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Review of solar-energy drying systems III: low temperature air-heating solar collectors for crop drying applications

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Abstract

The efficient design and construction of solar-energy air-heating collectors are critical to the overall performance of the distributed (indirect mode) and mixed-mode designs of either active or passive solar-energy crop dryers. A review of the various designs and the performance evaluation technique of flat-plate solar-energy air-heating collectors for low temperature (i.e. temperature elevations between 10\degree C–35\degree C above ambient) solar-energy crop drying applications are presented. The appropriateness of each design and the component materials selection guidelines are highlighted. \textcopyright{} 1998 Elsevier Science Ltd. All rights reserved.

\textit{Keywords:} Solar air-heating collectors; Designs; Bare-plate air heaters; Front-pass air heaters; Back-pass air heaters; Parallel-pass air heaters; Double-pass air heaters; Perforated-plate air heaters; Materials selection; Performance evaluation techniques

\textbf{Nomenclature}

\begin{itemize}
  \item[$A$] Collector solar-energy collection area (m\textsuperscript{2})
  \item[$C_P$] Specific heat capacity of working fluid (i.e. air) (J kg\textsuperscript{-1} K\textsuperscript{-1})
  \item[$F_R$] Collector heat removal factor
  \item[$I$] Insolation (W m\textsuperscript{-2})
  \item[$\dot{m}$] Mass flow rate of working fluid through collector (kg s\textsuperscript{-1})
  \item[$n$] Julian day number
  \item[$Q_u$] Useful heat gain by collector (J)
\end{itemize}

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1. Introduction

Solar-energy collectors are devices employed to gain useful heat energy from incident solar radiation. They can be of the concentrating or flat-plate type. Concentrating solar-energy collectors operate at higher temperatures than the flat-plate type. For solar-energy crop drying applications, the flat-plate collectors provide the temperature elevations desired and are more appropriate techno-economically than the more complex concentrating collectors [1]. A simple solar-energy collector consists basically of an absorbing surface (usually painted black) which absorbs the insolation and transmits it (in the form of heat) to a working fluid (commonly water or air). For solar crop drying applications, air is used commonly as the working fluid. Provision is made to circulate the air through a duct, one side of which is the absorber. For passive solar drying applications, air flow through the air heater is by natural convection.

2. Solar energy air heating collectors

Solar-energy air-heating collectors can be classified broadly into two types, viz: bare-plate and covered-plate solar-energy collectors [1, 2].

2.1. Bare-plate solar-energy air-heating collectors

These are the simplest forms of solar-energy air heaters. They consist simply of an air duct, the uppermost surface of which acts as the solar-energy absorber plate with the rear surface insulated (see Fig. 1). Bare-plate solar-energy collectors are used widely in crop drying operations (both for natural and forced-convection systems). Corrugated iron sheet roofs of buildings are being adapted frequently as bare-plate collectors for heating the air space within the building, as in some large solar-energy storage barns [3].

Generally, optical losses due to transmission reduction of the incoming solar radiation by transparent covers in solar-energy collectors are roughly 10% [4]. Thus, the optical efficiency (i.e. the maximum efficiency attainable at very low collector temperature rises, i.e. \( \Delta T \to 0 \)) of
covered-plate solar-energy collectors is 10% less than the efficiency of bare-plate collectors [4]. Though they experience minimal optical losses, bare-plate solar-energy collectors have huge thermal losses through the exposed surface. Consequently, they have low thermal efficiencies [2, 5] at moderately elevated temperatures but operate more efficiently at very low temperature elevations (≤ 10°C above ambient) [1]. Thus, they are only suited for very low temperature solar-energy drying applications, as in some storage facilities. The poor performance of bare-plate solar-energy collectors is, however, compensated by their simplicity and low cost of construction.

2.2. Covered-plate solar-energy air-heating collectors

Upward heat losses from solar-energy air heaters are minimised by the use of one or more transparent cover materials above and usually parallel to the absorber plate. Common cover materials used are glass, plexiglass and clear plastics. The cover material prevents convective heat losses from the absorbing plate, reduces long-wave radiative heat losses and protects the absorber plate against cooling by occasional rainfall. Appropriate cover materials must be reasonably opaque to long-wave radiation. Covered-plate solar-energy air heaters, thus, operate at higher efficiencies than bare-plate solar-energy air heaters at moderate temperature elevations. However, the cost of construction is increased, and since the cover materials are usually vulnerable to breakage, maintenance costs are also increased [2]. Covered-plate solar-energy air heaters are recommended generally for temperature elevations of between 10°C–35°C above ambient [1]. Generic types of covered-plate solar-energy air-heating collectors are described in the following paragraphs.

2.2.1. Front-pass covered-plate solar-energy air-heating collectors

Here, the air to be heated passes through the duct between the cover material and the absorber plate (the back side of which is insulated), see Fig. 2. Heat transfer to the air stream is, thus, through the front side of the absorber plate.

2.2.2. Back-pass covered-plate solar-energy air-heating collectors

Here the absorber plate is placed directly behind the transparent cover with a layer of static air separating it from the cover. The air to be heated flows between the inner surface of the
absorber plate and the layer of insulation, with heat transfer via the rear side of the absorber plate (see Fig. 3). Back-pass solar air heaters have generally been found to be more efficient than the front pass types [6].

2.2.3. Suspended-plate covered solar-energy air-heating collectors

The absorber plate here is fixed between the cover material and the backing layer of insulation. The air to be heated flows on either side of the absorber plate, thus increasing the heat transfer surface area. The absorber plate is, thus, at a lower temperature and, consequently, re-radiates less heat. The two generic configurations of suspended-plate solar-energy air heaters are the parallel-pass solar air heaters [see Fig. 4(a)] and the double-pass solar-energy air heaters [see Fig. 4(b)]. A less common triple-pass design has also been reported [7]. The suspended-plate solar-energy air heaters, thus, operate at higher efficiencies than the bare-plate, front-pass or back-pass solar air heaters [2]. An efficiency of up to 65% has been reported for the parallel-flow type [8], though test or collector details were not specified.

2.2.4. Perforated–plate covered solar-energy air-heating collectors

Also known as matrix solar air heaters, perforated-plate solar-energy air-heating collectors are modified forms of the suspended plate solar-energy collectors. They are made, usually, of a porous high surface area absorber [9], such as a blackened gauze or wood shavings (see Fig. 5). Thus, there is an increased heat-transfer surface area between the air and the absorber plate.
3. Performance evaluation theory of flat-plate solar-energy collectors

The useful heat gain by a collector can be expressed as [10]

\[ Q_u = \dot{m}C_p(T_o - T_i) \]  

and the following heat balance expresses the thermal performance of a collector under steady-state conditions [10, 11]

\[ Q_u = AF_R[I(\tau\alpha)_e - U_L(T_i - T_a)]. \]  

A measure of collector performance is the collector efficiency, defined as the ratio of useful heat gain over any time period to the incident solar radiation over the same period [12].

We can, thus, define efficiency as,

\[ \eta = \frac{Q_u}{I_A}. \]  

From Eqs. (1) and (3),

\[ \eta = \dot{m}C_p\frac{(T_o - T_i)}{I_A} \]  

Fig. 4. Suspended-plate air-heating solar-energy collectors: (a) parallel-pass; (b) Double-pass.
and from Eqs. (2) and (3),

\[ \eta - F_R(\tau z)_e - F_R U_L \left( \frac{T_i - T_a}{I} \right) \]  

(5)

The general test procedure is to determine \( Q_u \) from Eq. (1) and measure \( I, T_i \) and \( T_a \) (which are used for analysis based on Eq. (2)) by operating the collector under nearly steady-state conditions in test facilities (i.e. either indoor or outdoor). Instantaneous efficiencies calculated from Eq. (3) are plotted against \((T_i - T_a)/I\) and the intercept \((F_R(\tau z)_e)\) and slope \((-F_R U_L)\) determined [as in Eq. (5)]. These parameters are not constant, \( U_L \) depending on temperature and wind speed and \( F_R \) being a weak function of \( U_L \). However, the long term performance of many solar-energy air-heating collectors can be characterised by the determined intercept and slope [10].

Although natural-convection solar air heaters are being used frequently for crop drying applications, very little detailed information is available about their air flow rates, efficiencies and the general performance of even the simplest natural-convection solar air heaters [1]. Air flow measurements for natural-convection solar-energy air heaters (as indeed for most natural circulation systems) are very difficult. The measurement of natural-circulation solar-energy air-heating collector efficiencies based on Eq. (4) is not straight forward for this reason. An approach could be to determine the efficiency of such a collector under forced-convection at a given air-flow rate, characterise the collector by determining the parameters \((F_R(\tau z)_e)\) and \((-F_R U_L)\) in Eq. (5) and, then, use Eq. (5) as a basis for long term performance evaluation of the collector under free flow conditions [13]. The typical performance curves of generic types of solar-energy air-heating collectors are illustrated in Fig. 6 [13].

4. Design of solar-energy air-heating collectors

The amount of solar-energy absorbed by a solar-energy air heater depends largely on [1]:

- the level of insolation and the solar collector orientation;
- the absorptance of the absorber surface; and
- the transmittance of the cover material (not applicable to bare-plate solar collectors).
It is obvious that the higher the level of insolation, the greater is the solar-energy absorbed by the solar-energy air heater. Thus, the knowledge of typical insolation values is required for proper design (sizing) of the solar-energy air heater. Irrespective of the collector slope and orientation, the heat output of a solar collector varies considerably with the insolation on it, and insolation levels vary considerably with location and the period of the year. There is the need, therefore, to match the heat output of the solar collector with the drying load. A less rigorous approach is to design the collector such that the absorbing surface is perpendicular to the insolation at solar noon on a representative day during the period of the year and for the particular site where the drying is undertaken. The collector should be ideally oriented facing either north or south, depending on the site, and with its slope (to the horizontal) depending on the chosen period. The ideal collector slope at solar noon of a particular day for a chosen site can be computed from the following [1]

$$\beta = (\phi - \delta)$$

(6)

where the declination angle $\delta$ is given by [10]

$$\delta = 23.45 \sin \left(360 \frac{284 + n}{365}\right).$$

(7)
Another major factor that determines the amount of solar-energy absorbed by a collector is the absorptance of the absorbing surface (which is the fraction of the incident solar radiation that is absorbed by the surface). The absorber material, in addition to having a high absorptance of the incident radiation, should also have a low emissivity, good thermal conductivity and should be stable thermally under the temperature regimes encountered during operation and stagnation. It should also be durable, have a low weight per unit area and, most importantly, be cheap. Black-coated metal sheets (for example, corrugated galvanised iron sheets) are used frequently as absorbers due to their ease of use, availability and relatively low cost. Other absorber materials in use include black plastic sheets, black-painted rocks, charcoal and ash. The use of selective absorbing surfaces may not be justified economically for low cost drying operations. A major consideration in the choice of materials for the construction of solar-energy air heaters for crop drying operations would be their cost and local accessibility. The properties of common absorber materials are shown in Table 1 [1].

The transmittance of the cover material is also an important parameter that affects the amount of solar-energy absorbed by a collector. A good cover material should have a high transmittance in the visible range of the electromagnetic spectrum and a low transmittance to infra-red radiation in order to trap effectively the re-radiated heat from the absorber plate. Other qualities of a good cover material include low heat absorptivity, stability at the operating and stagnation temperatures, resistance to breakage, durability under adverse weather conditions and low cost.

Glass has been used very widely as a cover material due to its high transmittance to visible light, low transmittance to infra-red radiation and stability to high temperatures. Its high cost, low shatter resistance and relatively high weight per unit area (which increases the cost of supporting structures) have necessitated the need for alternative cover materials. Plastics are being used increasingly, their major limitations being their relatively low stability at higher collector operating temperatures and their low durability under weather conditions, particularly degradation under ultra-violet radiation. However, some plastics have been treated to overcome at least some of these shortcomings. Some plastic covers show high transmittance to visible light and equally low transmittance to infra-red. Plastics weigh about 10% for the same area of glass. The properties of some cover materials are given in Table 2 [14, 15]. It should be emphasized that the over riding factor in the choice of materials for the overall design of cheap

<table>
<thead>
<tr>
<th>Coating</th>
<th>Substrate</th>
<th>Absorptivity</th>
<th>Emissivity</th>
<th>Maximum temp.</th>
<th>Durability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Black nickel</td>
<td>Iron, copper, zinc/aluminium</td>
<td>0.85–0.96</td>
<td>0.05–0.15</td>
<td>288°C</td>
<td>medium</td>
</tr>
<tr>
<td>Black chrome</td>
<td>Nickel/aluminium copper, iron</td>
<td>0.82–0.96</td>
<td>0.04–0.15</td>
<td>427°C</td>
<td>Very good</td>
</tr>
<tr>
<td>Black copper</td>
<td>Copper</td>
<td>0.85–0.95</td>
<td>0.10–0.15</td>
<td>316°C</td>
<td>—</td>
</tr>
<tr>
<td>Copper oxide</td>
<td>Copper, iron, aluminium</td>
<td>0.87–0.90</td>
<td>0.08–0.16</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Anodic aluminium</td>
<td>Aluminium</td>
<td>0.90–0.96</td>
<td>0.10–0.23</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Metal carbide</td>
<td>Copper, glass</td>
<td>0.82–0.93</td>
<td>0.02–0.05</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>PbS paint</td>
<td>ANY</td>
<td>0.90</td>
<td>0.30</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Selective paint (corallur)</td>
<td>Most</td>
<td>0.93</td>
<td>0.30</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Black paint</td>
<td>Any</td>
<td>0.95–0.97</td>
<td>0.95–0.97</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Material</td>
<td>Thickness available (mm)</td>
<td>Transmittance of visible light&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Transmittance of infrared radiation</td>
<td>Weatherability&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Ultimate tensile strength (N mm&lt;sup&gt;-2&lt;/sup&gt;)</td>
</tr>
<tr>
<td>----------------------------------------------</td>
<td>--------------------------</td>
<td>--------------------------------------------</td>
<td>-------------------------------------</td>
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<td>----------------------------------------------</td>
</tr>
<tr>
<td><strong>Commonly available plastic films</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polyethylene (PE) (u.v.- inhibited)</td>
<td>0.01 upwards</td>
<td>0.86</td>
<td>0.77</td>
<td>Poor</td>
<td>10–30</td>
</tr>
<tr>
<td>Polypropylene (PP)</td>
<td>0.01–0.25</td>
<td>0.92</td>
<td>No data</td>
<td>Fair</td>
<td>30–275</td>
</tr>
<tr>
<td>Polyvinyl chloride (PVC)</td>
<td>0.015–0.75</td>
<td>0.90</td>
<td>0.12</td>
<td>Poor</td>
<td>10–70</td>
</tr>
<tr>
<td>Polyethylene teraphthalate (polyester) (PET)</td>
<td>0.002–0.35</td>
<td>0.88</td>
<td>0.24</td>
<td>Very good</td>
<td>140–275</td>
</tr>
<tr>
<td>Polyvinyl fluoride (PVF) e.g. Tedlar&lt;sup&gt;TM&lt;/sup&gt;</td>
<td>0.01–0.1</td>
<td>0.86–0.92</td>
<td>0.33</td>
<td>Very good</td>
<td>50–125</td>
</tr>
<tr>
<td>Ethylene/tetra-fluoro-ethylene Copolymer (ETFE) e.g. Teflon&lt;sup&gt;TM&lt;/sup&gt;</td>
<td>0.05–0.2</td>
<td>0.95</td>
<td>0.20</td>
<td>Very good</td>
<td>50–55</td>
</tr>
<tr>
<td><strong>Less common films</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cellulose acetate</td>
<td>0.02–0.75</td>
<td>0.93</td>
<td>0.03</td>
<td>Fair</td>
<td>50–110</td>
</tr>
<tr>
<td>Cellulose triacetate</td>
<td>0.05–0.5</td>
<td>0.93</td>
<td>0.11</td>
<td>Good</td>
<td>62–110</td>
</tr>
<tr>
<td>Cellulose acetate butyrate</td>
<td>0.28–0.75</td>
<td>0.93</td>
<td>—</td>
<td>Good</td>
<td>35–60</td>
</tr>
<tr>
<td>Ethylene/vinyl acetate copolymer (EVA)</td>
<td>0.02 upwards</td>
<td>—</td>
<td>—</td>
<td>Poor</td>
<td>6–24</td>
</tr>
<tr>
<td>Ethylene chlorotrifluoro-ethylene (ECTFE)</td>
<td>0.01–2.2</td>
<td>—</td>
<td>—</td>
<td>Very good</td>
<td>55–70</td>
</tr>
<tr>
<td>Fluoroethylene propylene (FEP)</td>
<td>0.01–0.75</td>
<td>0.93</td>
<td>—</td>
<td>Very good</td>
<td>17–20</td>
</tr>
<tr>
<td>Perfluoro-alkoxy (PFA)</td>
<td>0.01–0.75</td>
<td>—</td>
<td>—</td>
<td>Very good</td>
<td>27–50</td>
</tr>
<tr>
<td>Polychlorotrifluoro-ethylene (PCTFE)</td>
<td>0.02–0.25</td>
<td>—</td>
<td>—</td>
<td>Very good</td>
<td>34–70</td>
</tr>
<tr>
<td>Polycarbonate (PC)</td>
<td>0.006–0.35</td>
<td>0.87–0.92</td>
<td>—</td>
<td>Good</td>
<td>55–80</td>
</tr>
<tr>
<td>Polymethyl metacrylate (acrylic) (PMMA) e.g. Teflon&lt;sup&gt;TM&lt;/sup&gt;</td>
<td>0.05–0.25</td>
<td>0.87</td>
<td>0.01</td>
<td>Good</td>
<td>55–60</td>
</tr>
<tr>
<td>Polystyrene (PS)</td>
<td>0.006–0.5</td>
<td>0.87–0.92</td>
<td>0.35</td>
<td>Fair</td>
<td>55–80</td>
</tr>
<tr>
<td>Vinyl chloride/acetate copolymers</td>
<td>0.02–0.75</td>
<td>—</td>
<td>—</td>
<td>Fair</td>
<td>17–55</td>
</tr>
<tr>
<td><strong>Other materials</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horticultural glass</td>
<td>3.0</td>
<td>0.90</td>
<td>0.01</td>
<td>Very good</td>
<td>—</td>
</tr>
<tr>
<td>PVC-coated polyester cloth</td>
<td>—</td>
<td>0.10</td>
<td>—</td>
<td>Very good</td>
<td>150</td>
</tr>
</tbody>
</table>

<sup>a</sup>Where no data are given for visible light transmittance, the material is quoted as being “transparent” by Ref. [15].

<sup>b</sup>The ageing of materials depends on many factors, and there is no overall accepted standard criterion for weatherability. In moderate climates, polyethylene rarely lasts for more than 2 years, whereas some fluoroplastics can last for more than 15 years.
and simple solar dryers is cost, thus certain desired material properties may be compromised during design and construction of solar-energy air heaters.

5. Conclusion

For low temperature solar-energy drying applications (temperature elevations of $<40^\circ$C above ambient), single-glazed solar-energy air-heating collectors are adequate. Where higher temperature rises are desired, double or triple-glazed solar-energy air heaters can be used to reduce drastically the upward convective and re-radiative heat losses. However, the resulting higher temperature rise would imply more insulation than in bare-plate or single covered-plate solar-energy air heaters [1]. The additional cost of constructing double or triple-glazed solar-energy air heaters (with improved insulation) may not be justified economically for numerous low cost passive solar-energy dryer designs. Because of the considerable heat losses in bare-plate solar-energy air heaters (with temperature elevations below $10^\circ$C above ambient), they would require high air velocities ($\approx 5$ ms$^{-1}$) [1]. The limitation imposed by this is the use of fans which, thus, makes bare-plate solar-energy air heaters inappropriate for natural-circulation solar-energy dryers. For higher temperature rises, the reduction of heat losses from the absorber plate becomes necessary by the use of glazing. Generally, for temperature rises of between $10^\circ$C–$35^\circ$C, single-glazed solar-energy air heaters are more effective overall than double or triple-glazed ones [1]. Single-glazed solar-energy air-heating collectors are, thus, more appropriate for natural-circulation solar-energy drying applications.

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