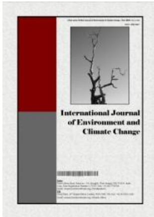

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Assessment of Heat and Mass Transfers by the Evaporation of a Large Impoundment under Dry and Hot Climate: Case of Burkina Faso

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Authors' contributions

This work was done in collaboration among all the seven authors. Author BA designed the study, performed the analysis and wrote the first draft of the manuscript. Authors IBK, KA, CX, ZB, KPF and BJ supervised the study. Authors ZB and KPF managed the literature search writing of the final manuscript. All authors read and approved the final manuscript.

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ABSTRACT

This paper aims to report a numerical study of the assessment of heat and mass transfers by evaporation of a large impoundment under Burkina Faso climate conditions. This impoundment is considered as a parallelepiped which upper face, in contact with the ambient environment and subject to solar radiation, is the seat of a natural convection-based evaporation. The intensity of this evaporation is modeled by a correlation in the literature. Transfers into water are made by natural convection. They are caused by temperature differences due to solar radiation and ambient conditions (wind, hygrometry of the air,) on water. These transfers are described by the Navier-Stokes equations and energy and the initial and boundary conditions associated with them. The finite volume method and the SIMPLE algorithm were used for speed-pressure coupling. The

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systems of algebraic equations deduced from the discretization of transfer equations and boundary conditions associated with them are solved with Thomas' algorithm, the SIMPLE algorithm and an iterative procedure because evaporated water quantity depends on the temperature and concentration of water vapor at the surface of the impoundment which are the unknowns of the problem. The numerical model developed is validated in relation to previous work and experimental data from Burkina Faso meteorology. The results obtained concern the evolution of the evaporated water flux under dense solar flows, a relative humidity of the air proportional to the wind speed and also the evolution of the evaporated water flux against the solar flux density for high relative moisture content. Also the evolution of the evaporated water flow against the depth of the impoundment for a solar flux density, relative humidity and the temperature of the surface of the body of water is given. The determination of evaporated water flux for typical years was calculated on a 10-year period. The results obtained show that the flux of evaporated water increases with a high solar flux rate and decreases for a high relative humidity level.

Keywords: Evaporation; velocity; relative humidity; flow rate; natural convection; water retention.

ABBREVIATIONS

C_i	:	*Concentration of air on the surface (mol/m^3)*
C_p	:	*Specific heat (J/kg/K)*
C_v	:	*Steam concentration (mol/m^3)*
C_{vs}	:	*Concentration of saturizing steam (mol/m^3)*
D	:	*broadcast coefficient (m²/s)*
E_s	:	*Solar constant (W/m²)*
$E(Z)$	:	*Incident solar flow (W/m²)*
g	:	*Acceleration of gravity (m/s²)*
H	:	*Height of the basin (m)*
H_r	:	*Relative humidity (%)*
h_c	:	*Convective exchange coefficient (W/m²)*
h_r	:	*Radiative exchange coefficient (W/m²)*
L	:	*Length of the basin (m)*
l	:	*Basin width (m)*
L_{evap}	:	*Latent evaporation heat (J/kg)*
P_a	:	*Steam pressure (Pa)*
P_{atm}	:	*Atmospheric pressure (Pa)*
P_{vs}	:	*Saaturizing steam pressure (Pa)*
T_{am}	:	*Ambient temperature (K)*
T_c	:	*Temperature of the sky (K)*
u	:	*Longitudinal component of speed (m/s)*
v	:	*Transversal component of speed (m/s)*
v_e	:	*Evaporation speed (m/s)*

1. INTRODUCTION

Literature is abundant of scientific works on the analysis of heat and mass transfers by evaporation in large impoundments, lakes, ponds through local and global methods, both in laminar [1,2] and turbulent regimes [3,4,5]. Thus, the natural or forced convection mechanism and the laminar or turbulent flux influence the evaporation rate [6,7]. Concerning the evaporation of water bodies, considerable efforts are made to correlate the evaporation rate of the free surface in immobile and moving air [6,8-10]. The main correlations to calculate the evaporation rate encountered in scientific literature include the one based on Dalton's law [11] and that based on the analogy between heat and mass transfer. Dalton's law states that the rate of evaporation at water bodies surface is proportional to the difference between the saturated vapor concentration at the surface and the vapor concentration at the air temperature and that this proportion gap is impacted by the wind speed. Several studies in literature are carried out based on Dalton's law [8,12-14]. In addition to both correlations, some so-called indirect methods (Penman method, energy balance) using meteorological data to assess the evaporation rate are still used by some authors [15 -20].

This work is devoted to a numerical study of the assessment of heat and mass transfers by evaporation of a large impoundment under Burkina Faso climatic conditions. This impoundment is considered as a parallelepiped whose upper face, in contact with the ambient environment and subject to a solar flux, is the seat of evaporation by natural convection. One of the aims of this study is to analyze the evolution of the evaporated water flow for a solar flux density, a relative humidity of the air according to wind speed and also the evolution of the evaporated water flow rate against a solar flux density for several relative humidities. We will also show the evolution of the evaporated water flow depending on the impoundment depth for relative density of solar flux, humidity and the temperature of the surface of the given water body.

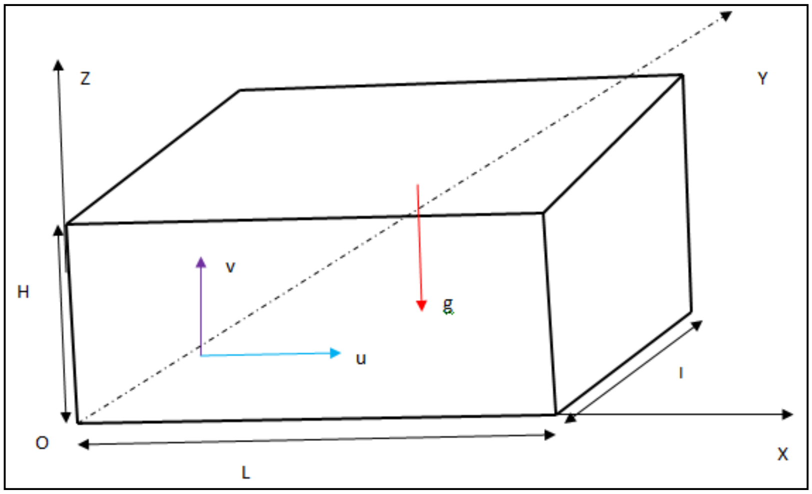

Fig. 1. Physical model

2. POSITION OF THE PROBLEM

Let's consider a parallelepiped impoundment domain with the length L = 2 m and the height H = 0.5 m. The upper face is in contact with the ambient environment and is therefore the seat of evaporation by natural convection. Under the solar flux, there is a difference in water temperature, generating natural convection transfers.

Let's consider the following simplification hypotheses:

- Transfers are bi-dimensional, the domain width is supposed to be very large compared to the other dimensions,
- Water is an incompressible and a Newtonian fluid
- Viscous dissipation according to the energy equation is not significant. There is no chemical reaction
- Water physical properties are constant, except the volume mass that aligns with BOUSSINESQ

3. MATHEMATICAL FORMULAS

The All By adopting the simplifying hypotheses made above, the equations that govern the natural convection transfers in the impoundment are written in the Cartesian reference system (O, X, Z):

- Continuity Equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial z} = 0 \quad (1)$$

- Equation of movement quantity

○ Following component [OX)

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial z^2}\right) \quad (2)$$

○ Following component [OZ)

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial z^2}\right) + \bar{g}\beta_T(\mathrm{T} - \mathrm{T_{am}}) \quad (3)$$

- Energy Equation

$$\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial z} = \frac{\lambda}{\rho c_p}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial z^2}\right) + \frac{1}{\rho c_p}\frac{dE(z)}{dZ} \quad (4)$$

Where $E(Z)$ is defined by :

$$E(z) = E_s e^{-\mu Z} \quad (5)$$

with $E(Z)$ the incident flux at z and $E(S)$ the solar constant.

4. INITIAL CONDITIONS AND CONDITIONS TO THE LIMITS

4.1 Initial Conditions

Based To avoid divergences, we must start from an initial state that is close to reality; physical volumes are therefore taken as follows:

v t < t_0, t_0 being the time when the solar flux is captured by the water surface.

$$T(x, z, t_0) = T_{am} \quad (6)$$

$$p(x, z, t_0) = P_{atm} \quad (7)$$

4.2 Conditions to Limits

These various conditions are summarized as follow:

v t > t_0, t_0 being the time when the solar flux is captured by the water surface.

– $x = 0 \; and \; 0 \leq z < H$

$$\left.\frac{\partial T}{\partial x}\right|_{x=0} = 0 \quad (8)$$

$$\left.\frac{\partial u}{\partial x}\right|_{x=0} = \left.\frac{\partial v}{\partial x}\right|_{x=0} = 0 \quad (9)$$

– $x = L \; and \; 0 \leq z \leq H$

$$\left.\frac{\partial T}{\partial x}\right|_{x=L} = 0 \quad (10)$$

$$\left.\frac{\partial u}{\partial x}\right|_{x=L} = \left.\frac{\partial v}{\partial x}\right|_{x=L} = 0 \quad (11)$$

– $z = 0 \; and \; 0 \leq x \leq L$

$$u(x,0,t) = v(x,0,t) = 0 \quad (12)$$

$$\left.\frac{\partial T}{\partial z}\right|_{x=0} = 0 \quad (13)$$

– $z = H \; and \; 0 \leq x \leq L$

$$u(x,z,t) = 0 \quad (14)$$

$$v(x,z,t) = v_e \quad (15)$$

$$k\left.\frac{\partial T}{\partial z}\right|_{z=H} + \varphi_s \alpha_{abs} = h_c(T(x,H,t) - T_a) + \sigma \varepsilon h_r(T(x,H,t) - Tc + \rho Levapkm Cvs(H) - Cv \quad (16)$$

Where v_e: The evaporation speed is written:

$$v_e = \frac{-D}{1-C_i}(C_{vs}(H) - C_v) \quad (17)$$

$$D = 2.26 \times 10^{-5} \times \frac{1}{P_{atm}} \times \frac{(T(x,H,t))^{1.8}}{273}{}^{1} \quad (18)$$

where $C_i \approx 0$.

5. METHODOLOGY AND VALIDATION OF THE MODEL

The integration of equations (1-4) and their boundary conditions (6-16) by the finite volume method described by Patankar [21] leads to an Algebraic equation system that we solved using Thomas' method and the SIMPLE algorithm. The meshing is uniform in both directions. In order to validate our calculation code, we compared our results to those obtained by V.P.SINGH and C.Y.XU [22] during the study. As shown in Figure 2, our results perfectly correlate with those obtained by V.P.SINGH and C.Y.XU. Indeed, the maximum relative gap between data noticed and those calculated by our code is 5.12%.

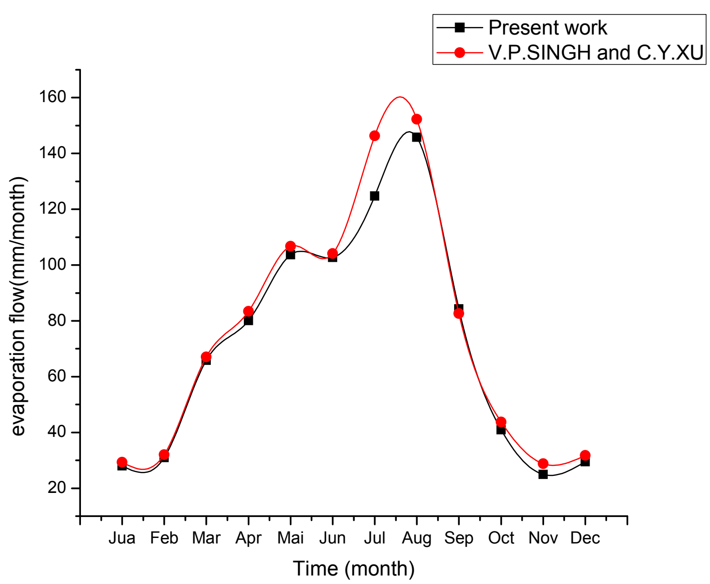

Fig. 2. Validation of the model

6. RESULTS AND DISCUSSION

The results presented here were obtained for the constant physical properties of the fluid (water). We analyze the influence of climate variables (relative humidity, solar flux, ambient temperature) on the evaporated water flow according to the evaporation rate, as well as the impoundment depth.

Fig. 3 shows the evolution curve of the evaporated water flow according to the evaporation speed. The analysis of this figure shows that the flow of evaporated water is all the higher as the speed is high. Indeed, heat transfer and mass coefficients between the surface of the impoundment and the ambient environment are proportional to the evaporated water flow rate, therefore to the evaporation rate. As a consequence, for a given relative humidity, the flow of evaporated water is even lower than that of smaller values of the solar flux.

Fig. 4 is the evolution curve of the evaporated water flow also according to the evaporation rate. Through this figure, we notice that for a given solar flux value, the flow of evaporated water is even higher than that of smaller values of the humidity rate.

Fig. 5 is the evolution curve of the evaporated water flow rate and the surface temperature of the water according to evaporation rate at a moisture content of 5%. Both quantities are almost proportional to the evaporation speed and increase when the evaporation speed increases. It also shows that the surface temperature increases with the evaporation rate.

Fig. 6 shows the evolution curve of the evaporated water flow according to the evaporation speed. The analysis of this figure shows that the flow of evaporated water is all the higher as the speed is high. Indeed, the heat transfer and mass coefficients between the surface of the impoundment and the ambient environment are proportional to the flow rate of water evaporated, therefore to the evaporation rate. Consequently, for a given relative humidity, the flow of evaporated water is even higher than that of highest values of the ambient temperature.

The answers of the evaporation rate to parameter variations have common features that can be fairly considered as a response to the first level flow; an overall decreasing trend variation going towards an asymptote which is here the depth of the impoundment. Indeed, the non-linearity is visible as well as that of the gain: We can state that the variable of the answer is not proportional to the variation of the entry parameter which includes the solar flux and the relative humidity.

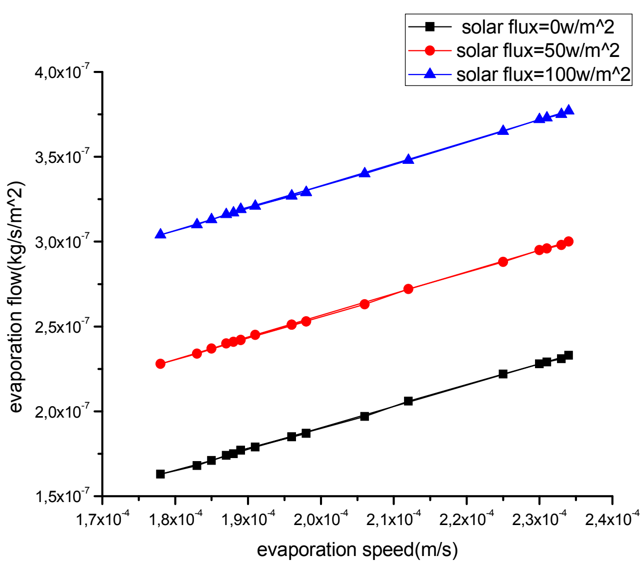

Fig. 3. Evolution of the evaporated flow according to the evaporation speed: Influence of solar flux

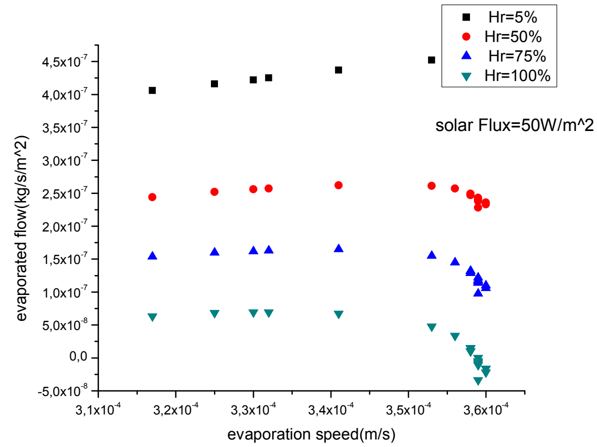

Fig. 4. Evolution of the evaporated flow according to the evaporation speed: Influence of humidity

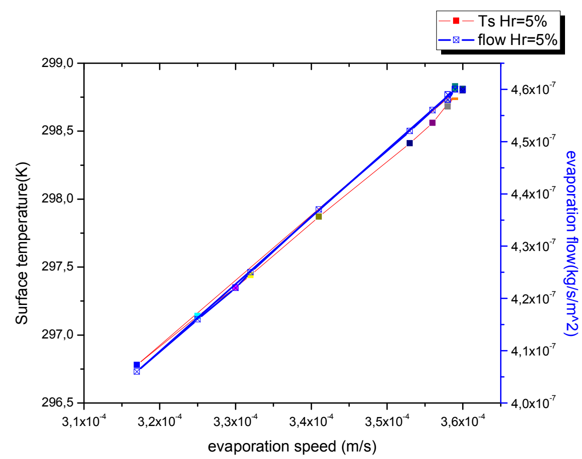

Fig. 5. Evolution of surface temperature and of the flow according to the evaporation speed

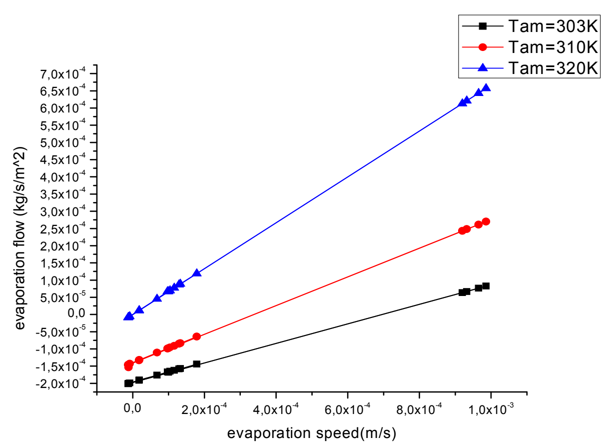

Fig. 6. Evolution of the evaporated rate according to the evaporation speed: Influence of temperature ambient

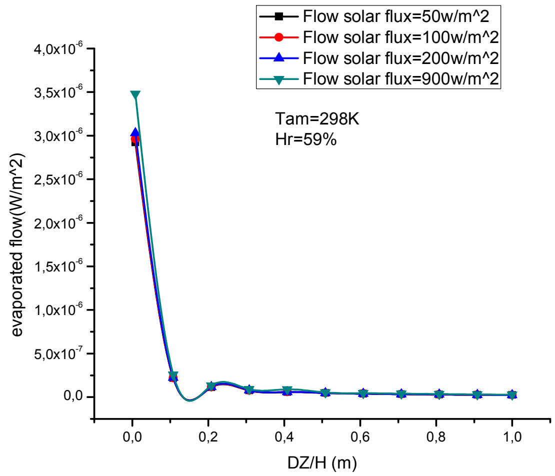

Fig. 7. Evolution of the evaporated flow according to the depth: Influence of the solar flux

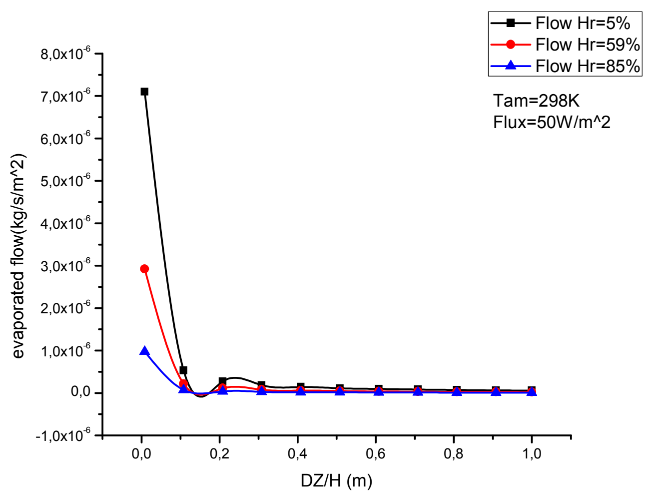

Fig. 8. Evolution of the evaporated flow according to the depth: Influence of humidity

The response of the evaporated water flow for an ambient temperature T_{am} = 298 and a relative humidity H_r = 59% at solar flux variations (Fig. 7) shows that the increase of the impoundment decreases with the value of the solar flux. We also notice that for large depths, the variation of the evaporation rate is almost linear, thus to show that for significant depths, the evaporation rate is almost negligible.

Fig. 8 shows the evolution curve of evaporated water flow according to the impoundment depth at variable relative humidity rates. We notice an increase in the evaporation rate for lower values of relative humidity. The decrease in evaporation rate is also noticed for a depth increase. Thus, the relative humidity influences the evaporation rate; either to increase it, or decrease it.

7. CONCLUSION

We have numerically studied the heat and mass transfers by evaporation of a large impoundment under Burkina Faso climate conditions. A modeling method is proposed. This method is based on the local results of heat and mass transfers on the impoundment surface, which is considered as a boundary condition at the surface and also the method of combining the Navier-Stokes equations and those of energy.

The influences of some parameters, including relative humidity and solar flux, on the evaporated water flow were studied according to the evaporation speed, then to the impoundment depth. Results obtained show that the evaporation rate is highly influenced by the solar flux and the relative humidity rate.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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