STUDY ON SOLAR AIR HEATER DUCT ROUGHENED WITH SPHERICAL AND INCLINED RIB PROTRUSIONS

Ph.D. THESIS

by

CHANDRA PRAKASH

DEPARTMENT OF HYDRO AND RENWABLE ENERGY
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE-247667 (INDIA)

MARCH, 2019

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A THESIS

Submitted in partial fulfilment of the
requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY

in

ALTERNATE HYDRO ENERGY CENTRE

by

CHANDRA PRAKASH

DEPARTMENT OF HYDRO AND RENWABLE ENERGY
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
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ABSTRACT

Solar energy is the most promising of all renewable energy resources because of its inexhaustibility, abundance and non-polluting nature. 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 turbulators of larger height produce substantially high heat transfer but are also responsible for high pressure drop. However, in case of artificial roughness, comparatively, the pressure drop is low due to smaller height of the obstacles. The height of the artificial roughness can be selected in such a way that it creates turbulence in laminar sub layer near to heat transferring surface without disturbing the main flow region.

It is revealed from the literature survey that lot of work has been carried out on various roughness geometries such as ribs of various cross section, orientation and dimensions. Artificial roughness having different shapes and geometries is provided on the underside of the absorber plate which creates two flow separation regions and vortices are responsible for turbulence in the laminar sub layer only, which promotes heat transfer rate between absorber plate and air. Heat transfer rate strongly depends on relative height, relative pitch and angle of inclination in case of inclined ribs. Inclination of the rib creates secondary flow along the rib. The vortices move along the rib to subsequently join the main stream, which increases the heat transfer rate. Enhancement of heat transfer is more in case of inclined ribs compared to transverse ribs.

So far very few studies have been reported using compound roughness geometries it is hypothesised that compound geometry using combination of spherical and inclined ribs protrusions will augment heat transfer compared to simple roughness geometries. It is further considered that protrusions produced by cold working of metal plate will save material and manufacturing cost of absorber plate.

In view of the above, following are the major objectives of the present study.

1. To investigate experimentally the heat transfer and fluid flow characteristics of a solar heater duct having combination of spherical and inclined rib protrusions as artificial roughness elements on the underside of the absorber plate.
2. To develop the correlations for the Nusselt number and friction factor for the solar air heater roughened duct as function of roughness and operating parameters.
3. To investigate thermal and thermodynamic performance of the proposed solar air heater roughened duct.
4. To optimize the roughness parameters based on thermo-hydraulic performance of the roughened solar air heater duct for given set of operating conditions.

In order to achieve these objectives, an indoor test facility was designed and fabricated to study the effect of different parameters of spherical and inclined rib protrusions roughness on heat transfer and fluid flow characteristics of an open loop cycle duct. The experimental data were collected under quasi steady state conditions in accordance with the recommendations of ASHARE (1977) for testing of solar collectors operating in open loop flow mode. The experimental data were recorded for each set of experiment included inlet and outlet air temperature at three and five points, respectively, in the transvers direction of flow in the duct, the temperature of the absorber plate at twelve locations, pressure drop across the orifice plate and pressure drop across the test section.

The range of parameters, of the present study, was decided on the basis of practical considerations of the system and operating conditions of solar air heaters. These are given below:

Parameter	**Values**
Duct aspect ratio (W/H)	12 (one value)
Reynolds number (Re)	2000-20000 (ten values)
Relative roughness pitch (p/e)	15-30 (four values)
Relative roughness height (e/D)	0.04 (one value)
Angle of attack (α)	60° (one value)
Relative roughness gap (g/e)	14 (one value)
Relative rib length (r/g)	0.4-1.0 (four values)
Relative rib pitch (Pr/P)	0.2-0.8 (three values)

The data for smooth duct under similar operating conditions were 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 spherical and inclined rib protrusions roughness.

Error analysis, for experimental measurements of different quantities, was carried out to determine uncertainties in the calculated values of the Reynolds number, Nusselt number and friction factor. Maximum fractional uncertainties determined from the analysis are given below:

Parameter	**Maximum fractional uncertainty**
Reynolds number	±0.0454
Nusselt number	±0.0456
Friction factor	±0.0917

The effect of roughness parameters on Nusselt number and friction factor has been investigated. It was found that Nusselt number increases with the increase in relative rib length, relative roughness pitch and relative rib pitch, attain a maxima and then decrease with further increase in their value. The maximum value of Nusselt number was found to correspond to relative rib length of 0.80, relative roughness pitch of 25.0 and relative rib pitch of 0.50. Friction factor values were found to increase with increasing values of relative rib length and relative rib pitch, whereas the friction factor values decrease with increasing relative roughness pitch. However, the value of roughness parameters that yield maximum friction factor correspond to relative rib length of 1.0, relative roughness pitch of 15.0 and relative rib pitch value of 0.80

Statistical correlations for Nusselt number and friction factor as function of Reynolds number and geometrical parameters of spherical and inclined rib protrusions have been developed, by curve fitting method, artificial neural network and genetic programming tool, using the experimental data. The correlations developed by artificial neural network and genetic programming tool are in the form of MATLAB files. The correlations developed by curve fitting method are given below:

$$\mathrm{Nu} = 6.14 \times 10^{-10} \times \mathrm{Re}^{1.2552} \left(\frac{\mathrm{r}}{\mathrm{g}}\right)^{-0.3373} \left(\frac{\mathrm{P}}{\mathrm{e}}\right)^{8.8946} \left(\frac{\mathrm{Pr}}{\mathrm{P}}\right)^{-0.7274}$$

$$\exp\left[-0.478 \ln\left\{\left(\frac{\mathrm{r}}{\mathrm{g}}\right)\right\}^2 - 1.4208 \ln\left\{\left(\frac{\mathrm{P}}{\mathrm{e}}\right)\right\}^2 - 0.4235 \ln\left\{\left(\frac{\mathrm{Pr}}{\mathrm{P}}\right)\right\}^2\right]$$

$$f = 0.2968\, Re^{-0.2276} \left(\frac{r}{g}\right)^{0.4339} \left(\frac{P}{e}\right)^{-0.2432} \left(\frac{Pr}{P}\right)^{0.0912}$$

For the range of parameters investigated, the error, in predicted value of Nusselt number and friction factor as compared to that of experimental value, has been quantified by root mean square error (RMSE), mean absolute error (MAE), coefficient of determination (R^2) and range of error. These error quantities in prediction of Nusselt number are as given below:

Method of prediction	**MAE**	**RMSE**	**R^2**	**Range of error**
Correlation (curve fitting)	2.32	3.42	0.9974	+ 5.5 % to – 7.5 %
Artificial neural network	1.37	1.64	0.9994	+ 6.5 % to – 6.3 %
Genetic programming tool	1.08	1.40	0.9996	+ 5.7% to – 6.1 %

The error quantities in prediction of friction factor are as given below:

Method of prediction	**MAE**	**RMSE**	**R^2**	**Range of error**
Correlation (curve fitting)	1.53×10^{-4}	1.84×10^{-4}	0.9963	+ 2.5 % to – 2.7 %
Artificial neural network	1.03×10^{-4}	1.30×10^{-4}	0.9982	+ 2.0 % to – 1.5 %
Genetic programming tool	0.56×10^{-4}	0.74×10^{-4}	0.9994	+ 1.5 % to – 1.2 %

Nusselt number and friction factor correlations, developed using curve fitting, artificial neural network and genetic programming tool, are having reasonable high accuracy for the prediction. However, the correlations developed with genetic programming tool are found most accurate, accordingly the same have been used for the prediction of Nusselt number and friction factor for a duct equipped with spherical and inclined rib protrusions roughness.

Thermal performance parameter i.e. thermal efficiency and thermo-hydraulic performance parameters i.e. effective and exergy efficiency of a numerically simulated solar air heater with spherical and inclined rib protrusions have been predicted using the above mentioned correlations developed for Nusselt number and friction factor with genetic programming tool.

Optimum values of variable roughness parameters, of spherical and inclined rib protrusions, corresponding to maximum thermal, effective and exergy efficiency have been calculated for specified range of temperature rise parameter and solar insolation.

The optimum values of variable roughness parameters corresponding to maximum thermal efficiency are found to be constant for entire specified range of temperature rise parameter and solar insolation. These optimum values are as, relative rib length of 0.78, relative roughness pitch of 23.0 and relative rib pitch of 0.42. Whereas, the optimum values corresponding to maximum effective and exergy efficiency are found to depend up on the temperature rise parameter and solar insolation.

A procedure has been suggested to determine the set of optimum values of roughness parameters and corresponding values of thermal efficiency, effective efficiency, exergy efficiency, mass flow rate of air and energy collection rate for desired values of temperature rise parameter and insolation, using design plot and tabulated dada.

Summarizing, an extensive analyses of experimental data collected on the heat transfer and friction characteristics of the solar air heater duct, having spherical and inclined rib protrusions as artificial roughness provided on absorber plate, reveals that Nusselt number and friction factor values are strong function of roughness parameters and flow parameter. Correlations have been developed for Nusselt number and friction factor as function of roughness and flow parameters. Thermal and Thermo-hydraulic performance analysis has been carried out to arrive at optimum values of roughness parameters that result in maximum performance. On the basis of prediction of performance of solar air heater using such roughness, it has been found that the presence of the roughness can bring about substantial enhancement in thermal energy collection. Design plots have been prepared to determine optimum values of roughness parameters as function of operating conditions.