EFFECT OF THERMAL STORAGE ON THE PERFORMANCE OF AN AIR COLLECTOR: A PERIODIC ANALYSIS

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Abstract—This communication presents parametric studies of an air collector consisting of different thermal energy storage materials (concrete, brick, sand, ground, phase change material (PCM)) on top, but with soil provided at the bottom. The effect of storage material, optimization of length and thickness of storage material, and the effect of flow rate on outlet air temperature, useful energy gain and daily efficiency is reported. Numerical computations have been carried out for a typical day in the month of June for Delhi climatic conditions. It is observed that there is a significant phase shift (10–12 h) owing to the storage effect. The hourly maximum useful energy gain decreases with the fraction of storage material thickness, whereas the minimum amount increases and approaches the maximum value.

Storage material Thermal storage Sensible heat Latent heat Air collector

NOMENCLATURE

\( A_r \) = Collector area (m²)
\( C_r \) = Specific heat of air (J/kg °C)
\( C_s \) = Specific heat of storage material for \( j \)th region (J/kg °C)
\( d \) = Duct depth (m)
\( dy \) = Elemental length coordinate in flow direction (m)
\( h \) = Convective heat transfer coefficient from cover to ambient (W/m² °C)
\( h_b \) = Convective heat transfer coefficient from bottom surface to ambient (W/m² °C)
\( h_f \) = Convective heat transfer coefficient from bottom of region I to fluid (W/m² °C)
\( h_f \) = Convective heat transfer coefficient from absorber to fluid (W/m² °C)
\( h_r \) = Radiative-convective heat transfer coefficient from absorber to ambient through cover (W/m² °C)
\( h_s \) = Latent heat of fusion (J/Kg °C)
\( h(t) \) = Solar radiation (W/m²)
\( I \) = Time independent part of solar intensity (W/m²)
\( K_r \) = Thermal conductivity of storage material for \( j \)th region (W/m °C)
\( L \) = Total thickness of air collector (m)
\( m \) = Air mass flow rate (Kg/h)
\( m_a \) = Air mass flow rate per unit collector area (Kg/s)
\( M_s \) = Specific mass flow rate (Kg/s m²)
\( n \) = Number of harmonics
\( \Delta P \) = Pressure drop (Pa)
\( \dot{Q}_c \) = Energy consumption (kW h/m²)
\( \dot{Q}_u \) = Useful energy collected (kW h/m²)
\( \dot{R} \) = Reynolds number
\( t \) = Time (s)
\( T_a \) = Ambient temperature (°C)
\( T_{in} \) = Time independent part of ambient temperature (°C)
\( T_c \) = Cover temperature (°C)
\( T_f \) = Fluid temperature (°C)
\( T_i \) = Inlet fluid temperature (°C)
\( T_{s,i} \) = Temperature at top surface in region I (°C)
\( T_{b,i} \) = Temperature at bottom surface in region I (°C)
\( T_{s,ii} \) = Temperature at top surface in region II (°C)
\( T_{b,ii} \) = Temperature at bottom surface in region II (°C)
\( T^\circ \) = Melting temperature (°C)
\( v \) = Speed of wind (m/s)
\( W \) = Width (m)  
\( Y \) = Length of air heater in direction of flow (m)  

**Greek symbols**  
\( \alpha \) = Absorptivity of blackened surface  
\( \eta \) = Daily efficiency (%)  
\( \mu \) = Viscosity of air (kg/m s)  
\( \rho \) = Density of air (kg/m³)  
\( \rho_s \) = Density of storage material for \( j \)-th region (kg/m³)  
\( \tau \) = Transmissivity of glass cover  
\( \omega \) = \( 2\pi/24 \) reciprocal of period (h⁻¹)  
\( \omega_n \) = \( 2\pi/(24 \times 3600) \)  

**Subscripts**  
\( 1 \) = Liquid  
\( s \) = Solid

**INTRODUCTION**

Solar air heaters can be used for many purposes, including crop drying, space heating and regenerating dehumidifying agents. These are classified according to their application and use (Table 1). Solar air heaters, of simple construction and employing cheap materials, can supply air at a temperature above 65°C and with good efficiency [1]. The operation of a conventional solar air heater with two covers in a two pass mode offers an inexpensive method of improving the collector efficiency by about 10–15% [2]. The efficiency of a flat plate solar air heater increases when the collector aspect ratio increases [3]. These systems have not been provided with built-in storage, whereas in many solar energy systems, the requirements of the system and the intermittent incoming radiation demand that energy should be stored so that it can be supplied during off-sunshine hours. The solar energy is stored in different ways for different purposes. Common systems used in storing thermal energy include water tanks [4] or gravel beds, ground, sand, concrete, etc. [5–10], where energy is stored in the form of sensible heat. Thermal energy is also stored in the form of latent heat through phase change materials [11]. Recently, air collectors with built-in thermal energy storage have proved successful with different materials, like ground, concrete, brick, etc., but the effect of the thickness of the material below the heat retrieval plane has not been considered, nor the effect of the ratio of the thickness of the storage material to the total thickness of the collector on the net daily energy gain and daily efficiency.

In the proposed study, a numerical model is proposed for an air collector as shown in Fig. 1. The system is divided into two regions: region I contains a thermal storage material and region II is provided with soil. Thermal energy is extracted between the bottom of region I and the top of region II. Periodic analysis has been performed for time dependent parameters.

Parametric studies have been performed on the design and climatic parameters for the month of June for Delhi climatic conditions.

<table>
<thead>
<tr>
<th>Table 1. Classifications of solar air heaters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Air Heaters</strong></td>
</tr>
<tr>
<td>Without Storage</td>
</tr>
<tr>
<td>Porous</td>
</tr>
<tr>
<td>Non-porous</td>
</tr>
<tr>
<td>With Storage</td>
</tr>
<tr>
<td>Sensible heat</td>
</tr>
<tr>
<td>Latent heat (PCM)</td>
</tr>
<tr>
<td>Water</td>
</tr>
<tr>
<td>Ground</td>
</tr>
<tr>
<td>Concrete</td>
</tr>
<tr>
<td>Sand</td>
</tr>
<tr>
<td>Brick</td>
</tr>
</tbody>
</table>
WORKING PRINCIPLE

The proposed system (Fig. 1) is comprised of two regions: region I is made of different storage materials and the top is blackened to absorb solar radiation. A glass cover is provided to reduce thermal losses. Region II is filled with soil. Absorbed solar energy is allowed to conduct vertically through its thickness. Air flowing under region I collects thermal energy from the bottom of region I, and part of it is convected to the top of region II, which is further conducted through to the ground. The main highlight of the study is that the thickness of the systems \( (L_1 + L_2 = \text{constant}) \) remains constant.

THERMAL ANALYSIS

Energy balance equations for each component of the system have been written with the following assumptions: (i) the heat capacities of the glass cover and air have been neglected, (ii) one dimensional heat conduction has been considered, (iii) flow is streamlined, (iv) no stratification exists perpendicular to the air flow and (v) heat transfer coefficients are constant. The resulting energy balances for the different components are given below.

At the blackened surface \( (X = -L_1) \)

\[
\alpha \pi f(t) = -K_i \left. \frac{\partial T_i}{\partial x} \right|_{x = -L_1} + h_i(T_i |_{x = -L_1} - T_i). \tag{1}
\]

At the bottom of region I \( (X = 0) \)

\[
-K_i \left. \frac{\partial T_i}{\partial x} \right|_{x = 0} = h_i(T_i |_{x = 0} - T_i). \tag{2}
\]

![Schematic view of an air collector](image_url)

**Fig. 1.** (a) Schematic view of an air collector. (b) Cross-section of heater in which air is moving in direction shown.
At the top of region II ($X = 0$)

$$h_a(T_1 - T_1|_{x = 0}) = -K_2 \frac{\partial T_1}{\partial x} \Big|_{x = 0}. \quad (3)$$

At the bottom of the second region ($X = L_2$)

$$-K_2 \frac{\partial T_2}{\partial x} \Big|_{x = L_2} = h_b(T_2|_{x = L_2} - T_s). \quad (4)$$

At the cover

$$h_m(T_1|_{x = -L_1} - T_2) = h_2(T_e - T_s). \quad (5)$$

For an elemental area of $W \cdot dy$ (see Fig. 1b),

$$h_a(T_1|_{x = 0} - T_1)W \cdot dy = \dot{m}_s C_s \frac{dT_1}{dy} \cdot dy + h_a(T_1 - T_2|_{x = 0})W \cdot dy. \quad (6)$$

Equations (1)–(6) have been solved analytically to get an expression for $T_i$ in terms of $T_1|_{x = 0}$ and $T_2|_{x = 0}$.
\[ \frac{dT_i}{dy} + aT_i = f(t). \] (7)

The solution of equation (7) is given as

\[ T_i = \frac{f(t)}{a} \left(1 - e^{-a}\right) + T_a e^{-a}, \] (8)

where

\[ a = \frac{W}{mC_a} (h_d + h_z), \]

\[ f(t) = \frac{W}{mC_a} (h_d T_i|_{t=0} + h_z T_z|_{t=0}). \]

The useful energy gain is expressed as

\[ Q_u = \dot{M}_a C_a (T_i - T_a) \cdot \frac{1}{1000}. \] (9)
Since the temperature at different depths and the fluid temperature are expressed periodically, the solar intensity and ambient temperature can be expressed periodically as a Fourier series in time with six harmonics, which is sufficient to represent the actual data. Thus:

\[ I(t) = I_0 + \sum_{n=1}^{6} I_n e^{i\omega t} \]  

(10)

and

\[ T_a = T_{a0} + \sum_{n=1}^{6} T_{a_n} e^{i\omega t}. \]  

(11)

Let us consider the configuration given in Fig. 1. The temperature distribution, \( T(x, t) \), in various regions is described by the one dimensional equation of heat conduction:

\[ \rho C \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial x^2}. \]  

(12)

The periodic solution for \( T(x, t) \) may be expressed as [12]:

\[ T_j(x, t) = A_j x + B_j + \sum_{n=1}^{6} (C_{jn} e^{\kappa_{jn} x} + D_{jn} e^{-\kappa_{jn} x}) e^{i\omega t}, \text{ where } j = 1, 2, \]  

(13)

\[ \beta_{jn} = \sqrt{\frac{\omega_j \rho C}{2K}} (1 + i). \]

With the help of equations (1)–(5), (10), (11) and (13), the values of the time independent constants, namely \( A_1, A_2, B_1 \) and \( B_2 \) are determined using a matrix method and are given in Table 2. Similarly, values of the time dependent parameters, \( C_n, C_{n+}, D_{n1} \) and \( D_{n2} \), have also been determined by
solving a matrix. These values are then used to determine the fluid temperature in equation (8). The pressure drop through the duct is determined using the following expression [13]:

$$\Delta P = F \left( \frac{M_c^2}{\rho_s} \right) \left( \frac{L}{d} \right),$$

where

$$F = F_0 + \frac{\gamma d}{\lambda}.$$  \hspace{1cm} (14)

For laminar flow ($R_e \leq 2550$):

$$F_0 = \frac{24}{R_e}; \quad \gamma = 0.9.$$  

For transitional flow ($2550 < R_e \leq 10^4$):

$$F_0 = 0.0094; \quad \gamma = 2.92 \times R_e^{-0.13}.$$ 

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**Fig. 7.** Effect of thickness of concrete on the daily efficiency for a given flow rate and collector length.

**Fig. 8.** Effect of thickness of concrete on daily net energy gain for different lengths.
For turbulent flow ($10^4 \leq R_e < 10^5$):

$$F_0 = 0.059 R_e^{-0.8}; \gamma = 0.73.$$

Now, the energy required to pump the air through the duct can be calculated with the help of equation (14) as

$$Q_r = \frac{\dot{m} \Delta P}{\rho_a} \left( \frac{1}{1000} \right)$$

(15)

The efficiency of the system is evaluated on a daily basis using the equation

$$\eta_d = \frac{\sum_{i=1}^{24} \dot{m}_i C_i (T_i - T_s)}{\sum_{i=1}^{24} I(t) A_s} \times 100.$$  

(16)
Table 3. Design and climatic parameters used in the study

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>d</td>
<td>0.03</td>
<td>h&lt;sub&gt;n&lt;/sub&gt;</td>
<td>9.6</td>
</tr>
<tr>
<td>W&lt;sup&gt;1&lt;/sup&gt;</td>
<td>1</td>
<td>h&lt;sub&gt;1&lt;/sub&gt;, h&lt;sub&gt;2&lt;/sub&gt;</td>
<td>2.5, 2.5</td>
</tr>
<tr>
<td>l&lt;sub&gt;c&lt;/sub&gt;</td>
<td>1 – 10</td>
<td>σ, τ</td>
<td>0.9, 0.9</td>
</tr>
<tr>
<td>m&lt;sub&gt;s&lt;/sub&gt;</td>
<td>30–200 Kg/h</td>
<td>T&lt;sub&gt;a&lt;/sub&gt;</td>
<td>33.59</td>
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<td>J&lt;sub&gt;n&lt;/sub&gt;</td>
<td>368,1667</td>
<td>ρ&lt;sub&gt;s&lt;/sub&gt;</td>
<td>1.126</td>
</tr>
<tr>
<td>v&lt;sup&gt;1&lt;/sup&gt;</td>
<td>1.5</td>
<td>h&lt;sub&gt;n&lt;/sub&gt;</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Table 4. Thermophysical properties of storage materials

<table>
<thead>
<tr>
<th>Property</th>
<th>Brick</th>
<th>Concrete</th>
<th>Sand</th>
<th>PCM (Paraffin wax: Sunoco-P166)</th>
<th>Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting temperature (°C)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>50</td>
<td>—</td>
</tr>
<tr>
<td>Latent heat of fusion (kJ/kg)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>190</td>
<td>—</td>
</tr>
<tr>
<td>Solid and liquid densities (kg/m&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>1500</td>
<td>2300</td>
<td>1600</td>
<td>930, 830, 2050</td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity (W/m·°C)</td>
<td>0.7</td>
<td>1.0</td>
<td>0.3</td>
<td>0.21, 0.52</td>
<td></td>
</tr>
<tr>
<td>Solid and liquid specific heat (kJ/kg·°C)</td>
<td>0.84</td>
<td>0.88</td>
<td>0.88</td>
<td>2.1, 1.84</td>
<td></td>
</tr>
</tbody>
</table>

With the help of equations (9) and (15), the daily net energy gain can be determined by subtracting the daily energy required from the useful energy gain as

\[ \bar{Q}_n = \Sigma \bar{Q}_a - \Sigma \bar{Q}_l. \]  

(17)

**NUMERICAL RESULTS AND DISCUSSION**

For the parametric study, the values of design and climatic parameters and heat transfer coefficients used in the study are given in Table 3. In the case of phase change material (Paraffin wax Sunoco-116), the method for determining \( K_{st} \) and \( \rho_{st} \) has been described in the Appendix. The thermophysical properties of all the storage materials considered are given in Table 4.

The hourly variations in ambient temperature and solar intensity calculated by Fourier analysis are shown in Fig. 2 for the month of June for Delhi climatic conditions. Figure 3 shows the hourly variations in temperature at \( x = -L_1, x = 0 \) in region I and \( x = 0, x = L_2 \) in region II and in outlet air temperature. The temperature in region I is higher due to direct absorption of solar radiation by the blackened surface. In region I, a phase difference of about 4 h is observed for a concrete thickness of 0.1 m. The effect of thickness of storage material (concrete) on useful energy gain (equation (9)) for a given air flow rate and collector length is shown in Fig. 4. It is observed that there is a significant phase shift as the thickness increases. Because of the storage effect, the magnitude of the energy gain reduces with a phase shift of about 10–12 h.

In order to observe the effect of different storage materials on outlet air temperature, region I is provided with thermal energy storage materials (brick, concrete, sand, PCM and ground), whereas only ground is provided in region II. The brick and concrete gives better results compared to the others (Fig. 5). In this study, concrete has been chosen for further analysis, as it is simple to prepare the required slab thickness.

The effects of collector length on daily efficiency (\( \eta_d \)) (equation (16)) and pressure drop (\( \Delta P \)) (equation (14)) for different flow rates is shown in Fig. 6. Both daily efficiency and pressure drop increase with collector length and flow rate, owing to the simple fact that energy gain increases at higher flow rates, resulting in a higher daily efficiency. Daily efficiency as a function of concrete thickness is also shown in Fig. 7 for a given flow rate and collector length. The daily efficiency decreases as the thickness increases, as expected. It is also found that the daily net energy gain (\( \bar{Q}_{ne} \)) decreases with both thickness of concrete and collector length (Fig. 8). The reason is simply that energy consumption is greater at a higher collector length.

Figures 9 and 10 show the daily useful energy gain (equation (17)) and maxima and minima of hourly useful energy gain as a function of the ratio of the thickness of the concrete to the total collector thickness. The daily useful energy gain decreases with increase in the ratio (Fig. 9), whereas the maxima in the energy gain decrease and its minima increase as \( L_1/L \) increases.
REFERENCES


APPENDIX

In the case of phase change materials, the effective thermal conductivity and specific heat are calculated using the following equations [14]:

\[ K_e = K_0 \left(1 - \frac{L_0}{L}\right) + K_1 \left(\frac{L_1}{L}\right) \]  \hspace{1cm} (A1)

\[ C_e = C_0 + \frac{H_s}{(T - T_0) \left(\frac{L_1}{L}\right)} \]  \hspace{1cm} (A2)

The steady state temperature arranged over the thickness of the PCM slab can be obtained from,

\[ T = \frac{1}{L} \int_0^L T(x) \, dx \]  \hspace{1cm} (A3)

\( T(x) \) can be analytically expressed after solving the energy balance equation for each component of the PCM slab.