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0038-092X/98/$ - see front matter

THE ‘‘EVAPORATIVE CAPACITY’’ AS A PERFORMANCE INDEX FOR A SOLAR-DRIER AIR-HEATER

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Abstract—This paper presents a new index, called the ‘‘evaporative capacity’’, for rating the performance of the solar air heater in a solar drier consisting of solar air heater and a drying chamber in series. The proposed index complements the widely-used ‘‘collector efficiency’’ as a performance indicator of the solar collector, by taking into account the specific use that is to be made with the heated air. Presented is a detailed method for calculating the evaporative capacity, and a comparison of this new index with the thermal efficiency index, demonstrating its superiority. General charts for a rapid determination of the evaporative capacity are presented, and some possible applications of these charts are described.

1. INTRODUCTION

Several authors, among them Fath (1995); Ahmad *et al*. (1996); Njomo (1995); Tris *et al*. (1995), have reported both theoretical and experimental studies on the optimization of solar air heaters. Most of them consider the pertinent performance indicator to be the collector's thermal efficiency, given by

$$\eta_c = \frac{\dot{m}_{ha} c_{pha}(t_1 - t_a)}{A_c G}. \quad (1)$$

On the other hand, for a solar air heater designed as a component in a solar drying (as shown in Fig. 1), it appears that this criterion may have some limits, as is underlined by considering an actual case, as follows.

Consider a solar air heater operating for mango drying in Ouagadougou in August at 9 am, and that the meteorological conditions at 9 am were: $t_a = 26.3$°C, $e_a = 77$%, $V_a = 2.6$ m/s and $G = 350$ W/m^2, as taken from an example treated by Jannot (1994). By applying the Whillier-Bliss formula (Duffie and Beckman, 1980), the calculation of the thermal efficiency of a glass covered solar air heater (similar to the one represented on Fig. 1) yields the following results for two specified air flow rates: (a) for an air flow rate to collector area ratio of 0.025 kg s^{-1}m^{-2}, $\eta_c = 35$%, and (b) for an air flow rate to collector area ratio of 0.05 kg s^{-1}m^{-2}, $\eta_c = 41$%. At the same time, the collector outlet air conditions would be as follows: (a) $t_1 = 32.7$°C and $e_1 = 53.4$%; (b) $t_1 = 30$°C and $e_1 = 61.8$%.

But for the mangoes to be sufficiently dried, their water content X must reach 12% dry basis, which corresponds to a water activity in the product of $a_w = 0.5$, according to Fournier and Guinebault (1995), who defined the water activity a_w as the relative humidity of air in equilibrium with the material at the same temperature. Thus mangos that have $X = 16$% dry basis (corresponding to $a_w = 0.6$) need to be further dried. It appears that in case (b) the collector outlet air cannot dry mangoes having $X = 16$% dry basis, since $e_1 = 61.8$% and $e_1 > 100a_w$, whereas in case (a), drying is still possible, since $e_1 = 53.4$% and $e_1 < 100a_w$. Nevertheless, the comparison of the thermal efficiencies in case (a) and (b) would lead us to choose an air flow rate to collector area ratio of 0.05 kg s^{-1} m^{-2}, whereas taking into account the particular use that is made with the heated air will lead us to choose a ratio of 0.025 kg s^{-1} m^{-2}. This consideration leads us to study a different performance index, to be used when a solar air heater is designed for food drying.

1.1. *Solar air heater evaporative capacity*

Consider air that is heated by a solar collector and passes through the drier, as represented schematically on the psychometric chart of Fig. 2. Air at point a enters the collector where it is

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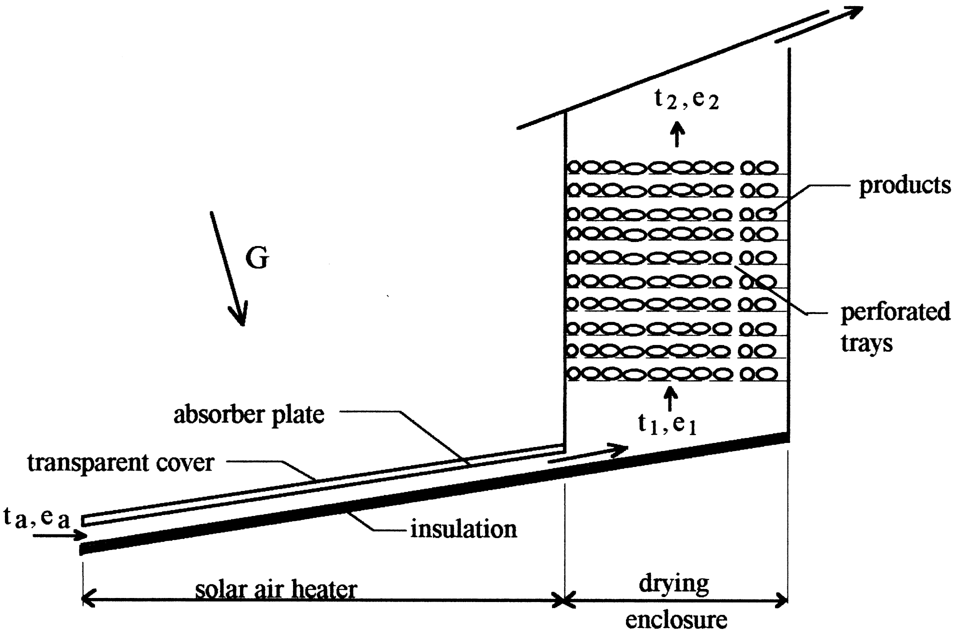

Fig. 1. Schematic view of the solar drier.

heated at a constant pressure. Then, at point 1 it enters the drying enclosure, where it is isenthalpically humidified before leaving the drier at point 2. If a_w is the water activity of food in the drier, the maximum rate at which water can be extracted by the air flow from the product is

$$E = \dot{m}_{da}(x_{2m} - x_a) \quad (2)$$

where $\dot{m}_{da}$ is the dry air flow rate, x_a is the ambient absolute humidity, and x_{2m} is the drier outlet absolute humidity when air leaves the drier in equilibrium with the product, i.e., when $e_{2m} =$

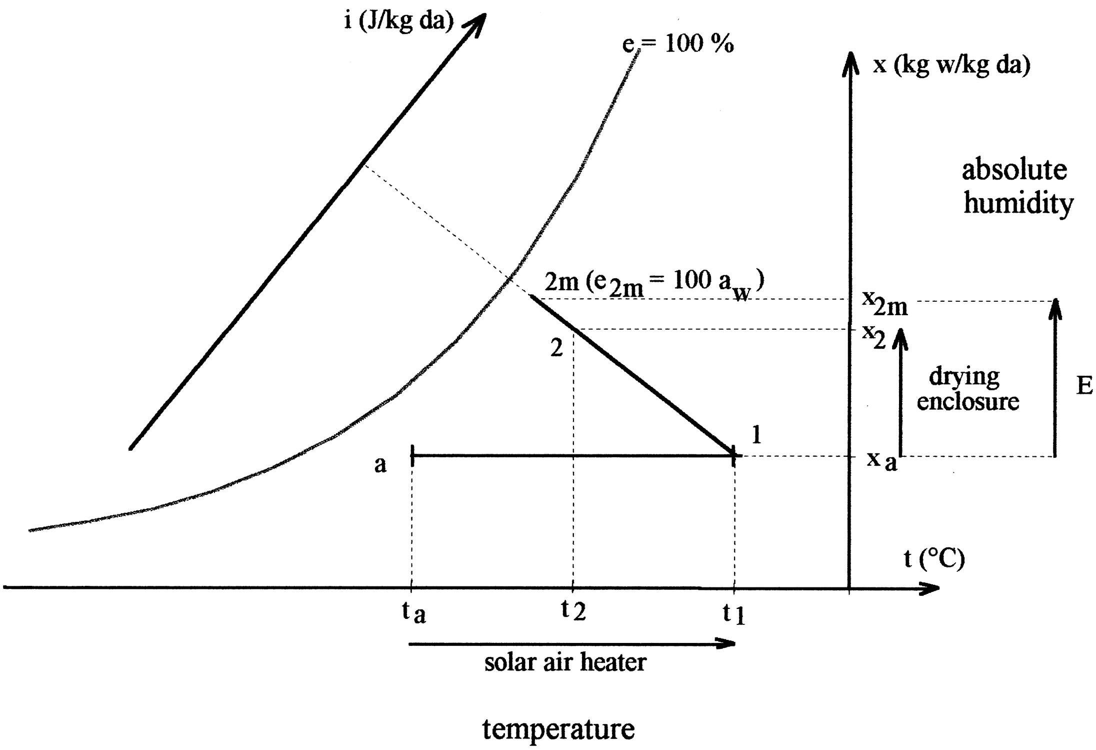

Fig. 2. Schematic representation on a psychrometric chart of the air evolution in a solar drier.

$100a_w$. E is called the evaporative capacity of the solar air heater, and by application of the formula of Jannot (1993), its calculation procedure is as follows:

Atmospheric conditions (t_a, e_a, v_a, G) are presumed to be known. The partial vapor pressure in air is first calculated as:

$$p_{va} = \frac{e_a}{100}\, p_s(t_a) \tag{3}$$

with

$$\log_{10}[p_s(t_a)] = 2708.2 - \frac{372544}{t_a} - 516.56 \log_{10}(t_a) \tag{4}$$

The thermal efficiency η_c of the solar collector is calculated by the Hottel-Whillier-Bliss equation (Duffie and Beckman, 1980; Sfeir and Guarracino, 1981). The collector outlet air temperature t_1 is then calculated from:

$$t_1 = t_a + \frac{A_c G \eta_c}{\dot{m}_{da} c_{pha}} \tag{5}$$

The corresponding wet bulb temperature t_{w1} is determined by solving the following equation:

$$p_{va} = p_s(t_{w1}) - \frac{c_{pha}(t_1 - t_{w1})[p_a - p_s(t_{w1})]}{0.622 L_v(t_{w1})} \tag{6}$$

with

$$L_v(t_{w1}) = 2.5018 \cdot 10^6 - 2.378 \cdot 10^3 t_{w1}\ \mathrm{J/kg} \tag{7}$$

Atmospheric air humidity is then determined from:

$$x_a = 0.622 \frac{p_{va}}{p_a - p_{va}} \tag{8}$$

and then the drier outlet temperature t_2 is determined by solving the following equation:

$$a_w p_s(t_2) = p_s(t_{w2}) - \frac{c_{pha}(t_2 - t_{w2})[p_a - p_s(t_{w2})]}{0.622 L_v(t_{w2})} \tag{9}$$

in which it is assumed that $t_{w2} = t_{w1}$. The drier outlet air humidity is then obtained from:

$$x_2 = 0.622 \frac{p_{v2}}{p_a - p_{v2}} \tag{10}$$

with

$$p_{v2} = a_w p_s(t_2) \tag{11}$$

Finally, the sought evaporative capacity E is calculated from:

$$E = \frac{\dot{m}_{ha}}{1 + x_a}(x_2 - x_1) \tag{12}$$

Applying this calculational procedure to cases (a) and (b) of the previously-discussed example (with a collector area of 10 m^2) leads to the following results for cases (a) and (b) respectively: (a) $E = 1.49\ 10^{-4}$ kg s^{-1}; (b) $E < 0$.

In contrast with the comparison of the collector's thermal efficiencies, a comparison of these two values of E would lead us to choose an air flow rate to collector area ratio of 0.025 kg s^{-1} m^{-2}, which enables the drying to go on. Thus the evaporative capacity seems to be a better criterion than the thermal efficiency to evaluate the performance of solar air heaters used in conjunction with food dryers. Fig. 3 presents the evolution of η_c and E for different air flow rate to collector area ratio, under the meteorological conditions prevailing in August at 9 am in Ouagadougou, for drying a product having $a_w = 0.6$. It can be deduced from Fig. 3 that the optimal air flow rate to collector area ratio is 0.15 kg s^{-1} m^{-2} under the assumed conditions.

2. APPLICATIONS

For rapid practical use, the previously-presented calculational procedure has been used to establish charts that are based on a specified air flow rate of 0.278 m^3 s^{-1} (corresponding to 1000 m^3 h^{-1}). These charts provide a reference evaporative capacity, denoted E_0, and it is given for products having various values of water activity a_w (each chart corresponds to a fixed value of a_w) as a function of the ambient air temperature and humidity (absolute or relative). Some of these charts are also presented in Fig. 4. These charts may be used to select the best air flow rate for a solar air heater at a giving time of the drying process – i.e.,one that maximizes the drying evaporative capacity – by the following procedure:

(i) calculate the collector outlet air conditions by the Hottel-Whillier-Bliss equation, or equivalent;

(ii) determine E_0 by using the relevant chart (depending on the water activity of the product); and

(iii) calculate E for the actual air flow rate $\dot{q}_{v_{ha}}$ (m^3 s^{-1}), using:

$$E = E_0 \dot{q}_{v_{ha}} / 0.278 \tag{13}$$

The influence of meteorological conditions on solar drier performance can be appreciated by use of these charts. For this purpose, marked on Fig. 5 are the representative points of the mean atmos-

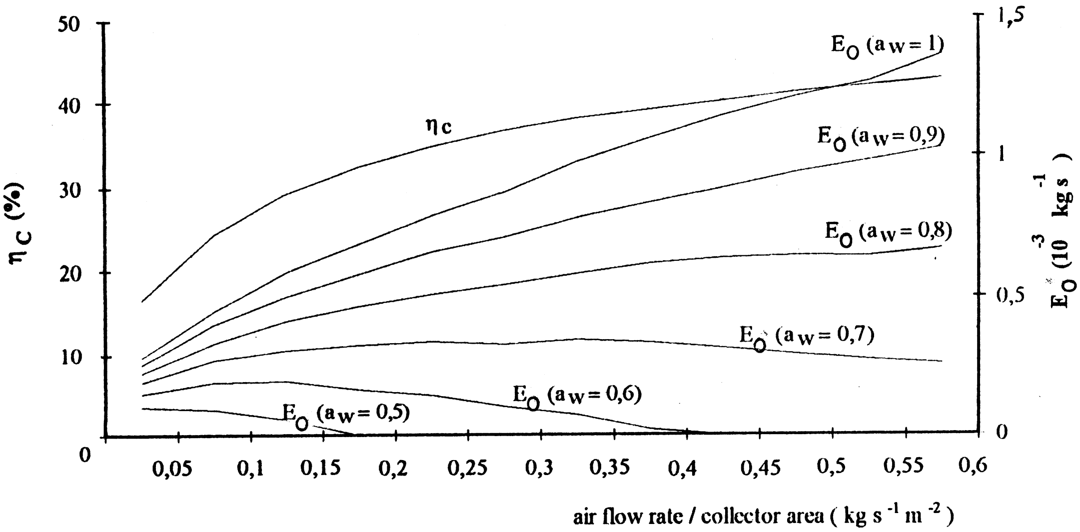

Fig. 3. Evolution of η_c and of E with the air flow rate/collector area ratio for a covered solar air heater operating under August conditions in Ouagadougou at 9 am.

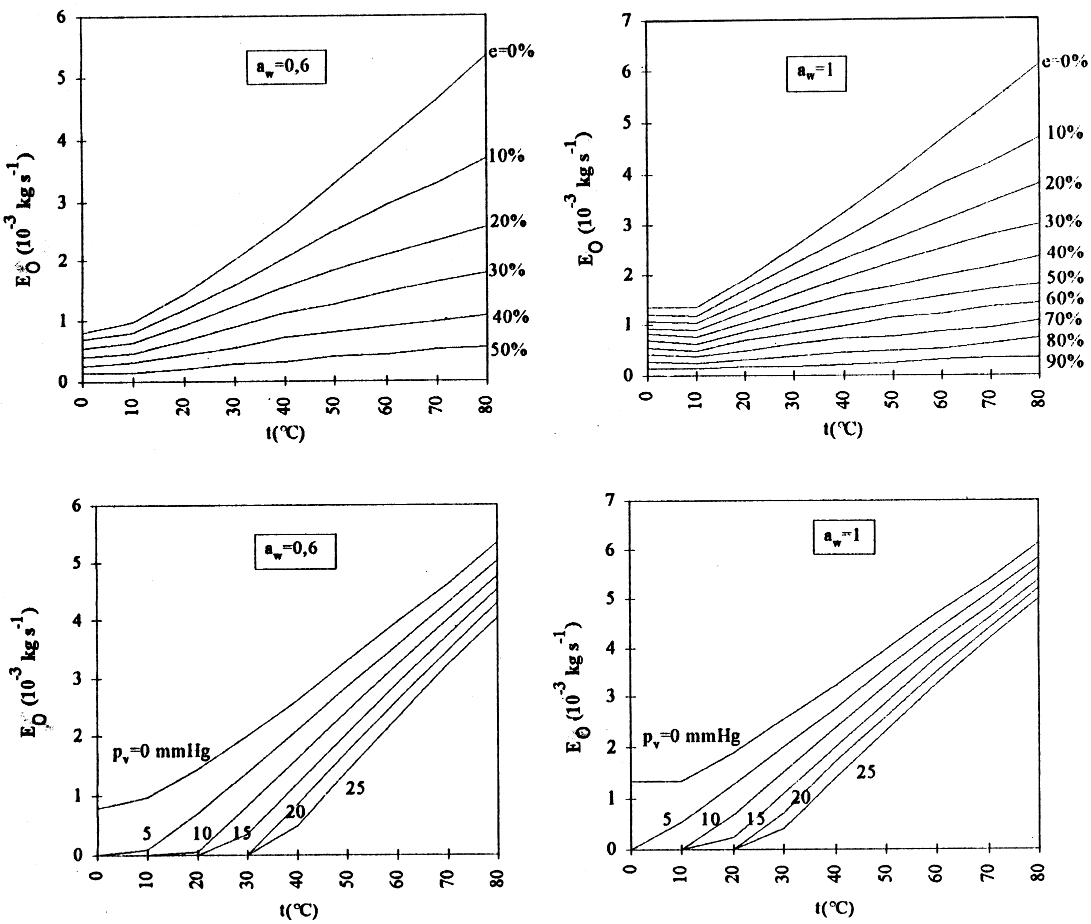

Fig. 4. Charts for the determination of the evaporative capacity. ($\dot{q}_{v_{ha}}$ = 0.278 m^3 s^{-1}; pa = 101300 Pa).

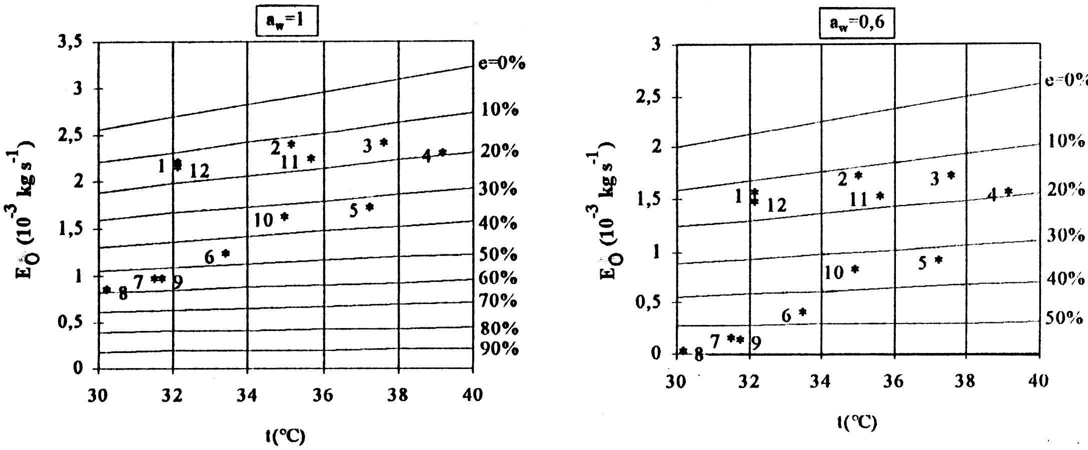

Fig. 5. Evaporative capacity of atmospheric air in Ouagadougou at 3 pm for each month (from 1 to 12).

pheric conditions in Ouagadougou at 3 pm (Jannot, 1994) for each month of the year. Very important differences in the corresponding values of E_0 are to be observed; they illustrate the important influence that ambient air temperature and humidity have on the performance of a solar drier. This influence is not properly taken into account when one considers only the collector efficiency.

3. CONCLUSION

A different performance index for solar air heaters used in conjunction with food dryers has been studied. It has been shown that this criterion can be a useful tool that complements and refines performance comparisons based just on the collector efficiency. It may also be helpful for selecting, at any given time, the best flow rate in a solar drier that has variable air flow, depending on the state of the food.

NOMENCLATURE

A	area (m^2)
a_w	water activity defined in Introduction
c_p	specific heat of air (J kg^{-1} °C^{-1})
e	relative humidity of air (%)
E	evaporative capacity (kg s^{-1})
G	solar irradiance (W m^{-2})
L_v	latent heat of vaporization of water (J kg^{-1})
$\dot{m}$	mass flow rate of air (kg s^{-1})
p	atmospheric pressure (Pa)
P_v	partial water vapor pressure (Pa)
$\dot{q}_v$	volume flow rate of air (m^3 s^{-1})
t	temperature (°C)
t_w	wet bulb temperature (°C)
V	wind velocity (m s^{-1})
x	absolute humidity (kg vapor per kg dry air: kg.kg^{-1})
X	dry basis water content of food (%)
η	thermal efficiency of collector (%)

Subscripts

a	ambient air
c	collector
da	dry air
ha	humid air
s	saturation
v	vapor
w	water or wet bulb
0	reference value
1	collector outlet
2	drier outlet

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