A Numerical and Experimental Investigation of Low-conductivity Unglazed, Transpired Solar Air Heaters

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The performance of low-conductivity unglazed, transpired solar collectors was determined numerically and experimentally. The numerical work consisted of modeling flow conditions, plate geometries, and plate conductivities with modified commercial computational fluid dynamics software, and the experimental work compared the performance of two plate geometries made with high and low conductivity materials under a variety of flow conditions. Good agreement was found between the numerical and experimental results. The results showed that for practical low-conductivity materials, performance differed little from the equivalent plate geometry in high-conductivity material.

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Background

Unglazed transpired collectors are perforated panels that are exposed to solar radiation and do not have a cover. Air is drawn through the perforations in a once-through manner by forced ventilation (Fig. 1). The collector temperature is low, relative to systems that recirculate the air, and the first law efficiency of the system can be over 80 percent. Mass fluxes of the air passing through the collector typically range from 0.01 to 0.05 kg/s-m^2. Aluminum corrugated plates are often used for the collector. Using other materials would reduce cost and, if they are thin and flexible, the collectors could be temporarily deployed in the field for applications such as crop drying. Polymer materials could also resist attack from airborne corrosive droplets, such as salt spray in coastal environments.

High- and low-conductivity plates differ in that radiation losses from the low-conductivity plate depend on local plate temperature, which varies with location on the surface, unlike a high-conductivity, isothermal plate. Net heat flux on a low-conductivity plate varies with position on the surface since there will be relatively high radiation losses in the areas where the plate temperature is high. Heat exchange effectiveness is also not clearly defined for a collector whose surface temperature varies.

A number of authors have studied transpired material heat transfer but their papers were not related to geometries, materials, or operating conditions appropriate to this study. Hubbell and Cain [1] used multiple plates with porosities of 9 to 25 percent and Sparrow and Ortiz [2] developed front surface heat transfer correlations for two plates at 14 and 22 percent porosity. Both of these studies used plates with much higher porosity than would be used for transpired solar collectors. Andrews et al. [3] studied discrete hole heat transfer from plates 3.3 to 6.4 mm in thickness, which are too thick for transpired collectors. Rhee and Edwards [4] analyzed transpired flat and corrugated collectors covered by two cover glasses and stretched teflon film. None of these studies addressed the issue of conductivity. Recent work concerning polymer heat exchangers has studied the long-term mechanical behavior of materials under high stresses in liquid service [5]. Unglazed transpired collectors are not subject to these conditions.

Kutscher [6] made an extensive study of unglazed flat plate transpired collectors used in ventilation preheat applications and developed heat transfer correlations using heat exchange effectiveness in the classic sense, namely the ratio of heat transfer to the air stream to the maximum possible heat transfer. For a high-conductivity plate, which he found to be isothermal, the effectiveness is algebraically equivalent to the temperature ratio, $(T_{out}-T_{amb})/(T_{plate}-T_{amb})$. For non-isothermal plates, other researchers [7] have defined effectiveness as the ratio $(T_{out}-T_{amb})/(T_{mean}-T_{amb})$ where T_{mean} is the mean radiant temperature on the front surface of the plate. However, that selection of mean temperature is somewhat arbitrary from the standpoint of total convective heat transfer, and the temperature ratio is no longer heat exchanger effectiveness in the classic sense. The mean radiant temperature over the front of the plate is not equal to the maximum possible temperature that the air can reach via convective heat exchange from three regions of a non-isothermal plate (front surface, hole and back surface) with varying local heat transfer coefficients. The quantity $(T_{out}-T_{amb})/(T_{mean}-T_{amb})$ may be useful for comparison purposes, but it is not true effectiveness, and its value is not thermodynamically constrained to be less than or equal to one. The problem of defining effectiveness for a non-isothermal collector was addressed by Gawlik [8]. Because of this issue, we have not used effectiveness as a measure of heat transfer performance in this study, but have used temperature rise for the heated air instead.

Experimental Work

The test facility consisted of a test plate mounting and suction system, an array of 16 300 W floodlamps illuminating the test plate to within ±2 percent uniformity at varying incident radiation levels, and a computerized data acquisition system. More details on the test facility can be found in [6].

Two plate geometries (Table 1) were studied. The geometries were known as types 5 and 8 in Kutscher [6]. The holes were arranged in an equilateral triangle pattern. Black-painted test plates in each geometry were fabricated out of aluminum, with a conductivity of 216 W/m-K, and styrene, with a conductivity of 0.16 W/m-K. An irradiation level of 840 W/m^2 was used. Mass fluxes were 0.02, 0.04, and 0.06 kg/s-m^2. Efficiency was defined as

$$\eta=\frac{\dot{m}c_p(T_{out}-T_{amb})}{I_tA_c}. \tag{1}$$

The results for air temperature rise and efficiency are presented in Table 2. For the plate 5 geometry, the only significant percentage difference in temperature rise between the plastic and aluminum plates occurred at 0.06 kg/s-m^2, where temperature rises are small relative to lower flow rates, and where small changes in absolute temperature have a large effect on total heat transfer to the air. For the plate 8 geometry, the greatest difference in temperature rise occurred at 0.02 kg/s-m^2 where the air heated by the plastic plate had a temperature rise 5.5 percent lower than the temperature rise provided by the aluminum plate. Differences in efficiency were also small.

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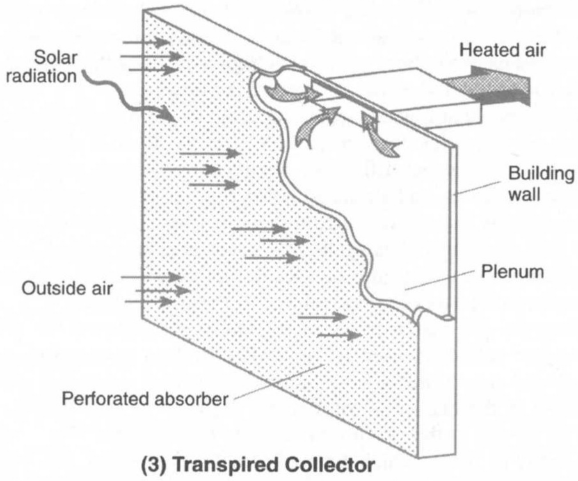

Fig. 1 Typical unglazed transpired collector installation for building ventilation air preheat applications [6].

Numerical Modeling

A finite-volume-based commercial code which solves the set of Navier–Stokes and energy equations was used to model the thermal performance of transpired collectors with hole diameter, hole pitch, thickness, material properties, air flowrate, incident radiation level, and sky temperature as variables. Net solar radiation on the plate was modeled by establishing the surface cells of the plate as heat sources. A custom version of the code was compiled with a routine that modified the enthalpy calculation for each surface cell. The heat flux for surface cells is given as

$$q''_{cell}=I_t-\sigma\varepsilon(T_p^4-T_{sky}^4) \qquad (2)$$

The numerical model was initially used to perform a full factorial analysis to determine how geometry and operational variables affect air temperature rise. The variables and their values are summarized in Table 3. Porosity ranged from 1.0 to 5.1 percent. It should be noted that while an increase in porosity decreases the effective conductivity of the material, porosities used in transpired collector installations are lower than 5 percent, so the effect of porosity on conductivity is small. The radiation level for all runs was 750 W/m^2 and the sky and approach air temperatures were 300 K. Analysis of variance (ANOVA) was performed on the results and a portion of the ANOVA results is also shown. With a standardized effect of 0.6 K, conductivity was found to have a small influence on the thermal performance of transpired collectors.

Table 1 Specifications of the two plate geometries studied experimentally

Plate designator	5	8
Hole diameter (mm)	3.2	1.6
Distance between hole centers (mm)	13.5	27
Porosity (%)	5.0	0.3
Thickness (mm)	1.6	1.6

Table 3 Values used in the factorial analysis and the effects of each variable on air temperature rise

Variable	Low value	High value	Standardized effect (K)
Diameter (m)	0.001524	0.002286	0.7
Pitch (m)	0.009677	0.014503	0.3
Thickness (m)	0.000794	0.001588	0.4
Mass Flux (kg/s-m^2)	0.02	0.04	11.4
Conductivity (W/m-K)	0.16	216	0.6

Figure 2 presents the results of the numerical simulations for the factorial analysis. The similarity in performance for the different conductivity plates between the numerical simulations and the experimental results is apparent. The percent differences in air temperature rise between the low- and high-conductivity cases varied from 0.4 to −7.9 percent, which compare favorably to the experimental results. The percent differences in efficiency between the plates are the same as for the temperature rise results.

To determine when performance does fall off, extreme values of insolation, sky temperature, and plate conductivity were tried. Significant reductions in heat transfer occurred at the very low conductivity value of 0.0016 W/m-K. Reductions in heat transfer compared to the aluminum plate ranged from −21.3 percent for the case of 750 W/m^2 insolation and 0 K sky temperature to −36.9 percent for the case of 7500 W/m^2 insolation and 300 K sky temperature at this conductivity.

An example was modeled of an agricultural collector made of plastic film for temporary crop drying purposes. The material was 0.15 mm thick polyethylene and had a hole diameter of 0.76 mm and hole pitch of 7.3 mm. At a mass flux of 0.02 kg/s-m^2, suitable to obtain a high outlet air temperature appropriate for drying, the collector efficiency is 68 percent. This result is shown in Fig. 3, a plot of efficiency as a function of conductance, the product of conductivity and material thickness. To explore a large range of conductances, the conductivity of 0.15 mm-thick material was varied in the model from 1600 to 0.00016 W/m-K, and the collector efficiency was determined at a mass flux of 0.02 kg/s-m^2. For the sake of comparison, the conductances of aluminum, steel, and styrene collectors at a thickness of 0.8 mm are also marked on the plot. The collector efficiency remains largely unaffected by conductance until values on the order of 10^{-6} W/K or lower are reached. The concept of high-performance low-conductance collectors has been patented by NREL [9].

A variation in surface temperature occurs for low conductance plates. However, the hole pitch is sufficiently small that a large temperature gradient cannot be supported. Also, the local convective heat transfer to the suction air is higher in regions of higher surface temperature (owing to the higher driving ΔT) and conversely lower in regions of lower surface temperature. This tends to flatten the temperature profile. Thus, the mean radiant surface temperature for a low conductance plate is close to the uniform temperature of a high conductance plate and the total radiation

Table 2 Summary of the experimental results for two plate geometries and two plate materials

Mass flux (kg/s-m^2) ±2%	Plate 5				Plate 8			
	Aluminum		Styrene		Aluminum		Styrene	
	ΔT (°C) ±0.5°C	η (%)	ΔT (°C) ±0.5°C	η (%)	ΔT (°C) ±0.5°C	η (%)	ΔT (°C) ±0.5°C	η (%)
0.02	26.5	63±4	26.4	63±4	26.2	63±4	24.8	60±3
0.04	15.7	76±5	15.7	75±5	16.0	77±5	15.8	75±5
0.06	11.3	82±6	10.7	77±5	11.7	84±6	11.6	83±6

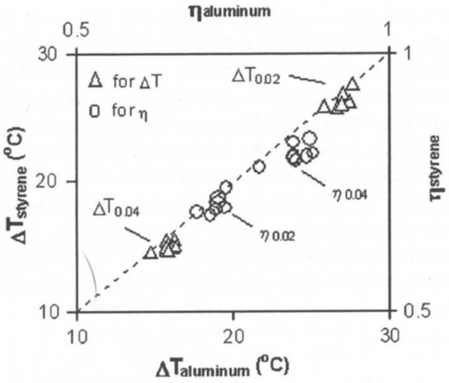

Fig. 2 Factorial analysis numerical results. Subscripts in plot area refer to mass flux (kg/s-m^2).

loss is then insensitive to conductance. Because the plate is not much hotter than ambient, the nonlinearity of radiation loss is not a significant factor.

This study has focused on flat collectors, but the results can be applied to corrugated collectors using a length scale argument. The effect of low conductivity is on the scale of the hole spacing; that is, conductivity alters the temperature gradient in the plate in a pattern which repeats for every hole. Since the characteristic dimensions of corrugated plates, i.e., the amplitude and pitch of the corrugations, are much larger than the hole-to-hole spacing, and since the effect of conductivity on the performance of flat plates is small, one can argue that the effect of conductivity on the performance of corrugated plates will be small.

Conclusions

For the conductivity range of interest, i.e., from high-conductivity aluminum to a low-conductivity but practical material like styrene or polyethylene, the effect of material conductivity on the thermal performance of transpired collectors was small. It was only by modeling the plates with unrealistically low-conductivity material that thermal performance was degraded. These results have an important ramification for the manufacture of flat and corrugated transpired collectors. Low-conductivity materials can be used with no thermal performance penalty but a great benefit in cost savings and corrosion resistance. Collectors can be made of flexible sheets to be rolled up and stored when not needed, such as after crop drying is completed.

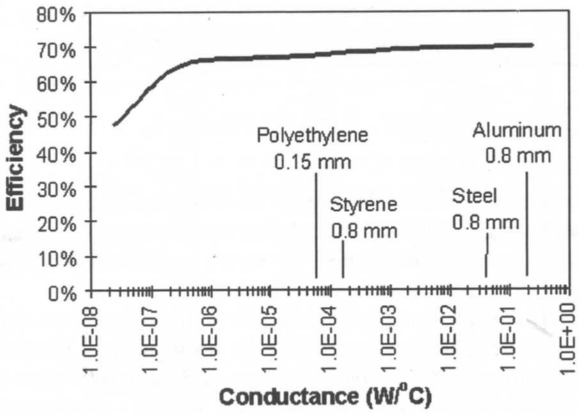

Fig. 3 Collector efficiency over a wide-range of conductances at a mass flux of 0.02 kg/s-m^2,

Nomenclature

A = area, m^2
c_p = specific heat of air, J/kg-K
I = incident radiation, W/m^2
$\dot{m}$ = mass flow rate of air through absorber, kg/s
q'' = heat flux, W/m^2
T = temperature, K

Subscripts

amb = ambient
c = collector
$cell$ = cell
$mean$ = average radiant temperature of plate surface
out = outlet conditions downstream of absorber
p = plate
sky = sky
t = total (direct+diffuse)

Greek

ε = plate emissivity
η = efficiency
σ = Stefan-Boltzmann constant, 5.67×10^{-8} W/m^2-K^4

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