ANALYTICAL STUDY OF FLOW AND HEAT TRANSFER IN CROSS AND NON CROSS FLOW JET PLATE SOLAR AIR HEATER

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ABSTRACT

This paper presents an analytical study of flow and heat transfer in cross and non - cross flow solar air heater for inline and staggered plates inserted between absorber and bottom plates. Results are presented for various parameters of cross and non - cross flow such as pitch to hole diameter of the jet plate (X / D = 6.0 – 10.0), height of the upper channel to hole diameter (Z/n / D = 6.0 – 10.0), height of the lower channel to hole diameter (Z/n / D = 8.0 - 14.0), Reynolds number (Re = 3000 - 43000). In this study, heat transfer coefficient, outlet temperature of air, collector efficiency and friction factor are calculated for the above parameters. In a cross - flow inline hole jet plate solar air heater, the considerable increment in collector efficiency has been found from 15.68 to 54.88% for \( \dot{m}_1 = 50 – 300 \) kg / hm\(^2\), X / D = 6.0 - 10.0 and N = 561 whereas the value of heat transfer coefficient is increased from 3.24 to 8.40 W/m\(^2\)K for X / D = 6.0 - 10.0 and \( \dot{m}_1 = 50 \) kg/hm\(^2\) which is higher than cross - flow staggered hole and non - cross flow inline/staggered hole jet plate solar air heater. The Nusselt number (Nu) increase with decrease in jet hole diameter (D) for fixed mass flow rate.

INTRODUCTION

In recent times, there has been a renewed interest in non conventional jet plate solar air heater because of having better performance with compared to a conventional solar air heater.

Several configurations of absorber plates are designed to improve the performance of a conventional solar air heater. By providing artificial roughness obstacles, baffles in various shapes with different arrangements and longitudinal fins over and underside [1], of the absorber plate were employed to increase the surface area of the absorber plate. As a result, the heat transfer co-efficient between the absorber plate and the air pass have been increased [2, 3, 4]. On other hand heat transfer

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Description</th>
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<tbody>
<tr>
<td>A</td>
<td>[m(^2)]</td>
<td>Surface area of absorber plate</td>
</tr>
<tr>
<td>A(_e)</td>
<td>[m(^2)]</td>
<td>Effective heat transfer area of jet plate</td>
</tr>
<tr>
<td>C</td>
<td>[Wh / kg°C]</td>
<td>Specific heat capacity of air, d</td>
</tr>
<tr>
<td>D(_1), D(_2)</td>
<td>[m]</td>
<td>Air thickness between absorber and cover</td>
</tr>
<tr>
<td>D</td>
<td>[m]</td>
<td>Hydraulic diameter</td>
</tr>
<tr>
<td>f(_j)</td>
<td></td>
<td>Diameter of jet hole</td>
</tr>
<tr>
<td>f(_c)</td>
<td></td>
<td>Friction factor</td>
</tr>
<tr>
<td>F(_1)</td>
<td></td>
<td>Dimensionless constant</td>
</tr>
<tr>
<td>F(_2)</td>
<td></td>
<td>Cross-flow degration factor</td>
</tr>
<tr>
<td>g</td>
<td>[m / s(^2)]</td>
<td>Acceleration due to gravity</td>
</tr>
<tr>
<td>G(_1)</td>
<td>[kg / hm(^2)]</td>
<td>Mass flow velocity of air impinging out of holes</td>
</tr>
<tr>
<td>G(_2)</td>
<td>[kg / hm(^2)]</td>
<td>Mass flow velocity of cross - flow air</td>
</tr>
<tr>
<td>Gr(_c)</td>
<td></td>
<td>Grashof number</td>
</tr>
<tr>
<td>h(_c)</td>
<td>[W/m(^2)K]</td>
<td>Heat transfer coefficient of cover plate to surrounding air</td>
</tr>
<tr>
<td>h(_ac)</td>
<td>[W/m(^2)K]</td>
<td>Heat transfer coefficient of absorber to the cover plate</td>
</tr>
<tr>
<td>h(_ja)</td>
<td>[W/m(^2)K]</td>
<td>Convective heat transfer coefficient of absorber plate to cover plate</td>
</tr>
<tr>
<td>h(_ja)</td>
<td>[W/m(^2)K]</td>
<td>Convective heat transfer coefficient of jet plate to lower channel air</td>
</tr>
<tr>
<td>h(_ja)</td>
<td>[W/m(^2)K]</td>
<td>Convective heat transfer coefficient of jet plate to upper channel air</td>
</tr>
<tr>
<td>h(_ba)</td>
<td>[W/m(^2)K]</td>
<td>Convective heat transfer coefficient of bottom plate to lower channel air</td>
</tr>
<tr>
<td>h(_bc)</td>
<td>[W/m(^2)K]</td>
<td>Radiative heat transfer coefficient of cover plate to surrounding air</td>
</tr>
<tr>
<td>h(_w)</td>
<td>[W/m(^2)K]</td>
<td>Coefficient of wind related heat transfer coefficient</td>
</tr>
<tr>
<td>h(_pj)</td>
<td>[W/m(^2)K]</td>
<td>Radiative heat transfer coefficient between absorber and jet plate</td>
</tr>
<tr>
<td>h(_pa)</td>
<td>[W/m(^2)K]</td>
<td>Heat transfer coefficient of absorber plate to upper channel air</td>
</tr>
<tr>
<td>h(_p)</td>
<td>[W/m(^2)K]</td>
<td>Average heat transfer coefficient of absorber plate to jet air</td>
</tr>
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</table>
A schematic view of jet plate solar air heater is shown in Fig. 1 which has blower for supplying air, bottom plate, jet plate with inline/staggered hole (shown in Figs. 2 and 3), black painted absorber plate, toughened glass cover plate, two flow -
channels with the mass flow rate of air $\dot{m}_1$ and $\dot{m}_2$, bottom insulation and thermocouples imbedded to each plate. In case of cross-flow condition, mass flow rate of air between jet plate and bottom plate ($\dot{m}_1$) impinges out of the hole and mixes with $\dot{m}_2$ as shown in Fig. 1 and subsequently the same comes out from the upper channel exit. Under non–cross flow condition, since inlet of upper channel is closed so air from the bottom channel passes through the holes and strikes the lower surface of the absorber plate, finally comes out from the upper channel exit.

**Energy Balance Equations under Steady State Conditions [15]:**

The steady state energy balance equations for the cover, absorber plate, jet plate, back plate, air passage between jet plate and bottom plate and absorber plate and jet plate are written as:

For cover plate,

$$h_{CS} (T_C - T_A) = h_{PC} (T_P - T_C)$$  \hspace{2cm} (1)

For absorber plate,

$$h_{CP} (T_P - T_A) + h_{rCP} (T_P - T_C)$$

For jet plate,

$$h_{jyj} (T_P - T_j) = h_{jyj}(T_j - T_{a1}) + h_{jyj}(T_j - T_{a2})$$  \hspace{2cm} (2)

For bottom plate,

$$h_{jyj}(T_b - T_j) = h_{jyj}(T_b - T_{a1}) + U_b(T_b - T_{a1})$$  \hspace{2cm} (3)

For air stream between jet plate and bottom plate,

$$\dot{m}_1 C(T_{a1} - T_A) = h_{jyj}(T_j - T_{a1}) + h_{cha}(T_b - T_{a1})$$  \hspace{2cm} (4)

For air stream between absorber plate and jet plate,

$$\dot{m}_1 C(T_o - T_{a1}) + m_2 C(T_o - T_{a2}) = h_{jyj}(T_j - T_{a2}) + h_{CPa2} (T_P - T_{a2})$$  \hspace{2cm} (5)

From equation (2) to (6) we get,

$$T_{a1} = \frac{T_A + T_{a1}}{2} \quad \text{and} \quad T_{a2} = \frac{T_I + T_o}{2}$$

$$T_I = \frac{m_1 T_{a1} + m_2 T_{a2}}{m_1 + m_2}$$  \hspace{2cm} (7)

$$h_{PA2} = h_{PJ} \frac{(T_P - T_{a1})}{(T_P - T_{a2})}$$  \hspace{2cm} (8)

In addition, Average collector efficiency be,

$$\eta = \frac{(\dot{m}_1 + \dot{m}_2) C (T_o - T_A)}{I}$$  \hspace{2cm} (9)

**Heat Transfer Coefficients [15]:**

The convective heat transfer coefficient $h_w$, for air flowing over the outside surface of the glass cover depends on the wind velocity, $V_w$. Adams [20], is obtained the experimental result as,

$$h_{CS} = h_w + h_{rcs}$$  \hspace{2cm} (10)

$$h_w = 5.7 + 3.8 V_w$$  \hspace{2cm} (11)

$$h_{rcs} = \varepsilon c \sigma (T_C^4 - T_S^4) (T_C - T_A)$$  \hspace{2cm} (12)

Neglecting the radiation heat transfer from cover to air with, $T_S = (0.0552) (T_A)^{1.5}$  \hspace{2cm} (13)

$$h_{PC} = h_{rPC} + h_{rPC}$$  \hspace{2cm} (14)

$$h_{cPC} = Nu_c \frac{k_a}{d}$$  \hspace{2cm} (15)

$$Nu_c = 0.093 (Gr_c)^{0.31}$$  \hspace{2cm} (16)

$$h_{rPC} = \alpha (T_P^2 + T_C^2) (T_P + T_C)$$

$$\frac{1}{\varepsilon} + \frac{1}{\varepsilon_c} - 1$$  \hspace{2cm} (17)

The average plate-to-jet air heat transfer coefficients [15] are

$$h_{PJ} = Nu_{PJ} \frac{k_a}{d}$$  \hspace{2cm} (18)

The forced convective heat transfer coefficients from jet plate to air above ($h_{jyj}$), from jet plate to air below ($h_{jyj}$) and from back plate to air ($h_{cha}$) are written as,
\[
\begin{align*}
   h_{cja2} &= \frac{A_e}{A} N_{u_{ja2}} \frac{k_a}{D_2} \\
   N_{u_{ja2}} &= 0.0293 \left(Re_{ja2}\right)^{0.8}
\end{align*}
\]

\[
Re_{ja2} = \frac{(\dot{m}_1 + \dot{m}_2)LD_2}{Z_1 \mu}
\]

\[
A_e = A - \pi D^2 + 2N_1/N
\]

\[
\begin{align*}
   h_{cja1} &= \frac{A_e}{A} N_{u_{ja1}} \frac{k_a}{D_2} \\
   N_{u_{ja1}} &= 0.0293 \left(Re_{ja1}\right)^{0.8}
\end{align*}
\]

\[
Re_{ja1} = \frac{\dot{m}_1 LD_2}{Z_2 \mu}
\]

\[
h_{bal} = h_{ja1} A_e/A_e
\]

The radiative heat transfer coefficient between the absorber and jet plate may be,

\[
h_{rpf} = \frac{\sigma \left(T_p^2 + T_f^2\right) (T_p + T_f)}{\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_f} - 1}
\]

Similarly, the radiative heat transfer coefficient between the absorber and jet plate can be written as,

\[
h_{rjb} = \frac{\sigma \left(T_j^2 + T_b^2\right) (T_j + T_b)}{\frac{1}{\varepsilon_j} + \frac{1}{\varepsilon_b} - 1}
\]

The bottom loss heat coefficient is calculated by using,

\[
U_b = \frac{k_i}{l}
\]

(Considering, heat loss from bottom is 0)

Calculation of friction factor

\[
f_s = 0.085 (Re_{ja2})^{0.25} \text{ (Blassius equation)}
\]

**PARAMETRIC RANGE OF THE PRESENT STUDY**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range</th>
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<tbody>
<tr>
<td>(Z_1/D)</td>
<td>6.0 - 10.0</td>
</tr>
<tr>
<td>(Z_2/D)</td>
<td>8.0 - 14.0</td>
</tr>
<tr>
<td>(X/D)</td>
<td>6.0 - 10.0</td>
</tr>
<tr>
<td>(Re)</td>
<td>3000 - 43000</td>
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</tbody>
</table>

**RESULTS AND DISCUSSIONS**

Variations of the outlet air temperature and collector efficiency (Cross and non - cross flow conditions) with mass flow rate of air:

Figs. 4 and 5 show that the outlet air temperature \((T_o)\) decreases and the collector efficiency \((\eta)\) increases with increase in mass flow rate of air. For \(X/D = 6.0 - 10.0\), the outlet air temperature \((T_o)\) of non - cross flow inline hole jet plate solar air heater is higher than non - cross flow staggered hole and cross-flow inline/staggered hole jet plate solar air heater. However, the collector efficiency \((\eta)\) of cross - flow inline hole jet plate solar air heater for the same range is more than cross - flow staggered hole and non - cross flow inline/staggered hole jet plate solar air heater. The lower value of outlet air temperature for cross flow is due to deterioration of its degradation factor \(F_2\).

At \(m_1 = 300 \text{ kg/} m^2\) and \(X/D = 10.0\), the outlet air temperature \((T_o)\) in non - cross flow inline hole jet plate solar air heater has been found 2.4%, 2.7% and 3.45% higher than non - cross flow staggered, cross -flow inline and cross flow staggered hole jet plate solar air heater respectively. Whereas the collector efficiency \((\eta)\) in cross-flow inline hole jet plate solar air heater is obtained 5.04%, 14.56% and 17.92% more than cross-flow staggered, non - cross flow inline and non-cross flow staggered hole jet plate solar air heater respectively. The present results (Figs. 4 and 5) reveals that the outlet air temperature \((T_o)\) and collector efficiency \((\eta)\) increases with decrease in jet hole diameter \((D)\) resulting in higher outlet air temperature \((T_o)\) and collector efficiency.

**Fig. 4. Outlet air temperature and collector efficiency as function of mass flow rate of air \((m_1)\)**
Effect of jet hole diameter on heat transfer coefficient of absorber plate to jet air and collector efficiency:

![Graph](Image)

Fig. 5. Outlet air temperature and collector efficiency as function of mass flow rate of air ($m_1^*$).

Effect of jet hole diameter on heat transfer coefficient of absorber plate to jet air:

![Graph](Image)

Fig. 6. Effect of jet hole diameter ($D$) on heat transfer coefficient ($h_{Pj}$) of absorber plate to jet air.

Effect of the jet hole diameter on Nusselt number ($Nu$):

![Graph](Image)

Fig. 8 (i)

Effects 6 and 7 show the effect of jet hole diameter on heat transfer coefficient ($h_{Pj}$) of absorber plate to jet air and collector efficiency ($\eta$). These curves reveal that under both the cases $h_{Pj}$ and $\eta$ increase with decrease in jet hole diameter. It is observed that both $h_{Pj}$ and $\eta$ are increased with decreasing the size of the hole of the jet plate for fixed mass flow rate ($m_1^*$) and the highest value of $h_{Pj}$ and $\eta$ are obtained at lowest jet plate hole diameter ($D = 6.0$ mm) because of getting higher velocity of jet air. The available literature [15] also shows the similar result in their presented work. For fixed mass flow rate ($m_1^*$) and jet hole diameter ($D$), both $h_{Pj}$ and $\eta$ are observed higher in cross-flow inline hole jet plate solar air heater. At $X / D = 10.0$ and $m_1^* = 50$ kg/hm$^2$, the $h_{Pj}$ and $\eta$ of cross-flow inline hole jet plate solar air heater are found 49.6% and 30.84% higher as compared to non-cross flow inline hole jet plate solar air heater.

Cross-flow (Inline jet plate, $N = 561$) 
Cross-flow (Staggered hole jet plate, $N = 1173$) 
Non-cross flow (Inline jet plate, $N = 561$) 
Non-cross flow (Staggered hole jet plate, $N = 1173$) 
$L = 2.0$ m, $X = 0.06$ m, $Z_1 = 0.06$ m, $Z_2 = 0.08$ m
The variation of D over results, the following conclusions are made as given below:

**Variation of friction factor with Reynolds number:**

For \( \dot{m}_1 = 50 - 300 \) kg/hm\(^2\) and \( X / D = 6.0 \), the variation of friction factor \( (f_s) \) as a function of Reynolds number \( (Re) \) under cross-flow and non-cross flow inline/staggered hole jet plate solar air heater are shown in figs. 9 and 10. Under both the cases, curves indicate friction factor \( (f_s) \) decreases with increase in Reynolds number. It is found that the value of gradient of curve in case of cross-flow condition is lower as compare to non-cross flow condition. For fixed mass flow rate \( (\dot{m}_1) \) and \( Re = 13000 - 43000 \), the friction factor \( (f_s) \) in non-cross flow condition is higher than cross-flow condition.

**CONCLUSION**

Based on the above results, the following conclusions are made as given below:

At fixed mass flow rate \( (\dot{m}_1) \) and jet hole diameter \( (D) \), the heat transfer coefficient \( (h_{tp}) \) of absorber plate to jet air, Nusselt number \( (Nu) \) and collector efficiency \( (\eta) \) are higher in cross-flow inline hole jet plate solar air heater than non-cross flow condition. For fixed mass flow rate \( (\dot{m}_1) \) and \( Re = 13000 - 43000 \), the friction factor \( (f_s) \) in non-cross flow condition is higher than cross-flow condition.

**Fig. 8 (ii)**

**Fig. 9. Variation of \( f_s \) with \( Re \) for non-cross flow**

(Inline and Staggered hole)

**Fig. 10. Variation of \( f_s \) with \( Re \) for cross-flow**

(Inline and Staggered hole)
friction factor \( (f_s) \) has been found more in non-cross flow inline/staggered hole than cross-flow inline/staggered hole jet plate solar air heater.

**REFERENCES**


[17] Irfan Kurtbas., Experimental investigation of solar air heater with free and fixed fins. Int. J. of Science and Technology 2006; Volume 1, No 1, 75-82.

