

EVALUATING THE CONTRIBUTION OF POROUS MEDIA TO THE INCREASE OF WATER EVAPORATION RATE

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Abstract. *Evaporation is a true phenomenon in our everyday activities. Thanks to evaporation, clothes are dried, and some food processes, bricks, concrete, and others obtained, or prepared. Though in certain cases it should be avoided or minimized, as in relation to swimming pools, or dams, in others, such as in solar distillation, it should be stimulated. In 1978, Jaguaribe observed that the evaporation rate of the wet surface of a porous medium within water, when exposed to solar radiation was higher than in the case of just water. Jaguaribe et al. (2002), using a correlation based on a semi-empirical expression for standard basin, and taking into account the classical solar still equations, came up with good agreement between the theoretical results and the experimental water evaporation data from basins containing either just water, or water plus a porous medium. The present work introduces a new correlation ,also based on the heat absorption capacity of the medium, and on the water thermal inertia, which offers extraordinary agreement between the experimental data and the theoretical result.*

Keywords. *porous media, thermal inertia, evaporation, semi-empirical expression.*

1. Introduction

Evaporation takes places in many processes of everyday life. Using industrial dryers for ore, making bricks, foods (sugar, pastas, fruits, etc.), or domestic operations such as using clothes-lines, or drying machines, or even when sweat evaporates from our clothes, are examples of the occurrence of this phenomenon. In some circumstances, however, this process should be blocked, or restrained, considering the damages it may cause, such as in swimming pools or in dams. (cf. Jamal et al., 1990; Hahne et al., 1994 e Charles et al., 1994). A case, however, in which evaporation should be stimulated is in the use of a conventional solar still. Indeed, several mechanisms have been used to increase the evaporation rate of this apparatus (Headley, 1973; Safwat et al., 1977; Sodha et al., 1981; Dunkle, 1961; Lobo and Araújo, 1977; Adhikari et al., 1995; and Sartori and Jaguaribe, 1984). The use of porous media may also increase this rate (Jaguaribe et al., 1995, Jaguaribe, 1973, and Chendo et al., 1991). One explanation for the positive contribution of the porous medium in evaporation is the reduction of vapor pressure in the capillary meniscus formation, which in turn, demands less energy to evaporate. However, as mentioned by Hatsopoulos (1965), such a contribution is only meaningful if there is a dense vapor formation around the meniscus, which is not the case in solar stills. Jaguaribe et. al. (2002a, 2002b, and 2002c) showed that the most effective factor of the porous media effect in the evaporation rate is the reduction it promotes in the water thermal inertia, when the water mass to be evaporated is reduced to just a film. They came to this conclusion using porous media in open trays filled with water, and taking into account a modified correlation valid to estimate the mass evaporation in standard evaporation basins.

The present work introduces a new correlation based on the absorvity, and on the thermal inertia parameters associated with the porous media, allowing better agreement between the theoretical and the experimental data.

2. Experimental

Figure 1 shows a sketch of the experimental apparatus used to evaluate the influence of porous media on the reduction of thermal inertia of water placed in open trays, under constant radiation, from a set of well-distributed incandescent lamps of 60 W. In average, a radiation flux of 477 W/m^2, as read by an Eppley precision pyranometer, may reach a tray containing just water (0.5 L), or water (0.5 L) plus a porous medium that emerged from the water free surface. The tray placed under the lamps was set over a scale which registered the total weight of the tray. Each tray was 270 mm long, 160 mm wide and 55 mm high, and was filled with 500 ml of water. T type thermocouples, were fixed on the internal side walls and the bottom of the trays. The trays with porous media had two thermocouples on the heated surface. The thermocouples were fixed with a silicone sealant, and protected from direct radiation with a shield formed by a white paint.

The humidity of the room where the experiments took place was also measured. All the thermocouples were connected with an electronic recorder which registered the temperature data at every minute, during the four-hour experiment.

2.1 The porous media

The porous media used in the experiments were: pieces of charcoal, a stretched black fabric (cotton mounted on a wire structure), and synthetic cotton (a silicone fiber) stuffed into the black fabric wire structure. The rectangular wire structure was 260 mm long, 150 mm wide and 45 mm high so as to adjust itself to the tray bottom surface.

The charcoal was produced in a rotary kiln, from low density wood heated from ambient temperature up to 450 °C, at heating rate of 5 °C/min.

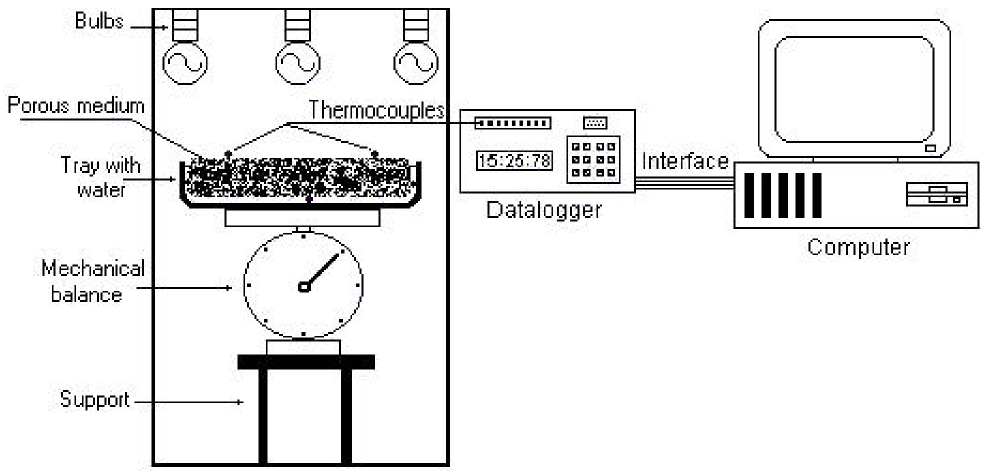

Figure 1. Scheme of the experimental apparatus, showing the tray filled with porous media.

3. Semi-empiric model

Considering a standard evaporation basin, in a stable atmosphere, the evaporation rate may be correlated with the following expression, Holmam (1983),

$$E_{cs} = 0.7 \cdot (3.21 + 0.0221\ \overline{u}).(p_s - p_{ag})^{0.88} \tag{1}$$

where

E_{cs} is the evaporated mass from a standard evaporation basin, mm/day;

$\overline{u}$ is the daily average wind velocity, measured at 150 mm from the standard basin rim, km/day;

p_s is the saturation vapor pressure at the dry-air-bulb temperature, measured 1.5 m above the soil surface, kN/m^2;

p_{ag} is the moisture vapor pressure in the air at temperature and humidity measured 1.5 m above the soil surface, kN/m^2.

From Eq. (1) and taking into consideration the saturation pressure at the water temperature, and the vapor saturation pressure at the air-dry-bulb temperature, an expression analogous to Eq. (1) may be written as

$$E_{cs} = C_c.(3.21 + 0.0221.u).[p_{sa}(T_a) - p_{bs}(T_{bs})]^{0.88} \tag{2}$$

where

$$C_c = \frac{3.5 \cdot 10^{-3} \cdot P_{cc}}{m_{ee}^{\ 2.5}} \tag{3}$$

E_{cs} is the evaporation rate, measured at the tray, mm/day;

u , the average daily wind velocity, km/day;

$p_{sa}(T_a)$, water saturation pressure at the water temperature, kN/m^2;

$p_{bs}(T_{bs})$, vapor saturation pressure at the dry-air-bulb temperature, kN/m^2;
T_a, water temperature, ºC;
T_{bs}, dry-bulb temperature, ºC;
C_c, Overall evaporation correction factor;
P_{cc}, Effective overall parameter;
m_{ee}, Amount of mass evaporated, (experimental), during the referred period (4 hours), kg.

The mass of water evaporated per day and per unit area, is given by

$$\frac{\dot{m}_{ag}}{A} = \frac{E_{cs}}{1000} \cdot \rho_{ag} \tag{4}$$

where,
$\dot{m}_{ag}$, the water evaporation rate, kg / day;
A, the tray area, m^2;
ρ_{ag}, water specific mass, kg / m^3.

Equation (4) gives the total amount of evaporated water. In the present study, Eq. (4) was adapted to make one minute the standard time interval. Thus, the total evaporated mass is evaluated, adding all the masses evaporated during a chosen period, that is

$$m_e = \sum_{i=0}^{n} \frac{E_{cs\,i}}{1440} \cdot \Delta t \cdot A \tag{5}$$

where:
$E_{cs\,i}$, is the mass of water evaporated for each i minute, mm / day;
Δt = 1 min,
m_e, is the total amount of water evaporated during the total period (4 hours).

4. Results and Comments

Figure (2) shows the temporal temperature distributions concerning the four different porous media surfaces, in trays containing water, under the artificial radiation flux. Fig. (3), also presents the temporal temperature distributions, measured on the surfaces of the porous media, but in this case the trays do not contain any water. From both experiments it was possible to see the influence of the water on the temperature measured on the porous media surfaces. In fact, the water decreases the temperature of the solid material not because of the increase of the mass of the system, but mainly due to the water evaporation.. The results presented in Figs. (2) and (3) show how drastic the temperature reduction is when the porous media are soaked into water.

Also from Fig. (2) one may infer the thermal inertia behavior of all the elements in the trays, including that of the water itself. The water in the tray containing no porous media, during the first 7 minutes, shows higher temperatures than those measured at the surface of the different porous media, plunged into the same amount of water, except for the black fabric filled with synthetic cotton. Again, one may notice in Fig. (2) that in all the cases of the trays containing water plus a porous medium, the maximum temperature was reached in less than 68 minutes. This means that the maximum capacity of the system to absorb heat happens within this period. However, this is not true for the water, whose temperature keeps going up during the rest of the experiment. In this case, a great fraction of the energy received is used to increase the water temperature. In consequence, after 117 min, the water temperature is higher than the temperature of the other porous mediaexcept for the black fabric filled with the synthetic cotton.

As mentioned above, Eq. (2) was adapted from Eq. (1), to evaluate the mass of water evaporated from a standard evaporation basin. Examining Eq. (2), it may be seen that the major change imposed on Eq. (2) was in its original constant. In fact, the correction factor C_c in Eq. (2) was meant to improve the generalization of the expression, turning it also valid for other media present in the water. The factor was deduced from a correlation using the average temperature of each medium, as given in Fig. (3), the water temperature, and the total evaporated mass of water.

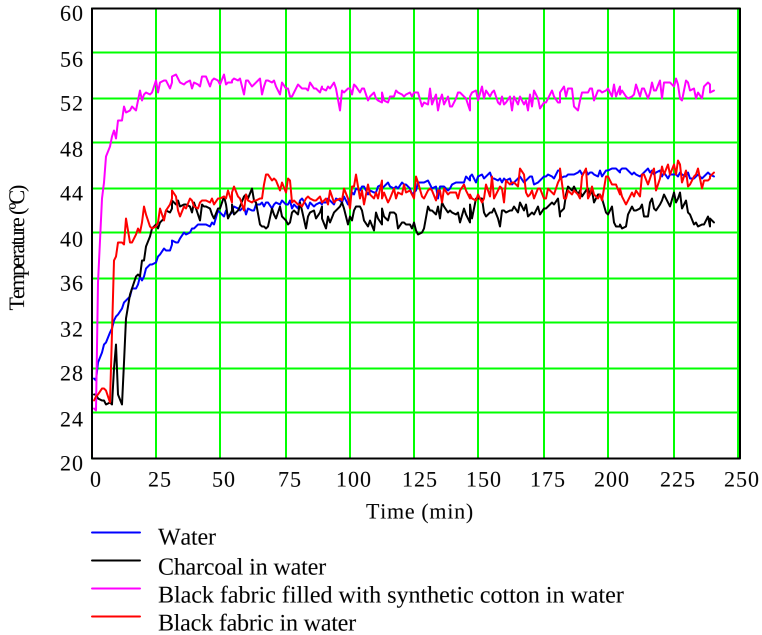

Figure 2. Temporal temperature distributions in trays containing water

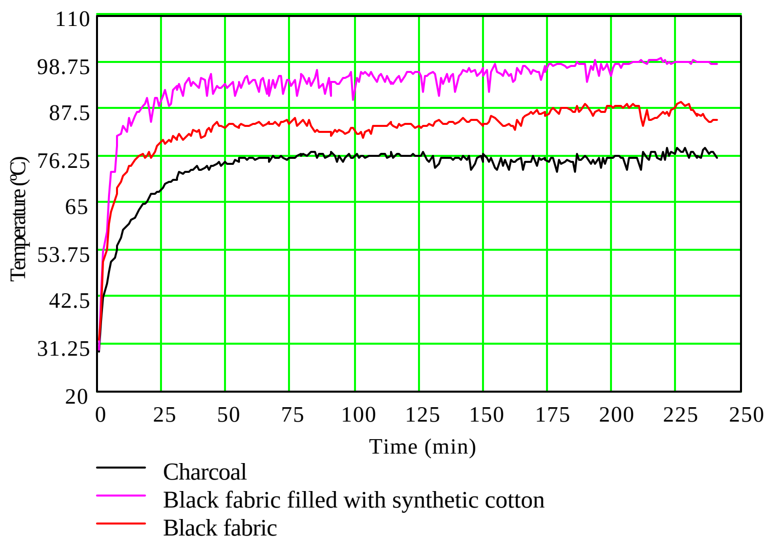

Figure 3. Temporal t emperature distributions of porous media surface in trays without water.

Figures (4) to (7) present experimental and theoretical curves which give the total amount of water evaporated at any instant within a four hour period. Theoretical curves were plotted using Eq. (2). The four different situations associated with these figures are related to the tray contents, such as: plain water - Fig. (4); black fabric filled with synthetic cotton – Fig. (5); charcoal emerging from water – Fig. (6)– and a stretched black fabric.

Examining Figs. (4) to (5) it is evident that Eq. (2) is efficient in simulating the experimental data. The worst situation is showed in Fig. (6), where the porous medium was the stretched black fabric. In this case the theoretical curve presents a gradual deviation between theoretical and experimental curves, right after 60 min. Those data yield a Pearson's correlation coefficient of 0.999 and a standard error of 0.195. The low density of the stretched fabric, may be the reason for such deviation, which increases when the temperature goes up, showing that the medium is not bringing the required amount of water to the radiated surface.

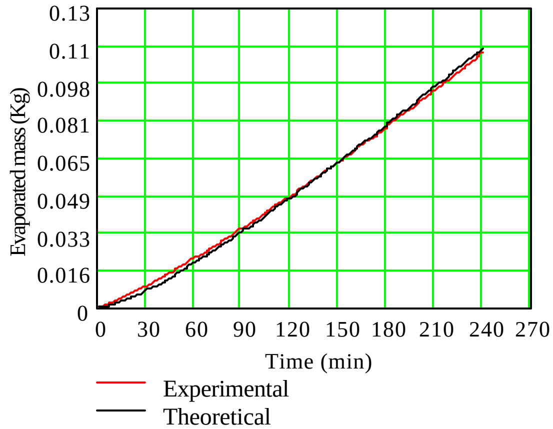

Figure 4. Amount of water evaporated from a tray just containing water.

It is evident, comparing the experimental curve in Fig. (4) with all the other experimental curves in Figs. (5) to (6), that the tray containing just water presents the worst performance in terms of evaporation. On the other hand, the most efficient porous media was the black fabric filled with synthetic cotton, see Fig. (7), which produced about 44% more evaporated water than the water by itself. It seems that the use of the association of the black fabric together with the synthetic cotton results in a very dynamic porous medium, capable of driving quickly, by capillarity the amount of water necessary to supply the mass of liquid evaporated at the surface. It is also true that the temperature levels for this medium were the highest among the others, showing this medium's great ability to absorb radiation.

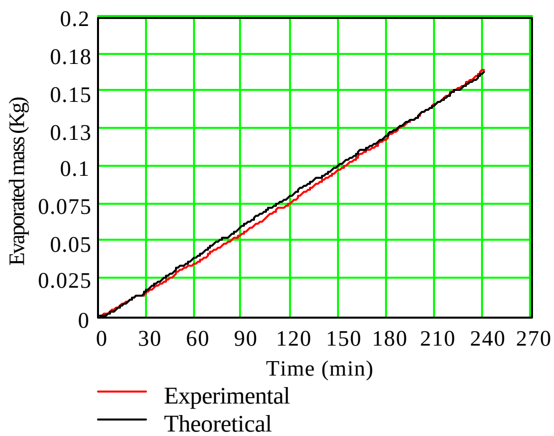

Figure 5. Amount of water evaporated from a tray containing water and a medium formed by black fabric filled with synthetic cotton

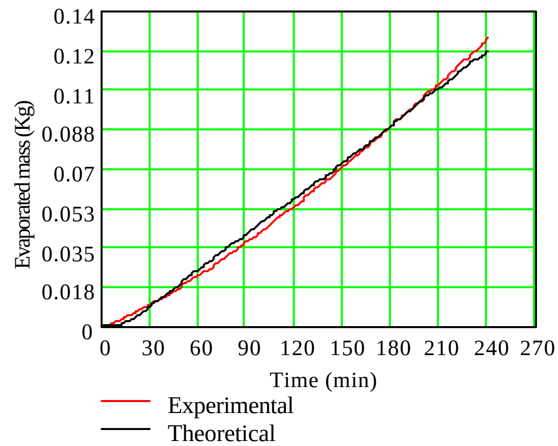

Figure 6. Amount of water evaporated from a tray containing water and a medium formed by pieces of charcoal.

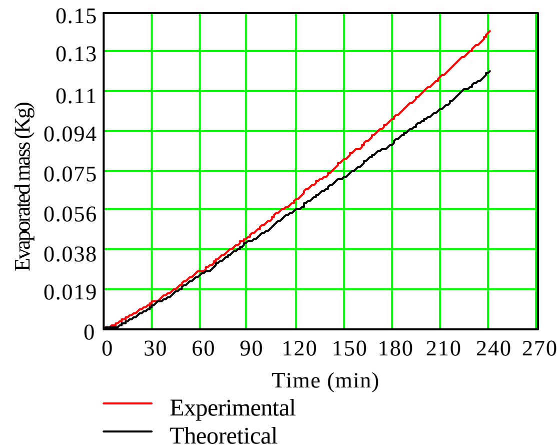

Figure 7. Amount of water evaporated from a tray containing water and a medium formed by a stretched black fabric.

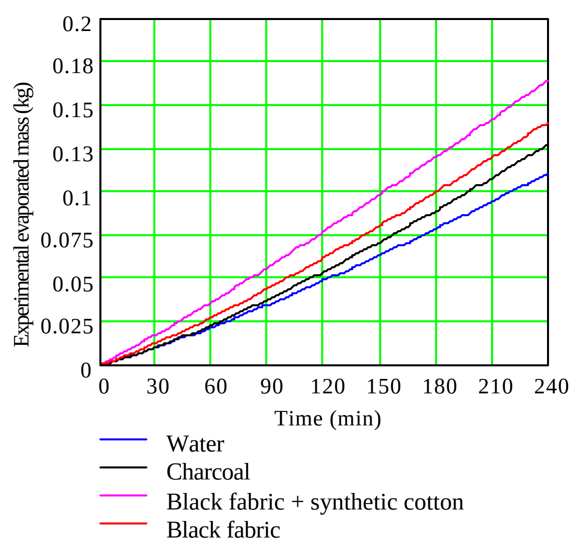

Figure 8. Accumulated mass evaporated as function of time.

6. Conclusion

Generally speaking, there is visible agreement between experimental and theoretical results, which demonstrates that Eq. (2) satisfactorily represents the examined experimental data.

No matter the type of porous media, it was observed that in all the cases, the trays containing a porous medium, produced much more evaporation than the trays with just water. This happens because of the capillary effect, which drives water to the surface, forming a very thin water layer covering the porous medium, thus causing a reduction in the thermal inertia of the evaporating water. As a consequence, the water is rapidly heated and evaporated.

Examining all the experiments, and considering the theoretical basis, it is evident that the most efficient porous medium to increase the water evaporation rate is that with high radiation absorptivity, excellent capillary effect, and low specific heat capacity.

Although the correlation given by Eq. (2) has demonstrated conformity in reproducing the experimental data, this study shows that one important parameter in a porous medium to increase the water evaporation rate is the capillary effect, which in part, depends on the material density. In other words, a more suitable expression to replace Eq.(2) should also contain the porous media density. One of the goals of the continuation of this study is, therefore, to determine another expression to replace Eq. (2), one, even more sensitive to the influence of the physical parameters of any kind of porous medium.

7. References

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