INVESTIGATION OF HEAT TRANSFER ENHANCEMENT BY USING V-SHAPED PERFORATED BLOCKS IN A RECTANGULAR SOLAR AIR HEATER DUCT

Ph.D. THESIS

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ABSTRACT

Solar air heater is one of the economically viable solar energy utilization system due to its simple design and low cost. However, the thermal efficiency of solar air heater has been found to be low because of high thermal resistance between absorber plate and flowing air in the duct. Various techniques have been employed to enhance the efficiency of solar air heater which essentially reduce the thermal resistance by promoting higher convective heat transfer with or without increase in surface area. These techniques include the use of turbulators such as artificial roughness, corrugated absorber, obstacles, fins and baffles/blocks to reduce the thermal resistance. The tabulators of larger height produce substantially high heat transfer but are also responsible for high pressure drop. However, in case of solid turbulators, a large low heat transfer area is usually generated just downstream from the rib as a result of flow separation leading to heat transfer deterioration around that position. This may result in hot spots that need to be eliminated.

Efforts have been made to accelerate flow by way of perforations produced in the blocks. The perforations enhance the heat transfer from these zones and reduce the pressure drop across the duct. The perforations in blocks allow a part of the flow to pass through these perforations and mix with the main flow to create a higher level of mixing and turbulence. Lateral mixing and strength as well as location of reattachment of flow from neighbouring jets issuing from perforation of flow is also affected by shape of perforation. Lateral mixing tends to increase as non-circularity (generally wider hole) of holes increases because of shortening of inter hole distance. Apart from the shape of perforation holes, V-shaping of blockage can also enhance the heat transfer rate as a result of generation of secondary flow along the limbs of the blockage. Review

of literature reveals that the effect of these parameters of blockages, namely, perforation shape (circularity) and V-shaping on heat transfer and friction characteristics of solar air heater duct having such V-shaped perforated blockages attached to absorber plate has not been extensively investigated. In view of the above, present investigation was taken up with the following major objectives:

1. Experimental investigation of heat transfer and friction characteristics of a duct with V-shaped perforated blockages attached to one broad heated wall.
2. Development of correlations for Nusselt number and friction factor as function of blockage parameters, namely, open area ratio, angle of attack, relative pitch ratio, relative height ratio, circularity and flow Reynolds number.
3. Investigation of enhancement of thermal performance of duct with V-shaped perforated blockages attached to heated surface as compared to that of smooth duct.
4. Thermo-hydraulic optimization of blockage parameters.

In order to achieve these objectives, an indoor test facility was designed and fabricated to study the effect of different parameters of V-shaped perforated blockages on heat transfer and fluid flow characteristics of the duct. The experimental data were collected under steady state conditions in accordance with the recommendations of ASHARE (1977) for testing of solar collectors operating in open loop flow mode. The data that were recorded for each set of experiment included inlet air temperature, outlet air temperature at five points in the span-wise direction of the duct, temperature of the absorber plate at twenty seven locations, pressure drop across the orifice plate and pressure drop across the test section.

The range of parameters of this study was decided on the basis of practical considerations of the system and operating conditions of solar air heaters and are as given below:

Parameters	**Range**
Circularity (ψ)	0.6-1.0 (Five Values)
Relative Blockage Height (e/H)	0.4-1.0 (Four Values)
Relative Pitch ratio (P/e)	4-12 (Five Values)
Angle of Attack (α)	30°-75° (Four Values)
Open Area Ratio (β)	5%-25% (Five Values)
Reynolds Number (Re)	2000-20000 (Ten Values)

The data for smooth duct under similar operating conditions was also collected in order to validate the experimental set-up and to determine the enhancement in heat transfer coefficients and friction factor as a result of using blockages.

Error analysis with respect to experimental measurements of different parameters was carried out to determine uncertainties in the values of heat gain, mass flow rate, Reynolds number, Nusselt number and friction factor. Maximum values of uncertainties determined from this analysis are given below:

Parameter	**Uncertainty**
Heat gain (Q)	5.69%
Mass flow rate (m)	3.34%
Reynolds number (Re)	3.39%
Nusselt number (Nu)	5.99%
Friction Factor (f)	6.76%

The effect of blockage parameters on Nusselt number and friction factor has been examined. It was found that both Nusselt number and friction factor increase with the increase in circularity, attain a maxima and then decrease with further increase in its value. The maximum values of Nusselt number and friction factor were found to correspond to circularity value of 0.69. The values of relative blockage height, relative pitch, angle of attack and open area ratio that yield maximum value of Nusselt number correspond respective to the values of 0.8, 8, 60° and 20%. Friction factor values were found to increase with increasing values of blockage height, angle of attack and circularity, whereas the friction factor values decrease with increasing pitch and open area ratio. However, the values of blockage parameters that yield maxima in the friction factor correspond to angle of attack of 60°, blockage height of 1.0 and circularity of 0.69.

Using the experimental data with respect to heat transfer and friction characteristics, statistical correlations of Nusselt number and friction factor as function of Reynolds number and geometrical parameters of blockages have been developed, as given below:

$$Nu = 0.0135 \times Re^{0.815} (e/H)^{-0.1215} (P/e)^{1.8368} \beta^{-0.2345} (\alpha/60)^{-0.0233} (\psi)^{-0.6379} e^{\left[-0.9105\{\ln(e/H)\}^2\right]} e^{\left[-0.4555\{\ln(P/e)\}^2\right]} e^{\left[-0.0714\{\ln(\beta)\}^2\right]} e^{\left[-0.2761\{\ln(\alpha/60)\}^2\right]} e^{\left[-0.9680\{\ln(\psi)\}^2\right]}$$

$$f = 0.4613 \times Re^{-0.0942} (e/H)^{1.3377} (P/e)^{-0.267} \beta^{-0.195} (\alpha/60)^{0.0017} (\psi)^{-0.4336} e^{\left[0.7097\{\ln(e/H)\}^2\right]} e^{\left[-0.2973\{\ln(\alpha/60)\}^2\right]} e^{\left[-0.6160\{\ln(\psi)\}^2\right]}$$

The correlation coefficient and average absolute percentage deviation between experimental values and those predicted by these correlations for Nusselt number and friction factor have been found to be as 0.96, 5.03% and 0.97, 4.99%, respectively. These correlations can therefore be used for the prediction of Nusselt number and friction factor of such ducts with reasonable accuracy.

In order to predict thermal and thermo-hydraulic performance of solar air heater having V-shaped blockages, a step-by-step procedure for the prediction of performance has been developed. Thermal performance of the duct with blockages has been predicted as a function of blockage parameters and operating parameters. Thermal performance of smooth duct has also been predicted to evaluate the enhancement factor as a result of use of blockages. The thermal efficiency has been found to increase 1.07 to 2.57 times that of conventional solar air heater for temperature rise parameter range from 0.002 to 0.024 $K.m^2/W$ and insolation values between 600 to 1000 W/m^2.

In order to determine the optimum values of blockage parameters, three optimization criteria mentioned below, have been considered.

1) Thermal Efficiency
2) Effective efficiency
3) Exergetic efficiency

The values of these optimization parameters were determined for all possible sets of values of blockage parameters for given set of values of operating conditions. Comparison of the values of optimization parameter yielded an optimum set of blockage parameters that corresponded to the maximum value of optimization parameter.

A single set of the optimum values of blockage parameters has been obtained for the entire range of operating parameters on the basis of thermal efficiency, as given below:

Circularity (ψ)	:	0.69
Relative Blockage Height (e/H)	:	0.80
Relative Pitch ratio (P/e)	:	8
Angle of Attack (α)	:	60°
Open Area Ratio (β)	:	20%

The set of optimum values of blockage parameters determined on the basis of effective and exergetic efficiency optimization criteria were seen to depend upon the values of temperature rise parameter and insolation.

The effective efficiency criterion has been proposed for use by the designer because it involves the evaluation of net thermal useful gain based on the equivalent thermal energy required to produce mechanical friction power and is therefore best suited for solar thermal systems.

Design plots have been prepared which can be employed to determine the values of blockage parameter that represent the optimum condition as a function of temperature rise parameter and insolation.

Summarizing, the experimental investigation carried out to collect extensive data for solar air heater equipped with V-shape perforated blockages reveals that Nusselt number and friction factor are strong function of blockage and flow parameters. Effect of blockage parameters, namely, circularity, relative blockage height ratio, relative pitch ratio, open area ratio and angle of attack on Nusselt number and friction factor has been investigated. On the basis of experimental data, Nusselt number and friction factor correlations have been developed and used to predict the performance of solar air heater. Optimum values of blockage parameters have been determined that yield maximum value of thermal, effective or exergetic efficiency. Based on these considerations, design plots have been prepared that can be utilized by the designer to determine optimum values of blockage parameters for desired design conditions.