International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:10, No:5, 2016

Effect of Collector Aspect Ratio on the Thermal Performance of Wavy Finned Absorber Solar Air Heater

Abhishek Priyam, Prabha Chand

***Abstract*—**A theoretical investigation on the effect of collector aspect ratio on the thermal performance of wavy finned absorber solar air heaters has been performed. For the constant collector area, the various performance parameters have been calculated for plane and wavy finned solar air heaters. It has been found that the performance of wavy finned solar air heater improved with the increase in the collector aspect ratio. The performance of wavy finned solar air heater has been found 30 percent higher than those of plane solar air heater. The obtained results for wavy fin solar air heaters are compared with the available experimental data of most common type solar air heaters.

***Keywords*—**Wavy fin, aspect ratio, solar air heater, thermal efficiency, collector efficiency factor, temperature rise.

I. Introduction

A solar air heater is a unique heat transfer equipment that absorbs the insolation and transforms in to heat and carried by the air flowing through the duct. A flat plate solar air heater with wavy fins below the absorber plate has been developed to collect the maximum amount of solar energy at minimum cost. The various applications include space heating, agricultural uses, industrial uses etc. [1]. The heat transfer characteristics of the wavy finned solar air heater have been studied broadly. The effect of collector aspect ratio on flat plate, upward baffled solar air heaters were studied by Yeh & Lin [2]. Thermal performance prediction on four types of solar air heaters were carried out by Ong [3]. The natural convection inside the channel between the flat plate cover and sine-wave absorber in a cross-corrugated solar air heater has been studied numerically by Gao. et al. [4]. Piao et al. [5], Goldstein & Sparrow [6] which showed the enhancement of heat transfer rate for the corrugated air channel were larger than those of a smooth parallel plate channel in the laminar region. Naphon & Kongtragool [7] applied mathematical models for predicting the heat transfer characteristics and performance of various configurations of flat plate solar air heaters. A mathematical model has been developed for the prediction of thermal performance of solar air heater with slats [8]. Baritto & Bracamonte [9] developed a dimensionless model for thermal behavior of flat plate solar heating collectors without glass cover. Also, optimal aspect ratios for non- isothermal flat plate collectors were identified. Use of wavy fins in a heat transfer equipment/ heat exchanger has already been reported analytically and experimentally by various researchers [10]-[13] to enhance the heat transfer rate. The published result usually covered a small range of test variables and were limited to specific test configuration. However, the use of wavy fin below the absorber plate in a conventional solar air heater has not yet been reported and the concept of using wavy fin in a solar air heater is totally a new concept explored in this paper.

The strength of forced convection and the fluid velocity can be influenced by the collector configuration. A simple procedure to alter the fluid velocity and the strength of the forced convection involves adjusting the aspect ratio of the flat plate collector with a constant mass flow rate and constant collector area. In response to the above, the present study focused on a theoretical investigation on the effect of the collector aspect ratio on the various performance parameters of the wavy finned solar air heater for the constant collector area and constant fin spacing.

II. Theoretical Analysis

Consider a solar air heater, which has an absorber plate of length 'L' and width 'W', and is provided with 'n' number of fins of uniform thickness 'δ_f' and height 'h_f', spaced at a mean distance of '*w*', as shown in Fig. 1. The geometric description of the fins is shown in Fig. 2. The distance between the absorber plate and bottom plate is 'H'. The solar air heater used is a single pass between the absorber plate and bottom plate. The thermal efficiency of a solar air heater is given by the equation [1]:

$$\eta_{th} = \frac{Q_u}{A_c \mathrm{x} \mathrm{I}} \quad (1)$$

The useful heat gain based on the inlet temperature and the ambient temperature is expressed as, known as Hottel-Whiller-Bliss equation:

$$Q_u = F_R A_c \left(S - U_L (T_{fi} - T_a) \right) \quad (2)$$

and the absorbed solar energy is defined as:

Abhishek Priyam is with the Mechanical Engineering Department, National Institute of Technology, Janshedpur, Jharkhand 831014 India (e-mail: priyamanik06@gmail.com).
Prabha Chand (Dr.) is with the Mechanical Engineering Department, National Institute of Technology, Janshedpur, Jharkhand 831014 India (phone: +91-9431382699; e-mail: pchand.me@nitjsr.ac.in).

$$S = I(\tau\alpha)_e \quad (3)$$

Also, the collector heat removal factor (F_R) is expressed as [1]:

$$F_R = \frac{\dot{m}C_p}{U_L A_c}\left(1-\exp\left(\frac{-A_c F' U_L}{\dot{m}C_p}\right)\right) \quad (4)$$

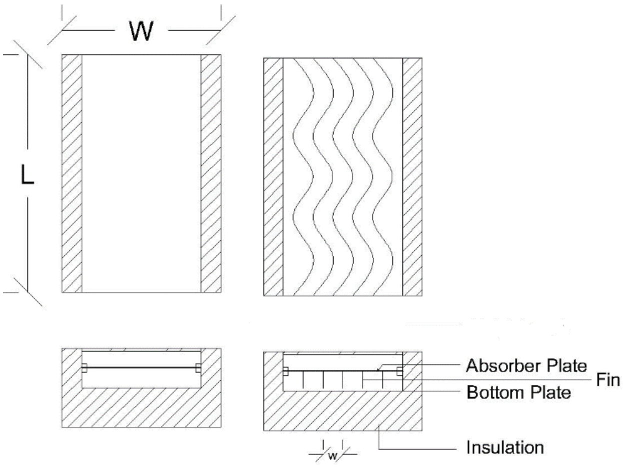

Fig. 1 Solar air heater with wavy fin absorber

The expression for useful energy gain [1] in terms of collector heat removal factor, collector overall loss.

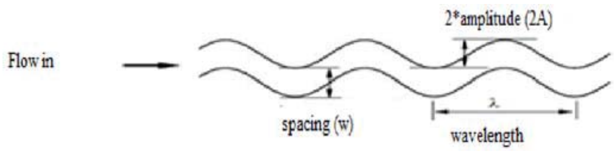

Fig. 2 Geometrical description of wavy fin

An empirical relation has been used for calculation of the top loss coefficient (U_t), which is given by Klein, and the bottom loss coefficient (U_b) [15].

$$U_t = \left[\frac{N_{gc}}{\left(\frac{C}{T_{pm}}\right)\left(\frac{T_{pm}-T_a}{N_{gc}+f'}\right)^{0.33}} + \frac{1}{H_w}\right]^{-1} + \quad (5)$$

$$\left[\frac{\sigma(T_{pm}^2+T_a^2)(T_{pm}+T_a)}{\frac{1}{\varepsilon_p+0.05N_{gc}(1-\varepsilon_p)}+\frac{2N_{gc}+f'+1}{\varepsilon_c}-N_{gc}}\right]$$

where

$$f' = (1+0.04H_w+0.0005H_w^2)(1+0.091N_{gc})$$
$$C = 365.9(1-0.00883\beta+0.0001298\beta^2)$$
$$H_w = 5.7+3.8V_w$$

The radiative heat transfer coefficient h_r is calculated by:

$$h_r = \sigma\varepsilon_p(T_{pm}^2+T_{sky}^2)(T_{pm}+T_{sky}) \quad (6)$$

where

$$T_{sky} = 0.0552T_a^{0.5}$$

The bottom loss coefficient is given by:

$$U_b = \frac{k_{ins}}{\delta_{ins}} \quad (7)$$

and the total loss coefficient is given as:

$$U_L = U_t + U_b \quad (8)$$

Also the collector efficiency factor is expressed as:

$$F' = \left(1+\frac{U_L}{h_e}\right)^{-1} \quad (9)$$

where, h_e is the equivalent heat transfer coefficient and can be derived from energy balance equations.

A. Conventional Solar Air Heater

The configuration of the flat plate collector is shown in Fig. 1. Energy balances for the absorber plate, bottom plate and air stream are shown in (10)-(12);

$$S - U_t(T_{pm}-T_a) - h_{fp}(T_{pm}-T_f) - h_r(T_{pm}-T_{bm}) = 0 \quad (10)$$

$$h_r(T_{pm}-T_{bm}) - h_{fb}(T_{bm}-T_f) - U_b(T_{bm}-T_a) = 0 \quad (11)$$

$$Q_u - h_{fp}(T_{pm}-T_f) - h_{fb}(T_{bm}-T_f) = 0 \quad (12)$$

Solving the above equations, the expression for T_{bm} is

$$T_{bm} = \frac{h_r T_{pm} + h_{fb} T_f}{h_r + h_{fb}} \quad (13)$$

Substituting this expression of T_{bm} into (10), we have

$$T_{pm} = \frac{S + U_L T_a + h_e T_f}{h_e + U_L} \quad (14)$$

where,

$$h_e = h_{fp} + \frac{h_r h_{fb}}{h_r + h_{fb}} \quad (15)$$

B. Wavy Finned Solar Air Heater

The configuration of a wavy finned solar air heater is shown in Fig. 1. Let β be the area enhancement factor which is defined as the heat transfer surface area of wavy fins to that of a plane (flat) rectangular fins of the same height and length [14]. Energy balances for the absorber plate, bottom plate and air stream are shown in (16)-(18):

$$S - U_t(T_{pm} - T_a) - h_{fp}(T_{pm} - T_f) - h_r(T_{pm} - T_{bm}) - (2/w)^* h_f \phi_f \beta h_{ff}(T_{pm} - T_f) = 0 \quad (16)$$

$$h_r(T_{pm} - T_{bm}) - h_{fb}(T_{bm} - T_f) - U_b(T_{bm} - T_a) = 0 \quad (17)$$

$$Q_u - h_{fp}(T_{pm} - T_f) - h_{fb}(T_{bm} - T_f) - (2/w)^* h_f \phi_f \beta h_{ff}(T_{pm} - T_f) = 0 \quad (18)$$

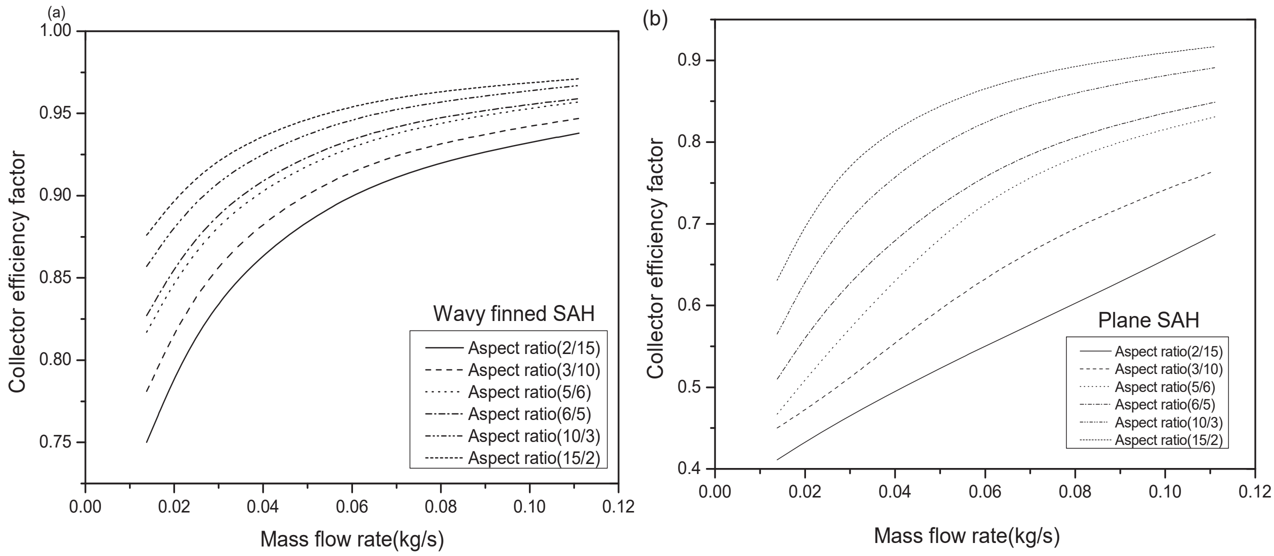

Fig. 3 Collector efficiency factor as a function of mass flow rate and collector aspect ratio for wavy finned solar air heater and plane solar air heater

Solving the above equations for the expression of T_{bm} and substituting the expression of T_{bm} in (16), the expression for T_{pm} is computed and the expression for h_e is given as:

$$h_e = h_{fp}\left(1 + \frac{2h_f \phi_f \beta h_{ff}}{w h_{fp}}\right) + \frac{h_r h_{fb}}{h_r + h_{fb}} \quad (19)$$

The heat transfer coefficients between the air and three sides of the duct walls may be assumed to be equal i.e.

$$h_{ff} = h_{fp} = h_{fb} = \frac{Nu.k_a}{D_h} \quad (20)$$

For air, the following correlation may be used for laminar flow in a rectangular duct [15],

$$Nu = 4.4 + \frac{0.00398(0.7\,\mathrm{Re}\, D_h/L)^{1.66}}{1 + 0.00114(0.7\,\mathrm{Re}\, D_h/L)^{1.12}} \quad (21)$$

For turbulent flow the correlation may be derived from Kay's data with the modification of McAdams for a rectangular channel as follows [15]:

$$Nu = 0.0158\,\mathrm{Re}^{0.8}[1 + (D_h / L)^{0.7}] \quad (22)$$

and for calculating the Nusselt number, the correlation of the Colburn factor (j) is recommended by Dong et al. [13] and used for wavy fin.

$$j = 0.0836\,\mathrm{Re}^{-0.2309}\left(\frac{w}{h_f}\right)^{0.1284}\left(\frac{w}{2.amp}\right)^{-0.153}\left(\frac{L}{\lambda}\right)^{-0.326} \quad (23)$$

where, $j = Nu/Re.Pr^{1/3}$.

The hydraulic diameter, D_h for Plane and wavy finned solar air heater is:

D_h= 4(H x W)/2(H + W) (For plane solar air heater) (24)

D_h=4pA_{fr}L/A_r (For wavy fin solar air heater) (25)

where, A_r, cross sectional area for wavy fin solar air heater:

A_r= (n x L' x δ_f) + (2n x L' x h_f) + ((n+1) x L x W) (26)

An iterative procedure is established to calculate the mean plate temperature [1].

$$T_{pcal} = T_a + \frac{Q_u(1-F_R)}{A_p U_L F_R} \quad (27)$$

First an assumption of mean plate temperature is made from which U_L is calculated, with approximate values of F_R, F' and Q_u, a new value of mean plate temperature is obtained from (27) and used to calculate a new value of top loss coefficient and this is repeated until the accuracy of 0.01 % is achieved.

The outlet temperature of the collector can be obtained as:

$$\frac{T_{fo} - T_a - S/U_L}{T_{fi} - T_a - S/U_L} = \exp\left[\frac{-A_C U_L F'}{\dot{m} C_P}\right] \quad (28)$$

III. Results and Discussions

In the following section, results of the heat transfer characteristics, thermal performance and exergetic efficiency of the solar air heater with wavy fin are presented. The numerical calculations were carried out by the suitable values of the relevant parameters and also taken into account as follows: I = 900 W/m^2, W = 3 m, 2 m, 1.2 m, 1 m, 0.6 m, 0.4 m, L =0.4 m, 0.6 m, 1 m, 1.2 m, 2 m, 3 m, H = 2.5 cm, h_f = 22 cm, $(\tau\alpha)_e$= 0.85, δ_{ins}= 5 cm, amp= 7.5 mm, λ= 70 mm, L'=0.46 m, 0.69 m, 1.15 m, 1.38 m, 2.3 m, 3.45 m, T_a = 30 °C, T_{fi} = 30 °C and V_w = 2.5 m/s. For the fin spacing, 1 cm and the mass flow range of 0.0138 kg/s- 0.1111 kg/s, the various performance curves (Figs. 3-6) have been plotted.

It has been found from Figs. 3-6 that with the constant collector area, the collector performances such as; collector efficiency factor, collector heat removal factor, thermal efficiency and rise in temperature rises with the increase in the collector aspect ratio. This may because increasing the aspect ratio results decrease in the cross sectional area of the duct and raises the velocity of air flow and the convective heat transfer rate from the absorber plate to the flowing air.

Fig. 3 shows the plot for collector efficiency factor as a function of mass flow rate and aspect ratio for wavy fin and plane solar air heater. Increasing the aspect ratio, collector efficiency factor increases. A maximum of collector efficiency factor as 0.971 has been obtained for the aspect ratio of 15/2. Fig. 4 shows that the increase in the collector heat removal factor increases the collector aspect ratio and the maximum value of the collector heat removal factor has been found for the maximum mass flow rate. The rise in temperature as a function of mass flow rate and aspect ratio is shown in Fig. 5. As the collector aspect ratio increases, the rise in temperature increases. This may because the lower aspect ratio leads to higher thermal losses. Thermal efficiency, as a function of mass flow rate and collector aspect ratio, is shown in Fig. 6. It can be seen from the plot that the increase in the aspect ratio increases the thermal efficiency in wavy fin, as well as plane solar air heater. Increase in the aspect ratio decreases the cross sectional area which results in increased air velocity and leads to higher thermal efficiency.

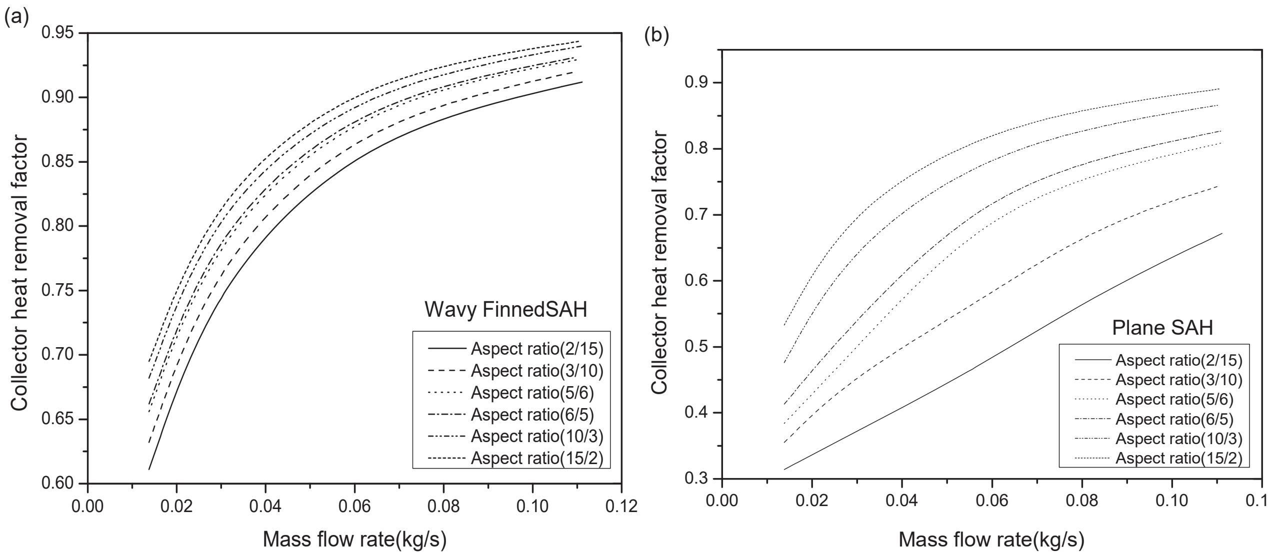

Fig. 4 Collector heat removal factor as a function of mass flow rate and collector aspect ratio for wavy finned solar air heater and plane solar air heater

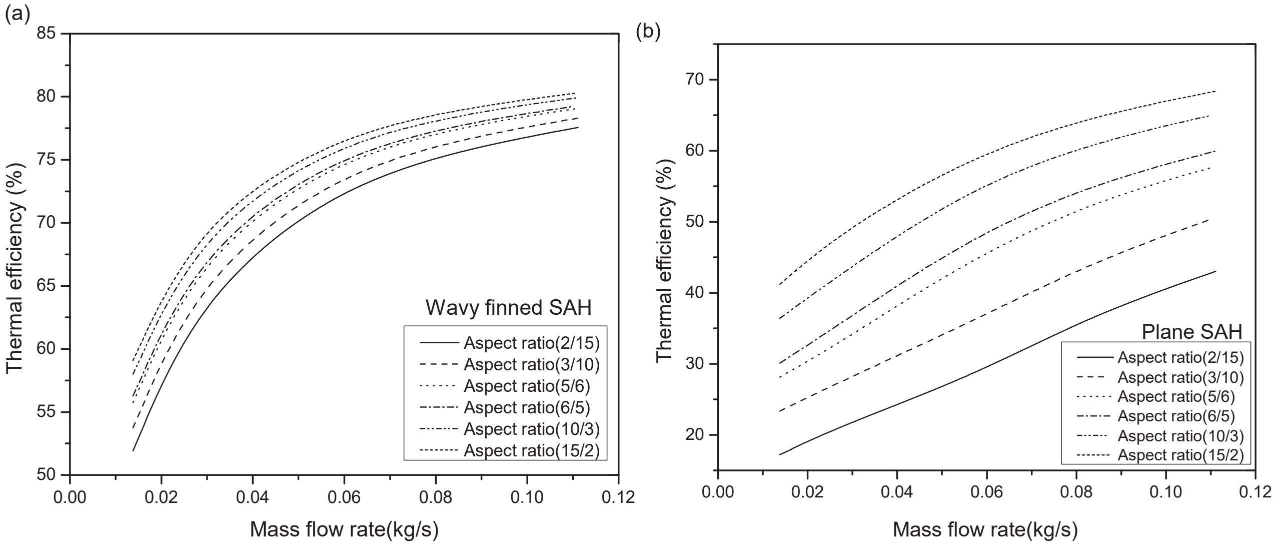

Fig. 6 Thermal efficiency as a function of mass flow rate and collector aspect ratio for wavy finned solar air heater and plane solar air heater

IV. Conclusion

The effects of the collector aspect ratio on the thermal performance of the wavy finned solar air heaters have been investigated. The expression for the estimation of the collector performance parameters has been developed to predict the thermal performance for such collectors. Empirical correlations were used for calculation. Considerable improvement in the collector performance of solar air heaters with the use of wavy fins below the absorber plate has been obtained. Based on the results and discussions it may be concluded that with the constant collector area, increasing the aspect ratio will improve the collector performance by 30 percent. Increasing the aspect ratio in wavy finned solar air heater increases the fixed charge, as well as increasing the fan power and therefore leads to higher operating cost.

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