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Optimization of Heat transfer and Pressure Drop in a Solar Air Heater with Ribbed Surface

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ABSTRACT: Repeated ribs are used to enhance heat transfer in turbine blades and solar air heaters. Ribs enhance heat transfer, however, simultaneously the pressure drop increases. As a result, a balance must be made between improvement in heat transfer and additional power consumption to overcome the elevated pressure drop. In this study, effect of ribs on the thermal performance of a flat plate solar air heater is investigated to find the optimum set of parameters in a flat plate solar air heater with ribbed surfaces. The optimization carried out using genetic algorithm to meet two objectives, to attain higher thermal efficiency and to guarantee a practical temperature difference in the inlet and outlet of air flow. It was found that the application of ribs in a flat plate solar air heater improves the thermal efficiency about 10% in low air mass flows, however at higher air flow the additional power due to the pressure drop diminish the effect and even might decrease the efficiency at higher flow rates.

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1- Introduction

Flat plate collectors are the simplest and most inexpensive solar energy harvesters. They could be utilized in solar water heating, solar space heating and similar applications. A typical flat plate collector is a metal box with a glass or plastic glazing on the top, an absorber plate on the base of the box. The outer frame is insulated to minimize the energy loss, except at the glazing part. It is inexpensive, light weight and easy to implement, however application of flat plate solar collector is faced with some limitations. In a solar air heater, as the solar heat gain decreases, the air flow must be reduced to keep the heated air temperature at a required level. As a result of reduced air velocity, the convection heat transfer coefficient decreases, building higher internal thermal resistance. Since the external thermal resistance remains nearly constant, higher amount of the solar heat gain will be wasted to the ambient.

Webb [1] was one of the first researchers who studied the repeated ribs extensively. He made a breakthrough in the application of the repeated ribs with his innovative designs. He provided several semi empirical correlations to estimate the heat transfer coefficient and pressure drop in the tubes with repeated ribs. Two non-dimensional numbers were introduced named, ratio of the height of the rib to the tube diameter e/D, and the ratio of the rib pitch to the rib height p/e. Han [2] investigated the application of the ribs in cooling of the turbine blades. They experimentally studied the heat transfer and friction in square ducts with two opposite rib-roughened walls in fully developed turbulent air flow. They investigated the effects of different rib pitch and height on friction factor and heat transfer coefficients. They found that in low Reynolds flows, higher ribs are needed. Different shapes of the ribs proposed and applied not only in turbine blade cooling but also in solar air heaters [3, 4].

In this study a thermal model of a solar air heater with ribbed surface was developed. Using Genetic algorithm an optimized set of parameters found for the design of solar air heater.

2- Methodology

Prior to any optimization study, a valid thermal model of the solar air heater is needed. The incoming energy from the sun is either wasted to surroundings or absorbed by the working fluid. The balance between absorbed and wasted heat is based on the thermal resistance of each side. The heat balance of the heater is given in Equations 1 to 3.

$$U_t\left(T_a - T_c\right) + h_r\left(T_p - T_c\right) + h_1\left(T_f - T_c\right) = 0 \tag{1}$$

$$S + U_b\left(T_a - T_p\right) + h_2\left(T_f - T_p\right) + h_r\left(T_c - T_p\right) = 0 \tag{2}$$

$$h_1\left(T_c - T_f\right) + h_2\left(T_p - T_f\right) = q_u \tag{3}$$

Where T_a is the air temperature, T_c is the glazing temperature, T_f is the flowing air temperature, U_b is the heat transfer coefficient of the bottom of the heater, U_t is the heat transfer coefficient of the top of the heater, h_r is the radiation heat transfer coefficient, h_1 and h_2 are heat transfer at higher and lower sides of the channel, respectively. q_u is the absorbed heat.

Most of the heat transfer coefficients can be calculated from corresponding equations given in literature [5]. However, for

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the convective heat transfer coefficient on the ribbed surface, the coefficient was calculated from semi experimental correlation proposed by Han [4]. Equation 4 provides pressure drop coefficient.

$$f=\frac{W}{W+H}\left\{\frac{H}{W}f_s+\frac{2}{\left[R-2.5\ln\left(\frac{2e}{d_h}\right)-2.5\right]^2}\right\} \quad (4)$$

Where W is the channel width, H is channel height, e is the rib height and d_h is the equivalent hydraulic diameter. R is defined according to Equation 5. Based on the analogy of pressure drop and heat transfer, the Equation 6 gives the Stanton number.

$$R=3.2\left(\frac{p/e}{10}\right)^{0.35} \quad (5)$$

$$St_r=\frac{\frac{f}{2}}{\sqrt{\frac{f}{2}}(G-R)+1} \quad (6)$$

Where G is defined in Equation 7.

$$G=3.7\left(e^+\right)^{0.28} \quad (7)$$

Finally, the magnitude of e+ can be calculated by eq. 8

$$e^+=\frac{e}{d_h}Re\sqrt{\frac{f}{2}} \quad (8)$$

The efficiency of a solar air heater is defined as a ratio of the absorbed heat by the passing air to the incoming solar energy. The most important factor in the efficiency of the solar air heater is the convective heat transfer coefficient inside the channel.

3- Discussion

In order to evaluate the performance of the solar air heater, two target functions were introduced. A first criterion is logically the overall efficiency (i.e. the extracted heat from the solar heat gain). On the other hand, since the solar air heater is used in comfort heating it must provide certain temperature difference as the air flows through the heater. In this study, a temperature difference of 10 K was selected. Lower values result in poor air heating, and higher values tend to waste more energy to the surrounding. Based on these two objectives, a multi-objective genetic algorithm optimization was conducted. The primary independent operating variables were the cannel height, Reynolds number rib relative height and relative pitch. Equations 9 and 10 describe the target functions.

$$\eta_{overall}=\frac{Q_u-W_p}{S} \quad (9)$$

$$\eta_{temp}=\frac{\Delta T_r}{\Delta T_r+\left|\Delta T_{act}-10\right|} \quad (10)$$

Where Q_U is the collected heat, W_P is the pumping power, S is the solar heat gain, ΔT_r is the target temperature difference and ΔT_{act} is the actual temperature difference between inlet and outlet of the air flow.

4- Results

The effects of mass flow rate (Reynolds number), channel height, relative rib height and spacing on the overall efficiency of the solar air heater were investigated. Fig. 1 shows the overall efficiency of the solar air heater in smooth and ribbed surface as a function of rib height and air mass flow rate. It is evident that at a certain flow rate, the overall efficiency is optimum.

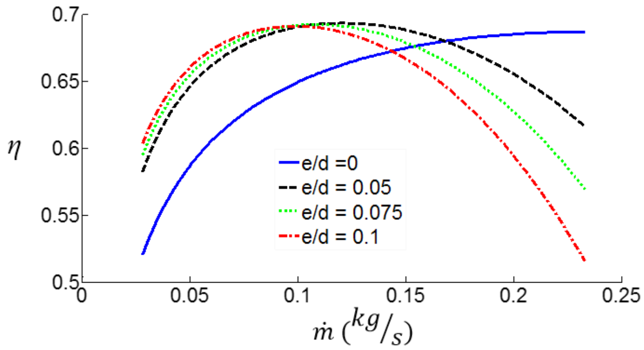

Figure 1. Overall efficiency of the solar air heater in smooth and ribbed surface as a function of rib height and air mass flow rate

The genetic algorithm was used to find the optimum set of the parameters, in the design of solar air heater. The blower consumes electrical energy to circulate the air. Since the cost of thermal and electrical energy is not equal, the optimization performed in two cases. In the first case the cost of both types of energy supposed to be equal. in the latter case, the actual cost of each energy type was estimated from the market prices. The optimum set of parameters in both cases is given in Table 1.

Table 1. The optimum set of the parameters

parameter	Unit	Equal cost	Actual cost
channel height	mm	12.9	40
Reynolds	-	7680	5700
relative height of the ribs	-	0.05	0.029
relative pitch of the ribs	-	7.5	22

5- Conclusions

In this study a thermal model of a solar air heater with ribbed surface was developed. Using genetic algorithm an optimized set of parameters was found for the design of solar air heater. It was found that the ribs can improve the thermal efficiency and alter the thermal behavior of the heater. At lower air flow rates, the ribs could improve the overall efficiency of the heater up to 10%, however after a point the required power to circulate the air exceeds the benefit from higher heat gain in the heater.

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