i. Relative roughness height (e/D_h) defined as the ratio of roughness height to hydraulic diameter of duct.
ii. Relative roughness pitch (p/e) defined as the ratio of the distance of two successive roughness elements to the height of the roughness.
iii. Angle of attack (α) defined as angle of roughness elements with respect to the flow direction.

3. Theoretical Analysis for Efficiency of Solar Collector [7, 8]

Several investigators have analyzed of thermal performance of flat plate solar air heaters. The thermal performance of the solar air heater is described by an energy balance, which indicates the distribution of incident solar energy into useful energy gain (Q_u) and various losses (Q_L) as shown in Fig.1. The detail of the performance analysis of a solar collector is given below [4].Energy balance on the collector can be written as:

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$$A_c\,[I\,R\,(\tau\,\alpha)] = Q_u + Q_L \tag{1}$$

The useful energy Q_u, can be written in the terms of known temperature "T_i" and other system and operating parameters as

$$Q_u = A_c \cdot F_R\left[I(\tau\alpha) - U_L\left(T_i - T_a\right)\right] \tag{2}$$

The thermal efficiency of a collector can be written as

$$\eta_{th} = F_R\left[(\tau\alpha) - U_L\left(\frac{T_i - T_a}{I}\right)\right] \tag{3}$$

The heat removal factor can be expressed as:

$$F_R = \frac{GC_P}{U_L}\left[1 - \exp\left(\frac{-F_P U_L}{GC_P}\right)\right] \tag{4}$$

Where F_p is the collector efficiency factor defined as the ratio of actual useful heat collection rate to that attainable with entire absorber plate at average fluid temperature. The collector efficiency factor for solar air heater can be expressed as:

$$F_p = \frac{h}{h + U_L} \tag{5}$$

A parameter F″, known as flow factor is defined as follows

$$F'' = \frac{GC_P}{U_L F_p}\left[1 - \exp\left(\frac{-F_P U_L}{GC_P}\right)\right] \tag{6}$$

Knowing the value of factors F_R , F″ and other parameters the mean fluid temperature ($\bar{T}_f$) and the mean plate temperature $\bar{T}_p$ can be calculated from the following equations,

$$\bar{T}_f = T_i + \left[\frac{Q_u / A_c}{U_L F_R}\right](1 - F'') \tag{7}$$

$$\bar{T}_p = T_i + \left[\frac{Q_u / A_c}{U_L F_R}\right](1 - F_R) \tag{8}$$

The air heater performance was computed for the most useful range of designs and working conditions. In particular condition of a solar air heater drawing air from the atmosphere, the inlet air temperature coincides with the ambient and the Eq. (3) then reduces to,

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$$\eta_{th} = F_R(\tau\alpha) \tag{9}$$

This expression of efficiency does not allow the real operative temperature to be shown. In view of these limitations, [2] proposed the following equation for the efficiency of the solar air heater,

$$\eta_{th} = F_o\left[(\tau\alpha) - U_L\left(\frac{T_o - T_i}{I}\right)\right] \tag{10}$$

where, F_o is the heat removal factor referred to outlet air temperature and is expressed as:

$$F_o = \frac{GC_P}{U_L}\left[\exp\left(\frac{F_P U_L}{G \cdot C_P}\right) - 1\right] \tag{11}$$

Further, performance can also be expressed by another equation, containing temperature gain by the fluid flowing through the collector as given below,

$$\eta_{th} = GC_p\left[\frac{T_o - T_i}{I}\right] \tag{12}$$

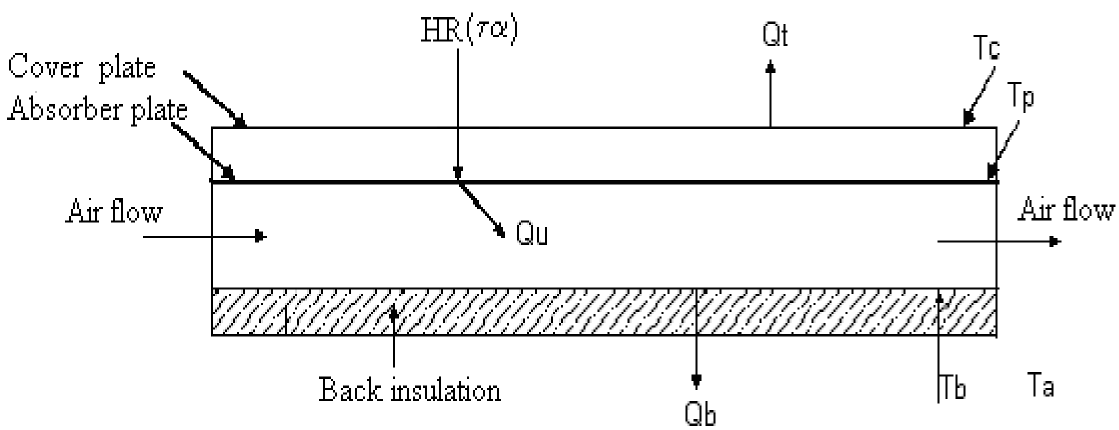

Fig. 1 Energy balance of collector

4. Roughnessparameters:

1 Reynolds number, (Re) = 2000 to 14000

2 Relative roughness pitch,(p/e) =6-21

3 Relative roughness pitch,(e/D_h)=0.036

4 Angle of attack=90°

5. Experimental Program

An experimental setupas recommended in ASHRAE Standard 93-77(1977) [1] is shown in Fig.2 consists of wooden rectangular duct. The wooden rectangular duct of internal size 2100 mm X 200 mm X 25 mm includes entrance section, test section and exit sections mixing, length of 400 mm, 1500 mm, and 200 mm respectively. An electrical heater of size 1500 mm X 200 mmwas fabricated by nichrome wire as desired requirement.The calibrated copper constantan 28 SWG thermocouples were used to measure the air and the heated plate temperature at different locations, as shown in Fig.4.A thermos flask is used to maintain temperature of ice water mixture. A digital multimeter is used to indicate the output of the thermocouples through the selector switch. The air flow is measured by means of orifice meter fitted in pipe line and sucked through the rectangular duct by means of a blower driven by a 3-phase 440V, 2.3kW and 1420 rpm, A.C. motor. Before starting the experimental all the thermocouples were checked carefully so that they give the room temperature and all the pressure tapings were checked for the leakage problem.

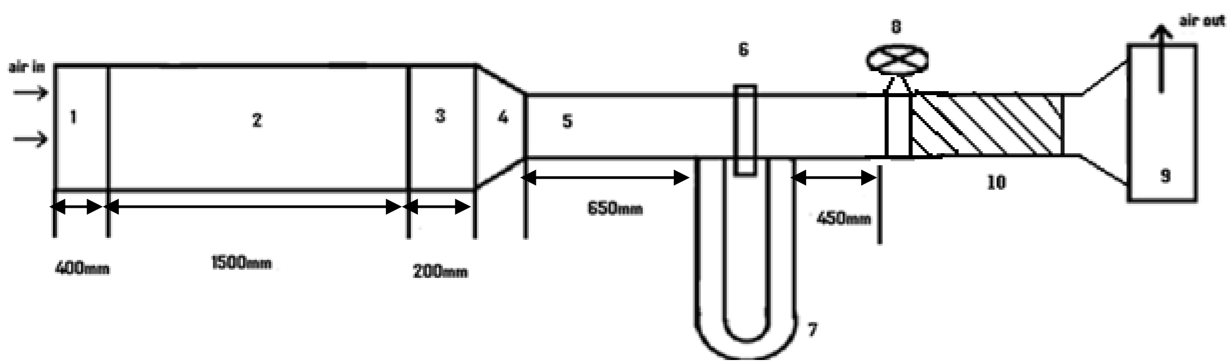

Figure 2 Experimental Set Up

1.Entrance Length
2.Test Length
3.Exit Section
4.Transition Section
5. GI Pipe
6.Orifice Plate
7.U Tube Manometer
8.Control Valve
9.Blower
10.Flexible pipe 300mm

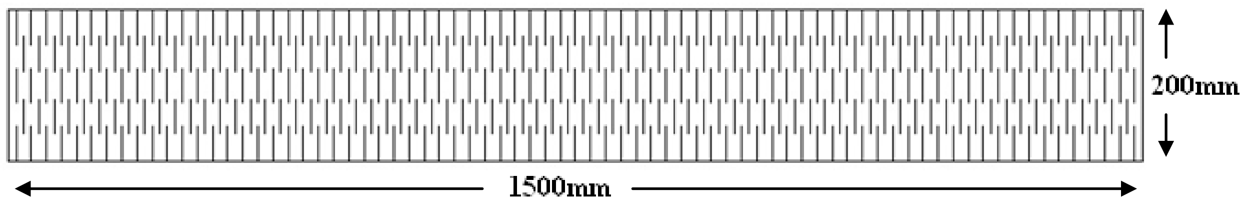

Figure 3: Roughness Geometry

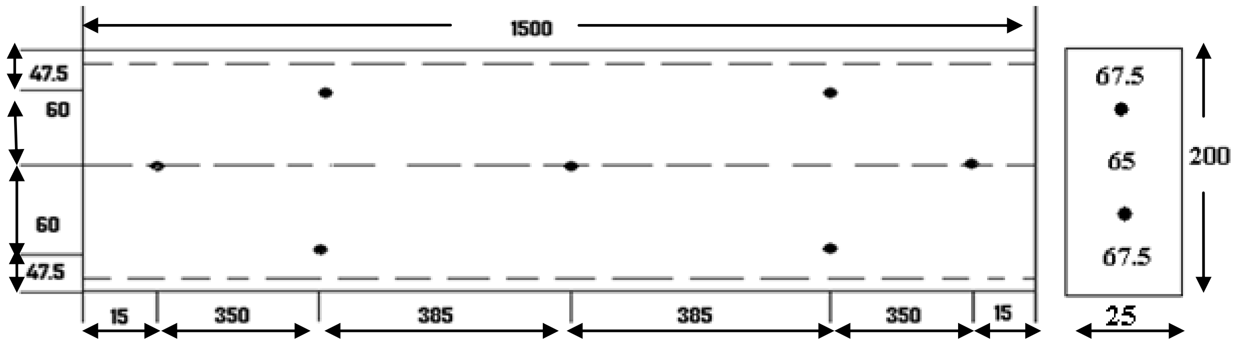

Figure 4: Position of thermocouples (All dimensions in mm)

6. Experimental Procedure

The test runs to collect relevant heat transfer were conducted under quasi-steady state conditions. The quasi-steady state condition was assumed have to been reached when the temperature at the point does not change for about 10 minutes. When a change in the operating conditions is made, it takes about 30 min to reach such a quasi-steady state. Six values of flow rates were used for each set at a fixed heat flux of the test. After each of flow rate, the system is allowed to attain a steady state before the data were recorded.[5, 6, 7, 8]

The following parameters were measured:

1. Temperature of heated plate
2. Temperature of air at inlet and outlet of the test section
3. Pressure difference across orifice meter

7. VALIDITY TEST

The nusselt number evaluated from experimental data (Fig.5) for smooth duct have been compared with that of smooth duct have been compared with the values obtained from dittus boelter equation as:

$Nu_S = 0.023\ Re^{0.8}\ Pr^{\ 0.4}$

The above equation is used to estimate the nusselt number at different Reynolds number and compared with experimental measured values.

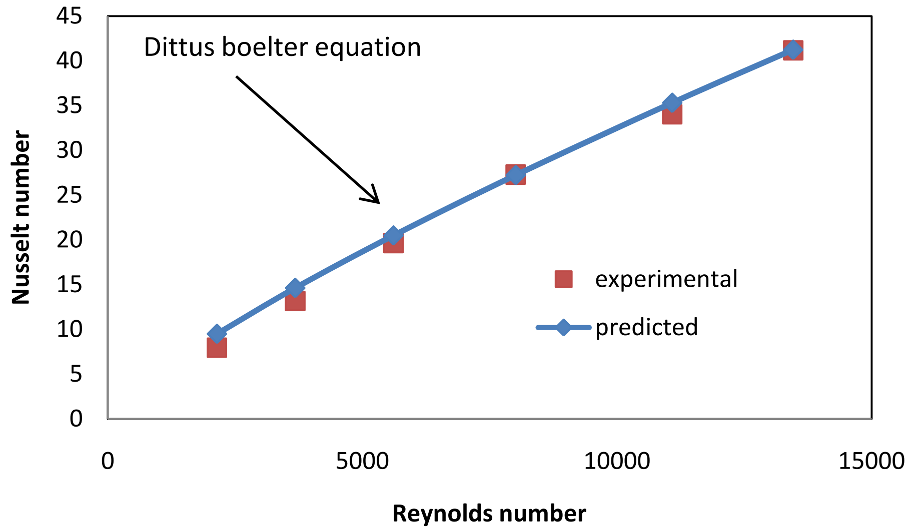

Figure 5 Variation of Reynolds number with nusselt number for smooth duct

8. Results and Discussion

The effect of various flow and roughness parameters on heat transfer characteristics in rectangular duct has been shown below. In each graph the results of smooth duct have been compared with that of roughened duct under similar operating conditions in order to determine the enhancement in heat transfer.

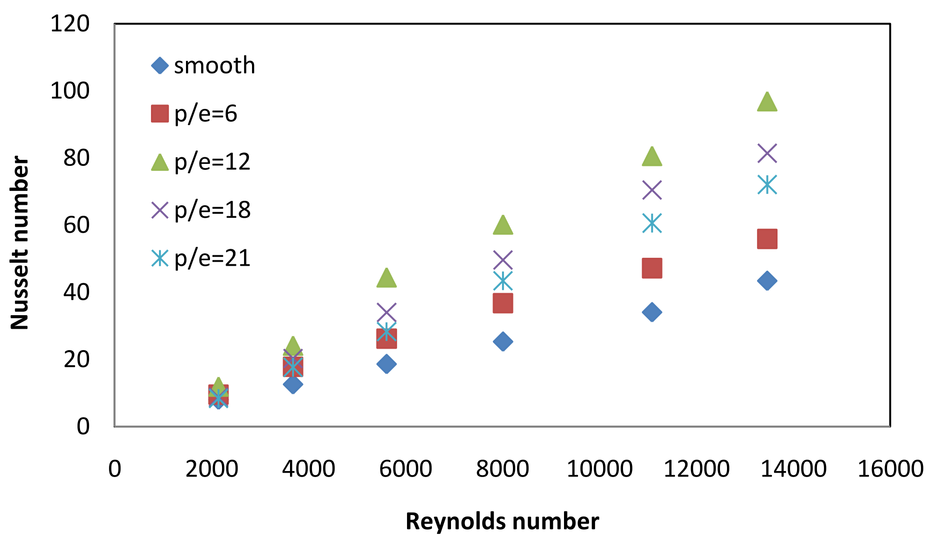

Figure 6: Nusselt vs. Reynolds number for different values of p/e

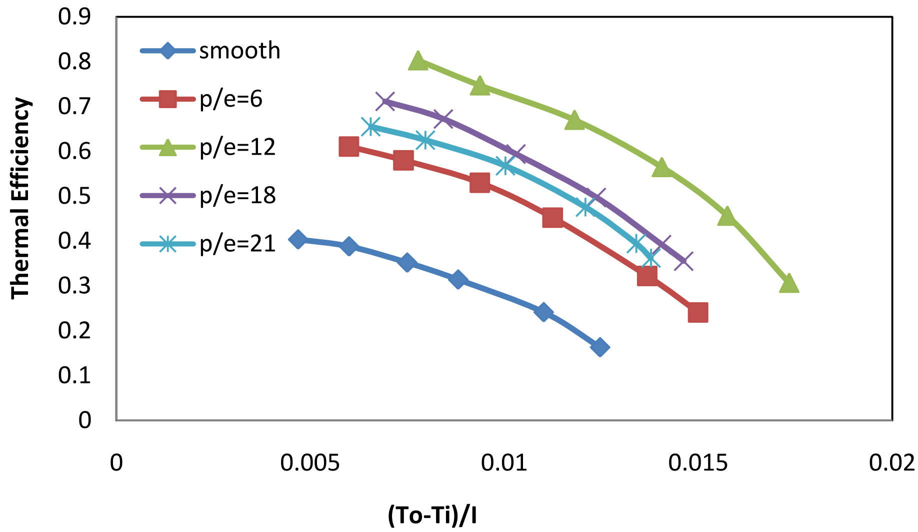

Figure 7: Effect of roughness pitch on thermal performance

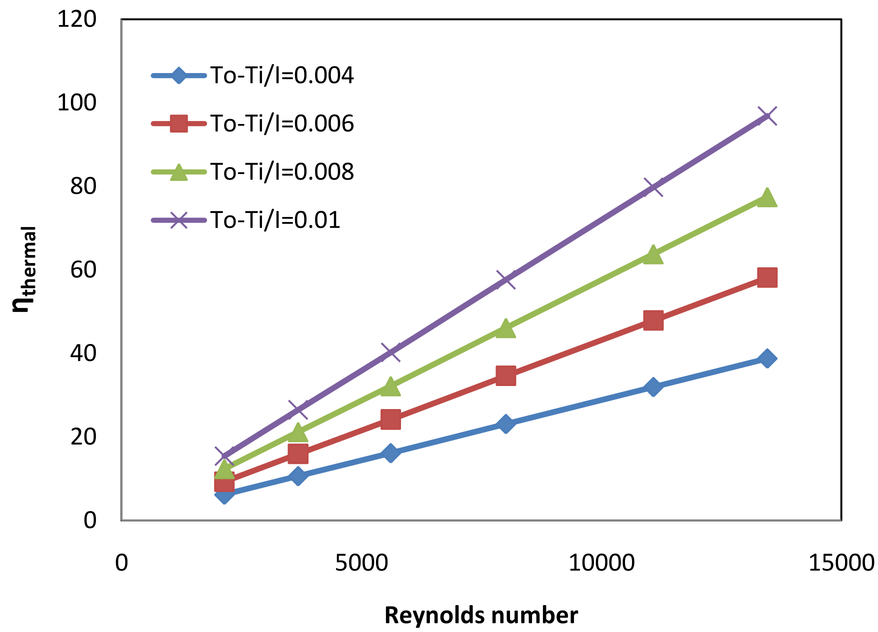

Figure 8: Effect of temperature rise parameter on thermal efficiency

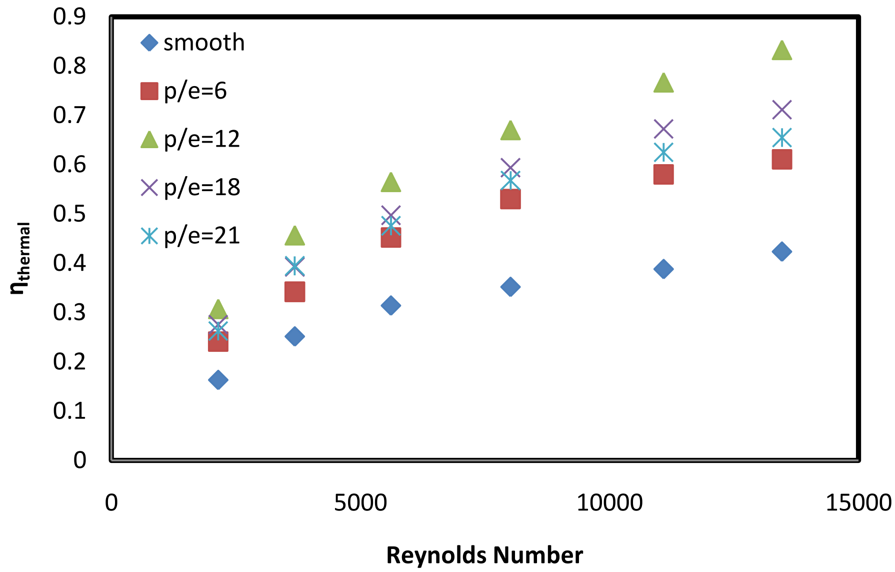

Figure 9: Variation of thermal efficiency at different values of p/e

Figure 6 shows the variation of Nusselt number with Reynolds number. The nusselt number increases with increase in Reynolds number because the value of heat transfer coefficient increases as the value of Reynolds number approaches from laminar to turbulent region due to decrease in convective resistance.It is also noticed that at lower Reynolds number (Re < 5000) the roughness has negligible effect on nusselt number and the results are nearly equal to that of smooth duct.It is so because the rib retarded the fluid flow thus laminar sub layer will be formed and the laminar sub layer remains unbreakable which offers resistance to fluid flow and hence lower value of heat transfer coefficient. Figure 7 shows the effect of temperature rise parameter on thermal efficiency at different values of relative roughness pitch.As the value of temperature rise parameter increases the efficiency increases. Figure 8 shows the effect of temperature rise parameter at different Reynolds number. Thermal efficiency decreases at lower value of temperature rise parameter.Figure 9 shows the values of thermal efficiency at different relative roughness pitch and compared with those of smooth duct. And it was found that the maximum value of thermal efficiency was 83% at a relative roughness pitch of 12.

9. Conclusion:

From the experimental results of heat transfer for rectangular duct with transverse staggered discrete ribs in one broad wall subjected to constant heat flux, the main findings are:

1. Heat transfer and thermal performance of solar air heater ducthave higher values than that of the smooth solar heater.

2. The nusselt number for the roughened rib is2.26 times higher as compared to smooth rectangular duct under similar conditions.
3. It was found that the maximum enhancement inefficiency is 2.07 times higher than that of smooth rectangular duct.

Nomenclature

A_c	area of absorber plate, m^2	T_i	inlet air temperature, K
C_p	specific heat at constant	T_a	ambient temperature, K
	pressure, J/Kg K	U_L	overall heat loss
D_h	equivalent or hydraulic	coefficient/m^2K	
	Diameter of duct, m	T_f	bulk mean air temperature,K
F_R	Heat removal factor	v	velocity of fluid, m/s
G	mass flow rate per unit area	W	width of duct,m
	of collector, kg/sm^2	*Dimensionless parameters*	
h	heat transfercoefficient	e/D_h	relative roughness height
	W/m^2K	Nu	Nusselt number
H	height of air duct,m	Pr	Prandtl number
I,S	Intensity of solar	p/e	relative roughness pitch
	radiations,W/m^2	Re	Reynolds number
K	Thermal conductivity of	*Greek Symbols*	
	air,W/mK	$\tau\alpha$	transmittance absorptance
Q_u	Useful heat gain, W		product
T_b	bottom plate temperature,K	α	angle of attack
T_o	outlet air temperature, K	$\eta_{thermal}$	thermal efficiency

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