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Analysis of Tomato Drying by Using a Solar Tower Dryer in Natural Convection

Sié Kam[1], Germain Wende Pouiré Ouedraogo[1*], Boureima Kaboré[1], Bienvenu Magloire Pakouzou[1,2], Moctar Ousmane[3] and Dieudonné Joseph Bathiébo[1]

[1]Laboratory of Renewable Thermal Energy, University Ouaga I, Pr Joseph KI-Zerbo, P.O.Box: 03-7021 Ouagadougou 03, Burkina Faso.
[2]Carnot Laboratory of Energetics, Faculty of Sciences, University of Bangui, Central African Republic.
[3]University of Agadez, P.O.Box: 199, Niger.

Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

This work presents an experimental study of the drying process of tomato in thin layer thanks to an indirect solar dryer operating in natural convection called "solar tower dryer". This experiment was performed under varying conditions of solar radiation. The objective of this study is to present the drying kinetics of the tomato and determine its physicochemical parameters such as diffusion coefficient and activation energy. The results show that the diffusion coefficient of the tomato is 6.2687 $\times 10^{-9}$ m^2s^{-1} with an activation energy estimated at 20.091 $kJ.mol^{-1}$.

Keywords: Tomato; convective solar drying; diffusion coefficient; activation energy; thin layer.

**Corresponding author: E-mail: wenpoui@gmail.com;*

1. INTRODUCTION

The tomato of scientific name (Lycopersicum esculentum) is a fruit which is much cultivated in Burkina Faso and its culture is seasonal [1]. However, its fresh storage causes enormous difficulties due to its estimated water content of over 92% [2]. This makes it a highly perishable product that experiences losses during the peak production period [3].

Drying is an operation that allows the extraction of moisture from a product to reach the moisture conservation of the product. This is a method that several authors propose for the conservation of tomatoes [1,4,5]. But it's a method that consumes huge amounts of energy. Thus solar energy being an inexhaustible source will solve this energy problem. Hence the use of solar dryers. There are several types of solar dryers that depend on how the product is exposed to solar radiation [6]. Hybrid dryers operating with extra energy (electric, gas...) and solar radiation are the ones with the best performance because they do not depend solely on solar radiation [7]. In the literature, the most commonly used solar dryers are indirect dryers in which the products to be dried are protected from solar radiation and receive hot air, heated upstream in a solar collector by greenhouse effect [8,9]. However other preservation methods exist such as freezing, ionization, genetic manipulation of the product, industrial drying etc., but they are very expensive in technology and electrical energy [10]. But solar drying requires only the presence of solar.

The objective of this work is to test the solar drying of tomato in thin layer using a new dryer called "solar tower dryer" [11] in order to determine the kinetics of drying and the physicochemical properties of the tomato.

2. MATERIALS AND METHODS

2.1 Materials

The equipment used for the experiment consists of:

- ✓ a solar tower dryer (Fig. 1) which is an indirect dryer consisting of a collector of about 4m² where the incoming air is heated by the greenhouse and a chimney diameter of 20cm and height of 3 m in which product to be dried is spread [11];
- ✓ a pyranometer (brand: Hukseflux, model: LP02, country: France) which is used to measure the solar radiation of the day whose sensitivity is 9.54 µV / W.m^{-2};
- ✓ an electronic scale (brand: PCE, country: France, model: BSH 6000) with a precision of 0.1g;
- ✓ a temperature logger (Brand: GRAPHTEC, Model: midi logger GL220 Country: France) coupled to type K thermocouples. The margin of error is ± 0.05% of the measured value + 1˚C for temperatures between -100˚C and 1370˚C;
- ✓ a hygrometer (brand: Velleman, model: DVM171THD, country: Belgium) whose accuracies are ± 3% for humidity between 40% and 60% and ± 3.5% for humidity between 60% and 80%.

2.2 Methods or Procedure

Before any drying operation, the fresh tomato of variety "Red cherry" is bought according to its degree of maturation (red fruit) and its external morphology (healthy fruit without cracks on its surface). Then we wash and cut into a slice of 1cm thick. Finally, the slices obtained are placed on the first rack and then introduced into the chamber to be dried.

The initial mass of the product to be dried is set at 173.6 g. The drying process started at 9am and ended at 17h for the first day but continued the next day at the same time because it is at this time that there is a good solar radiation. The tomato from the rack is weighed every hour (1h) apart until the end of the drying process.

3. MATHEMATICAL MODELING

3.1 Instantaneous Water Content

There is a type of water content of a product:

- ✓ the instantaneous dry water content is defined by equation (1)

$$\chi(t) = \frac{m_h(t) - m_s}{m_s} \quad (1)$$

Where $\chi(t)$: instantaneous water content in dry basis (kg $_{water}$.kg^{-1}$_{dry\ matter}$), $m_h(t)$: wet mass of

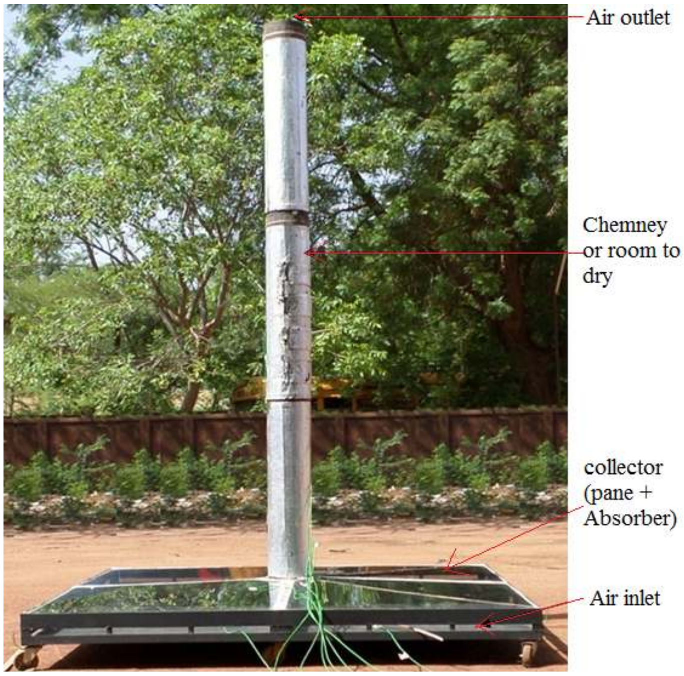

Fig. 1. Solar tower dryer

product (kg) at time t, m_s : dry mass (kg) or anhydrous product and t: time

- ✓ the instant wet water content or the moisture content of the product is defined by:

$$\chi_h(t) = \frac{m_h(t) - m_s}{m_h(t)} \quad (2)$$

where $\chi(t)$ instantaneous water content in wet base (%)

The equilibrium water content can be calculated from equation (3)

$$\chi_{eq} = \frac{m_{hf} - m_s}{m_s} \quad (3)$$

where m_{hf} is the final wet mass, namely the final mass of the product obtained after drying.

3.2 Drying velocity

The drying velocity ($-\frac{d\chi}{dt}$) expresses the rapidity of water transfer from the inside of the product to the outside. Its expression is:

$$-\frac{d\chi}{dt} = \frac{\chi(t_2) - \chi(t_1)}{t_2 - t_1} \quad (4)$$

3.3 Coefficient of diffusion

The diffusion coefficient is a physical quantity whose equation depends on the shape of the product. It will be determined by adopting the form assimilated to an infinite plate that reflects our slice cut. The experimental results obtained during the solar drying of the tomato are analyzed by applying the second law of Fick depending on the shape of the product.

$$\frac{\partial \chi}{\partial t} = D_{eff}\frac{\partial^2 \chi}{\partial x^2} \quad (5)$$

Where χ is the dry water content (kg $_{water}$.kg^{-1}$_{dry\ matter}$), D_{eff} is the diffusion coefficient (m^2s^{-1}), t is the time (s) and x the propagation length water (m)

The analytical solution of equation (5) is given by equation (6) [12]:

$$MR = \frac{\chi_t - \chi_{eq}}{\chi_0 - \chi_{eq}} = \frac{8}{\pi^2} exp\left(-\frac{\pi D_{eff}\, t}{4\, l^2}\right) \quad (6)$$

Where MR is the water content or moisture ratio, χ_t is the water content of the product at time t, χ_0 is the initial moisture content, χ_{eq} is the equilibrium moisture content, l is the water content thickness and t time.

The number of Fourier humidity is defined by equation (7):

$$F_0 = D_{eff}\frac{t}{l^2} \tag{7}$$

By introducing this Fourier number into equation (6), we obtain:

$$F_0 = \frac{4}{\pi}\left(ln\left(\frac{8}{\pi^2}\right) - ln(MR)\right) \tag{8}$$

Then we get

$$D_{eff} = \frac{F_0}{(t/l^2)_{experimental}} \tag{9}$$

The diffusion coefficient D_{eff} is calculated by substituting the positive values of F_0, the drying time and the average thickness of the tomato in equation (9). Finally we perform the arithmetic mean of the different values of D_{eff} to determine the diffusion coefficient of the tomato.

3.4 Activation Energy

The activation energy is the amount of energy that must be supplied to a product so that it can initiate a transfer of water from the inside of the product to the outside. It is a function of the temperature and the diffusion coefficient. The activation energy is deduced from the Arrhenius equation:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{R(T+273.15)}\right) \tag{10}$$

Where D_0 is the pre-exponential factor of the Arrhenius equation ($m^2.s^{-1}$), E_a is the activation energy ($kJ.mol^{-1}$), T is the drying temperature (℃) et R is the perfect gas constant ($kJ.mol^{-1}.K^{-1}$).

The preceding equation (10) can be written in the following form:

$$\ln(D_{eff}) = \ln(D_0) - \frac{E_a}{R(T+273.15)} \tag{11}$$

To determine the activation energy, simply:

- ✓ calculate D_{eff} values for different experiments
- ✓ draw the curve of the diffusion coefficients according to the inverse of the temperatures
- ✓ Deduce the activation energy by identifying the equation of the line obtained and the logarithmic of the Arrhenius equation (11)

4. RESULTS AND DISCUSSION

The dry tomato obtained after two days of solar drying is presented in Fig. 2.

4.1 Variation of Solar Radiation

Fig. 3 gives the appearance of the variation of the solar radiation of the two days of the experimentation. The day of 8/10/2017 was sunnier compared to that of 9 october with a maximum irradiation of 876 $W.m^{-2}$ against 864 $W.m^{-2}$. The different fluctuations of solar radiation

a) Before drying b) After drying

Fig. 2. Aspects of tomato before and after drying

are caused by the repeated passage of clouds around the sun, which create areas of shadows on the dryer. This type of passage was observed a lot on the experimental site between 14h and 17h for the first day and almost all the day of 9 October 2017.

4.2 Variation in Moisture Content of Tomato

Fig. 4 shows the variation in moisture content of the dried tomato at the first rack of the solar tower dryer. With an initial water content of 22.36 $kg_{water}.kg^{-1}_{dry\ matter}$ (namely a humidity of 95.72%), the final water content obtained after 17 hours of drying (two days of drying) is 0, 15 $kg_{water}.kg^{-1}_{dry\ matter}$ with a humidity of 0.67%. This gives a loss of water mass estimated at 165g. The decreasing trend of the curve reflects the loss of the water mass during the drying process.

On the curve, at the drying time of 9h, we have two values. The first value of 5.70 $kg_{water}.kg^{-1}_{dry\ matter}$ is that of the moisture content of the tomato obtained at the end of the first day of drying. The product was removed from the dryer and kept in a dry room overnight, saw the water content dropped to 4.62 $kg_{water}.kg^{-1}_{dry\ matter}$ which represents the second value.

With an initial water content of 12.8 $kg_{water}.kg^{-1}_{dry\ matter}$, D. Mennouche et al. [13] obtain, after 17 hours of drying, a water content of 0.13 $kg_{water}.kg^{-1}_{dry\ matter}$, namely three days of drying (1st day: 7h, 2nd day: 7h, 3rd day: 3h).

The mass loss curve obtained by N. Kherrour et al [7] is similar to that of Fig.4 but the product required three days of solar drying using an indirect drier. The water content of the "Zahra" variety tomato tends rapidly to its equilibrium moisture content when it is dried with an indirect forced convection dryer with the same in natural convection [14].

4.3 Variation of Drying Velocity

The drying rate expresses the amount of water lost per unit of time. Fig.5 shows the variation of the drying rate as a function of the drying time. Between the first four hours of drying, the rate of drying increases and reaches its maximum of 2.66 $kg_{water}.kg^{-1}_{dry\ matter}.h^{-1}$ to four hours of drying. This explains why the amount of water lost per unit of time is due to the variation of solar radiation. This velocity becomes very low when the tomato tends to its dry state because the amount of water to be extracted becomes low.

The drying speed curve of Fig. 5 represents two out of three phases with respect to the general drying velocity curve [6]: the warm-up phase for the upward velocity and the decreasing velocity phase for the velocity decreasing which shows the water loss of the product.

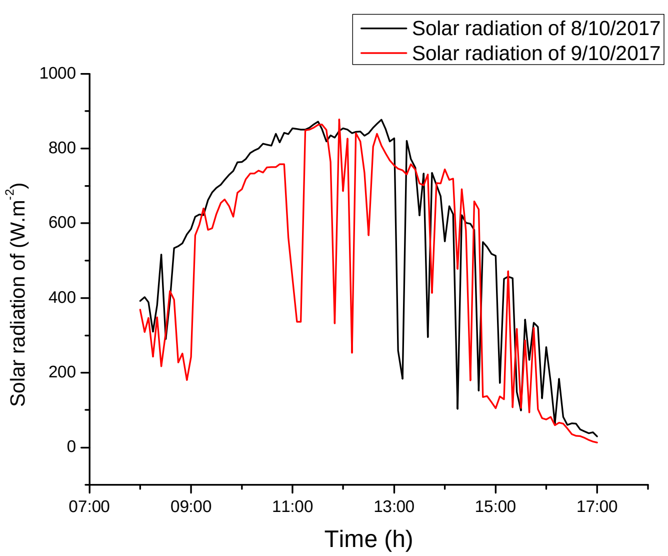

Fig. 3. Daily variation of solar radiation

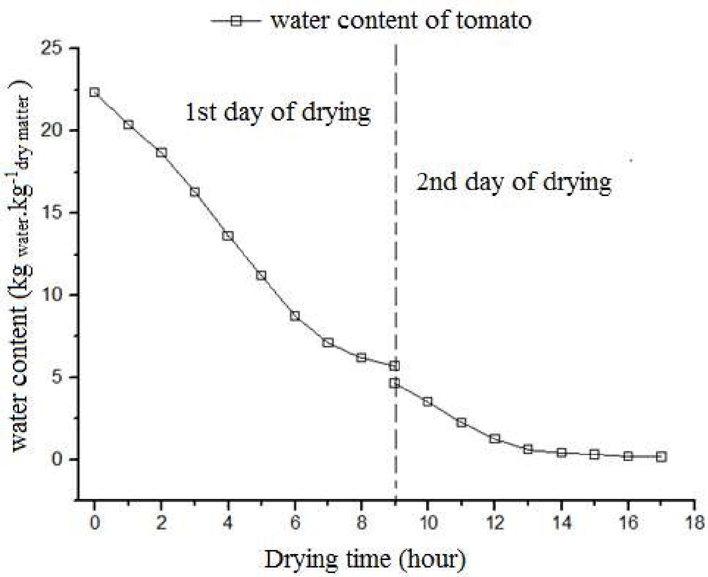

Fig. 4. Variation in moisture content of tomato as a function of drying time

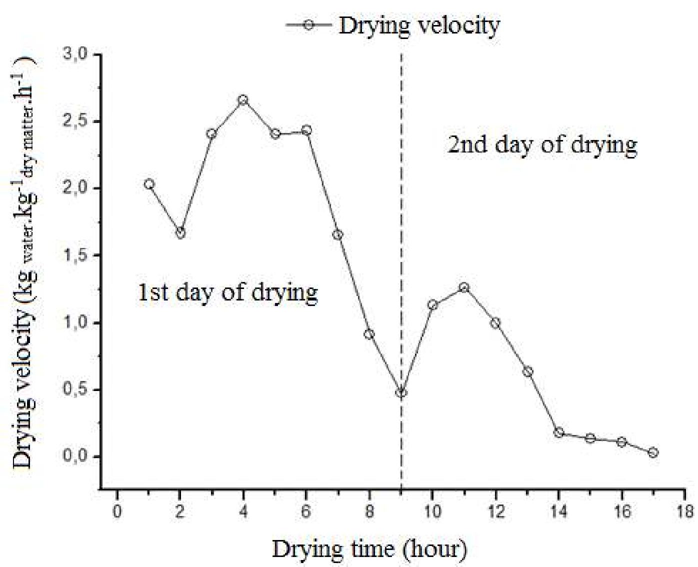

Fig. 5. Variation in drying speed of tomato as a function of drying time

4.4 Coefficient of Diffusion

The diffusion coefficient determined during the solar drying of the tomato is 6.2687×10^{-9} m²s^{-1}. This value is between those obtained by Sana Ben Mariem et al. [15] in 2014 which vary from 3.0722×10^{-9} to 6.7881×10^{-9} m²s^{-1} for temperatures between 38℃ and 64℃. However, the diffusion coefficient determined in 2016 by R. Khama et al. [16] is between 2.56×10^{-11} and 7.67×10^{-11} m²s^{-1} for temperatures ranging from 40℃ to 70℃. By varying the temperature of a climatic chamber from 50℃ to 60℃ and the velocity from 0.1 m.s^{-1} to 0.5 m.s^{-1}, Dianda et al. [1] estimated that the diffusion coefficient varies from 1, 33 $\times10^{-6}$ m²s^{-1} to 5,11 $\times10^{-6}$ m²s^{-1}. The values of the tomato diffusion coefficient determined by N. Lahmari et al. [14] are between 9.11×10^{-8} and 1.21×10^{-7} m^{2}s^{-1}. G. Cakmak et al. [17] found similar values ranging from 5.47×10^{-10} to 1.35×10^{-9} m^{2}s^{-1}. All these values of the diffusion coefficient determined by the different

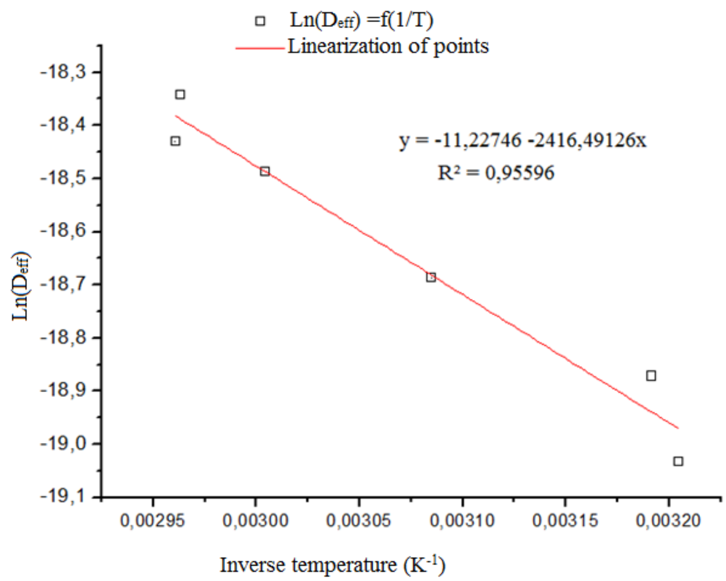

Fig. 6. Linearization of the functions $Ln(D_{eff})$ = f (1/T)

authors are in the range of 10^{-12} to 10^{-8} m^2s^{-1}, given by N. Zogza et al. [18] for the majority of agricultural products with a high water content.

Using the same dryer, G. Ouedraogo et al. [19] obtain okra diffusion coefficients of 6.16 $\times 10^{-10}$ $m^2.s^{-1}$; 8.99 $\times 10^{-10}$ $m^2.s^{-1}$ and 47.8 $\times$ 10^{-10} $m^2.s^{-1}$ respectively for okra cut longitudinally into two parts, in four parts and in cylindrical form.

4.5 Activation Energy

Fig. 6 gives the linearization equation of $Ln(D_{eff})$ as a function of the inverse of the temperature. The Arrhenius coefficient obtained thanks to this equation is close to 1.3304 $\times$ 10^{-5} m^2s^{-1}. The activation energy is 20,091 $kJ.mol^{-1}$. This value is higher compared to those determined by Sana Ben Mariem et al. [15] which are 13.56 $kJ.mol^{-1}$ and 10.67 $kJ.mol^{-1}$ with respectively air velocities of 2$m.s^{-1}$ and 1 $m.s^{-1}$. Using the variety tomato "Zahra", N. Lahmari et al [14] record activation energies ranging from 21.26 to 38.23 $kJ.mol^{-1}$ depending on the pressure of the vacuum dryer.

R. Khama et al. [16] determined activation energies of 50.43 $kJ.mol^{-1}$ and 17.64 $kJ.mol^{-1}$ respectively for tomato with skin and tomato without skin. For okra, the activation energy varies between 20,497 and 39,864 $kJ.mol^{-1}$ depending on the cutout considered according to G. Ouedraogo et al. [19].

5. CONCLUSION

The drying curves of the tomato inform us about the overall behavior of the product during the entire drying operation of the product as a function of the time elapsed. Its drying in the solar tower dryer took two days, namely about 17 hours of drying with a maximum drying speed of 2.66 $kg_{water}.kg^{-1}_{dry\ matter}.h^{-1}$. With an initial mass of 173.6 g, we obtain after drying a mass of 8.6 g, namely a water loss of 165 g.

From its results, we were able to determine the diffusion coefficient of the tomato which is estimated at 6.2687$\times 10^{-9}$ m^2s^{-1}. The activation energy required for the transfer of water from the product interior to the outside is 20.091 kJ mol^{-1}.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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