TRANSPARENT INSULATION CHARACTERISTICS OF HONEYCOMB AND SLAT ARRAYS

N. D. KAUSHIKA,† R. PADMAPRIYA, M. ARULANANTHAM, and P. K. SHARMA
Centre for Energy Studies, Indian Institute of Technology, New Delhi-110 016, India
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Abstract—A mathematical model is formulated for solar optical and thermal processes in cellular arrays. Explicit computational results are presented on optimization of wall separation and aspect ratio of arrays with square and parallel slat cross sections. The arrays with wall spacings of 0.5–1.25 cm and aspect ratios of 10–17 are found to be suitable for solar-collector and storage applications. A performance comparison is described for square-cell honeycomb and parallel-slat devices. For a horizontal collection surface, the honeycomb is superior to the slat device. On the other hand for a surface inclined at more than 30° with respect to the horizontal, a slat device is preferable.

INTRODUCTION

Transparent insulation materials (TIMs) represent a class of thermal insulation for which air gaps are used to reduce unwanted heat losses. They consist of transparent cellular structures immersed in an air layer. TIMs are finding application in solar thermal conversion systems because of their low heat-loss coefficient with high solar transmittance. They may be classified into four types depending on the cellular geometry, viz., absorber-parallel, absorber-vertical, cavity, and quasi-homogeneous. Vertical absorber structures include honeycomb and parallel-slat arrays.

Hollands first presented the theoretical performance characteristics for a honeycomb device. Subsequently, it was the subject of several theoretical and experimental investigations related to their convective, radiative and solar transmittance characteristics. Lalude and Buchberg determined optimum values of design parameters for opaque rectangular honeycombs, as well as the design for a honeycomb-based, porous-bed solar air heater. The design of cylindrical glass honeycombs, which minimize the cost of energy collected, was investigated by Buchberg and Edwards. The performance of a flat-plate collector with a slatted convection-suppression device made of thin glass was studied experimentally by Charters and Guthrie. However, relatively less attention seems to have been paid to the generation of detailed design and performance data of honeycombs; their relative merits with respect to parallel-slat devices are also not known. These may be found from an accurate determination of the solar transmittance and convective (for the critical and post-critical Rayleigh regimes) and other thermal transfer characteristics of the TIM device. Here, we present a model in which the important physical processes are included to characterize the effectiveness of square-celled honeycomb devices and of parallel-slat devices.

MODEL AND ANALYSIS

The steady-state energy balance for an absorber plane covered with TIM at the top is

\[ Q_U = S \times T(\theta, r) - Q_L, \]

where \( S \) is the solar intensity. The solar transmittance \( T(\theta, r) \) of the TIM is

\[ T(\theta, r) = f(\theta, r, L, d, \delta, \mu, \ldots). \]

1037
The total heat loss from the absorber plane \((Q_L)\) includes heat losses through the bottom insulation \((q_b)\) and the TIM \((q_s)\) which involve convection through the cell and conduction and radiation through both the cell and wall. It may be expressed as

\[
q_i = h_c (T_p - T_e) + \sigma F_{12} (T_p^4 - T_e^4).
\]

The combined conduction and convection heat-loss coefficient across the TIM is

\[
h_c = [(NuKa/L) Aa + (Kw/L) Aw] / (Aa + Aw).
\]

The total form factor \(F_{12}\) with absorber plate emissivity \(\varepsilon_a\) and top-cover emissivity \(\varepsilon_c\) is given by

\[
1/F_{12} = (1/F1R2) + (1 - \varepsilon_a)/\varepsilon_a + (1 - \varepsilon_c)/\varepsilon_c.
\]

where \(F1R2\) is the i.r. radiation geometrical shape factor for the cellular TIM.\(^{10}\)

Following Smart et al.\(^{11}\) and Cane et al.\(^{12}\) the relations based on correlations for the Nusselt number are given as follows. For a square-celled honeycomb

\[
Nu = 1.0 + 0.89 \times \cos [\beta_0 - (\pi/3)] \times [Ra/(2420 \times A^4)]^n,
\]

where \(n = 2.88 - 1.64 \times \sin(\beta_0)\) and the range of validity is \((Ra/A^4) < 6000\), \(30 < \beta_0 < 90\) and \(A > 4\).

For a parallel-slat device,

\[
Nu = 1 + c \times (Ra \times \cos \beta_0)^{1/3} \times \{1 - \exp[-(a + b \times \beta_0) \times ((Ra/Rc)^{n} - 1)]\},
\]

where \(a = 0.18, b = 1.2 \times 10^{-3} \text{ deg}^{-1}, c = 0.131,\) and \(n = 0.513\).

The heat loss \(q_2\) from the top cover to the atmosphere is

\[
q_2 = h_w (T_e - T_a) + \sigma \varepsilon_a (T_e^4 - T_a^4),
\]

where

\[
h_w = 5.7 + 3.8 \times V.
\]

At the steady state, \(q_1 = q_2\). Using Eqs. (3) and (8), we find a fourth degree equation in \(T_e\). It is solved by using the Newton–Raphson method. The resultant value of \(T_e\) in conjunction with subroutines for evaluation of solar transmittance and of \(h_c\), is used to calculate the total heat-loss coefficient \(U_L\) and the efficiency of heat collection \(\eta\) as follows:

\[
U_L = Q_L/(T_p - T_e),
\]

\[
\eta = T(\theta, r) - (Q_L/S).
\]

RESULTS AND DISCUSSION

We have used our results to investigate heat-loss reduction and solar gain characteristics of honeycomb and parallel-slat arrays as a function of geometric and operational parameters. The following thermophysical parameters were used: \(V = 3.0 \text{ m/sec.} \varepsilon_a = \varepsilon_c = 0.9\), \(Ka = 0.0284 \text{ W/mK}\), \(T_p = 293 K\), \(Kw = 0.21 \text{ W/mK}\), \(\delta = 0.076 \times 10^{-3} \text{ m} \), \(Li = 0.1 \text{ m}, \ S = 220.0 \text{ W/m}^2\).

The effect of honeycomb depth \((L)\) on efficiency for various absorber-plate temperatures is shown in Figs. 1(a,b). The variation of efficiency with wall spacing for different angles of incidence is depicted in Fig. 1(c). From these figures, it can be observed that the optimum wall separation and aspect ratio depend on operating conditions. A wall separation of 5–12.5 mm and an aspect ratio of 10–17 seem to be optimal for solar collector and storage applications.

Figures 2(a) and 2(b) show the effects of slat-depth and wall separation on the solar-collection
efficiency for various angles of incidence and absorber temperatures. A wall separation of 3–5 mm and an aspect ratio in the range of 8–12 are optimal.

The effects of absorber temperature on overall heat-loss coefficients for honeycombs and slats with different cell depths are shown in Fig. 3. The overall heat-loss coefficient is almost constant for a ΔT range of 30–70°C. It is always lower for the honeycomb device.

To examine heat-loss-reduction characteristics of square-celled honeycomb and parallel-slat devices, we show the total heat loss in Table 1. Four device configurations made from lexan film are considered. Slat I corresponds to a parallel-slat device with the same wall separation as the square-celled honeycomb, whereas slats IIa and IIb correspond to the parallel-slat device made from the same amount of fabrication material as the square-celled honeycomb. Results for solar energy-collection efficiency are
Fig. 2. (a) Effect of slat depth on efficiency for various tilt angles and absorber temperatures. (b) Effect of slat wall separation on efficiency for various tilt angles and absorber temperatures.

Fig. 3. Effect of absorber temperatures on heat-loss coefficient for honeycomb and slat devices.

Table 1. Heat loss across honeycomb (L = 0.05 m, d = 0.009 m) and slat devices (slat I: L = 0.05 m, d = 0.009 m, r = 0°; slat IIa: L = 0.05 m, d = 0.0045 m, r = 40°; slat IIb: L = 0.05 m, d = 0.0045 m, r = 80°) at various tilt angles.

<table>
<thead>
<tr>
<th>θ</th>
<th>Device</th>
<th>β₀ = 0°</th>
<th>β₀ = 15°</th>
<th>β₀ = 30°</th>
<th>β₀ = 45°</th>
<th>β₀ = 60°</th>
</tr>
</thead>
<tbody>
<tr>
<td>10°</td>
<td>Honeycomb</td>
<td>2.645</td>
<td>2.655</td>
<td>2.666</td>
<td>2.686</td>
<td>2.706</td>
</tr>
<tr>
<td></td>
<td>Slat I</td>
<td>4.470</td>
<td>4.480</td>
<td>4.490</td>
<td>4.520</td>
<td>4.580</td>
</tr>
<tr>
<td>70°</td>
<td>Slat IIa</td>
<td>2.957</td>
<td>2.967</td>
<td>2.976</td>
<td>2.986</td>
<td>2.988</td>
</tr>
<tr>
<td></td>
<td>Slat IIb</td>
<td>2.957</td>
<td>2.967</td>
<td>2.976</td>
<td>2.986</td>
<td>2.988</td>
</tr>
</tbody>
</table>
Table 2. Efficiency of the honeycomb ($L = 0.05 \text{ m}$, $d = 0.009 \text{ m}$) and slat devices (slat I: $L = 0.05 \text{ m}$, $d = 0.009 \text{ m}$, $r = 0^\circ$; slat IIa: $L = 0.05 \text{ m}$, $d = 0.0045 \text{ m}$, $r = 40^\circ$; slat IIb: $L = 0.05 \text{ m}$, $d = 0.0045 \text{ m}$, $r = 70^\circ$) at various tilt angles.

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>Device</th>
<th>$\eta(\theta,r)$</th>
<th>$\beta_0 = 0^\circ$</th>
<th>$\beta_0 = 15^\circ$</th>
<th>$\beta_0 = 30^\circ$</th>
<th>$\beta_0 = 45^\circ$</th>
<th>$\beta_0 = 60^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10$^\circ$</td>
<td>Honeycomb</td>
<td>0.975</td>
<td>0.613</td>
<td>0.612</td>
<td>0.611</td>
<td>0.609</td>
<td>0.606</td>
</tr>
<tr>
<td></td>
<td>Slat I</td>
<td>0.993</td>
<td>0.433</td>
<td>0.426</td>
<td>0.432</td>
<td>0.445</td>
<td>0.494</td>
</tr>
<tr>
<td></td>
<td>Slat IIa</td>
<td>0.987</td>
<td>0.589</td>
<td>0.588</td>
<td>0.594</td>
<td>0.611</td>
<td>0.631</td>
</tr>
<tr>
<td></td>
<td>Slat IIb</td>
<td>0.970</td>
<td>0.573</td>
<td>0.571</td>
<td>0.578</td>
<td>0.595</td>
<td>0.615</td>
</tr>
<tr>
<td>40$^\circ$</td>
<td>Honeycomb</td>
<td>0.935</td>
<td>0.574</td>
<td>0.573</td>
<td>0.571</td>
<td>0.569</td>
<td>0.567</td>
</tr>
<tr>
<td></td>
<td>Slat I</td>
<td>0.983</td>
<td>0.424</td>
<td>0.416</td>
<td>0.423</td>
<td>0.444</td>
<td>0.485</td>
</tr>
<tr>
<td></td>
<td>Slat IIa</td>
<td>0.969</td>
<td>0.571</td>
<td>0.569</td>
<td>0.576</td>
<td>0.593</td>
<td>0.613</td>
</tr>
<tr>
<td></td>
<td>Slat IIb</td>
<td>0.901</td>
<td>0.505</td>
<td>0.502</td>
<td>0.511</td>
<td>0.527</td>
<td>0.547</td>
</tr>
<tr>
<td>70$^\circ$</td>
<td>Honeycomb</td>
<td>0.845</td>
<td>0.484</td>
<td>0.482</td>
<td>0.481</td>
<td>0.479</td>
<td>0.477</td>
</tr>
<tr>
<td></td>
<td>Slat I</td>
<td>0.955</td>
<td>0.394</td>
<td>0.387</td>
<td>0.393</td>
<td>0.415</td>
<td>0.452</td>
</tr>
<tr>
<td></td>
<td>Slat IIa</td>
<td>0.918</td>
<td>0.522</td>
<td>0.520</td>
<td>0.527</td>
<td>0.544</td>
<td>0.584</td>
</tr>
<tr>
<td></td>
<td>Slat IIb</td>
<td>0.765</td>
<td>0.372</td>
<td>0.370</td>
<td>0.377</td>
<td>0.394</td>
<td>0.414</td>
</tr>
</tbody>
</table>

Illustrated in Table 2. It is noted that for horizontal absorber planes, the honeycomb exhibits superior performance whereas a slat configuration is preferable for applications on inclined ($\beta_0 > 30^\circ$) planes.

REFERENCES


NOMENCLATURE

- $A = \text{aspect ratio } (L/d)$
- $A_a = \text{area of air cell (m}^2\text{)}$
- $A_w = \text{area of side wall media (m}^2\text{)}$
- $d = \text{wall spacing in the TIM (m)}$
- $h_c = \text{convective heat-transfer coefficient (W/m}^2\text{K)}$
- $k_a = \text{thermal conductivity of air (W/m K)}$
- $k_i = \text{thermal conductivity of bottom insulation (W/m K)}$
- $k_w = \text{thermal conductivity of TIM wall material (W/m K)}$
- $L = \text{depth of the TIM (m)}$
- $L_i = \text{length of the insulation (m)}$
- $R_c = \text{critical Rayleigh number}$
- $r = \text{azimuth angle}$
- $S = \text{solar intensity (W/m}^2\text{)}$
- $T_a = \text{ambient air temperature (K)}$
- $T_c = \text{top-cover temperature (K)}$
- $T_p = \text{absorber-plate temperature (K)}$
- $V = \text{velocity of air (m/sec)}$
- $\beta_0 = \text{tilt angle}$
- $\theta = \text{angle of incidence}$
- $\sigma = \text{Stefan–Boltzmann constant}$
- $\epsilon_c = \text{emissivity of cover plates}$
- $\epsilon_a = \text{emissivity of absorber}$
- $\delta = \text{thickness of cell walls (m)}$
- $\Delta T = (T_b - T_c) (K)$

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