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Numerical Investigation of Solar Drying under Open Sun and in a Greenhouse Solar Dryer

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Abstract— **The aim of this study is to develop a thermal modelling of the drying under open sun and in a greenhouse solar dryer in hot and cold climates. The process of greenhouse solar drying is showing its efficiency as it is able to support the product with more heat than the traditional process of open sun drying. A configuration was thus proposed and simulated using the software Comsol Multiphysics in order to solve the equations governing our problem. The resulting simulations were used to evaluate the temperature and velocity distributions after hours of sunshine and to provide a quantification of both drying processes. These results have the same profiles as expected and the influence of the greenhouse effect on the drying is highlighted.**

Keywords— **greenhouse solar dryer, open sun drying, Comsol Multiphysics, simulations, quantification, drying process.**

I. INTRODUCTION

Solar drying is considered as a basic operation in many industrial processes. Open sun drying, where solar radiation falls directly on the product surface and is absorbed, is one of the oldest and traditional solar drying methods. The sun's free energy for this process is offset by a variety of shortcomings, like sudden rain damage, mildew, insect infestation etc.

Thanks to the great solar potential of Tunisia, greenhouse drying could be an alternative to open sun drying while it can reduce the drying time and increase the quality of the products.

Modeling a drying process is a complex is a complex problem including simultaneous heat and mass transfer. Simulation models play a significant role in the development of such problem. Actually, it helps engineers to design new drying systems, to improve existing ones or to control the drying operation.

In the last decade, both processes of drying have been significantly developed and compared in many researches. Anil et al.[1] studied the effect of mass on the convective mass transfer coefficient during open sun and greenhouse drying of onions flakes. They found also that during the off sunshine hours, the rate of moisture evaporation for a greenhouse drying is more than that in open sun drying due to the stored energy inside the greenhouse. Laboratory drying experiments were carried out to study the drying of red pepper under open sun and greenhouse drying conditions[2]. The effect of drying parameters on drying time and moisture content were determined. A drying model of red pepper was developed and validated. A correction factor was introduced to the formulation of this model while it overestimates the drying process. Dilip Jain et al.[3] proposed mathematical models to study the drying kinetics of crops (cabbage and peas) for open sun drying and inside a greenhouse dryer under both natural and forced convection. The results have been computed in Matlab Software and validated with experimental ones. Fadhel et al.[4] investigated the phosphate drying kinetics for a solar drying under open sun, in a greenhouse and by a parabolic dish concentrator. Compared to the open sun and the greenhouse drying, they indicated that the use of parabolic dish concentrator ensures a faster drying rate.

Greenhouse dryer can be used not only for the preservation of agricultural products but also as a first step before developing further applications like in the case of wastewater. Under arid climate, Belloulid, M.O[5] recommended the greenhouse solar drying in hot as in cold periods. The studied process provided significant energetic and financial advantages. Sanae et al[6] compared the drying performance of the processes of open sun and greenhouse drying (for natural and forced convection) of olive mill wastewater. The purpose of this study is to make this waste ready for valorization and utilization as a fuel.

In the concept of this study, water was evaporated under open sun and in a greenhouse dryer in both hot and cold seasons.

II. MODELLING CONSIDERATIONS

A. Model Formulation

The drying process involves coupled heat and mass transfer. For its modelling, it is necessary to solve the fluid mechanics equations, namely mass, momentum, energy and species conservation equations. These equations are written as follow:

$$\nabla(\rho u) = 0 \tag{1}$$

$$\rho \frac{\partial u}{\partial t} + \rho(u\nabla)u = -\nabla\left[P.I + \mu\left(\nabla u + (\nabla u)^T\right)\right] + F \tag{2}$$

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$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p u \nabla T = \nabla(\lambda \nabla T) + Q_{sol} + Q_{conv} + Q_{rad} + Q_{evp} \quad (3)$$

$$\rho \frac{\partial w_i}{\partial t} + \nabla j_i + \rho(u\nabla) w_i = \dot{m} \quad (4)$$

Where:

$$j_i = -\left(\rho D_i^f \nabla w_i + \rho w_i D_i^f \frac{\nabla M_n}{M_n} + D_i^T \frac{\nabla T}{T} \right)$$

And

$$M_n = \left(\sum \frac{w_i}{M_i} \right)^{-1}$$

Herein D_i^f and D_i^T are respectively the diffusion coeifficient and the thermal diffusion coeifficient.

Q_{sol}, Q_{conv}, Q_{rad} and Q_{evp} are respectively the absorbed solar radiation, the convective, the radiative and the evaporated flux which are presented in the next section.

At the air-water interface surface, the initial thermal, hydrodynamic and mass transfer boundary conditions can be written as follows:

$$u(x, \mathrm{y}=0) = 0\,; T(x, \mathrm{y}=0) = T_0\,; \mathrm{w}(x, \mathrm{y}=0) = w_0$$

B. Heat Transfer Model

The heat transfer of a drying process can be described by means of different heat flux. The fluid surface received the solar radiation and transmitted a convective, evaporative and long-wave radiation flux.

In this study, the Charles Edwards and Acock model for the radiation flux density for the N^{th} day and at a certain day time is adopted [8]:

$$\mathrm{E(t)} = \begin{cases} \dfrac{J_N}{g_N}\left\{1+\cos\left[\dfrac{2\pi}{g_N}(t_d - 0.05)\right]\right\}; & 0.5 - \dfrac{1}{2} g_N \le t_d \le 0.5 + \dfrac{1}{2} g_N \\ 0 & ;\ \text{otherwise} \end{cases}$$

Where t_d represents the fractional part of a day time, J_N is the N^{th} day's global radiation and g_N is the daylength which depends on the dryer location's latitude j and the solar declination d .Each variable can be estimated using the following equations:

$$t_d = \frac{t(h)}{24}$$

$$g_N = \frac{2\arccos(-\tan j \tan d)}{2p}$$

Where,

$$d = 0.38092 - 0.76996\cos(y) + 23.26500\sin(y) + 0.36958\cos(2y) + 0.10868\sin(2y) + 0.01834\cos(3y) - 0.16650\sin(3y) - 0.00392\cos(4y) + 0.00072\sin(4y) - 0.00051\cos(5y) + 0.00250\sin(5y) + 0.00442\cos(6y)$$

Herein, y is the year angle at the climatological day number N (N starts on the first day of May) and can be written as:

$$y = \left(\frac{N - 21}{365}\right) 2p$$

Therefore, the received solar radiation can be written as:

$$Q_{sol} = \alpha E(t)$$

With α is the absorptivity of the fluid.

As concerns the radiative, convective and evaporative flux, they can be respectively expressed as:

$$Q_{conv} = h(\mathrm{T} - \mathrm{T}_a)$$

$$Q_{rad} = \varepsilon\sigma(\mathrm{T} - \mathrm{T}_a)$$

And

$$Q_{evp} = \dot{m} L_v$$

Where h is the convective mass transfer coefficient (m/s), T_a is the air temperature, ε is the emissivity of the fluid, σ is the Stefane Boltzmann constant ($5.6704.10^{-8}$ $W.m^{-2}.K^{-4}$), Lv is the latent heat of vaporization (J.kg-1) and $\dot{m}$ represents the mass of evaporated water (kg)

Meteorological effects were also included in the model. The ambient air temperature variation throughout the day can be described by the following expression:

$$T_{amb}(t) = T_{avg} + \Delta T \cos(2\pi \frac{t-14}{24})$$

Where T_{avg} is the average temperature and ΔT is the half diurnal temperature variation.

C. Mass Transfer Model

The mass transfer can be considered as controlled diffusion. Therefore, the interfacial evaporating mass flux is assessed by the Fick's law as expressed in the following equation:

$$\dot{m} = -\rho\, D\, \nabla w$$

According to the Raoult's law and by assuming the interface to be at local thermodynamic equilibrium and the air-vapour mixture as an ideal gas mixture, the mass fraction of vapour can be evaluated by:

$$w(x, \mathrm{y}=0) = \frac{M_v P_{vs}}{M_v P_{vs} + (P - P_{vs}) M_a}$$

Where P and P_{vs} presents respectively the reference pressure and the equilibrium vapour pressure at the interfacial temperature T_i, which can be written as follows:

$$P_{vs} = \exp(28.59051 - 8.2\frac{Log(\mathrm{T}_i)}{Log(10)} + 0.0024804 T_i - \frac{3142.42}{T_i}) Log(10)$$

M_a and M_v are the molecular mass respectively of air and water vapour ($kg.mol^{-1}$).

III. NUMERICAL MODEL

A. Geometry of the Computational Area

COMSOL Multiphysics software is a valuable tool for solving coupled heat and mass transfer problems. However, such problem requires long running time and high computing power. Therefore, the modelled object's geometry should be simplified as far as practicable. In this study, the proposed geometry is assumed to be two-dimensional and axisymmetric to the axis projecting from the center of the curve and perpendicular to the water surface. In this way, the computational process is considerably accelerated allowing studying higher number of cases.

The assumed geometry is presented in Fig 1 and its dimensions are given in Table I.

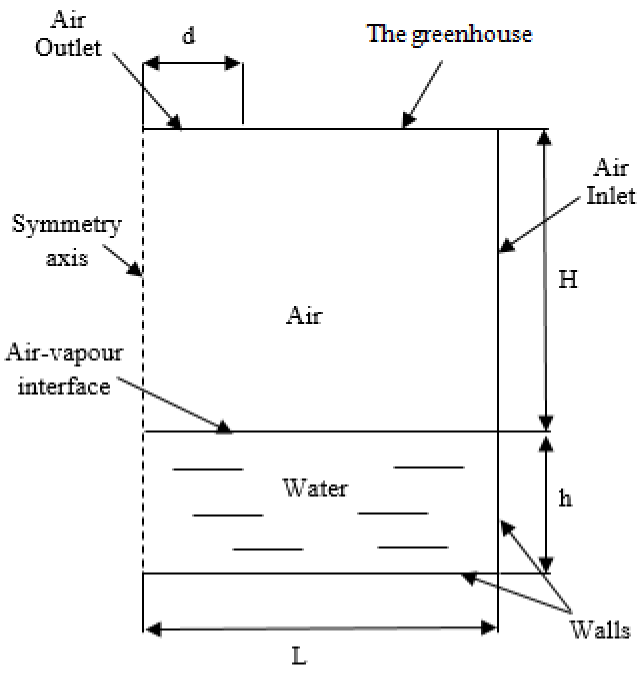


Fig. 1 Geometry of the simulated area

TABLE I
GEOMETRY OF THE SIMULATED AREA

Dimensions	**Value(m)**
L	0.12
H	0.05
h	0.0263

B. Method

In order to study the temperature effect on the drying process, a curve fulfilled with water, was taken under hot and cold climatic conditions. A typical day was considered for the two periods. During the hot period, the average temperature was about 304 K and the solar radiation reached 850 W/m^2, whereas, during the cold one, the average temperature was about 285 K and the solar radiation reached 400 W/m^2. The variation of the average temperature and the solar radiation throughout a hot and cold day are showed in fig. 2 and 3. They were calculated using data related to Tunisian meteorological conditions.

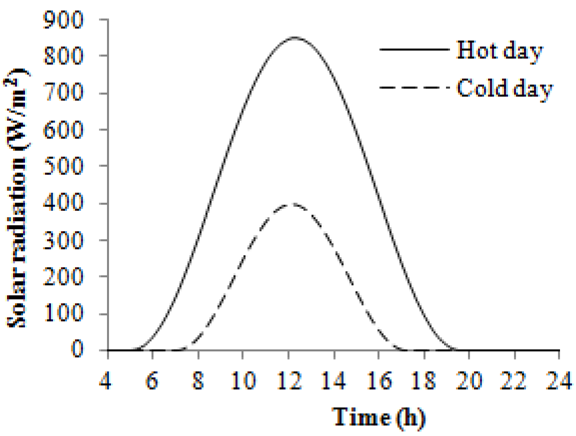


Fig. 2 Daily variation of solar radiation

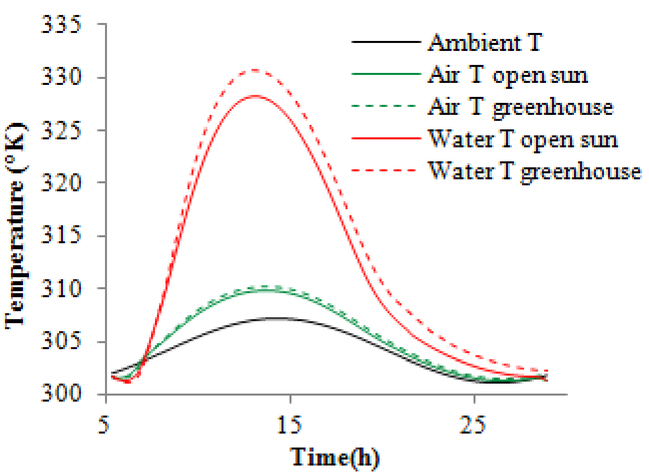
IV. RESULTS AND DISCUSSION

For the hot and cold day, the average air, as well as the average water temperatures under open sun and inside a greenhouse solar dryer are shown in fig. 3. Their thermal behaviour is slightly asymmetrical with respect to the solar midday.

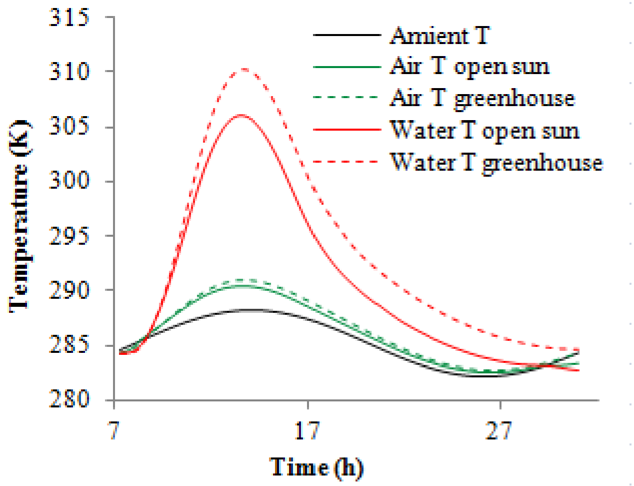
Within the greenhouse, the air temperature, ranged between 301,7°K and 310,5°K during the hot day and between 282,5°K and 291,5°K during the cold one, was not significantly different to that under open sun which ranged between 301,7°K and 309,5°K during the hot day and between 282,5 ° K and 290,5 °K for the cold one.

The solar radiation was trapped and stored in the greenhouse, therefore, the water temperature there, which reached 330,6°K during the hot day and 310,3°K during the cold day, was high compared to the water temperature during open sun drying which reached 328°K during the hot day and between 306°K during the cold day.

Moreover, it can be noticed that water temperature always exceeded the air temperature due to its high heat capacity compared to that of air.



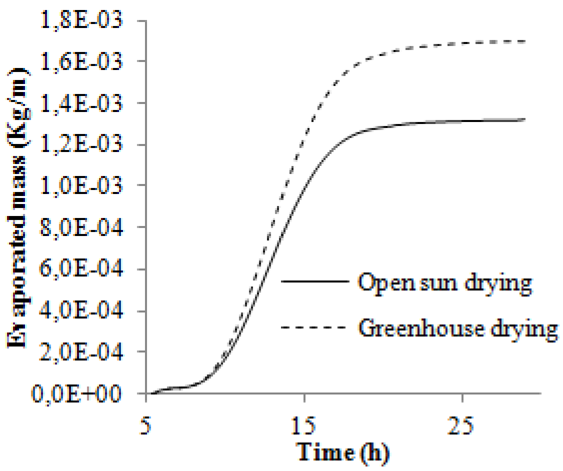
(a)



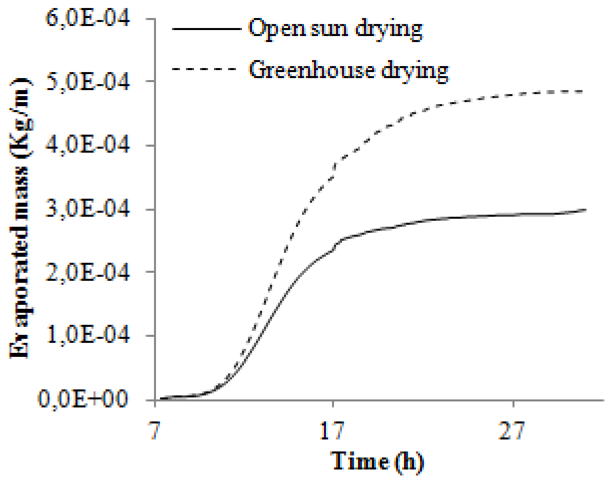
(b)

Fig. 3 Ambient, average air and water Temperature under open sun and inside the greenhouse for (a) a hot day and (b) a cold day.

From fig. 4 , it was observed that , whether for hot or cold days , the evaporated water mass under open sun and within the greenhouse dryer increased rapidly for about the 15 hours and slowly for the rest of the day. This can be explained by the increasing of the solar radiation until midday and its decreasing for the rest of the day. In addition, it was obvious that the evaporated water mass reached its higher value, with about 1,7 g/m, during the hot day and within a greenhouse compared to about 1,32 g/m under open sun for the same day, and to 0,3 g/m and 0,485 g/m respectively inside the greenhouse and under open sun for the cold day.



(a)

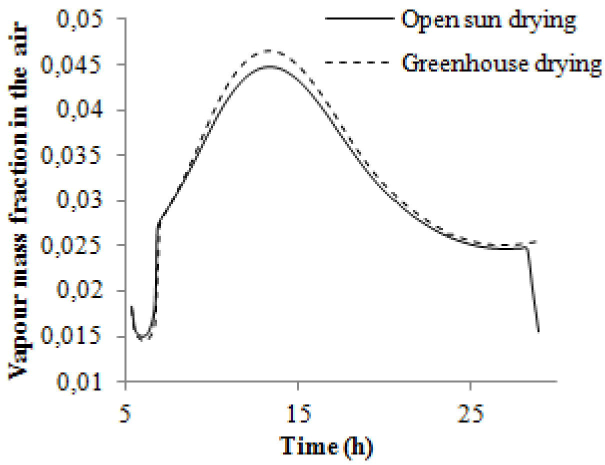


(b)

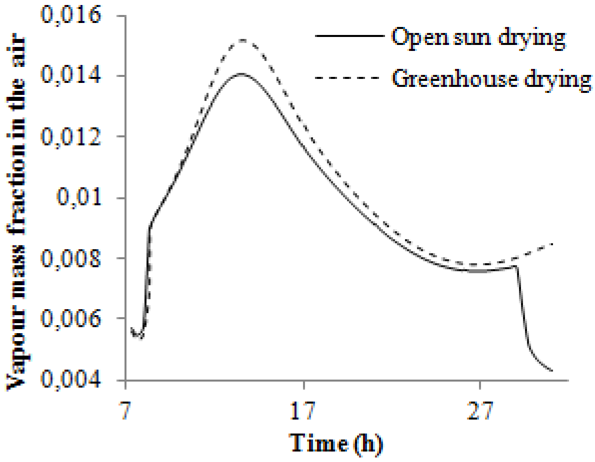
Fig. 4 Evaporated water mass under open sun and inside the greenhouse for (a) a hot day and (b) a cold day.

The vapour mass fraction in the air during the drying processes is presented in fig. 5. During the two days, it increased for the first 8 hours and decreased for the rest of the days. While the kinetic energy of a molecule is proportional to its temperature, evaporation can proceed more quickly at higher temperatures. Thus, when the water molecules located at the surface have enough kinetic energy, they escape from the liquid to the air and therefore, the vapour mass fraction in the air increased.

This vapour mass fraction in the air is more important in the greenhouse, reaching 0,047 and 0,152 respectively during the hot and cold day compared to 0,045 and 0,014 during open sun drying and respectively for the hot and cold day.



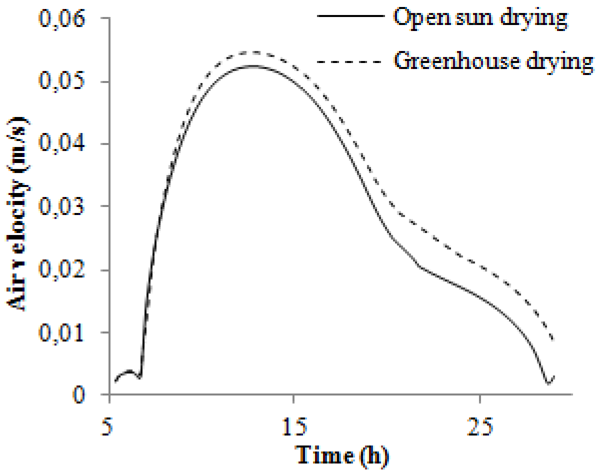
(a)



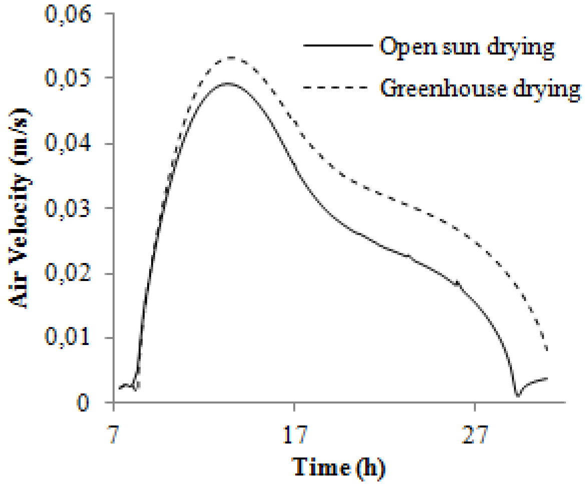
(b)

Fig. 5 Vapour mass fraction in the air under open sun and within the greenhouse dryer for (a) a hot day and (b) a cold day

It is evident that the rise and fall of air temperature affected the natural convection during the evaporation of water, therefore, air velocity increased with the rise of air temperature and decreased with its fall as shown in fig. 6. For both days, the air velocity was not significantly different. In the greenhouse, it was slightly higher than under open sun and reached 0,054 m/s compared to 0,052 m/s under open sun during the hot day.



(a)



(b)

Fig. 6 Air velocity under open sun and within the greenhouse dryer for (a) a hot day and (b) a cold day

V. Conclusions

A numerical study was developed to highlight the efficiency of greenhouse solar drying compared to open sun one for hot and cold periods. The results of the current simulation are as expected. Thanks to the greenhouse effect, the evaporated water quantity increased from about 1,32 g/m to 1,7 g/m and from 0,3 g/m to 0,485 g/m, respectively in hot and cold days. Thus, using greenhouse solar drying plays an interesting role, allowing more evaporation in less time.

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