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# Numerical study of conjugate heat and mass transfer in a solar still device

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## HIGHLIGHT

- A solar still device was studied numerically as a cavity considering surface thermal radiation.
- The effects of solar still device were studied with and without surface thermal radiation.
- The surface thermal radiation modifies the fluid flow from one-cell to multi-cellular pattern.
- The average $Nu_{conv}$ and $Sh$ numbers are increased about 25% and 15% respectively.
- The most suitable case for a solar distillation device studied is $\mathrm{Ra}_T = 10^6$, $A = 16$ and $\theta \geq 25°$.

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## ABSTRACT

Double-diffusive natural convection and surface thermal radiation in an inclined cavity that simulates a solar still device is studied numerically. The parameters considered were $10^3 \leq Ra_T\,(Ra_M) \leq 10^6$, $8 \leq A \leq 16$ and $15° \leq \theta \leq 35°$. The steady state 2-D governing equations have been solved by the finite volume method. Streamlines, isotherms, isolines of water vapor, mass flow rate of distillate and average Nusselt and Sherwood numbers as a function of Rayleigh number for different inclination angle are presented. The results show that surface thermal radiation modifies the fluid flow from one-cell to multi-cellular pattern due to the surface thermal radiation increases the velocity near the walls, as a consequence the average convective Nusselt number, the total Nusselt number and the Sherwood number were increased about 25%, 175% and 15%, respectively. The mass flow rate of distillate increases as $A$, $Ra$ and $\theta$ increase. The most suitable case for a solar still device is that for $Ra_T = 10^6$, $A = 16$ and $\theta \geq 25°$.



## 1. Introduction

Solar distillation is a technology for producing potable water from brackish and underground water of low-quality at low cost. It can reduce water scarcity problems together with other water purification technologies. Solar distillation is analogous to natural hydrological cycle. It uses an apparatus called a solar still in which water is evaporated using solar energy and collected as distillate after condensation of the vapor. The major advantage of this is the use of solar energy instead of electrical energy generated from conventional fuels. This helps in producing potable water without degrading our environment. Over time, researchers have studied several designs of solar stills to evaluate its performance for different climatic, operational, and design parameters [1]. An extensive review of variety of solar still device and systems used to convert seawater into fresh water suitable for human use is presented in references [2–5]. From above references it can be concluded that most of the studies of the performance of conventional solar distillation system can be studied doing experiments of solar still device and/or balances of energy and mass transfer. There are few studies of numerical methods, like CFD, that simulate natural convection in rectangular driven by thermal and solutal gradients.

The numerical study of heat and mass transfer in rectangular cavities with humid air in a solar distillation system was studied by Jabrallah et al. (2002) [6]. They concluded that the performance of the cell can be improved by increasing the heat on the hot plate, raising the temperature of the incoming water and increasing the aspect ratio. Snoussi et al. (2005) [7] made the numerical study of heat and mass transfer for $A = 1$ and 4. The authors concluded that Nusselt number changes with the cavity height and the heat and mass transfer increase as a function of thermal or mass Rayleigh number. The study of the effects of the inclination cavity for $A = 10$ and $0° \leq \theta \leq 90°$ was analyzed by Chouikh et al. (2007) [8]. The authors concluded that the local Nusselt number decreases when increasing the height and that a flow pattern with one single cell is desirable. Sun et al. (2011) [9] studied the heat and mass transfer of the wall surface condensation or evaporation in a cavity filled with humid air for $A = 0.25$–4. In this study variable

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thermo-physical properties were studied. From results it was concluded that for cavities with constant volume but with different aspect ratios, the thickness distributions of water films greatly varies according to the different convective patterns encountered. Some studies that are focused on surface thermal radiation have concluded that radiation has an important effect on the heat transfer and the movement of the fluid. The effects of the radiation on natural convection in a Rayleigh–Benard square enclosure were reported by Ridouane et at. (2004) [10]. The study analyzed two values of emissivity (0.05 and 0.85). Periodic simulations were obtained due to the effect of the walls emissivity. Bouali et al. (2006) [11] studied the effects of surface thermal radiation and inclination angle in a rectangular enclosure with a centered inner body. The parameters considered were $A = 2$ and $1.25 \times 10^4 \leq Ra_T \leq 7.5 \times 10^4$. Their results showed that the inclination angle reduces the total heat transfer in the cavity and the radiation increases the average Nusselt number. The numerical study of a slender tilted cavity that simulates a solar collector was studied by Alvarado et al. (2008) [12]. The study considered surface natural convection and surface thermal radiation for $10^4 \leq Ra_T \leq 10^6$ and $8 \leq A \leq 16$. The authors concluded that the total heat transfer increases when the inclination angle increases; and the total heat transfer decreases when the aspect ratio increases.

The above literature review focuses on analyzing the effect of the $Ra_T$, $Ra_M$, $\theta$, $A$ and surface thermal radiation, however it was found that: 1) the effect of surface thermal radiation is neglected in numerical studies when mass transfer is considered and 2) the effect of the mass transfer is neglected in studies when surface thermal radiation is considered. This study analyzes the effect of surface thermal radiation on a slender tilted cavity heated from below, considering the conjugate heat and mass transfer with application to a solar still device.

## 2. Problem statement

### 2.1. Physical model

The solar still device uses the principles of greenhouse effect for the evaporation and condensation of water. Several designs are possible as was reported in [1]. Fig. 1 (left) shows the schematic diagram of an inclined solar water distillation system which has a deposit of saline/brackish water. The water is supplied to the solar still by gravity from a tank with higher height than the solar still. The flow rate is controlled with a valve. The solar still has a glass cover at the top and an absorber at the bottom, on which a thin film of water is flowing. The water on the hot plate is vaporized from the liquid–vapor interface (thin water film). The vapor moves through the air and is condensed at the glass. On the left-top side the condensate water is collected. On the left-bottom side a pipe is connected to drain brine to waste. On the right side of Fig. 1 shows a schematic diagram of a rectangular cavity with a length $L$ and a height $H$, which simulates an evaporation–condensation cell of the solar distiller. Left and right walls are impermeable and thermally insulated. The bottom wall is heated and the top wall is cooled at constant temperatures $T_h$ and $T_c$, respectively. The concentrations of water vapor are fixed at the top and the bottom of the cavity, $C_c$ and $C_h$ respectively.

### 2.2. Governing equations

The steady state governing equation for 2-D and laminar flow are the conservation of mass, momentum, energy and concentration of water vapor equations:

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0 \tag{1}$$

$$\frac{\partial(\rho u \cdot u)}{\partial x} + \frac{\partial(\rho v \cdot u)}{\partial y} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}(\tau_{xx}) + \frac{\partial}{\partial y}\left(\tau_{xy}\right) + B_x \tag{2}$$

$$\frac{\partial(\rho u \cdot v)}{\partial x} + \frac{\partial(\rho v \cdot v)}{\partial y} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\tau_{yx}\right) + \frac{\partial}{\partial y}\left(\tau_{yy}\right) + B_y \tag{3}$$

$$\frac{\partial\left(\rho C_p u \cdot T\right)}{\partial x} + \frac{\partial\left(\rho C_p v \cdot T\right)}{\partial y} = \frac{\partial}{\partial x}\left[\lambda \frac{\partial T}{\partial x}\right] + \frac{\partial}{\partial y}\left[\lambda \frac{\partial T}{\partial y}\right] \tag{4}$$

$$\frac{\partial(\rho u \cdot C)}{\partial x} + \frac{\partial(\rho v \cdot C)}{\partial y} = \frac{\partial}{\partial x}\left[\rho D_{w,a} \frac{\partial C}{\partial x}\right] + \frac{\partial}{\partial y}\left[\rho D_{w,a} \frac{\partial C}{\partial y}\right] \tag{5}$$

where $B_x$ and $B_y$ are the buoyancy forces in $x$ and $y$ direction. The normal and shear stresses are:

$$\begin{aligned} &\tau_{xx} = \mu\left(\frac{\partial u}{\partial x} + \frac{\partial u}{\partial x}\right) = 2\mu\frac{\partial u}{\partial x} \quad \tau_{yy} = \mu\left(\frac{\partial v}{\partial y} + \frac{\partial v}{\partial y}\right) = 2\mu\frac{\partial v}{\partial y} \\ &\tau_{xy} = \tau_{yx} = \mu\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right) \end{aligned} \tag{6}$$

The following assumptions were done: the mixture of air and water vapor is assumed to be incompressible and Newtonian. The fluid is assumed radiatively non-participating. The viscous dissipation is assumed to be negligible due to the Mach number is low. The heat flux driven by concentration gradients (Soret effect) and the mass flux driven by temperature gradients (Dufour effect) are neglected because they are of a smaller order of magnitude than the effects described by Fourier's and Fick's laws. Thermodynamic equilibrium is assumed at the liquid–air interface. The thermophysical properties are taken constantly except in the buoyancy term, where it is linearized in terms of temperature and concentration (Oberbeck–Boussinesq approximation). The steady state governing equation for 2-D and laminar flow under the above considerations are the conservation of mass, momentum, energy and concentration of water vapor equations:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \tag{7}$$

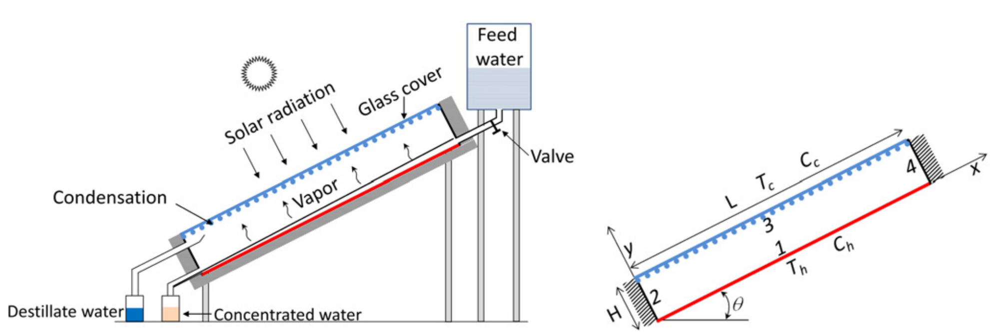


**Fig. 1.** Schematic diagram of inclined solar water distillation system (left) and physical model of the cavity (right).