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Thermal Analysis and Recent Developments in Artificially Roughened Solar air Heater

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Abstract: **Artificial roughness in different shapes and sizes are used to enhance the convective heat transfer coefficient in solar air heaters and heat exchangers. Artificial roughness can be provided in the form of ribs / wires of different shapes, dimples / protrusions, wire mesh, delta winglet, baffles etc. very near to the heat transferring surface. Investigations have been carried out to determine the dependence of these roughened geometries on the thermal and thermohydraulic performance of solar air heaters. In this article an attempt has been made to review recent developments in context of solar air heaters using artificial roughness. The heat transfer and friction characteristics studied by the investigators have been presented and concluded that the use of artificial roughness in the laminar sub layer helps in creating turbulence very near to the absorber surface which results in enhanced thermal and thermohydraulic performance.**

1. INTRODUCTION

Solar air heaters because of their inherent simplicity are most commonly used collection devices in solar energy applications, requiring low grade thermal energy such as space heating, seasoning of wood, drying of agricultural produce, curing of industrial products, solar induced ventilation [1]. All heat exchangers with provision for radiant input and moving fluid as air would qualify as solar air heater. Thermal performance of a solar air heater depends upon different parameters such as incident solar radiations, losses from the absorber plate and rate of heat transfer from the absorber plate to the air. Broadly, the performance enhancement of solar air heaters may be carried out by: Enhancement of intensity of incident solar radiation on the collector; Reduction of thermal losses from the collector; Flow passage modifications for enhancement in rate of heat transfer.

Thermal performance of a solar air heater has generally been found to be poor due to poor rate of heat transfer from the heated absorber plate to the air flowing beneath. This low value of heat transfer coefficient is generally attributed due to the presence of viscous sub layer, which has to be disturbed or minimized so that the maximum heat can be transferred from the absorber plate to the air. This can be done by providing modifications near the heat transferring surface such as artificial roughness which helps in creating turbulence and thereby increasing the rate of heat transfer. Artificial roughness in the form of form of ribs / wires of different shapes, dimples / protrusions, wire mesh, delta winglet, baffles etc. helps in disrupting the laminar sub layer and thus helps in reducing the thermal resistance to the flow of heat and thereby makes the system efficient.

2. THERMAL PERFORMANCE OF SOLAR AIR HEATER

The performance of a system represents the degree of utilization of input provided to the system. Fig. 1 shows the schematic diagram of conventional solar air heater. Under steady state conditions, the useful heat gained by solar air heater is equal to the energy absorbed by the carrier fluid minus direct and indirect heat losses from the collector to the surroundings. The useful energy collected from the flat plate collector can be obtained using following relation:

$$Q_u = A_p[I(\tau\alpha) - U_L(T_{pm} - T_a)] = \dot{m}C_p(T_{fo} - T_{fi}) \qquad (1)$$

Eqn. 1 can be modified by substituting inlet fluid temperature (T_{fi}) for the average plate temperature T_{pm}, if a suitable correction factor is included. The resulting equation takes the form [2]

$$Q_u = A_p F_R[I(\tau\alpha) - U_L(T_{fi} - T_a)] \qquad (2)$$

Where, F_R is the correction factor or is also known as collector heat removal factor and is affected by the solar air heater characteristics and the fluid flow rate through the collector. The heat removal factor F_R may be obtained as [2]:

$$F_R = \frac{\dot{m}C_p}{A_p U_L}\left(1 - \exp\left[\frac{U_L F' A_p}{\dot{m}C_p}\right]\right) \qquad (3)$$

In Eqn. 3 F' is the collector efficiency factor and is essentially a constant factor for any collector design, fluid flow rate and is given by

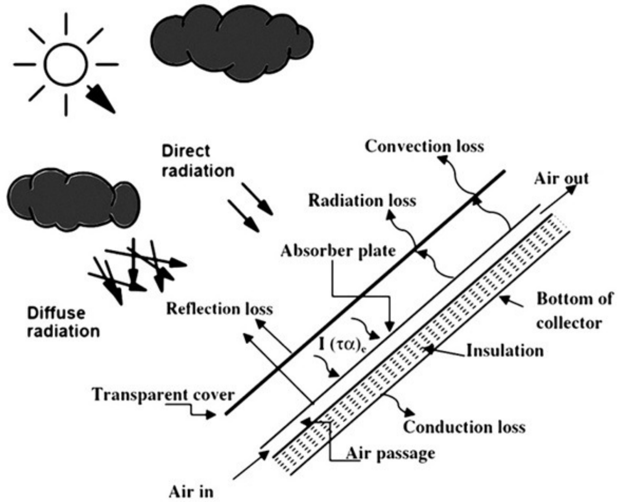

Figure 1: Schematic diagram of conventional solar air heater

$$F' = \frac{h}{h + U_L} \tag{4}$$

Where, U_L is the overall loss coefficient whose increase results a decrease in collector efficiency factor. The overall heat loss coefficient is the heat transfer resistance from the absorber plate to the ambient air. It is the sum of top loss (U_t), bottom loss (U_b) and edge loss (U_e) coefficients and is a complicated function of the collector construction and its operating conditions.

$$U_L = U_t + U_b + U_e \tag{5}$$

In flat plate solar collectors, providing glazing not only help in admitting shortwave solar radiations and retaining longwave thermal radiations, thereby creating greenhouse effect but also reduces heat loss by convection. The insulation effect of the glazing is enhanced by the use of several sheets of glass or glass plus plastic. An empirical equation for U_t was developed by Klein [3] and is given as:

$$U_t = \left[\frac{N}{\frac{c_t}{T_{pm}} \left(\frac{T_{pm} - T_a}{N + f_t} \right)^{0.33}} + \frac{1}{h_w} \right]^{-1} + \left[\frac{\sigma \left(T_{pm}^2 + T_a^2 \right) \left(T_{pm} + T_a \right)}{\frac{1}{\left(\epsilon_p + 0.05 \times N (1 - \epsilon_p) \right)} + \frac{2 \times N + f_t - 1}{\epsilon_g} - 1} \right] \tag{6}$$

Usually, a good insulation provided in the construction of the collector, the bottom and edge loss coefficient, U_b and U_e are almost constant and their estimation is straight forward. The heat loss from the back of plate rarely exceeds 10% of the upward loss. Finally, the thermal efficiency of solar air heater can be obtained as:

$$\eta_{th} = F_R \left[(\tau\alpha) - U_L \left(\frac{T_{fi} - T_a}{I} \right) \right] \tag{7}$$

However, while evaluating the performance of solar air heater, the energy expenditure should also be taken into account along with thermal energy gain. The parameter which takes into account both these characteristics was proposed by Cortes and Piacentini [4] on the basis of net thermal gain and is expressed as:

$$\eta_{eff} = \eta_{th} - \frac{P_m}{C} \tag{8}$$

Where, C is the net conversion factor accounting for the net conversion efficiency from high grade mechanical energy to thermal energy.

3. SOLAR AIR HEATER: DESIGNS AND DEVELOPMENTS

Solar air heater can be of two basic types: single pass or double pass. In single pass solar air heater the air is constrained to enter at one end and exits from the other. In its simplest form it is composed of one or two glazing over an absorber plate, and a back plate. The path of air flow may be either above or below the absorber plate. The heated air can be used more effectively for drying under controlled conditions and also for heating of buildings. The schematic diagram of single pass solar air heater is as shown in Fig. 1. In double pass solar air heater the air first passes from the passage formed between the cover and the absorber plate and then between the covers as shown in Fig. 2. The concept of double pass air heater was first given by Satcunanathan and Deonarine [5]. They concluded that the two pass design had an efficiency of 10-15% higher than that of single pass solar air heater. It was reported that the outer glass temperature was lowered by 2 - 5 °C over the day and was much nearer to the atmospheric temperatures compared to those when collector was operated in a conventional single pass mode.

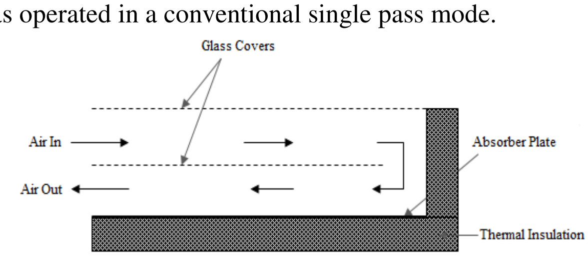

Fig. 2: Double pass solar air heater

4. ARTIFICIALLY ROUGHENED SOLAR AIR HEATERS

Artificial roughness provided under the absorber surface of solar air heater duct is one of the effective means to break down the laminar sub-layer and enhance heat transfer coefficient. Artificial roughness helps in creating favorable conditions for efficient heat transfer with minimal increase in friction factor by: disrupting laminar sub layer developed in vicinity of heat transferring surface; increasing turbulence intensity; increasing heat transferring surface area; generating vortex and / or secondary flows.

4.1. Roughness in the form of ribs / wires

Ribs in different shapes and orientations have been investigated by the researchers to study the heat transfer and friction characteristics in a duct flow of solar air heater. Such surface modifications help in disrupting the flow pattern very close to heat transferring surface and thereby increases heat transfer. Singh et al. [6] carried out experimental investigation to study heat transfer and friction characteristics of solar air heater artificially roughened with discrete v-down ribs on one broad wall as shown in Fig. 3. Authors concluded that there was about 3.04 and 3.11 times enhancement in heat transfer and friction factor compared to the smooth duct. Also the correlations for Nu and f were determined. Kumar et al. [7] investigated the effect of multi V-shaped ribs with gap on heat transfer and friction characteristics in solar air heater duct. It was concluded that there was about 6.32 and 6.12 times enhancement in heat transfer and friction factor compared with smooth duct. Also the correlations for Nusselt number and friction factor were developed by the authors within the range of investigated parameters.

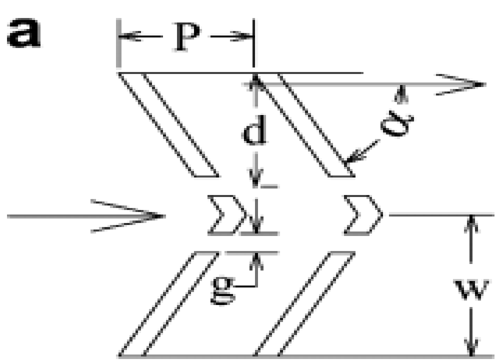

Fig. 3: Discrete V-down arrangement

4.2. Roughness in the form of Dimples / Protrusions

Protrusions and dimples in fluid flow help in accelerating heat transfer rate and has been investigated in case of heat exchangers and solar air heaters. Yadav et al. [8] developed correlations for Nusselt number and friction factor for solar air heater duct artificially roughened with protrusions on one broad wall. It was concluded that there was 2.89 and 2.93 times enhancement in heat transfer and friction factor. The schematic diagram of roughened absorber plate is given in Fig. 2. Experimental investigation carried out by Brij Bhushan and Ranjit Singh [9] with protruded roughness geometry also confirms 3.8 and 2.2 times enhancement in heat transfer and friction factor. Sethi et al. [10] carried out investigations over dimpled roughness geometry arranged in arc shape and concluded that maximum enhancement in heat transfer takes place at p/e of 10 and angle of attack 60°. Thus it can be concluded that protrusions / dimples in different shapes and orientations helps in heat transfer enhancement with minimal increase in friction factor.

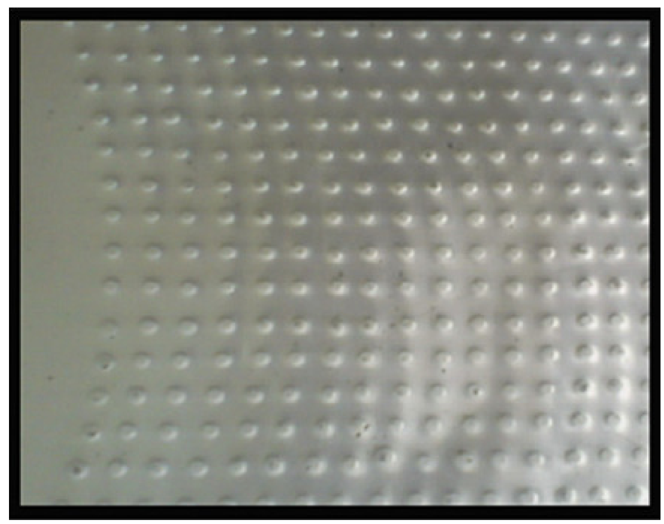

Fig. 4: Protruded roughness geometry

4.3. Roughness in the form of Baffles

An experimental investigation was carried out by Promvonge [11] to assess forced convection heat transfer and friction behaviour for air flow in a channel fitted with multiple 60° V-shaped baffles. Considerable enhancement in heat transfer was obtained with baffles operating under e/H of 0.10, 0.20, 0.30; PR equal to 1, 2 and 3 and the transverse pitch of V-baffle was set at 2H. the effect of solid Z-shaped baffles on heat transfer augmentation fitted at 45° in phase and out phase was investigated experimentally by Sriromreun et al. [12] aligned in zigzag fashion on the isothermally fluxed top wall. The effect of baffle height and pitch spacing was examined to arrive at optimal values for maximum enhancement in thermal performance. Baffles with different orientations help in increasing heat transfer. However due to recirculation of the flow, hot zone gets developed just behind the baffles which deteriorate the heat transfer from these zones. This problem has been identified by the researchers and attempted to provide perforations in the baffles which allow a part of flow to pass through these perforations and mix with the main flow which creates higher level of mixing and creates turbulence which enhance the rate of heat transfer. Karwa and Maheshwari [13] experimentally studied the effect of such perforated baffles as shown in Fig. 5 and obtained an enhancement of about 79 – 169 % in Nusselt number than that of smooth duct.

5. CONCLUSIONS

An attempt has been made to study the recent heat transfer enhancements in solar air heaters by artificial roughness provided under the heat transferring absorber plate. It can be concluded that the roughness on the underside of the absorber plate helps in accelerating the rate of heat transfer and thus making the system efficient. Also the roughness geometries are so selected that the system is thermo-hydraulically best and thus can be used for commercial purpose. The use of baffles half or fully perforated exhibits higher rate of heat transfer than solid baffles. Thus experimental investigations should be carried out using perforated baffles inline or staggered and with different orientations to determine the best suited geometry and optimization of the related working and operating parameters may be boost the system towards commercialization.

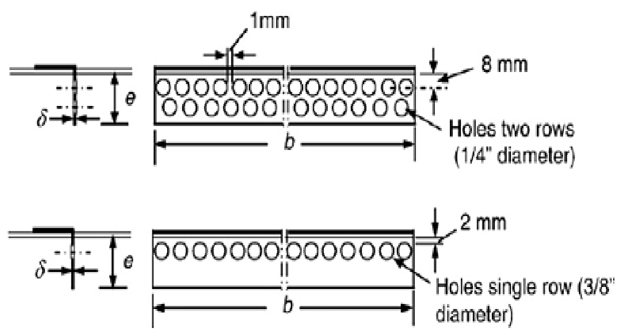

Fig. 5: Fully perforated baffles and half perforated baffles with two and single row of holes respectively

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