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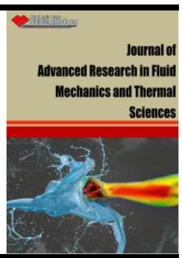

Theoretical Drying Model of Water Vapor Pressure for Imbibed Porous Material with Sea Water Subjected to Weather Conditions

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ABSTRACT

The drying model of porous material has been studied and solved. The drying model solves the drying of porous material if the porous material is saturated or unsaturated with salt solution. Local thermodynamic equilibrium was not assumed in the mathematical model for describing the multi-phase flow in the unsaturated porous media using the energy and mass conservation equations to describe the heat and mass transfer during the drying. The vapor pressure inside porous material voids is built from the vapor mass transport through material thickness and from the void's water content evaporation. The new equation in the model is water vapor pressure's equation. The drying model included advection and capillary transport of the water in porous material pores, the gases transport by advection and diffusion and soluble salt transports by diffusion only. The environment of the boundary condition of the model is atmospheric condition in the day's hours. The model consists of 5 equations for mass and heat transfer phenomenon. The model was solved by Matlab software. The case study of the model is concrete block.

1. Introduction

It is reported [1] that the mass transfer occurs in the liquid and vapor phases, each phase phenomenon is used alone to calculate the liquid saturation and water vapor pressure, respectively. The evaporative term is estimated, and the water vapor pressure is calculated depending upon the physical phenomenon of water vapor mass transfer inside porous medium.

Lu *et al.,* [2] considered that local thermodynamic equilibrium in the mathematical model describing the multi-phase flow in the unsaturated porous media using the energy and mass conservation equations to describe the heat and mass transfer during the drying. Nicolai and Grunewald [3] studied the influence and importance of the parameters of a salt transport. A phase transition model is investigated using simulations of drying experiments. In drying experiments with pure water, an almost constant drying rate period followed by a falling rate drying was also observed. For the constant rate, the process is controlled only by surface conditions at the evaporation side. Moisture transport from the inside of the moist material to the evaporation side

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is fast and air movement over the evaporation surface, which is considered in the model through the heat and vapor exchange coefficients, is the limiting factors. In the falling rate period, the moisture transport to the evaporation side decreases and the drying rate is controlled by liquid and vapor transport properties of the material. Zhang *et al.,* [4] studied the influence of the material's permeability on drying behavior. For porous materials with higher permeability, the drying rate was smaller in the constant rate drying period and higher in the falling rate drying period. This is because the gradient of moisture is smaller inside these materials, and the migration of moisture is slower in the constant rate drying period. But in the falling rate drying period the drying rate is higher, because the movement of gas mixture and the diffusion of vapor are easy for materials with high permeability. The results obtained by Bolaji [5] indicated prospect for higher rate of moisture removal in solar dryer than open-air sun drying. The results also showed that at lower liquid concentration in the food items, the moisture flux increased with increasing in the liquid concentration and was constant at higher liquid concentrations above $70\,\mathrm{kg/m^3}$. The rate of moisture removal from the food item is a function of both the temperature inside the dryer and radiation flux. Most of natural and biological phenomena such as solute transport in porous media exhibit variability which cannot be modeled by using deterministic approaches. Therefore, more sophisticated concepts and theories are needed to capture the complexity of system behavior. Study of fluid and heat flow within porous media is also of significant importance in many other fields of science and engineering. Such fields include drying of biological materials and biomedical studies. In these situations, the micro-structure of the material can be studied and the transfer processes in relation to the micro-structure can be understood. So, the problem of prediction can be simplified with the assistance of the detailed knowledge of the system and real-time data. Mohamed *et al.,* [6] found the solar beam radiation is almost vertical on the horizontal surface, which makes the best fixation of the surfaces to be horizontal in the summer season, but in the equinox season, the angles of the solar beam are changed, which makes the inclined surfaces receive a noticeable part of the sun's rays and the installation at an angle of inclination with the horizontal is the best in the equinox seasons. It is reported [7, 8] that, the models range from traditional energy and mass transport models to elaborated models involving internal moisture transport and porous-media approaches. Advances in technology and simulation software may now allow further development of models that can capture the complexity of heat–mass transfer physics that takes place in industrial meat processing. Kowalski [9] has presented his model which describing the mechanical behavior of the fluid-saturated capillary-porous material during drying. He was developing the system of equations describing the deformations of moist material during drying and the drying induced stresses, he selected those phenomena which were relevant for the drying process and neglect those which were of slight importance. Rattanadecho and Wongwises [10] have studied the characteristics of heat transport and water infiltration in granular packed bed due to supplied hot water was investigated experimentally and numerically. They found by using a larger particle size the results in a faster in filtration rate and forms a wider infiltration layer, especially in the direction of gravity. But they have released the extension of the heated layer which is not as much as that of the infiltration layer because the temperature of water infiltration gradually drops due to upstream heat transport. Suwannapum and Rattanadecho [11] has used successfully a mathematical model for analysis of heat and mass transfer and pressure buildup in typical porous packed beds subjecting to microwave energy to describe transport phenomena in several conditions. The results showed that the effect of particle sizes and thicknesses of porous packed bed were primary factors determining heat and mass transport with multiphase flow. Their model can explain the phenomena taking place inside unsaturated porous media in a microwave drying process using a rectangular waveguide. Kolditz and Jonge [12] considered non-isothermal two phase flow of two components (air and water) in gaseous and liquid phases in extremely low-permeable porous media through the use of the finite element method (FEM). Also, they considered the impact of swelling/shrinking processes on porosity and permeability changes. Gawin and Pesavento [13] presented the application of mechanics of multi-phase porous media for modeling cement-based materials at high temperature. They have developed main stages of a mathematical model by means of hygrothermo-mechanics of porous media have been briefly presented. Mechanics of multi-phase porous media has proved its usefulness for better understanding and predicting concrete performance at high temperature. The model had been validated and the authors presented and analyzed two examples of its application for numerical simulation and analysis of concrete structures exposed to fire conditions, including also a cooling phase. Perré [14] had devoted to multiscale approaches to transfer in porous media, with particular attention to drying. He presented a macroscopic description which generated a dramatic demand in physical and mechanical characterization and fails in some, not especially unusual configurations. He emphasized the difference between formulations that need to be fed by experimental measurements or identified parameters and approaches that permit. Tomczak *et al.,* [15] compared the most popular natural drying methods for stem wood of transpiration and air drying. For moisture content and mass all methods were comparable. In each method, during storage, moisture content and mass decreased significantly. After three months, the initial moisture content above 50% can drop to between 27% and 35%, making logs an excellent fuel. Within three months, the density of the round wood stored in piles was about 140 kg/m3 less than other methods, what is important for transport efficiency. Grementieri *et al.,* [16] studied different drying kinetics in presence of the two types of efflorescence which have been confirmed by two experimental campaigns. The model showed to be able to describe the different kinetics of drying (saturation curves) occurring at different values of environmental humidity as well as the amount of crystallized salt precipitated in the specimen over time and the distribution pattern of the crystallized salt with a very good agreement with the experimental data. Mohsin *et al.,* [17] studied the evaporation of salt (NaCl) solutions from porous media in the presence of surfactants, because surfactants are often used as cleaning agents for salt-contaminated stones. They concluded that the presence of the surfactant increased the total drying time when compared to pure NaCl solutions dried under the same conditions.

2. Mathematical Model

2.1 Mass Balance Equation

$$\phi \frac{\partial}{\partial t}\left(\rho_l S_l\right) + \dot{m}'''_{evp} = -\left(\frac{\partial}{\partial z}\left(-\rho_l \frac{KK_{r,l}}{\mu_l}\left(\frac{\partial P_l}{\partial z} - \rho_l \vec{g}\right)\right)\right) \tag{1}$$

$$\phi \frac{\partial}{\partial t}\left(\rho_v S_{g'}\right) = -\frac{\partial}{\partial z}\left(-\rho_v \frac{KK_{r,g'}}{\mu_{g'}}\frac{\partial P}{\partial z} - \frac{C_{g'}^2}{\rho_{g'}} M_a M_v D_{eff} \frac{\partial\left(P_v / P\right)}{\partial z}\right) + \dot{m}'''_{evp} \tag{2}$$

$$\phi \frac{\partial}{\partial t}\left(S_{g'}\rho_a\right) = -\frac{\partial}{\partial z}\left(-\rho_a \frac{KK_{r,g'}}{\mu_{g'}}\frac{\partial P}{\partial z} - \frac{C_{g'}^2}{\rho_{g'}} M_v M_a D_{eff} \frac{\partial\left(P_a / P\right)}{\partial z}\right) \tag{3}$$

$$\phi \frac{\partial}{\partial t}\begin{pmatrix}\rho_l C_s S_l \\ +\rho_p S_p\end{pmatrix} = -\frac{\partial}{\partial z}\left(-\rho_l C_s \frac{KK_{r,l}}{\mu_l}\left(\frac{\partial P_l}{\partial z} - \rho_l \vec{g}\right) - \phi \rho_l S_l D_{sal} \frac{\partial C_s}{\partial z}\right) \tag{4}$$

2.2 Energy Equation

Mass transfer boundary condition

$$\left(\left(\rho C_p\right)_{eff}\frac{\partial T}{\partial t}\right)=\begin{pmatrix}-\frac{\partial}{\partial z}\left(-K_{eff}\frac{\partial T}{\partial z}\right)-\left(\dot{m}_l''C_{pl}+\dot{m}_v''C_{pv}+\dot{m}_a''C_{pa}\right)\frac{\partial T}{\partial z}\\ -\dot{m}_{evp}'''h_{fg}-\dot{m}_{crs}'''h_{cr}+q_{solo}''\gamma_{eff}\ \exp\left(-\gamma_{eff}\left(L-z\right)\right)\end{pmatrix} \tag{5}$$

Heat transfer boundary condition

At z=L, $\left.\begin{matrix}\dot{m}_l''=\dot{m}_{evap1}''\\ \dot{m}_v''=\dot{m}_{evap2}''\\ \dot{m}_{salt}''=0\\ P=P_{ha}\end{matrix}\right\}$, At z=0, $\left.\begin{matrix}\dot{m}_l''=0\\ \dot{m}_v''=0\\ \dot{m}_{salt}''=0\\ \dot{m}_a''=0\end{matrix}\right\}$

At z=L

$\dot{m}_v''h_v+-K_{eff,sur}\frac{\partial T}{\partial z}=\dot{m}_{vD}''h_v+\dot{m}_{evp1}''h_{fg}+q_{rad}''+q_{conv}''$ At z=0, $\left(-K_{eff}\frac{\partial T}{\partial z}\right)=q_{10}$

3. Model Solution

The model considered the salt concentration in the solution, surface and internal water diffusions to humid air as well as salt crystallization. The transient system of one-dimensional differential equations for liquid, vapor and dry air mass and momentum and energy conservations was developed together with the boundaries and initial conditions. Capillary motion has been considered for gas and liquid solution. A finite volume method was used for discretisation of the differential equations. A fully implicit scheme was used for unsteady term discretisation while the convective terms (liquid solution, vapor and dry air) in the energy equation are handled by an upwind scheme method. The system of equations is solved by direct method (inverse matrix). The coefficients matrix is a function of five dependent variables (liquid saturation, salt solution concentration, gas pressure, temperature and vapor pressure). The nonlinear system of equations is solved simultaneously by updating the coefficients matrix at one time step until the five variables converge to prescribed tolerances [18]. The numerical code is written in Matlab. Solution of the model is obtained and discussed.

4. Nodes Independent

Figure 1 shows nodes independent number test.

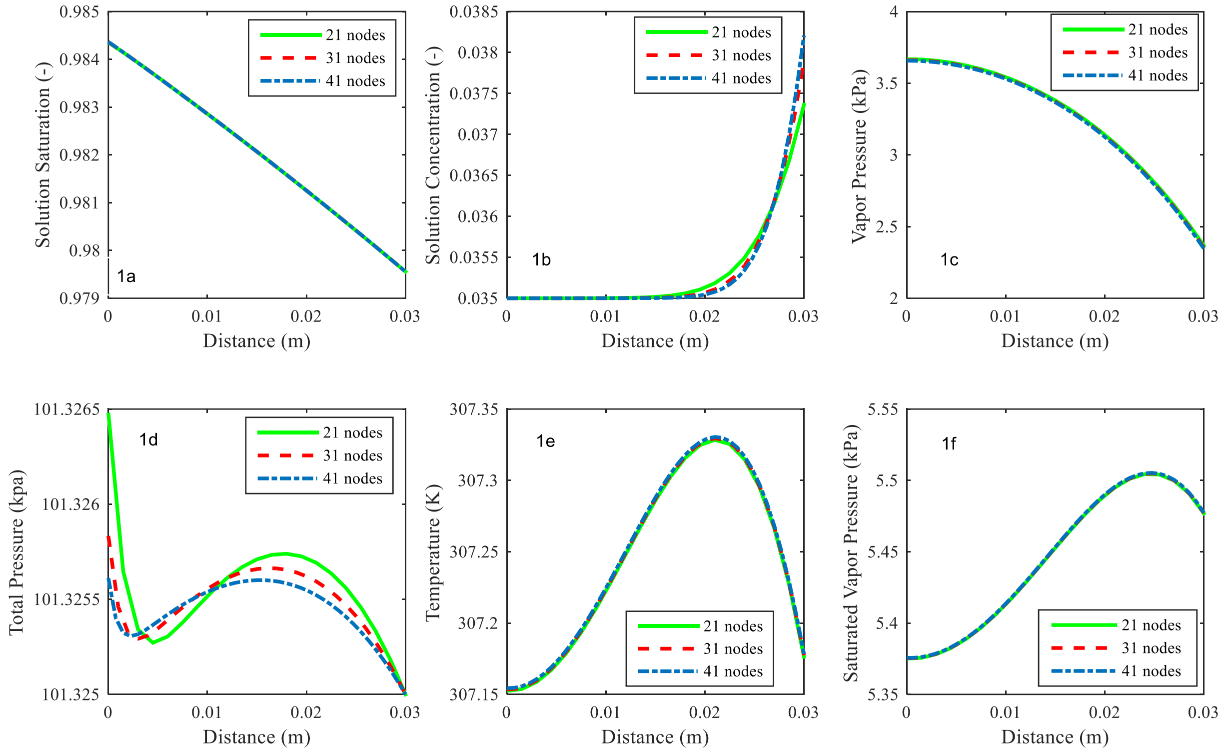

Fig. 1. Nodes independent numbers test

5. Results and Discussion

The case study is concrete block of 30.0 mm thick and 0.22 porosity with sea salinity of 0.035 kg solute/kg solution. Figure 2 and 3 show the water saturation, solute concentration, water vapor pressure, temperature, total pressure and saturation water vapor pressure inside porous material bed through two days of cold and hot weather.

It is clear the difference between the vapor pressure and the saturated vapor pressure every day in either of the two figures. This proves that the vapor pressure depends on the vapor mass present in the voids of the porous material and does not depend on the thermodynamic equilibrium. In cold climates, the rate of evaporation is low, which led to a decrease in the salinity of the water on the surface of the porous material and it continued to gradually rise to about hours of the day in temperature degrees. In hot climates, the rate of evaporation was high, which led to a high salinity of water on the surface of the porous material, and after sunset the salt spreading process continues to reach the dynamic equilibrium. The effect of capillary property and capillary pressure was shown in the saturation curve of water for the possibility of compensation by the capillary tubes in low evaporation for the cold day. And it happened that the capillary property compensation was less in the case of evaporation in hot weather day as in the water saturation curve for the month of May.

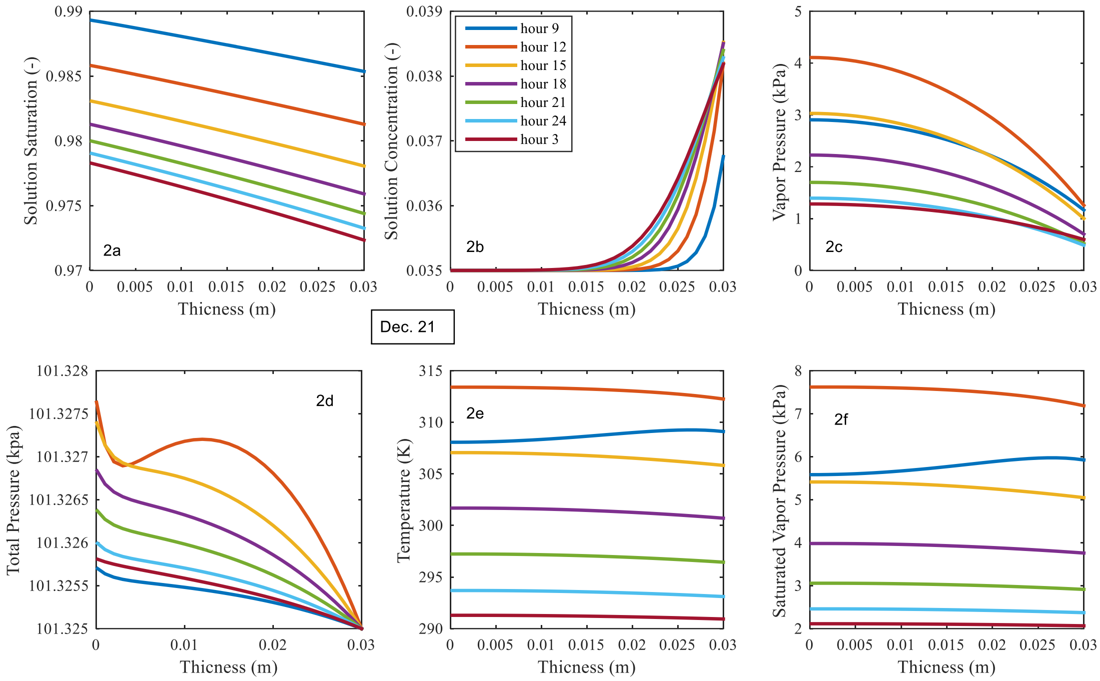

Fig. 2. S, C, P_v, P_t and P_{vs} distribution with porous material thickness for drying in Dec. 21

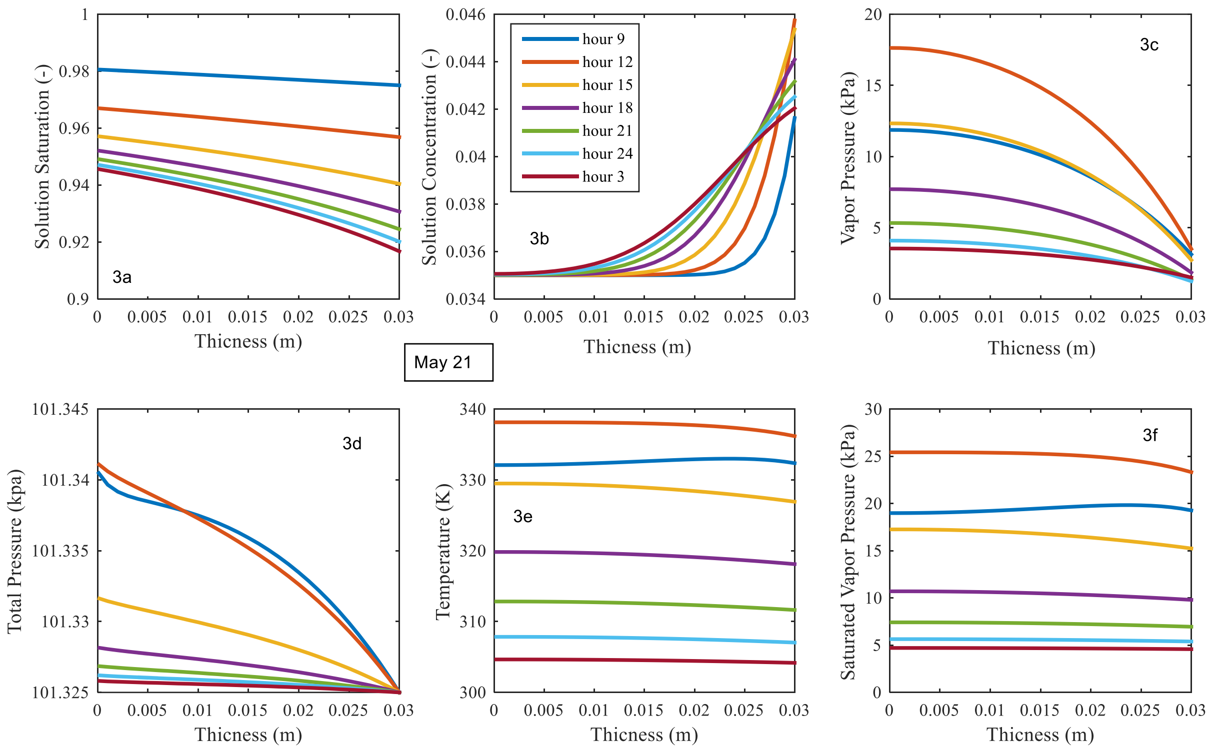

Fig. 3. S, C, P_v, P_t and P_{vs} distribution with porous material thickness for drying in May 21

Figure 4 and 5 shows 7 days continuously evaporation and all variables values were taken at time of hour 15 along whole day for the cold and the hot days. In every subfigure in each two Figure 4 and 5 there are curves that represent the 15th hour of every day. The results show the drying time for hot weather day is less than in the cold weather day. The stored sea water in the porous material block for the hot weather day is less than one in the cold weather day. For the two figures the stored vapor mass and the heat stored in the porous material helped increase the vapor pressure in the following days and then increased the amount of evaporation rate in ascending manner.

The difference in the rate of water evaporation between the first and the second day was greater than it between the second and third days, and this difference began to stabilize from the third day and then the fourth day. The rate of increase in water salinity was evident as the porous material dried and the rate of evaporation increased. The salinity was increased significantly in between sixth and seventh days. As for the vapor pressure, it is noticeable that the vapor pressure increases in accending order as the porous material dries up. As for the total pressure inside the porous material, it decreased in descending manner until the seventh day. The temperature and water vapor saturation pressure were decreased in descending manner. The rate of evaporation increased on the first and second days because the porous material was still almost saturated with water, and the temperature of the porous material was high, which increased the rate of evaporation. The higher the evaporation rate, the greater the mass of water vapor in the porous material. This led to an increase in the vapor pressure inside the porous material, in addition to a decrease in the saturated vapor pressure due to its dependence on the saturation temperature. The rate of decrease in the total pressure is due to the filling of the porous material with water vapor and the equalization of pressure with atmospheric pressure.

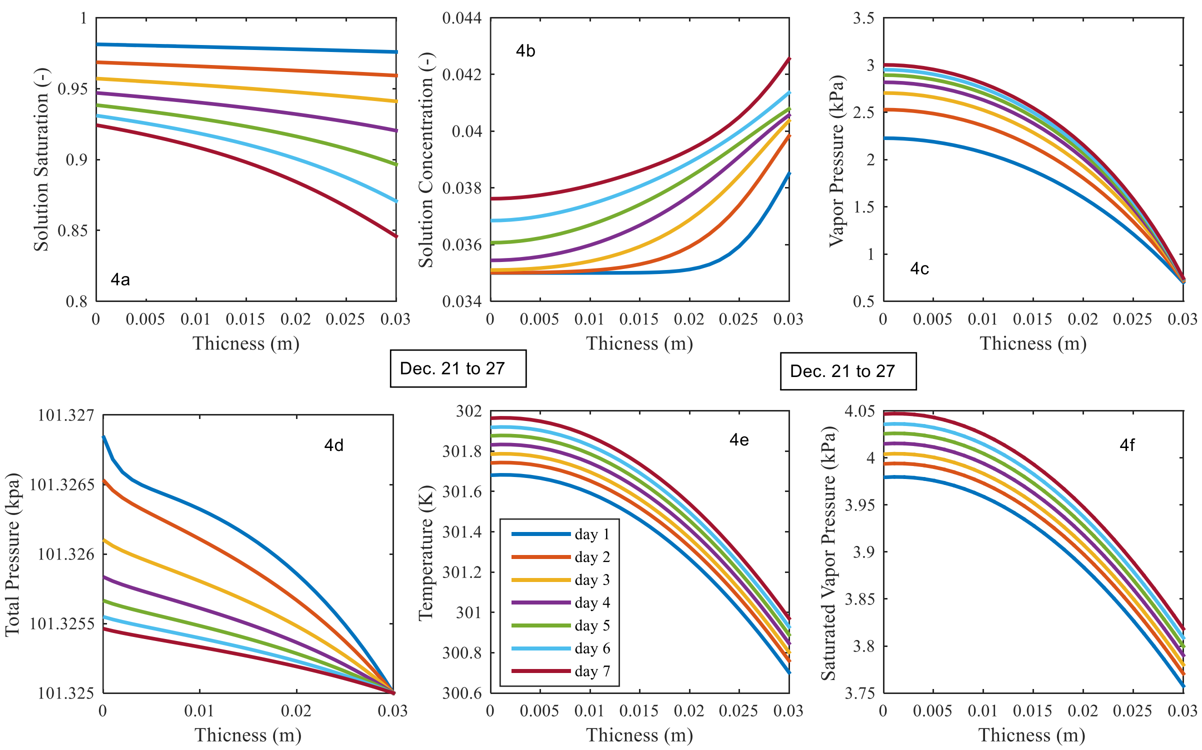

Fig. 4. S, C, P_v , P_t and P_{vs} distribution with porous material thickness for 7 days drying in Dec. month

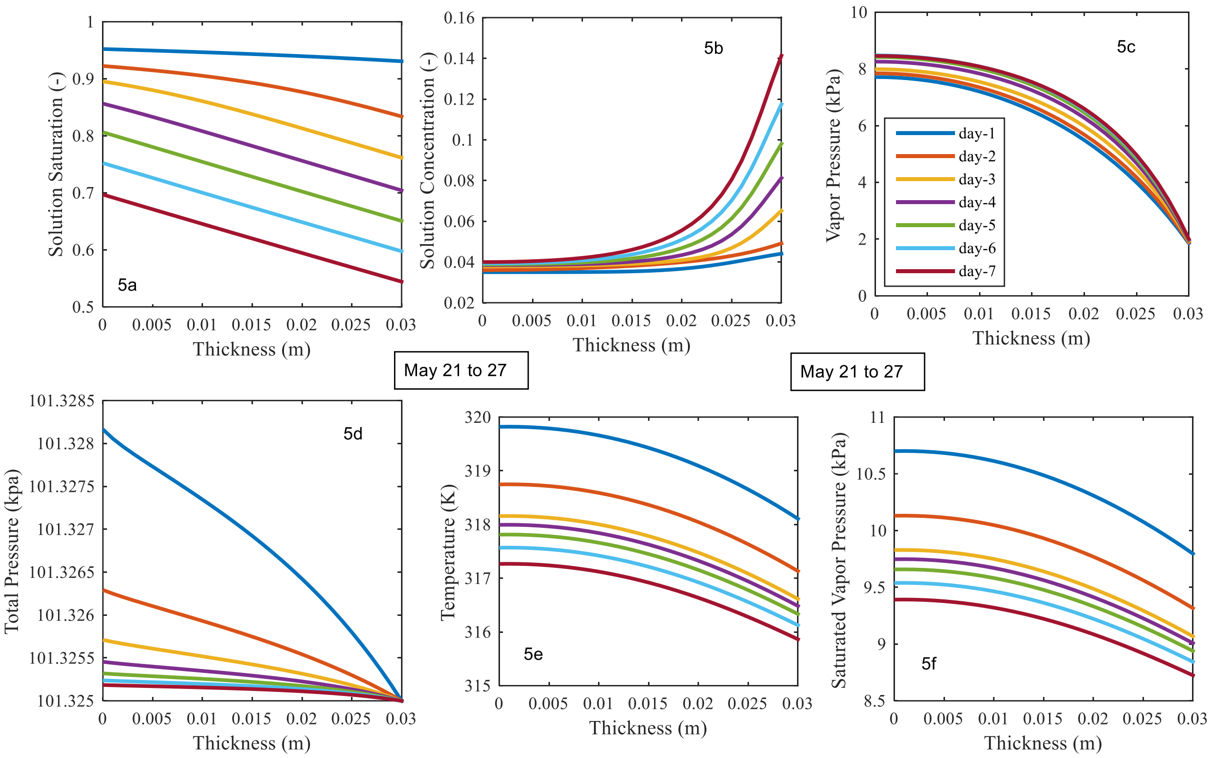

Fig. 5. S, C, P_v, P_t and P_{vs} distribution with porous material thickness for 7 days drying in May month

4. Conclusions

The mass equation for water vapor has been added with the four equations to calculate the amount of vaporization based on the mass transfer within the porous material and not based on the saturated vapor pressure, and then the results came to the following

i. The vapor pressure is not saturated which depends on the vapor mass transfer in the voids of the porous material and did not depend on the thermodynamic equilibrium as in the previous studies.
ii. It is not necessary for the water vapor to be saturated as mentioned in previous studies. But water vapor is not saturated during all the results of vapor pressure of winter and summer. This is because the vapor pressure results from the mass of vapor being transported and the stored mass. And it is not only saturated vapor without mass transmission.
iii. The rate of evaporation is low for the cold climates, which led to a little increase in the salinity of the water on the surface of the porous material and it continued to gradually rise for the hours of the day in temperature degrees.
iv. In hot climates, the rate of evaporation was high, which led to a high salinity of water on the surface of the porous material, and after sunset the salt spreading process continues to reach the dynamic equilibrium.
v. The effect of capillary action and capillary pressure makes the possibility of compensation by the capillary tubes in low evaporation rate of water for the cold day. But it happened that the capillary action compensation was less in the case of hot weather day as in the water saturation curve for the month of May.

vi. In hot climates, the rate of evaporation was high, which led to a high salinity of water-solution on the surface of the porous material, and after sunset the salt spreading process continues to reach the dynamic equilibrium.
vii. The heat energy stored in the porous material and the stored vapor from the current day to the next day, this helped to increase the evaporation progressively in the successive days of some of them, and it became clear and noticeably on hot days.

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References
[1] Mohamed, Sherif A., Ibrahim S. Taha, Mahmoud G. Morsy, Hany A. Mohamed, and Mahmoud S. Ahmed. "Numerical solution of solar energy absorbed in porous medium with a new approach for vapor pressure calculation and consideration of solute crystallization." *American Journal of Aerospace Engineering* 2, no. 1 (2015): 93-105. https://doi.org/10.11648/j.ajae.s.2015020101.18
[2] Lu, Tao, Peixue Jiang, and Shengqiang Shen. "Numerical and experimental investigation of convective drying in unsaturated porous media with bound water." *Heat and mass transfer* 41, no. 12 (2005): 1103-1111. https://doi.org/10.1007/s00231-005-0634-9
[3] Nicolai, Andreas, and J. Grunewald. "Parametric Study of Salt Transport and Phase Transition Parameters in Simulations of Porous Materials Saturated with Salt Solutions under Drying Conditions." In *Proceedings of the 8th Symposium for Building Physics in the Nordic Countries*, vol. 1, pp. 299-306. 2008.
[4] Zhang, Zhe, Shiming Yang, and Dengying Liu. "Mechanism and mathematical model of heat and mass transfer during convective drying of porous materials." *Heat Transfer—Asian Research: Co-sponsored by the Society of Chemical Engineers of Japan and the Heat Transfer Division of ASME* 28, no. 5 (1999): 337-351. https://doi.org/10.1002/(SICI)1523-1496(1999)28:5<337::AID-HTJ1>3.0.CO;2-9
[5] Bolaji, Bukola Olalekan. "Analysis of moisture transport in the solar drying of food items." Ph.D thesis, Department of Mechanical Engineering; University of Agriculture PMB 2240, Abeokuta, Nigeria (2008).
[6] Mohamed, Sherif A., M. Attalla, and Ahmed N. Shmroukh. "New solar seawater desalination system using wick material and obtuse surface: experimental evaluation." *International Journal of Energy and Water Resources* 5, no. 2 (2021): 113-124. https://doi.org/10.1007/s42108-020-00103-3
[7] J. F. Cepeda, C. L. Weller, M. Negahban, J. Subbiah, H. Thippareddi. "Heat and Mass Transfer Modeling for Microbial Food Safety Applications in the Meat Industry: A Review" *Food Eng Rev*. (2013). https://doi.org/10.1007/s12393-013-9063-6
[8] Wiem Nasri, Ridha Djebali, Marjan Goodarzi, Mohamed Ammar Abbassi and Said Abboudi. "Apple convective drying - Part I: Finite elements parametric study for appraising the operating conditions effects." *CFD Letters* 11, no. 3 (2019): 28-41.
[9] Kowalski, Stefan Jan. "Toward a thermodynamics and mechanics of drying processes." *Chemical Engineering Science* 55, no. 7 (2000): 1289-1304. https://doi.org/10.1016/S0009-2509(99)00400-5
[10] Rattanadecho, P., and S. Wongwises. "The Numerical and Experimental Investigation of Heat Transport and Water Infiltration in Granular Packed beds due to Supplied Hot Water (One-and Two-Dimensional Models)." *Science & Technology Asia* (2005): 63-72.
[11] Suwannapum, Nattawut, and Phadungsak Rattanadecho. "Analysis of heat–mass transport and pressure buildup induced inside unsaturated porous media subjected to microwave energy using a single (TE10) mode cavity." *Drying Technology* 29, no. 9 (2011): 1010-1024. https://doi.org/10.1080/07373937.2010.548110
[12] Kolditz, Olaf, and Joëlle De Jonge. "Non-isothermal two-phase flow in low-permeable porous media." *Computational Mechanics* 33, no. 5 (2004): 345-364. https://doi.org/10.1007/s00466-003-0537-x
[13] Gawin, Dariusz, and Francesco Pesavento. "An overview of modeling cement based materials at elevated temperatures with mechanics of multi-phase porous media." *Fire technology* 48, no. 3 (2012): 753-793. https://doi.org/10.1007/s10694-011-0216-y
[14] Perré, Patrick. "Multiscale aspects of heat and mass transfer during drying." In *Drying of Porous Materials*, pp. 59-76. Springer, Dordrecht, 2006. https://doi.org/10.1007/978-1-4020-5480-8_6
[15] Tomczak, Karol, Arkadiusz Tomczak, and Tomasz Jelonek. "Effect of Natural Drying Methods on Moisture Content

and Mass Change of Scots Pine Roundwood." *Forests* 11, no. 6 (2020): 668. https://doi.org/10.3390/f11060668

[16] Grementieri, L., L. Molari, Hannelore Derluyn, J. Desarnaud, Veerle Cnudde, N. Shahidzadeh, and S. De Miranda. "Numerical simulation of salt transport and crystallization in drying Prague sandstone using an experimentally consistent multiphase model." *Building and Environment* 123 (2017): 289-298. https://doi.org/10.1016/j.buildenv.2017.06.049

[17] Qazi, Mohsin J., Daniel Bonn, and Noushine Shahidzadeh. "Drying of salt solutions from porous media: Effect of surfactants." *Transport in Porous Media* 128, no. 3 (2019): 881-894. https://doi.org/10.1007/s11242-018-1164-5

[18] Patankar, Suhas V. *Numerical heat transfer and fluid flow*. CRC press, 2018. https://doi.org/10.1201/9781482234213