ISSN: 0976-3376

Available Online at http://www.journalajst.com

ASIAN JOURNAL OF SCIENCE AND TECHNOLOGY

Asian Journal of Science and Technology
Vol. 10, Issue, 08, pp.10021-10028, August, 2019

RESEARCH ARTICLE

MODELING OF TOMATO CONVECTIVE DRYING WITH COMSOL SOFTWARE

[1]*DIANDA Boureima, [2]KY Thierry S.M.,[1]COMPAORE Abdoulaye, [1]GUENGANE Hassim, [1]OUEDRAOGO Salifou and [1]BATHIEBO D. Joseph

[1]Institute of Research in Applied science and Technologies, 03 BP 7047 Ouagadougou 03, Burkina, Faso
[2]University Joseph KI ZERBO,03 BP 7021 Ouagadougou 03, Burkina Faso

ARTICLE INFO

Article History:
Received 19th May, 2019
Received in revised form
24th June, 2019
Accepted 07th July, 2019
Published online 31st August, 2019

Key words:
Drying, Tomato,
Simulation, Time,
Temperature.

ABSTRACT

The goal of this study is to determine a theoretical model to define tomato drying curves. For this, a mathematical model based on the conservation of heat and mass is used. Heat and matterdiffusion equations have been developed and used in the COMSOL computation code. The theoretical model is validated by experimental measurements. The experimental data are obtained in a tunnel dryer with values of 0.1m/s, 0.25m/s and 0.5m/s for the drying air velocity and 50°C; 60°C for air temperatures. The theoretical simulations have shown that the temperature of the fruit gradually increases to the drying temperature of the air. The results also show that increasing the temperature and speed of the air reduces the drying time. The comparison of theoretical and experimental drying kinetics shows a Root Mean Square Error (RMSE) of 8%. The theoretical model developed can therefore be used to predict drying kinetics of tomato.

Citation: DIANDA Boureima, KY Thierry S.M., COMPAORE Abdoulaye, GUENGANE Hassim, OUEDRAOGO Salifou and BATHIEBO D. Joseph, 2019. "Modeling of tomato convective drying with comsol software", *Asian Journal of Science and Technology*, 10, (08), 10021-10028.

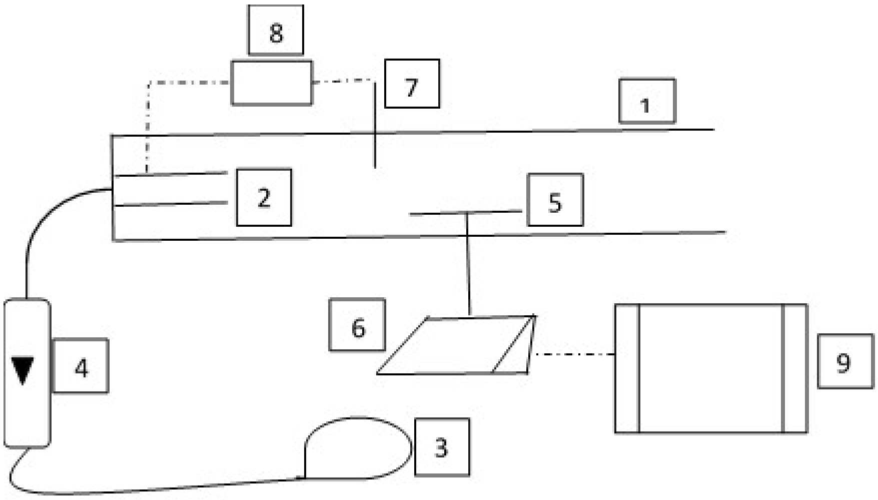
INTRODUCTION

Tomato is one of the most grown and consumed products in the world. Burkina Faso, like most countries in the world, is steadily increasing its production. Unfortunately much of the production is lost by rotting. There are several reasons for this situation. Tomatoes are products that contain a very large amount of water, about 93% to 96%. This high water content is one of the reasons for the rapid decay of the product when exposed to the open air. One solution to this problem is drying. Drying is a process that has been used for a long time to preserve products. However the requirements of the consumer increase more and more to that must be added the industrial constraints. Indeed consumers want a dry product that largely preserves the organoleptic components and vitamins. The industry must also play on energy consumption. It is therefore necessary to reduce the drying time, thus to control the evolution of the drying kinetics. The most appropriate aspects of drying technology are the mathematical modeling of the process and the experimental organization (Akpinar et al., 2006). There are three approaches to modeling the drying of agricultural products. These approaches are: the theoretical approach, the semi-theoretical approach and the empirical approach (Midilli et al, 2002, Panchariya et al, 2002). The first considers only the internal resistance to moisture transfer while the two others consider only the external resistance to moisture transfer between product and air (Bruce 1985, Özdemir and Devres 1999, Party 1993). A theoretical equation gives a better understanding of the transport processes. The most widely studied theoretical drying model was the second diffusion law of Fick. Empirical approaches derive from a direct relationship between average moisture content and drying time. These approaches neglect fundamental principles of drying, the process and their parameters have no physical meaning. As a result, they cannot give an accurate, clear view of the important processes that occur during drying (Özdemir and Devres, 1999 ...). An empirical equation gives a better fit to the experimental data, obviously without any understanding of the transport processes involved, among them, the Wang and Singh model. The semi-theoretical equation includes understanding of transport processes (Janjai S et al, 2011). Among them are the Newton model, the Page model, the modified Page model, the Henderson and Pabis model, the logarithmic model, the two terms model, the exponential of the two terms model, the model of approximate diffusion, the modified Henderson and Pabis model, the Verma et al model and the widely used Midilli- Kucuk model. The aim of this study is to propose a theoretical model of tomato drying kinetics by COMSOL software using transfer equations. Then this theoretical model will be confronted with experimental data for its validation.

Corresponding author: **DIANDA Boureima,**
Institute of Research in Applied science and Technologies, 03 BP 7047 Ouagadougou 03, Burkina, Faso.

MATERIAL AND METHODS

Description of the device: The drying device used is a plexiglass tunnel dryer with a length of 1.4m and a cross section of 110.25cm2. The device comprises a support on which is placed the slice of tomato to be dried as shown in Figure 1. The air is heated using two heating resistors placed inside the dryer and its temperature is given by a thermocouple connected to an adjustable device with digital display. A blowing device connected to the dryer allows the air circulation inside the tunnel. The air flow is adjustable using a valve. The mass of the sample is measured every five minutes, using a SARTORIUS brand electronic balance with ab accuracy 0.01g connected to a computer. This device is already described in previous works (Dianda et al,2015).



1: plexiglass tube (drying box), 2: heating elements, 3: blower, 4: flowmeter, 5: plate, 6: scale, 7: thermocouple, 8: temperature controller, 9: computer.

Figure 1. Schematic of the experimental device

METHODS

- **Product preparation:** Tomatoes are bought on the market. They are sorted to use those that are mature, firm and have about the same dimensions. They are then washed, and cut to size with a knife and a dimensioning box.
- **Initial water content:** The initial water content X0 was determined in the oven. A large slice of the tomato to be dried was placed under study set at 70 °C for 24 hours. The measurement of the mass of the tomato slice before and after its passage in the oven makes it possible to determine its initial water content. It is on average 17.5 kg of water / kg of dried matter in dry basis, which is about 94.6% in wet basis. These values are in agreement with those of the literature between 93% and 96% (JavadKhazaei et al, 2008, Ibrahim Doymaz, 2007, EnginDemiray and Yahya Tulek, 2012, Brooks MS et al, 2008, Sacilik Kamil et al, 2006).
- **Acquisition of mass:** The tomato slice prepared beforehand is placed on the support in the drying chamber. The support is placed on a precision 0.01g SARTORIUS CPA22025 scale which is connected to a computer for the acquisition of mass. The masses are recorded every five minutes.
- **Moisture content and dry mass:** The mass of the product after passing through the Memmert brand oven at 70 ° C constitutes its dry mass. The initial water content (dry basis) of the tomato is therefore the quotient of its mass of water and its dry mass. So:

$$\mathrm{X(t)} = \frac{\mathrm{m(t)} - \mathrm{m_s}}{\mathrm{m_s}} \qquad (1)$$

with X (t), the water content at a time t, m (t) the mass of the product at time t and m_s the dry mass of the product. The drying curve is generally represented by the reduced water content as a function of time. The reduced water content is determined by the following expression:

$$X^* = \frac{X(t) - Xe}{\mathrm{X0} - \mathrm{Xe}} \qquad (2)$$

where Xe represents the equilibrium water content and X0 the initial moisture content. This expression of the reduced water content can be simplified in water relative content by the following expression: :$X^* = \frac{X(t)}{\mathrm{X_0}}$because the equilibrium moisture content values Xe are relatively low compared to those at a time t X (t) and at the initial water content X0. The error is therefore very small (MAnashi Das Purkayastha et al, 2011, DuyguEvin, 2012, Ala'a H. Al-Muhtaseb et al, 2010, KamyarMovagharnejad and Maryam Nikzad, 2007). In this study we will therefore consider the relative water content X/X0.

Modeling of convective drying in a climatic chamber: The objective is to present a model of drying kinetics that adapts to experimental curves. This model then makes it possible to control the drying of the tomato. Thermal balances are then established. We consider a slice of tomato exchanging on its faces, placed in a hot and dry air flow.

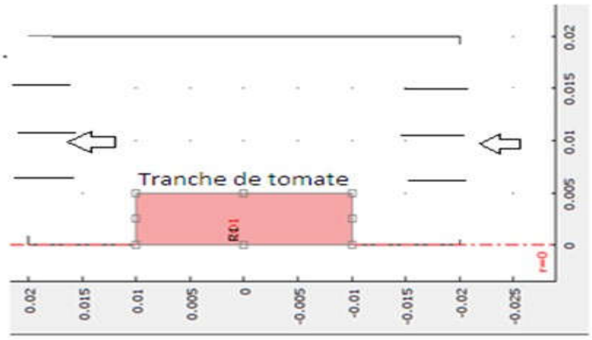


Figure 2. Diagram of the studied system

The transfer equations: The physical model used is based on the works of Aversa et al (2007) to which we add the equations of effective mass diffusion and water activity of the product. These equations are a function of the temperature and the water content of the product.

The equation of heat: The equation translating the conservation of energy in the system is:

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} + \left(\vec{\mathrm{V}}.\overrightarrow{\mathrm{grad}}\right)\mathrm{T} = \frac{\lambda}{\rho \mathrm{C_p}}\nabla^2 \mathrm{T} \tag{3}$$

In the product the transfers are done by conduction and we then retain

$$\frac{\partial \mathrm{T}}{\partial \mathrm{t}} = \frac{\lambda}{\rho \mathrm{C_p}}\nabla^2 \mathrm{T} \tag{4}$$

where ρ is the density of the product, Cp its specific heat, T its temperature, λ its thermal conductivity and t the time.

The matter diffusion equation

$$\frac{\partial \mathrm{X}}{\partial t} = \mathrm{D}.\nabla^2 \mathrm{X} \tag{5}$$

X is the water content, D is the mass diffusion coefficient.

Thermal boundary conditions

$$\vec{\mathrm{n}}(\lambda.\nabla \mathrm{T}) = \mathrm{ha}.(\mathrm{Ta} - \mathrm{Ts}) - \mathrm{Lv}.\mathrm{k}.\rho_{\mathrm{air}}.(\mathrm{Ya} - \mathrm{Ys}) \tag{6}$$

$\vec{n}$is a normal unitary vector at the surface, Lv is the latent heat of water vaporization (J.kg-1), k is the mass transfer coefficient between hot and dry air and the surface of the product (m.s-1), Ya is the water content of the drying air (kg water.kg-1 moist air) and Ys is the moisture content of the air which is in equilibrium with the product surface (kg water.kg-1 moist air). The latter parameter is related to the water content of the product surface by the relation:

$$\frac{\mathrm{Y_s}}{1-\mathrm{Y_s}} = 0.622.\frac{\mathrm{HRs.PVS(T)}}{\mathrm{P_0} - \mathrm{HRs} * \mathrm{PVS(T)}} \tag{7}$$

$$PVS(T) = P_0.\exp\left(13.7 - \frac{5120}{T(K)}\right) \tag{8}$$

where HRs is the product water activity corresponding to its surface water content, PVS is the saturation vapor pressure at the surface temperature (Pa) and $\mathrm{P_{atm}}$ is the atmospheric pressure (Pa).

Massive boundary conditions

The conservation of the mass on the surface of the product can be written in the following way:

$$\vec{n}.\rho_{ms}(D.\nabla \mathrm{X}) = k.\rho_{air}.(Ya - Ys) \tag{9}$$

Calculation of the convective heat transfer coefficient: From the volume of the sample, an equivalent diameter can be evaluated.

$$\mathrm{Nu} = \frac{\mathrm{ha.dp}}{\lambda_{\mathrm{air}}} = 2 + 0.6.\mathrm{Re}^{1/2}.\mathrm{Pr}^{1/3} \tag{10}$$

Calculation of the convective mass transfer coefficient

$$\mathrm{Sh} = \frac{\mathrm{k.dp}}{\mathrm{D_{eau}}} = 2 + 0.6.\,\mathrm{Re}^{1/2}.\,\mathrm{Sc}^{1/3} \tag{11}$$

Expression of the diffusion coefficient taking into account the shrinkage

$$\mathrm{D_{eff}} = \mathrm{D_0}.\,\mathrm{P(X)} \tag{12}$$

where P(X) is a 4 degreepolynomial

DIGITAL RESOLUTION

The mathematical models have been solved using the COMSOL MULTIPHYSICS computation code, which uses the finite element method to solve the equations of the model.

Results of the simulation: Simulated results in terms of fluid flow direction on product, spatial distribution of product temperature, product concentration and water content were presented. However, only the water content profile of the model was compared with the experimental data.

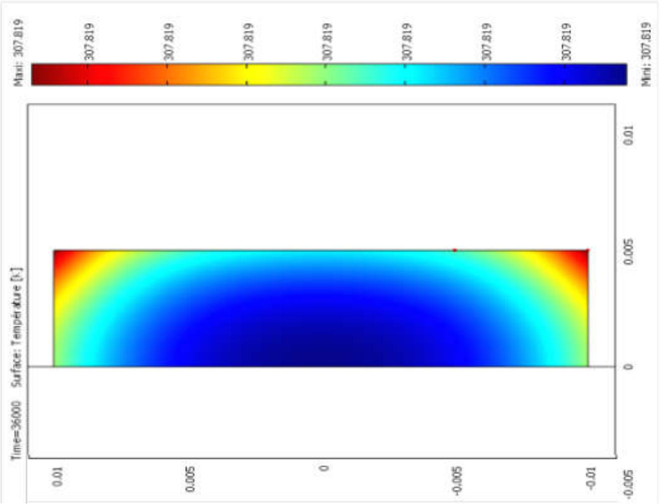


Figure 3. Spatial distribution of the temperature at t= 10h (Ti=290 K; Ta=333K)

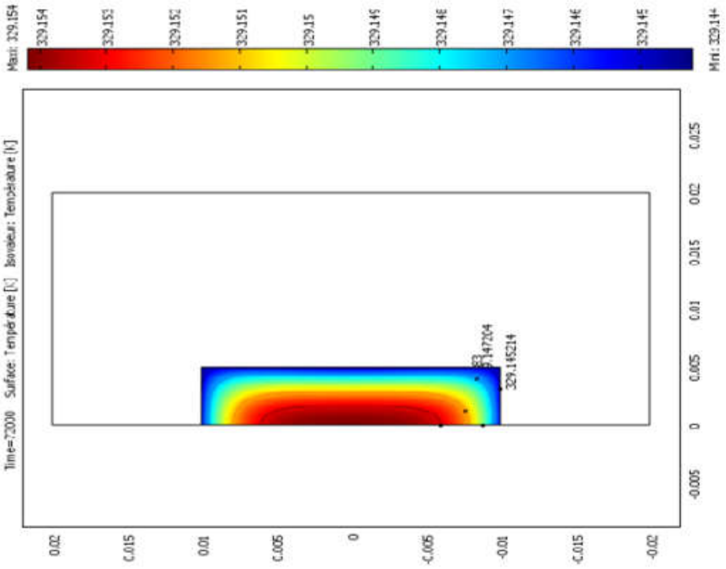


Figure 4. Spatial distribution of temperature at t=20h (Ti=290K; Ta=333K)

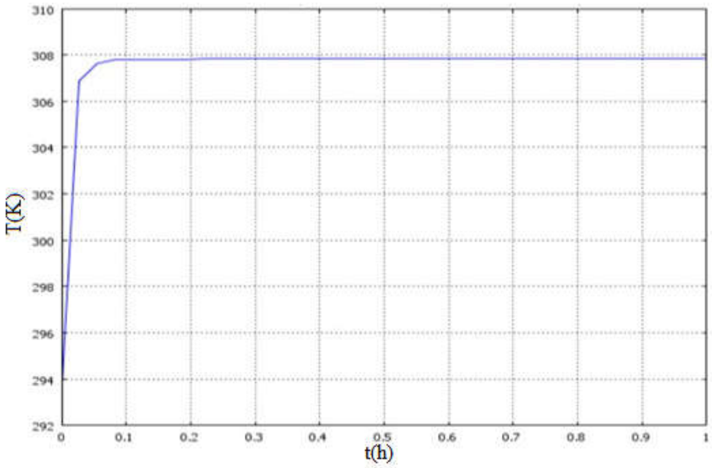


Figure 5. Mean temperature evolution of the sample (t<1h; Tair=60°C; Vair=0.25m/s)

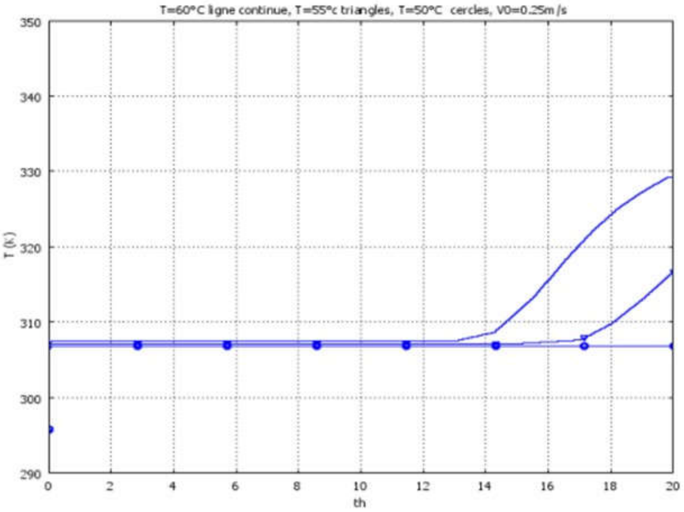


Figure 6. Evolution of the sample temperatures with a drying air of 50 ° C, 55 ° C and 60 ° C

Figures 3, 4, 5 and 6 show the variation in temperature of the tomato slice for various drying times. It gradually increases from 17 ° C until reaching the temperature of the drying air (60 ° C) after an infinite time. We observe aheating phase of the product (Figure 5), then a phase during which there is evaporation and therefore substantially constant temperature. This is because the heat transferred from the air to the product is mainly used for evaporation of water. As the product dries, less heat is used for the evaporation of the water and the sensible heat of the air is transmitted to the tomato slice which then sees its temperature increase. Such a result was also presented by Ramadan El Gamala et al (2013). This evolution of the temperature of the product is in agreement with that presented by Michel Daguenet (1985).

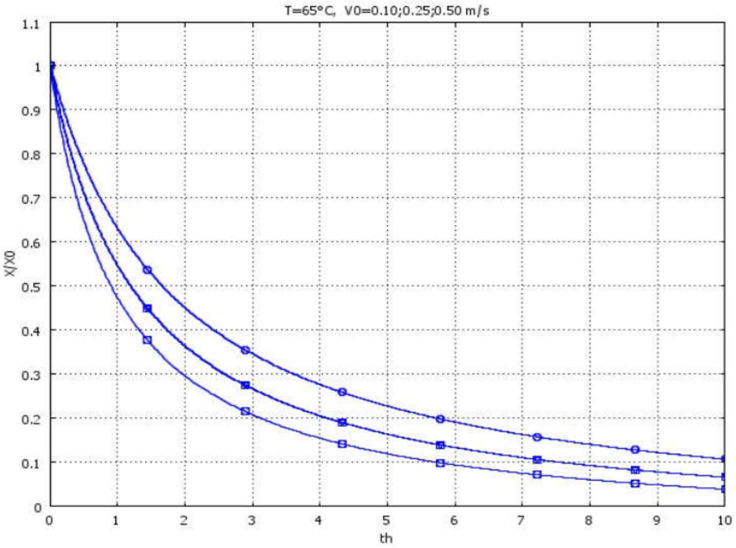


Figure 7. Influence of air velocity on drying kinetics

Figure 7 shows the influence of the drying air speed on the drying kinetics. It shows that the higher the speed of the air, the faster the product dries. This result is in agreement with the results of the literature.

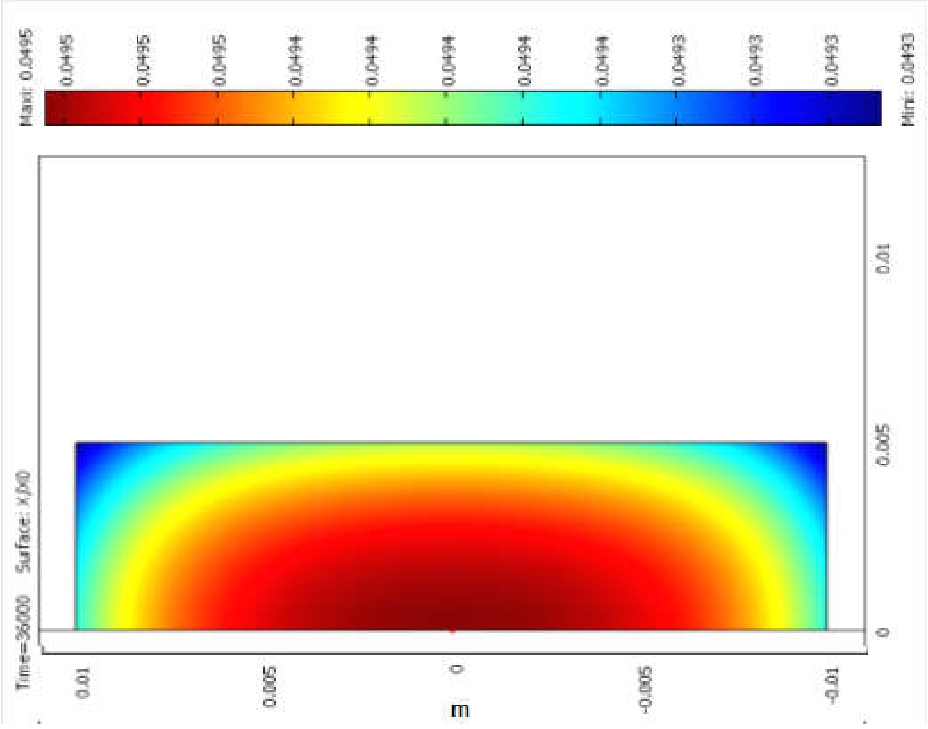


Figure 8. Dimensional concentration within the sample at t = 10h

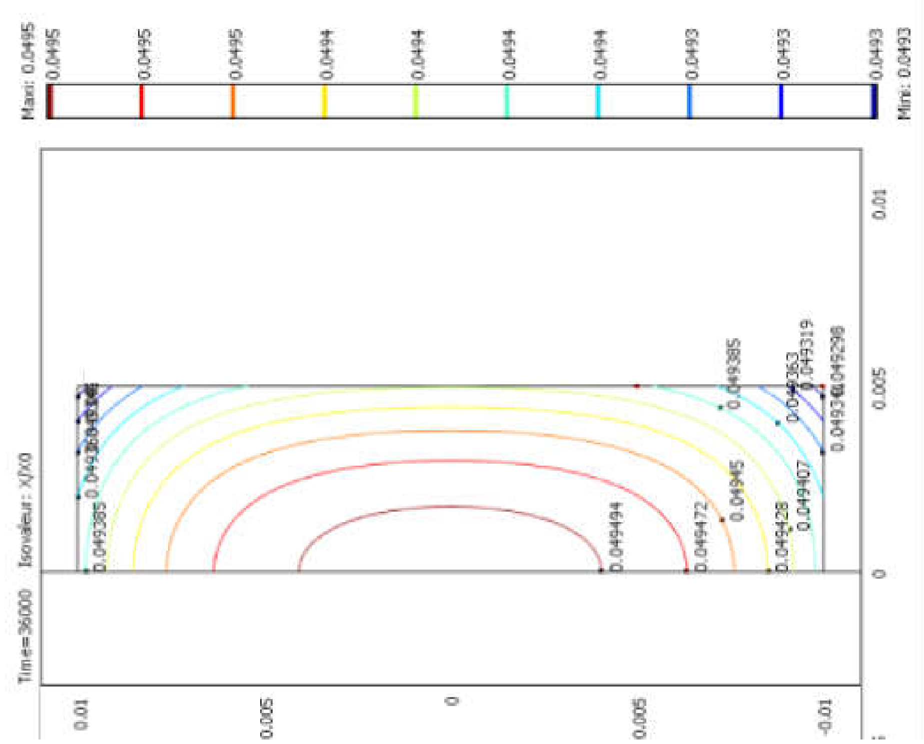


Figure 9. Concentration isovalues at the end of drying

The final concentrations are shown in FIGS. 8 and 9. It is of course found that they are low at the end of drying, they change in a decreasing manner from the external surface to the center of the product.

Mass and heat transfers at the surface in contact with the air are more efficient. Knowing the distribution of moisture concentration in the dried product is important because the deterioration can start from the wettest area. Figure 10 shows simulated curves under COMSOL with a drying air velocity set at 0.25m/s and at temperatures of 50 ° C and 60 ° C. It shows faster drying with higher temperature as above.

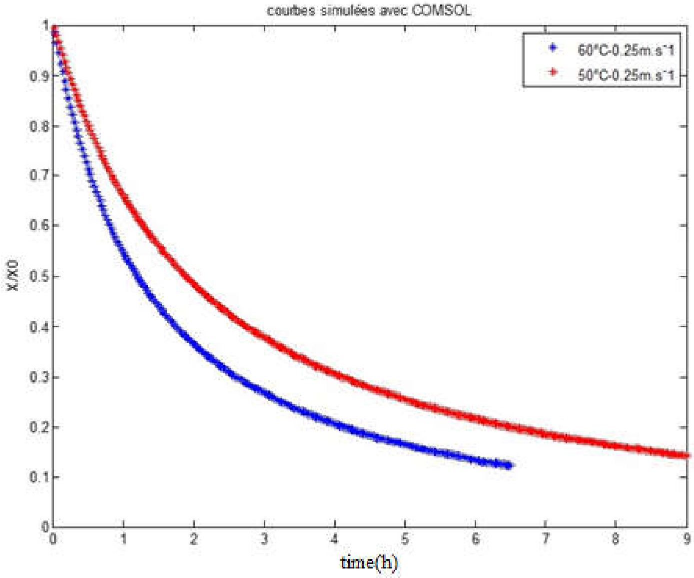


Figure 10. Simulated curves with the COMSOL calculation code

Validation of the model: To validate the results of the numerical simulation, it is compared to the experimental data. The quality of the simulation was determined by calculating the square root of the mean error (RMSE).

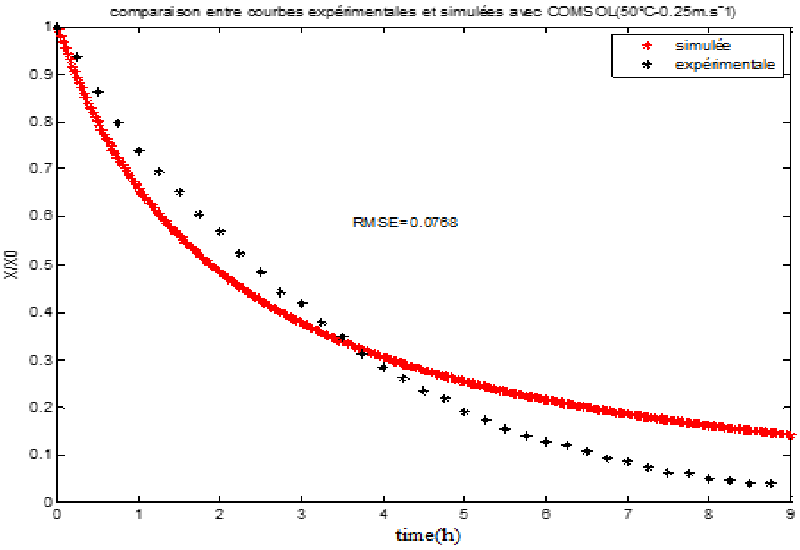


Figure 11. Simulated an experimental curves (50°C ; 0.25m/s)

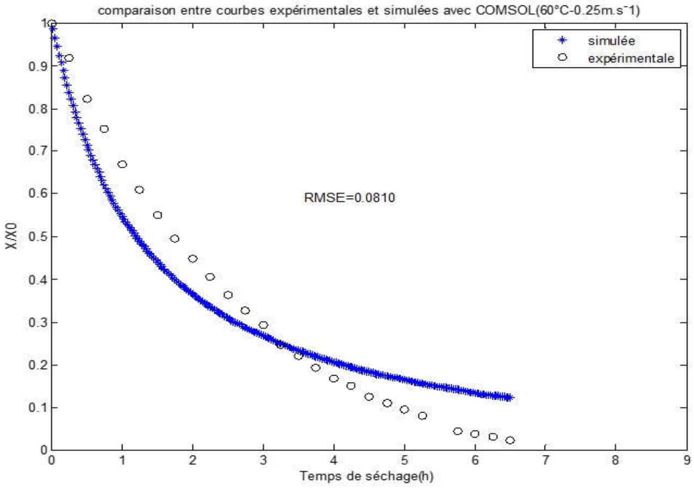


Figure 12. Simulated curve and experimental curve (60 ° C, 0.25m / s)

It can be seen in Figures 11 and 12 that with the two drying temperatures used (50 ° C and 60 ° C) the model gives a fairly acceptable accuracy of the water content of the tomato during drying. In both cases the square root of the average error is between 7.6% and 8.1%.

Conclusion

We used a mathematical model based on heat and mass conservation equations in a dryer (tunnel) where a slice of tomato is placed parallel to the direction of air flow for drying in laboratory. The parameters' influence such as the drying air temperature is confirmed by the COMSOL code. In fact, the more the values of this parameter increase, the faster the dries. The simulation of the distribution of moisture in the product made with the COMSOL code shows that the concentration is naturally decreasing from the inside of the product towards its external surface, but especially that the concentration isolines are half ellipses. By comparing the curves of the model to the experimental curves, we can say that the model used is quite satisfactory. It allows to predefine kinetics of convective drying of the tomato under several conditions.

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