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Thermal Performance Comparison of Solar Air Heater Having Wavy Fin and Longitudinal Fin

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***Abstract*- The thermal performance of a solar air heater with wavy fins attached were investigated theoretically. The fluid channel has been formed by using wavy fins parallel to fluid flow below the absorber plate. The effects of mass flow rate and fin spacing on the thermal performance and rise in temperature were studied. The indicated results show that fin spacing of 1 cm yields maximum thermal efficiency and the maximum enhancement of 1.29 times in thermal efficiency has been obtained with the use of wavy fins as compared to longitudinal fins. Also, a maximum enhancement in temperature rise has been found as 1.25 times as compared to longitudinal fins at lower mass flow rate of 0.0134kg/s.**

***Keywords*- Wavy Fin, Thermal Efficiency, Temperature Rise**

Nomenclature

λ	Wavelength of wavy fin (mm)
ρ	Density of air (kg/m^3)
σ	Stefan-Boltzmann Constant
$(\tau\alpha)_e$	Effective transmittance absorptance product
$\dot{m}$	Mass flow rate (kg/s)
A_c	Collector area (m^2)
Amp	Amplitude of wavy fin (mm)
A_p	Area of absorber plate (m^2)
Ar	Total heat transfer area (m^2)
D_h	Hydraulic diameter (m)
G	Mass velocity (kg/s/m^2)
h_r	Radiative heat transfer coefficient (W/m^{2}K)
I	Intensity of Solar radiation (W/m^2)
k_a	Thermal conductivity of air (W/mK)
k_{GI}	Thermal conductivity of G.I sheet (W/mK)
L'	Actual length of wavy fin (m)
Nu	Nusselt number
P	Porosity
Pr	Prandtl number
Re	Reynolds number
S	Absorbed Solar Energy (W/m^2)
T_{fo}	Outlet air temperature (°C)
U_b	Bottom loss coefficient (W/m^{2}K)
U_t	Top loss coefficient (W/m^{2}K)

I. INTRODUCTION

In conventional solar air heaters the heat transfer among the absorber plate and flowing air is poor, results in lower efficiency. The simplest form of flat plate solar air heater consists of a transparent cover above an absorber plate and the air flows either above or below the absorber plate [1-3]. Various designs have been proposed in literature to enhance the heat transfer. These include the use of rectangular offset fins, plate fins, corrugated absorbers, turbulence promoters and packed beds.

Ho et al. studied the influence of recycle on the performance of baffled double pass flat plate solar air heater with attached internal fins[4]. Another study was carried out to determine the comparative performance of single pass corrugated air heaters with various air channel lengths and for different mass flow rates of air[5].Akpinar et al. analyzed experimentally the performance of a new flat plate solar air heater with various obstacles at different angles and without obstacles[6]. Thermal performance of double pass finned plate and v- corrugated absorber solar air heater were investigated theoretically and experimentally[7]. Ammari proposed another mathematical of a solar air heating system with slats connecting the absorber plate to the bottom plate to enhance the thermal performance of the solar air heater [8]. Flat plate , v-corrugated and finned air heaters were investigated both experimentally and theoretically in order to improve the performance of conventional solar air heaters [9]. Ozgen et al. inserted aluminium cans in zig-zag way as well as in staggered way to compute the thermal performance[10]. Solar equipped offset rectangular plate fin was studied experimentally and numerically to determine the thermal performance [11]. It is well known that collector configuration will influence the fluid velocity as well as the strength of the forced convection. A simple procedure for changing the fluid velocity and also the strength of forced convection involves adjusting the flow channel geometry with wavy fins below the absorber plate.

In this paper, an analytical investigation on uniform cross sectional area wavy fins attached to the absorber plate is being presented. wavy fins can enhanced the heat transfer area as well as heat transfer coefficient in order to enhance heat transfer rate due to its waviness structure. These are considered as high heat transfer per unit volume [12]. The fluid channel is formed by two transversely positioned wavy fins, bottom side thermally insulated and the upper surface of the absorber is subjected to uniform heat flux. In many studies , wavy fins were studied in heat exchangers [13-14]. Present study has been focussed on the comparative performance of wavy fin and longitudinal fin absorber solar air heater Furthermore, performance study of plane solar air heater has also been done. A theoretical analysis, using the step by step method has been developed to determine the effect of mass flow rate and the fin spacing on the thermal performances of the modified solar air heater. Higher thermal performances for wavy fin have been obtained in comparison to longitudinal fin followed by plane solar air heater.

II. THEORETICAL ANALYSIS

The wavy finned absorber solar air heater used has a single pass between below the absorber plate and the bottom plate. The wavy fin increases the thermal performances of the flat plate collector, which enhance the outlet temperature.

Energy Balance Equations:-

Consider a solar air heater, which has an absorber plate of length 'L' and width 'W' and it is provided with 'n' number of wavy fins of uniform thickness 'δ_f' and height 'h_f' are spaced at a mean distance of 'w' as shown in fig.1. The geometric description of a wavy fin has been shown in fig.2.The distance between the absorber plate and bottom plate is 'H'. Since the thermo physical properties of air is least dependent on the temperature (50°C to 150°C), we assume these properties to be constant.

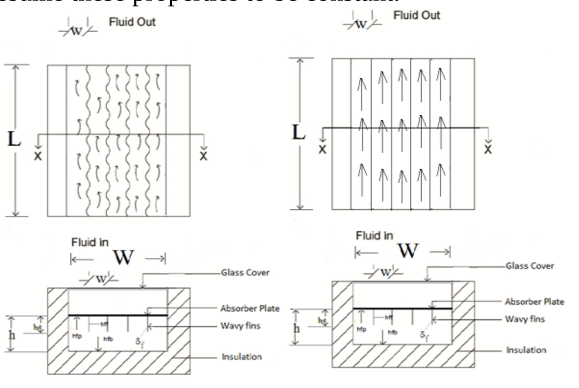

Fig.1 Solar air heater with wavy & longitudinal finned absorber

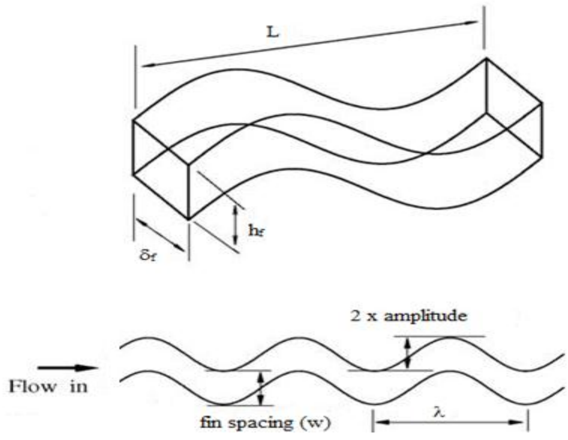

Fig.2 Geometric description and flow representation of a wavy fin

Let β is 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 [5]. The mean temperature of the absorber plate is T_{pm} and that of the bottom plate is T_{bm}. The air mass flow rate is $\dot{m}$ and the bulk mean temperature of the air changes from T_f to (T_f + dT_f).

Consider a slice of average width w and thickness dx at a distance x from the inlet. The energy balance equations for the absorber plate, the bottom plate and the air flowing in between respectively can be written as:

$$S.w.dx = U_t.w.dx(T_{pm} - T_a) + h_{fp}.w.dx(T_{pm} - T_f) + h_{ff}.2.h_f.dx.\beta.\Phi_f(T_{pm} - T_f) + h_r.w.dx(T_{pm} - T_{bm}) \quad (1)$$

$$h_r.w.dx(T_{pm} - T_{bm}) = h_{fb}.w.dx(T_{bm} - T_f) + U_b.w.dx(T_{bm} - T_a) \quad (2)$$

$$\left(\frac{w}{W}\right)\dot{m}.C_p.dT_f = h_{fb}.w.dx(T_{bm} - T_f) + h_{fp}.w.dx(T_{pm} - T_f) + 2h_f.dx.\Phi_f.\beta.h_{ff}(T_{pm} - T_f) \quad (3)$$

Where Φ_f is the fin efficiency and can be expressed as

$$\Phi_f = \frac{\tanh\ mh_f}{mh_f} \quad (4)$$

$$\text{where, } m = \left[\frac{2h_{ff}}{k_a\delta_f}\right]^{1/2} \quad (5)$$

Combining equations (1),(2),(3) we get,

$$S = U_L(T_{pm} - T_a) + \left\{h_{fp} + \frac{2h_f.\Phi_f.\beta.h_{ff}}{w}\right\}(T_{pm} - T_f) + h_r\left\{T_{pm} - \left(\frac{h_rT_{pm} - h_{fb}T_f}{h_r + h_{fb}}\right)\right\} \quad (6)$$

$$S + U_LT_a + h_eT_f = T_{pm}(U_L + h_e) \quad (7)$$

Where h_e is an effective heat transfer coefficient between the absorber plate and the air stream which can be written as

$$h_e = h_{fp} + \frac{2h_f.\Phi_f.\beta.h_{ff}}{w} + \frac{h_r.h_{fb}}{h_r + h_{fb}} \quad (8)$$

The expression for collector efficiency factor (F') for wavy finned absorber solar air heater can be given as

$$F' = \frac{h_e}{h_e + U_L} \quad (9)$$

For the longitudinal finned solar air heater, β=1 and the equation (8) reduces to

$$h_e = h_{fp} + \frac{2h_f.\Phi_f.h_{ff}}{w} + \frac{h_r.h_{fb}}{h_r + h_{fb}} \quad (10)$$

For the plane solar air heater, β=0 and the equation (8) reduces to

$$h_e = h_{fp} + \frac{h_r h_{fb}}{h_r + h_{fb}} \quad (11)$$

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

$$h_{ff} = h_{fp} = h_{fb} = \frac{Nu.k_a}{D_h} \quad (12)$$

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

$$Nu = 4.4 + \frac{0.00398(0.7\,\mathrm{Re}\,D_h/L)^{1.66}}{1 + 0.00114(0.7\,\mathrm{Re}\,D_h/L)^{1.12}} \quad (13)$$

For turbulent flow the correlation may be derived from Kay's [16] data with the modification of Mc Adams [17] for a rectangular channel as follows.

$$Nu = 0.0158\,\mathrm{Re}^{0.8}[1 + (D_h/L)^{0.7}] \quad (14)$$

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.

$$j = 0.0836\,\mathrm{Re}^{-0.2309}\left(\frac{w}{h_f}\right)^{0.1284}\left(\frac{w}{2.amp}\right)^{-0.153}\left(\frac{L}{\lambda}\right)^{-0.326} \quad (15)$$

Where,

$$j = \frac{Nu}{\mathrm{Re}\,\mathrm{Pr}^{1/3}}$$

Expression for the mass velocity (G) and the hydraulic diameter (D_h) of the duct defined by Kays and London [18],

$$G = \frac{\dot{m}}{p.A_{fr}} \quad (16)$$

$$D_h = \frac{4pA_{fr}L}{Ar} \quad (17)$$

Total heat transfer area is given as,

$$Ar = (n \times L' \times \delta_f) + (2n \times L' \times h_f) + ((n+1) \times L \times w) \quad (18)$$

An empirical relation has been used for calculation of top loss coefficient and bottom loss coefficient is given by Klein [2]

Total loss coefficient is

$$U_L = U_t + U_b \quad (19)$$

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

$$T_{pcal} = T_a + \frac{Q_u(1 - F_R)}{A_P U_L F_R} \quad (20)$$

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 equation (26) 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

$$\frac{T_{fo} - T_a - S/U_L}{T_{fi} - T_a - S/U_L} = \exp\left[\frac{-A_C U_L F'}{\dot{m}C_P}\right] \quad (21)$$

Collector heat removal factor (FR) is expressed as

$$F_R = \frac{\dot{m}C_p}{U_L A_c}\left(1 - \exp\left(\frac{-A_c F' U_L}{\dot{m}C_p}\right)\right) \quad (22)$$

Total Useful energy gain by the collector can be expressed as

$$Q_u = F_R A_c\left(S - U_L(T_{fi} - T_a)\right) \quad (23)$$

The thermal efficiency of the collector can be expressed as [3].

$$\eta_{th} = \frac{Q_u}{A_c \times I} \quad (24)$$

III. RESULTS AND DISCUSSIONS

In this section, results of thermal such as rise in temperature, thermal efficiency of the proposed solar air heaters are presented. The following values of the relevant parameters are used for the theoretical calculations:

I = 900 W/m^2, W = 1 m, L = 1.2 m, H = 2.5cm, N_{gc}=1, h_f = 2.2cm, δ_f = 1mm, k_{ins}=0.1W/mK, $(\tau\alpha)_e$= 0.85,

k_a=0.029W/mK, δ_{ins}= 5cm, amp= 7.5 mm, λ= 70 mm, L'=1.551m, δ_{gc}= 4mm ,T_a = 30°C, T_{fi} = 30°C, ε_p = 0.95, ε_b = 0.95, ε_c= 0.88 and V_w = 2.5m/s. For the fin spacing (1cm - 5cm) and the mass flow range of 0.0138 kg/s- 0.0834 kg/s, the various performance curves (fig. 3-8) has been plotted.
Fig.3 represents that for entire range of mass flow rate, fin spacing of 1 cm yields maximum thermal efficiency. For a given value of fin spacing, thermal efficiency increases with increase in mass flow rate. It can also be observed from fig. 4 that for entire range of mass flow rate, maximum thermal efficiency has been achieved with the use of wavy fin under the same conditions. A maximum enhancement of 1.29 times in thermal efficiency has been obtained with wavy fin as compared to longitudinal fin. This may because at that value, heat transfer is maximum due to the enhanced heat transfer area and increased heat transfer coefficient by using wavy fins.

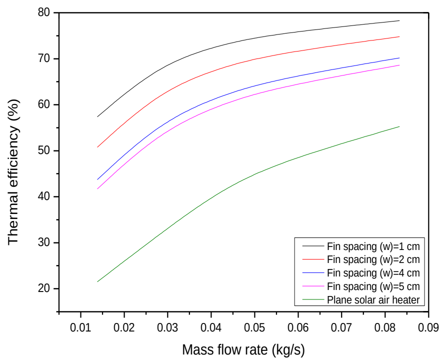

Fig.3 Thermal efficiency as a function of mass flow rate for various values of (wavy) fin spacing

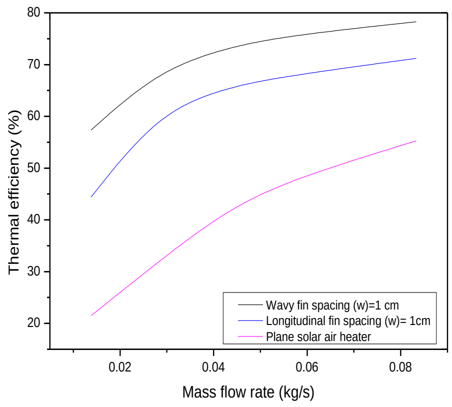

Fig.4 Comparison of thermal efficiency for wavy fin and longitudinal fin

Fig. 5 shows that for entire range of mass flow rate, fin spacing of 1 cm yields the maximum temperature rise. For a given value of fin spacing, temperature rise decreases as the mass flow rate increases. Decreasing the fin spacing increases the heat transfer area which increases the temperature rise. it can also be observed from fig.6 that for the constant fin spacing of 1 cm, wavy

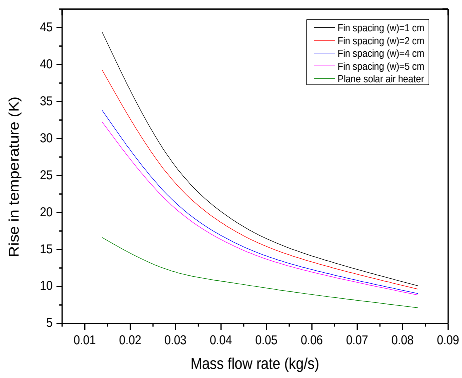

Fig.5 Rise in temperature as a function of mass flow rate for various values of (wavy) fin spacing

fin achieved the maximum temperature rise for all mass flow rates. A maximum enhancement of 1.25 times as compared to longitudinal fins has been found at lower mass flow rate of 0.0134kg/s. Because at this value of mass flow rate, heat transfer coefficient and heat transfer area is maximum due to geometrical structure of the fin.

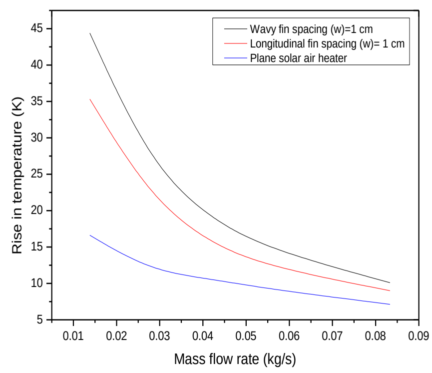

Fig.6 Comparison of rise in temperature for wavy fin and longitudinal fin

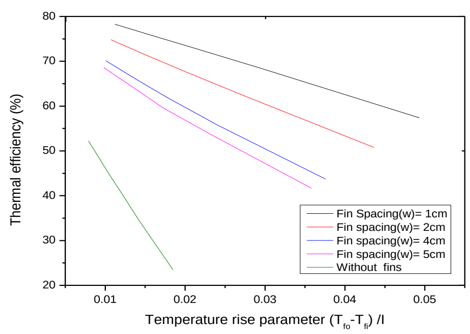

Fig.7 Thermal efficiency as a function of temperature rise parameter for various values of (wavy)fin spacing

Fig.7 shows that for entire range of temperature rise parameter, fin spacing of 1cm yields maximum thermal efficiency. For a given value of fin spacing , thermal efficiency decreases with the increase in temperature rise parameter. It can also be observed from fig.8 that for the constant fin spacing of 1 cm, wavy fin achieved the maximum thermal efficiency for the entire range of temperature rise parameter. For the same temperature rise parameter, use of wavy fins enhanced a maximum of 1.46 times thermal efficiency as compared to longitudinal fins.

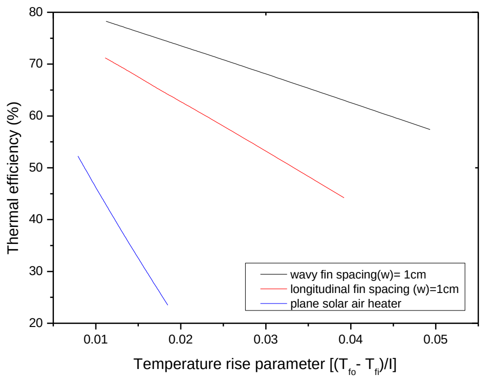

Fig.8 Thermal efficiency as a function of temperature rise parameter for wavy fin and longitudinal fin

IV. VALIDATION OF WORK

Thermal efficiency determined from computational data for plane solar air heater and wavy finned solar air heater have been compared with the experimental values obtained from Karim et al.[9] for the thermal efficiency. The comparison of theoretical and experimental values of thermal efficiency for the same parameters have been shown in fig.9. The average deviation of theoretical values of thermal efficiency is

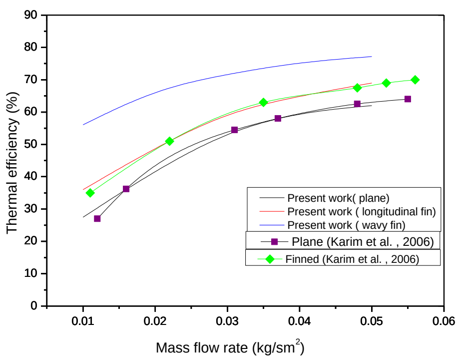

Fig.9 Comparison of available experimental and theoretical results of thermal efficiency for plane and finned solar air heater

±6.92% from the experimental values of Karim et al. . Also in comparison with finned solar air heater, there is an efficiency enhancement of 41.9% at the mass flow rate of 0.018kg/sm^2 and 13.15% at 0.05kg/sm^2 [9]. This shows good agreement between the experimental values and theoretical values, which makes sure tha perfection of the data collected with mathematical modelling.

V. CONCLUSION

In this paper the effect of mass flow rate and number of fins on the thermal performance of the plane, longitudinal and wavy fin absorber solar air heater has been investigated analytically. On the basis of previous discussions the following conclusions may be drawn:

1. The developed mathematical model provides reasonable predictions of the performance of a wavy fin absorber solar air heater.
2. The various performance parameters of wavy finned solar air heater have been compared to the corresponding values of longitudinal finned and plane solar air heater.
3. Increasing the air flow rate through the solar air heater results in higher thermal efficiency but decreases temperature rise.
4. It has been found that the wavy finned absorber solar air heater gives higher values of thermal efficiency and temperature rise in comparison to corresponding longitudinally finned and flat plate collector operating under similar conditions.
5. Increasing the temperature rise parameter decreases the thermal efficiency.

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