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# Modeling of simultaneous transfers of heat and mass in a trapezoidal solar distiller

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## HIGHLIGHTS

- Modeling of heat and mass transfer at low temperatures in a trapezoidal cavity
- Simulation of simultaneous transfer of heat and mass in a solar trapezoidal distiller
- Numerical heat and mass transfer in a trapezoidal cavity

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## ABSTRACT

A model of heat and mass transfer phenomena in a trapezoidal cavity is established. This work is partly based on the experimental results obtained in the case of a trapezoidal-shaped solar distiller. The resolution of the related system of equations gives results that are in a good agreement with those obtained experimentally. The modeling was made on the basis of a stagnant zone within the closed cavity, whose walls are at different temperatures. The numerical simulation could contribute to the study and design of numerous applications such small solar distillation units, solar driers and solar greenhouses, among others.



## 1. Introduction

Many countries, such as those of the south bank of the Mediterranean Sea, having an important solar energy potential and brackish water, suffer from the scarceness of drinking water due to low rainfalls. These difficulties can be overcome by small solar distillation units, locally usable and inexpensive. The operating principle of these units is based on trapping by greenhouse effects, the solar energy entering a closed cavity. This energy will serve partly for evaporating the brackish water. The distillate is collected by condensation on one or several surfaces. In this respect, the most important point is the outputs of these distillation units. The mastery of the phenomena of simultaneous heat and mass transfer in the distillers could contribute to improve their efficiency. To this end, we propose an experimental study on simultaneous heat and mass transfers in a trapezoidal cavity with three non-adiabatic walls, in view of developing a more general mathematical model to simulate the distillation unit. With respect to the theoretical study, the proposed cavity is dimensioned so that the moist air flow inside it could be two-dimensional.

Published research material shows that most of the theoretical studies [1–4, 6–8] and experimental works [5,8] undertaken on the heat and mass transfer in trapezoidal and triangular closed cavities, concern differentially heated systems. Two walls contribute to heat and mass (condensation) exchange, the others are adiabatic. In the theoretical studies, the flow of fluid inside these cavities is, most often, treated in laminar regime. Very few theoretical studies are undertaken in turbulent regime [9].

To the author's knowledge no work regarding two different surfaces of condensation has been done.

The design of the proposed experimental system takes into account the results obtained by R. Tripathi and GN Tiwari [10] and Anil Kr Tiwari, and GN Tiwari [11], which state that increasing the thickness of the strip of water, in a solar distiller, negatively influences the performance and a lid inclination of 30° leads to better results than inclination values of 15° and 45°. The use of experimental results led us to propose correlation expressions for the average of the Sherwood and Nusselt numbers of the isothermal flat plate, established for the laminar flow regime.

To model these simultaneous heat and mass transfer phenomena, we relied on our experimental results [12] and on a preliminary study of the structure of a laminar and stationary saturated moist air flow, in a cavity similar in shape and having the same geometrical dimensions as those of the experiment setup. Writing the global balance equations along with

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the appropriate initial conditions identical to those of the experiment, leads to the establishment of the theoretical model. The validation of the model is performed through comparison with the experimental results.

The trapezoidal configuration is chosen with three non-adiabatic walls, and different orientations, nature and temperatures.

The analysis of the experimental results, the study of the structure of the flow in the cavity, the formulated model, the resolution method, the numerical results and the other structure configurations used in solar distillation are presented below.

*Nomenclature*

| | |
|---|---|
| $A_j$ | Area of the wall j ($m^2$). |
| $D(T_i)$ | Mass diffusion coefficient at temperature $T_i$, ($m^2/s$). |
| $C_i$ | Heat capacity of the material medium i, (J/K). |
| $C_p$ | Specific heat at constant pressure, (J/kg K). |
| $F_{ij}$ | Form factor of surfaces i and j. |
| $g$ | Gravitational acceleration ($m/s^2$). |
| $G_r^T$ | Grashoff thermal number. |
| $G_r^*$ | Grashoff mass number. |
| $h_{ij}$ | Coefficient of heat exchange between moist air and surface j, ($W/m^2$ K). |
| $h_{ij}^*$ | Coefficient of mass exchange between medium i and medium j (m/s). |
| $h_{rij}$ | Radiance heat exchange coefficient between surfaces i and j (W/K). |
| $h_b$ | Heat transfer coefficient between the bottom of the tray and indoor air, ($W/m^2$ K). |
| $h_e$ | Global exchange coefficient between glass and external environment, ($W/m^2$ K). |
| $H_s$ | Global incident solar flux, ($W/m^2$). |
| $l_1$ | Glass width ($l_1 = 0.70$ m). |
| $l_2$ | Width of strip of water ($l_2 = 0.63$ m). |
| $l_5$ | Width of aluminum plate ($l_5 = 0.36$ m). |
| $L$ | Length of cavity (L = 1.60 m). |
| $L_j$ | Reference length (m). |
| $L_w(T_i)$ | Latent heat of phase change of water at temperature $T_i$, (J/kg). |
| $m_i$ | Mass flow at wall i, (kg/s). |
| $\overline{NU_L}$ | Average number of Nusselt. |
| $P_r$ | Prandtl number. |
| $q_{ij}$ | Heat flow received by medium j from medium i, (W). |
| $q_{ij}^*$ | Heat flow received by medium j from medium i through mass transfer, (W).$q_{rij}$: Heat flow received by medium j from medium i by infrared radiation, (W). |
| $\rho_i$ | Density of moist air at temperature $T_i$, ($kg/m^3$) |
| $S_c$ | Schmidt number. |
| $\overline{SH_L}$ | Average Sherwood number. |
| $T_i$ | Average temperature of medium i material, (K). |
| u | Component of velocity along Ox, (m/s). |
| v | Component of velocity along Oy, (m/s). |
| $\alpha_i$ | Absorption coefficient for medium i. |
| $\varepsilon_i$ | Emission factor of surface i. |
| $\varphi_i$ | Concentration of water vapor in air at temperature $T_i$, ($mol/m^3$). |
| $\lambda$ | Thermal conductivity, (W/m K). |
| $\mu$ | Dynamic viscosity, (Pa·s). |
| $\rho$ | Density of moist air at temperature T, ($kg/m^3$) |
| $\sigma$ | Boltzmann's constant |
| $\tau_i$ | Total solar radiation absorption coefficient for medium i. |

*Subscript*

| | |
|---|---|
| $e$ | Refers to outside cavity. |
| $i$ or $j = 1$ | Refers to glass. |
| $i$ or $j = 2$ | Refers to water in the tank. |
| $i$ or $j = 3$ | Refers to absorbent tank. |
| $i$ or $j = 4$ | Refers to moist air inside the cavity. |
| $i$ or $j = 5$ | Refers to aluminum plate. |
| $i$ or $j = 6$ | Refers to atmospheric air outside the cavity. |
| $r$ | Refers to radiance. |

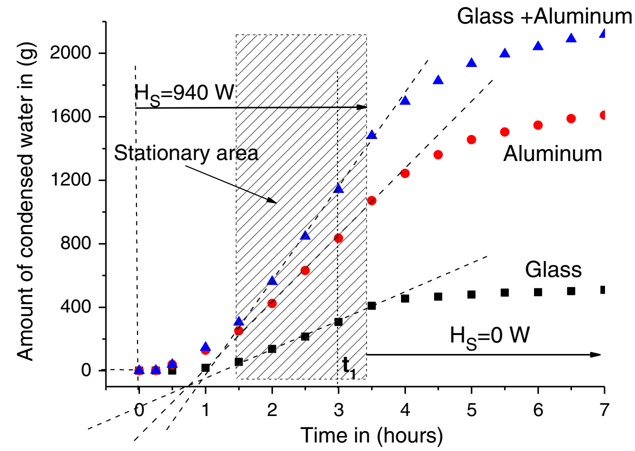


**Fig. 1.** Experimental results.

## 2. Analysis of the experimental results

The experimental study [12] showed a stationary region defined by a constant mass flow (Fig. 1).

In view of defining the simulation model of the distiller operation, the knowledge of the simultaneous heat and mass transfer modes within the distiller is required. To have an idea about these modes of transfer, the knowledge of the saturated humid air flow structure within the distiller experimental setup is needed. To this end, a preliminary study on the humid air flow structure within a theoretical cavity (see Fig. 3), similar and with the same dimensions than those of the experimental distiller (see Fig. 2) before a simulation model is proposed.

## 3. Study of the flow

### 3.1. Introduction

The flow of saturated humid air in a cavity (Fig. 3), of the same shape and size as that of Fig. 2, where the non-adiabatic wall temperatures are different and constant, is studied. These temperatures are equal to those of their counterparts in the experimental device at time instant $t_1$ corresponding to the constant flow rate, Fig. 1. The theoretical study is then extended to the trapezoidal cavity of Fig. 4.

### 3.2. Study of the flow

The equations established for natural convection at steady state, make use of simplifying hypotheses that are in agreement with experiment.

#### 3.2.1. Basic hypotheses

- The length (L = 160 cm) of the cavity is about four times its height ($l_5$ = 36 cm); the flow of humid air in the cavity, Fig. 3, is then assumed to be two-dimensional.
- The air within the cavity is saturated with vapor (condensation on the walls). Its pressure P is the atmospheric one since the cavity communicates with the outside air through recovery pipes. The thermal conductivity λ, the specific heat $C_p$ and the dynamic viscosity μ are taken equal to those of saturated moist air at normal atmospheric pressure and at temperature corresponding to time instant $t_1$, Fig. 1; their values are, respectively, 0.025 (W/m K), 1006 (J/kg K) and $1.9 \cdot 10^{-5}$ (Pa·s).
- Due to the low moist air flow velocities (natural convection), we can