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Drying kinetics and thermodynamic analysis of tomato in a tunnel dryer[†]

Cinética de secado y análisis termodinámico del tomate en un secador de túnel

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ABSTRACT

In this study, drying kinetics and thermodynamic analysis of tomato were conducted in a tunnel dryer. Drying experiments were performed at three temperatures (100, 115, and 130 °C) and an air velocity of 1.45 m/s. From the drying curves, only a falling rate period was observed. Under these conditions, a characteristic drying curve was determined. It is observed that at the 40 minutes of the drying process, the outlet gas enthalpy achieved a maximum value that is very close to the inlet value and remained constant until the end of the process. Entropy exhibited similar behaviour to enthalpy. The maximum value of the exergy efficiency curve corresponds to the maximum value observed within the drying rate curves. This maximum value represents the stage when the available energy is efficiently used in moisture removal. As the drying rate decreases the available energy is started to be less employed.

Keywords: Tomato; Drying kinetics; Energy; Exergy; Efficiency

RESUMEN

En este estudio, la cinética de secado y el análisis termodinámico del tomate se realizaron en un secador de túnel. Los experimentos de secado se realizaron a tres temperaturas (100, 115 y 130 °C) y una velocidad de aire de 1.45 m/s. A partir de las curvas de secado, solo se observó un período decreciente. En estas condiciones, se determinó una curva de secado característica. Se observa que, a los 40 minutos del proceso de secado, la entalpía del gas de salida alcanza un valor máximo muy cercano al valor de entrada y permaneció constante hasta el final del proceso. La entropía exhibió un comportamiento similar a la entalpía. El valor máximo de la curva de eficiencia de exergía corresponde al valor máximo observado dentro de las curvas de velocidad de secado. Este valor máximo representa la etapa en que la energía disponible se usa eficientemente en la eliminación de humedad. A medida que disminuye la velocidad de secado, la energía disponible comienza a emplearse menos.

Palabra claves: Tomate; Cinética de secado; Energía; Exergía; Eficiencia

[†] Dedicated to Prof. em. Dr.-Ing. habil. Luis Moreno on the occasion of his 77th birthday.

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1. INTRODUCTION

Tomato (*Lycopersicon esculentum* Miller) is one of the most commercially produced vegetables all over the world. The tomato is a native of South America and Mexico (Kalloo and Bergh, 1993). Tomato is a major source of the antioxidant lycopene, which helps in the prevention of many chronic diseases, such as cancer and heart diseases because of its ability to protect cell components against oxidative damages (Yaping *et al*., 2002). Apart from lycopene, tomato also contains various nutritional (vitamin A, C, and E) and non-nutritional (beta-carotene, carotenoid, flavonoids, flavone and total phenolic) antioxidants (Chang *et al*., 2006).

The worldwide demand for tomato is increasing day by day with the increase in population and its preference for tomato. However, tomato is highly perishable in the fresh state leading to wastage and losses during the peak harvesting period. The prevention of these losses and wastage is of major interest especially when there is a subsequent imbalance in supply and demand at the harvesting off-season. In this context, the drying of food remains a very widespread operation in the food industry both for the preservation of foods in their final form and as an intermediate operation. Fresh vegetables and fruits are highly perishable due to increased moisture contents. Drying is one of the best ways to minimise losses and it makes easier and cheaper the packing, handling, and transporting of the dried products because of less weight and volume (Nazghelichi *et al*., 2010).

Many vegetables and fruits have been dried successfully including tomato. For instance, Patil *et al*. (2015) conducted a study of the dehydration characteristics of tomato slices in a recirculatory tray dryer. They determined that dehydration of tomato slices under 75% recirculation at both drying air temperatures (70/60 °C and 70/65 °C) resulted in a high colour index, high rehydration ratios, and high ascorbic acid content than the samples dried without any recirculation (0%) of exhaust air. Mariem and Mabrouk (2014) reported the drying kinetics of tomato slices under various temperatures and airflow rates. The logarithmic and two-term models provided the best representation of the drying kinetics of tomato slices. Das Purkayastha *et al*. (2013) studied the air convective drying characteristics of blanched tomato slices. They reported that the logarithmic model provided the best representation of the drying kinetics of blanched tomato slices, which was closely followed by the Henderson-Pabis model.

In practice, drying is a process that requires high energy input because of latent heat of water evaporation and the relatively low energy efficiency of industrial dryers. Drying accounts for 10% of all energy consumption in the food industry. The utilisation of high amounts of energy in industrial drying makes it one of the most energy-intensive operations with great industrial significance. Thus, one of the most important challenges of industrial drying is to reduce the cost of energy sources for good quality dried products (Mujumdar, 2014).

In this regard, it is essential to perform effective thermal analysis of the drying process to provide energy savings and optimum processing conditions. As known, exergy analysis evaluates the available energy at different points in a system. Exergy is defined as the maximum amount of work that can be produced by a stream of matter, heat, or work as it comes to equilibrium with a reference environment (Akbukut and Durmuş, 2010). Exergy analysis leads to a better understanding of the influence of thermodynamic phenomena on the process efficiency, comparison of the importance of different thermodynamic factors, and the determination of the most efficient ways of improving the process under consideration (Sogut *et al*., 2010).

Recently, several studies have been undertaken on energy and exergy analyses of food drying, however, information on the energy and exergy analyses of tomato drying appears to be scanty in the scientific literature. The main objective of this study was to investigate the energetics and exergetics of tomato drying in a tunnel dryer at different drying air temperatures.

2. MATERIALS AND METHODS

2.1 Material

Tomatoes were procured from a local vegetable market and then washed under running water to remove the adhering impurities. Tomatoes of similar size, shape and free from injury were selected and sliced into chunks before drying experiments. This was necessary because the tomatoes skin represents a barrier to moisture removal and higher exposure of the tomatoes flesh improves water diffusion, thus shortening the drying process.

2.2 Experimental apparatus

A schematic arrangement of the experimental apparatus is shown in Fig. 1. The equipment may be divided into four main sections as follows: gas supply and dehumidification section, heating section, drying chamber, and analysing equipment. The blower (B) supplies a gas flow--a broad range of flow rates are possible by changing the rpm setting through the frequency inverter (FI). The air passes through an adsorption column (AC) containing a dehumidificant (silica gel) to obtain a process air of low humidity content (less than 1.0 % relative humidity) measured by a hygrometer. The air velocity is measured by an anemometer. After dehumidification, the air is pre-heated with electrical resistance (ER) heaters of up to 2 kW each. Temperature is controlled by means of a temperature controller (TC) that supplies heat by means of an electrical resistance heater as its final control element. Before entering the drying chamber, a static mixer homogenises temperature by mixing the gas. The sample is put in the sample holder (SH) inside the drying chamber and is supported on a weighing balance (WB) through an oil-sealed shaft. The cross-sectional area and depth of the sample holder are 30.65 mm× 109.8 mm and 3 mm, respectively. The drying chamber has a uniform cross-sectional area of 90 mm× 110 mm. The sample's weight history is recorded on a computer (C). It is possible to take a reading every 12 seconds (Mendieta *et al.*, 2015).

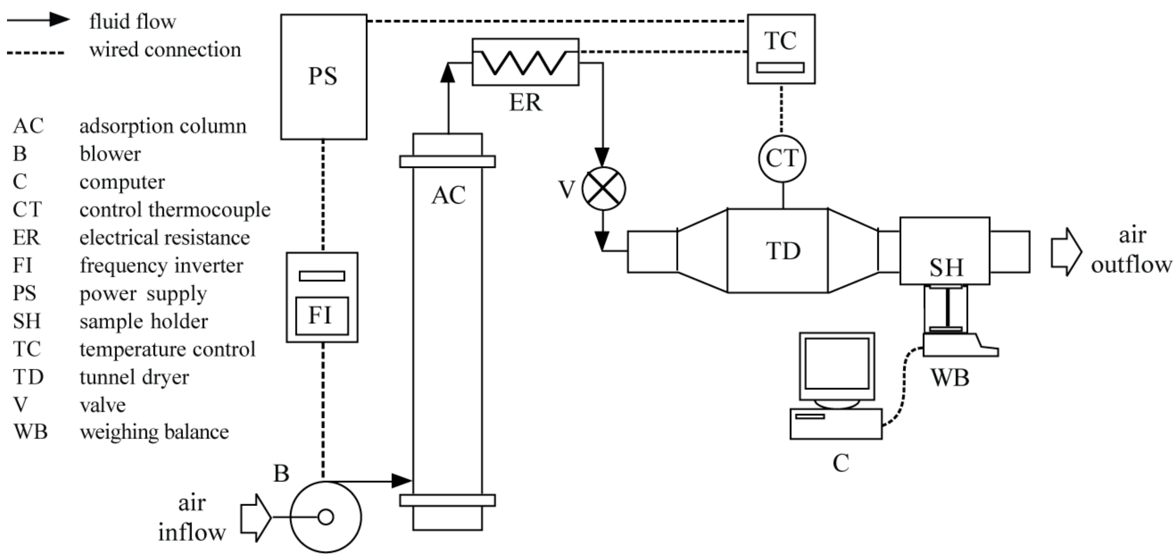

Fig. 1 A schematic diagram of a tunnel drying system.

2.3 Experimental procedure

The experiments were performed at an airflow rate of 1.45 m/s and three different temperatures (100, 115, and 130 °C). Before starting an experiment, the apparatus was run for at least half an hour to obtain steady-state conditions. The sample was loaded evenly in the sample holder, which covered the whole drying area. The sample holder was put into the tunnel dryer. The drying time and mass of the sample were recorded. The test was stopped until the mass was invariable. After drying by the apparatus above, the sample was further dried in an oven at 110 °C for 24 hours to determine its oven-dry mass (m_s). The initial mass, drying mass and oven-dry mass were determined with a precise analytical balance. The temperature and humidity of the air were measured employing a Testo® thermal hygrometer. The solid surface temperature was directly measured employing a thermocouple connected to the computer (C). All the drying experiments were performed in triplicate. Post-processing of these data yields the drying kinetics.

2.4. Drying kinetics

The moisture content was computed as follows:

$$X_i = X_{i-1} + \frac{1}{m_s}\left(\frac{m_i - m_{i-1}}{t_i - t_{i-1}}\right) \tag{1}$$

where X is the moisture content at any time (on a dry basis), m is the mass of the sample at any time, and t is the time. The drying rate is defined as:

$$N_v = -\frac{m_s}{A_s}\frac{dX}{dt} \tag{2}$$

where N_v is the drying rate at any time and A_s is the drying area. Using the moisture content data as a function of time and a centred approximation of the derivative, it is possible to determine the drying rate as follows (Picado *et al.*, 2006):

$$N_v\left(X_i\right) = -\frac{m_s}{A_s\left(X_i\right)}\left(\frac{X_{i+1} - X_{i-1}}{t_{i+1} - t_{i-1}}\right) \tag{3}$$

The processing of the experimental data is performed using a program written in MATLAB®, this program reads the experimental data obtained and plots the drying curves and drying rate curves according to Eqs. (1) and (3).

Shrinkage is an important phenomenon that appears during the drying process of food. The decrease of the volume can, usually, reach more than 90% of its initial volume. For this study, the following equation was employed to consider the shrinkage of tomatoes (Bennamoun *et al*., 2015):

$$\frac{V}{V_0} = 0.942\left(\frac{X}{X_0}\right) + 0.058 \tag{4}$$

where V is the volume. The subscript 0 denotes initial. In this context, volumetric analysis is the most efficient to describe the true shrinkage of highly deformable samples.

The characteristic drying curve (CDC) concept, firstly introduced by van Meel (1958), relies on an appropriate transformation of the drying rate curve coordinates to look for a single normalised drying rate curve, which does not depend on external parameters (e.g., air conditions). The variable transformations proposed by van Meel (1958) are:

$$\phi = \frac{X - X_{eq}}{X_c - X_{eq}} \tag{5}$$

and

$$f = \frac{N_v}{N_w} \tag{6}$$

where ϕ is the characteristic moisture content, f is the relative drying rate, X_{eq} is the equilibrium moisture content, X_c is the critical moisture content, and N_w is the drying rate at the constant rate period. The general form of the CDC is given by $f = f(\phi)$.

By plotting f vs. ϕ at the different temperatures tested, a group of curves is obtained whose behaviour, if common, describes a characteristic drying curve to which a mathematical function (e.g., a polynomial function) can be determined. It is assumed that a unique relationship between f and ϕ can be found for a specific material.

2.5 Energy analysis

The data obtained from drying experiments were used to perform the energy analysis of the tomato drying process. Drying process was considered as a steady flow process and from the first law of thermodynamics, for an open system, the energy balance can be written as follows (Çengel *et al.*, 2019):

$$\dot{Q} = \sum \dot{m}_{g,o} h_o - \sum \dot{m}_{g,i} h_i \tag{7}$$

where $\dot{Q}$ is the heat energy inflow, $\dot{m}$ is the mass flow, and h is the enthalpy. The subscripts o, i, g denote inlet, outlet, and gas, respectively. By assuming the equality of entering and leaving the mass flow rates of the drying system ($\dot{m}_{g,o} = \dot{m}_{g,i}$), Eq. (7) can be written as follows:

$$\dot{Q} = \dot{m}_g \left(h_o - h_i \right) = \dot{m}_g \Delta h \tag{8}$$

The enthalpy of the drying air is calculated as:

$$h = c_{p,g} T_g + \lambda w \tag{9}$$

where c_p is the specific heat, T is the temperature, λ is the latent heat of vaporisation, and w is the humidity ratio.

2.6 Exergy analysis

Exergy analysis of the drying process was carried out based on the second law of thermodynamics, which asserts that energy has quality as well as quantity and that the actual process occurs in the direction of decreasing quality of energy (Çengel *et al.*, 2019). The second law notes that part of the exergy entering a thermal system is destroyed within the system due to irreversibilities. In the light of the above postulation, the total exergy inflow, outflow and losses of the drying process were estimated. The basic procedure followed was to determine the exergy values at steady-state points using the properties of the working medium from the first law energy balance. For this purpose, the mathematical formulations used to carry out the exergy balance are, for an open system, as follows:

$$E_x = c_{p,g}\left[\left(T_g - T_\infty\right) - T_\infty \ln\frac{T_g}{T_\infty}\right] \tag{10}$$

where E_x is the exergy and ∞ denotes ambient condition. Equation (10) can be used to calculate the exergy inflow and outflow at the inlet and outlet temperatures, respectively. Then, the exergy loss throughout the process is determined using the following expression:

Exergy loss = Exergy inflow – Exergy outflow (11)

$$\sum E_{x,L} = \sum E_{x,i} - \sum E_{x,o} \tag{12}$$

where L denotes loss. The exergetic efficiency has been defined as the ration of exergy outflow in the drying of the product to exergy of the drying air supplied to the system. This is given by the expression:

$$Exergy\,efficiency = \frac{Exergy\,inflow - Exergy\,loss}{Exergy\,inflow} \tag{13}$$

or

$$Exergy\,efficiency = 1 - \frac{Exergy\,loss}{Exergy\,inflow} \tag{14}$$

Equation (14) can be stated as

$$\eta_x = 1 - \frac{E_{x,L}}{E_{x,o}} \tag{15}$$

where η_x is exergy efficiency.

2.7 Entropy balance

The general entropy balance is expressed as function of the mass flows (the input and output flows), their entropies, and the transferred heat through the walls of the drying chamber. This heat can have negative or positive signs, depending upon the heat transferred to or from the control volume, in this case the dryer.

3. RESULTS AND DISCUSSION

3.1 Drying kinetics

The variation of moisture content with drying time at air temperatures of 100, 115, and 130 °C for tomato and an air velocity of 1.45 m/s is shown in Fig. 2. The moisture content of tomato samples decreased continually with drying time. As expected, an increase in the drying air temperature reduces the time required to reach any given level of moisture content since the heat transfer increases. This can be explained by the increasing temperature difference between the drying air and the tomato and the resultant moisture (water) migration.

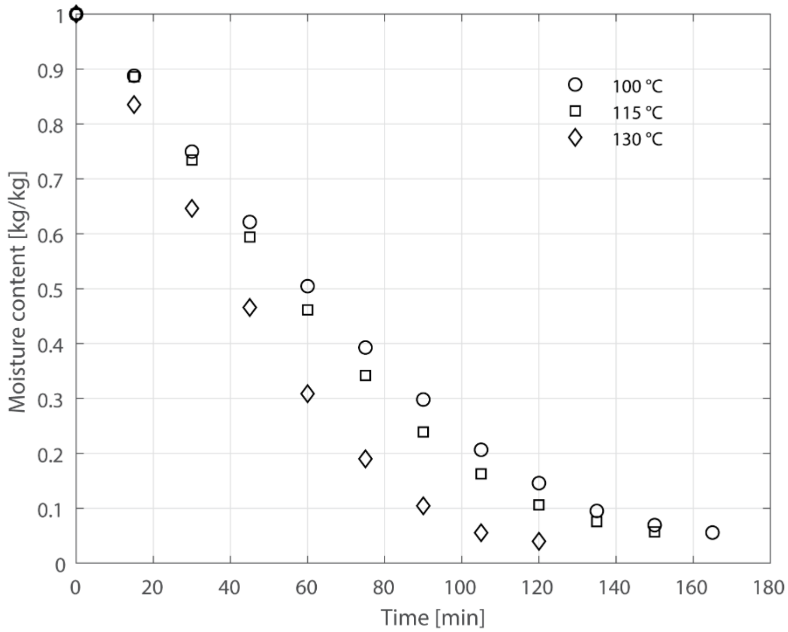

Fig. 2 Drying curves for various temperatures at an air velocity of 1.45 m/s.

The drying rate was estimated based on Eq. (3) and its changes with moisture content are as shown in Fig. 3. An important influence of air-drying temperature on the drying rate is observed in the curves. As expected, an increase in the drying air temperature increases the drying rate because higher air temperature causes a higher reduction of moisture content – in other words, at high temperatures the transfer of heat and mass is high and liquid (water) loss is excessive. As can be seen from Fig. 3, one (1) drying rate period (i.e., falling rate period) was observed in the drying of tomato. These results are in good agreement with earlier observations (Hawlader *et al*., 1991; Demiray and Tulek, 2002; Patil *et al*., 2015).

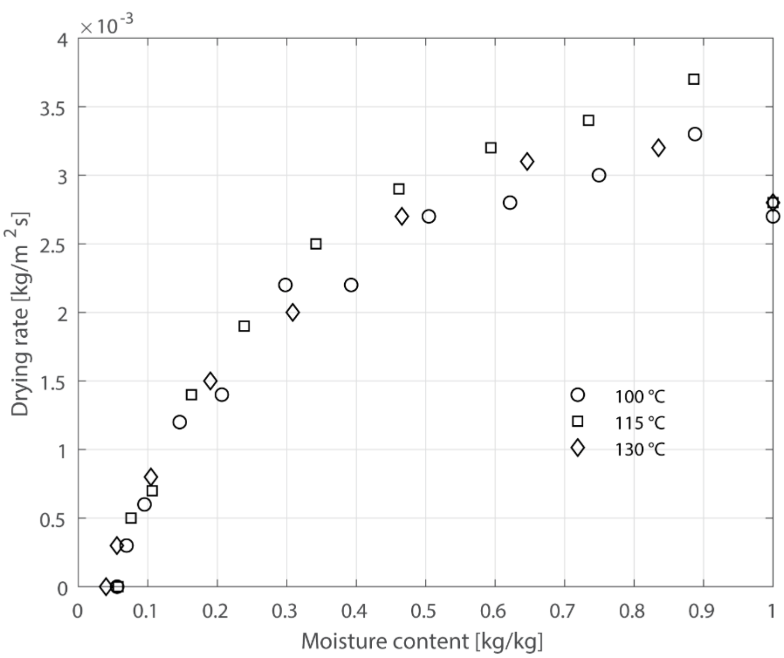

Fig. 3 Drying rate curves for various temperatures at an air velocity of 1.5 m/s.

The drying rate and moisture content are normalised by the constant drying rate and critical moisture content, respectively. However, for tomato, no constant drying rate period was observed, and another approach must be found to normalise the drying data. In this case, the critical moisture content and the maximum drying rate were determined at the beginning of the falling rate period (Bellagha *et al*., 2002; Picado *et al*., 2006).

Tomato is considered to be rather complex with an inner wall structure resembling a fibrous material while the pulpous areas containing the seeds resemble a non-porous material; it is considered to be hygroscopic. In this study, the equilibrium moisture content was calculated by employing the GAB isotherm equation with parameters determined by Akanbi *et al*. (2006).

In Fig. 4, experimental drying data are plotted to represent $f = f(\phi)$. Figure (4) shows that all drying curves obtained with the characteristic moisture content (ϕ) and relative drying rate (f), for the different tested conditions, fall into a tight band, thus indicating that the effect of variation in different conditions is small over the range tested.

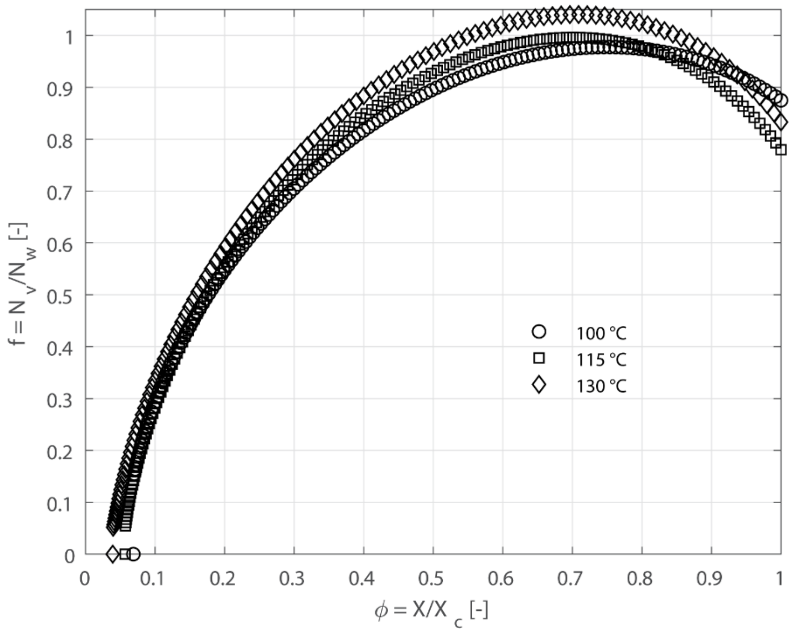

Fig. 4 Characteristic drying curve for tomato.

The regression analysis was performed using MatLab®'s Curve Fitting Tool to find the best equation for the tomato characteristics drying curve. A polynomial equation was found to fit the best experimental data:

$$f = 6.11\phi^5 - 20.02\phi^4 + 24.57\phi^3 - 15.65\phi^2 + 5.99\phi - 0.17 \tag{16}$$

The changes in temperature for tomato and air along the drying process are shown in Fig. 5. In the first 10 minutes, the tomato exhibits a steep increase in temperature. Then, a period of slow increase is observed during the following 35 minutes, which is because moisture (water) to be evaporated comes from within the tomato structure and must be transported to the surface. Further, a linear behaviour is observed in which moisture transported from within the tomato structure did not show resistance to heat transfer, thus allowing the temperature to remain constant until the end of the drying process. The outlet airflow is greater than the inlet airflow due to the absorption of the evaporated moisture (water) leaving the tomato structure during the drying process.

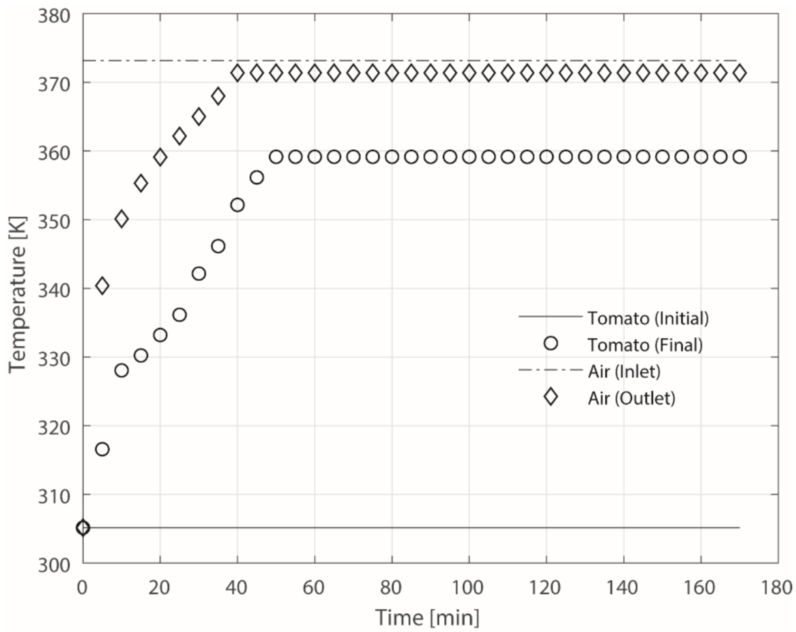

Fig. 5 Temperature curves for tomato at an air temperature of 100 °C and 1.45 m/s.

3.2 Energy analysis

The enthalpy variation during the drying of tomato was measured to determine the time that takes to reach its maximum enthalpy value and the characteristics of its curve (see Fig. 6), which is the amount of energy transferred from the hot airflow to the tomato necessary for moisture removal.

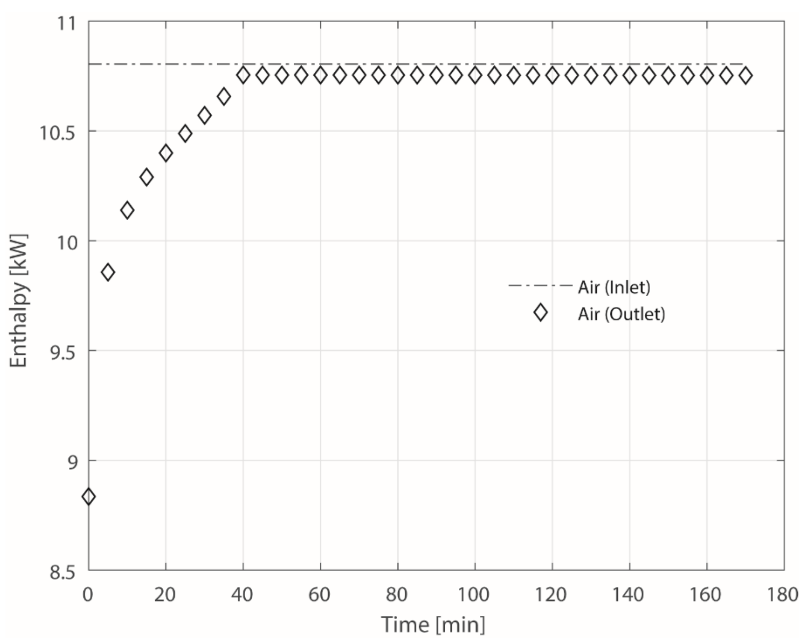

Fig. 6 Enthalpy at an air temperature of 100 °C and 1.45 m/s.

In Fig. 6, the enthalpy of the gas experienced an increase over time according to its respective increase in temperature. It was noted that at the 40 minutes, the outlet gas enthalpy reached a maximum value very close to the inlet value and remained constant until the end of the process. Consequently, the -Δ*h* values in Fig. 7 show a decrease. This behaviour is due to the reduction of the total enthalpy within the system, or in other words, the reduction of the effective heat transfer of the hot airflow to the tomato.

This phenomenon occurs because, after contact with hot air, the tomato's temperature reaches its equilibrium state. In this equilibrium, the temperature of the wet tomato surface is the same as the wet bulb of the drying air, this is when the maximum enthalpy point is reached because the critical moisture content is reached. Then as the moisture content decreases and the surface moisture dries (evaporation) more than the water being transporting to the surface from within the tomato structure (mass transfer), thus allowing the enthalpy to remain constant because the tomato reached the equilibrium with drying conditions.

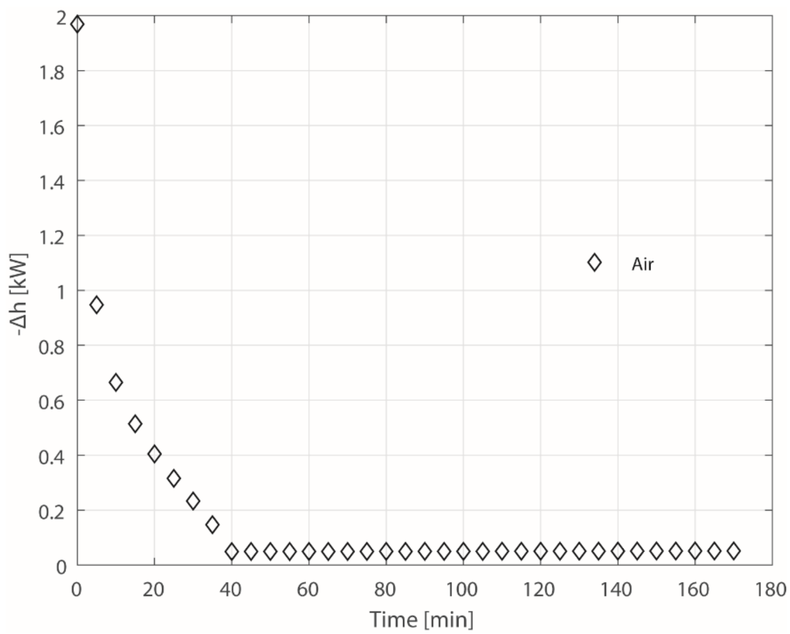

Fig. 7 Δ*h* values at an air temperature of 100 °C and 1.45 m/s.

3.3 Entropy

The entropy variation is shown in Fig. 8. As observed, the entropy variation exhibits similar behaviour to the enthalpy variation. In this case, entropy is calculated because it serves to measure the degree of disorder within a process and allows to distinguish useful energy, which is what is converted into work entirely, from useless energy, which is lost in the environment.

It was noted that the entropy calculated at the dryer outlet experiences a significant increase not only due to the temperature variation but also to the increase of the water vapour phase within the hot airflow because of evaporation of the moisture content. For this reason, there is a short stage in which the outlet entropy slightly increases with respect to the inlet entropy. As a result of this particularity, the -Δ*s* of the system (gas stream) falls slightly (see Fig. 9). By remaining nearly constant after the 40 minutes, the ability to generate useful energy is lost or transformed into other less usable energy. The point of the least degree of system disorder is reached. Picado *et al*. (2017) reported a similar experimentally behaviour for pineapples thin layer drying.

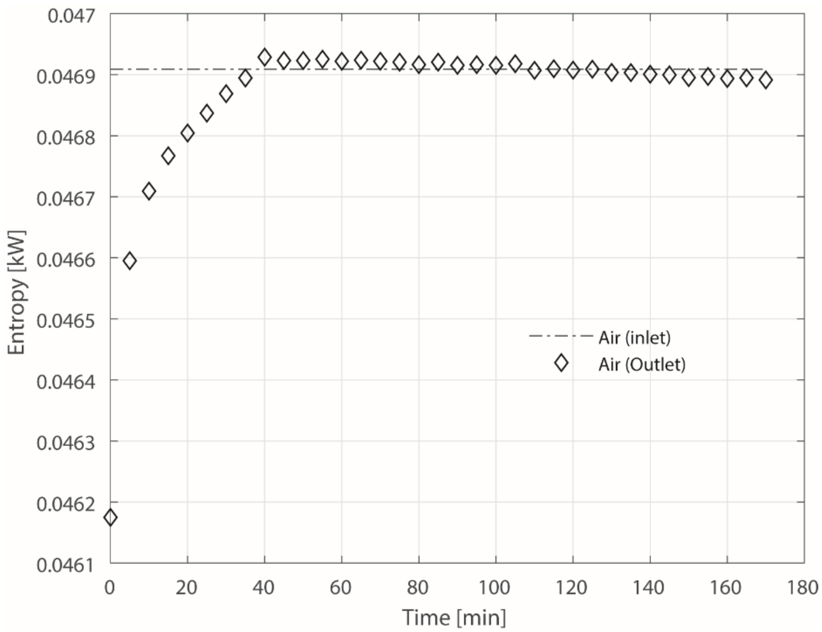

Fig. 8 Entropy at an air temperature of 100 °C and 1.45 m/s.

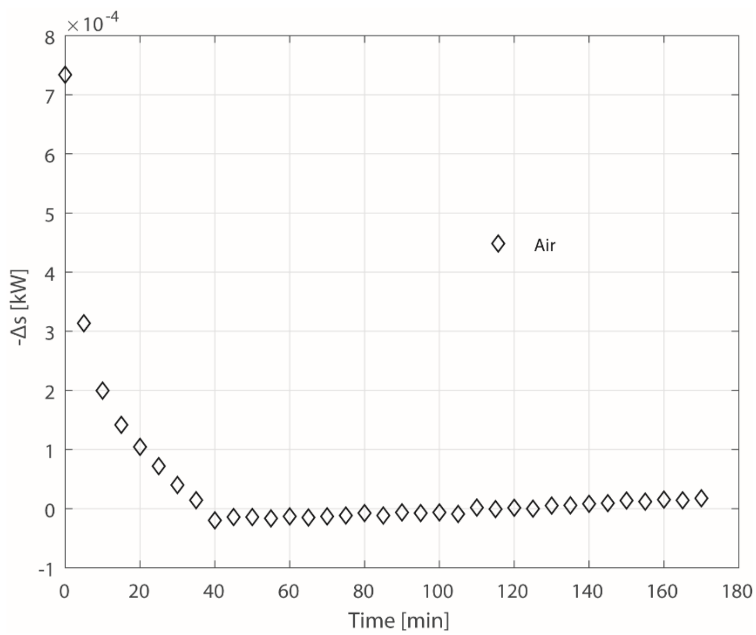

Fig. 9 Δ*s* values at an air temperature of 100 °C and 1.45 m/s.

3.4 Exergy analysis

The exergy variation is shown in Fig. 10. By observing the exergy over time, the quality of the energy is determined and at what exact stage the maximum exergy is reached (maximum energy quality). In this case, the exergy value is 1.6986 kW. Further, the available outlet energy has a significant increase because only in the first stage (ascending stage) is efficiently used in moisture evaporation. The tomato at 40 minutes begins to remain slightly constant near its maximum exergy value, while pineapple until at 80 minutes (Picado *et al.*, 2017). It means that the tomato is exergetically efficient since in 40 minutes less than pineapple reaches its highest point of conversion of useful energy into pure work, thus providing a higher value of energy quality.

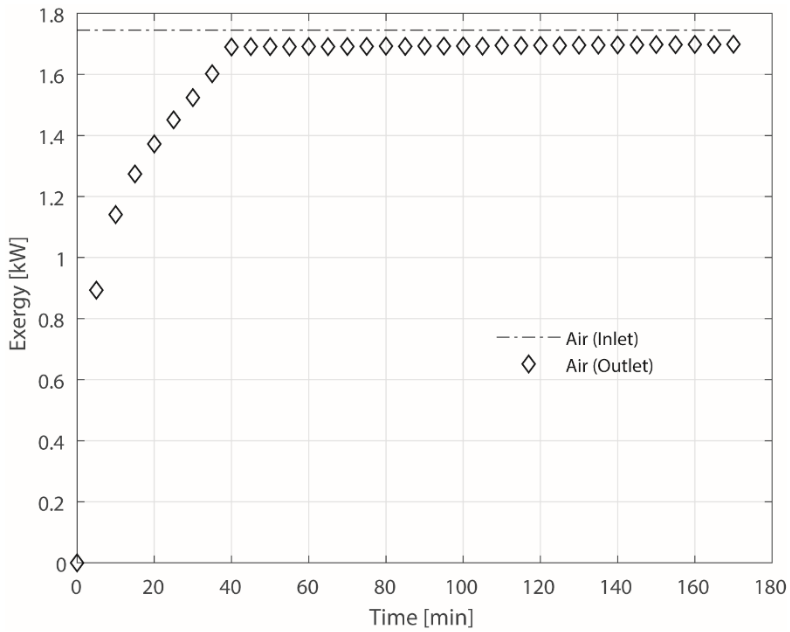

Fig. 10 Exergy at an air temperature of 100 °C and 1.45 m/s.

3.5 Exergy efficiency

The variation in exergy efficiency overtime was calculated (see Fig. 11) to determine the stage in which the tomato and drying conditions could be improved to gradually eliminate the irreversibilities of the drying process and improve the use of available energy in useful energy.

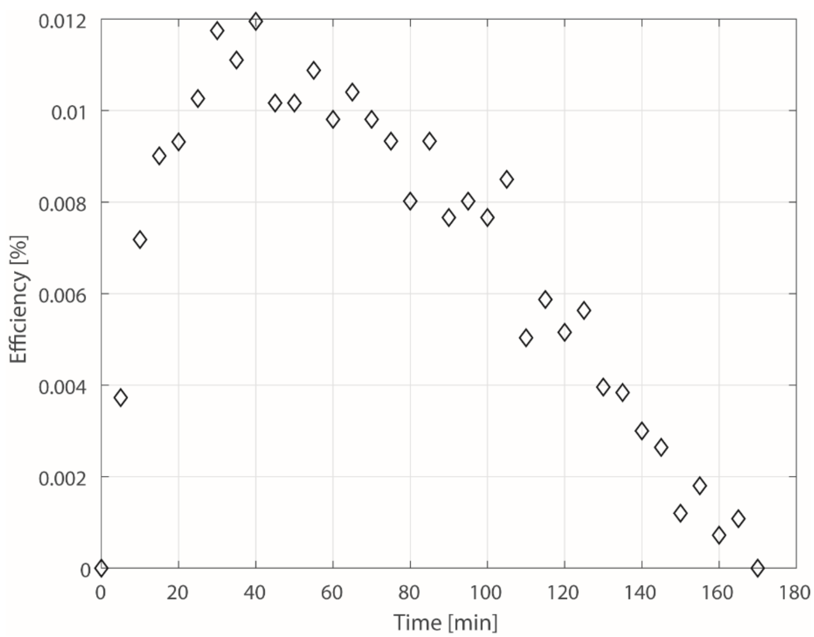

Fig. 11 Exergy efficiency at an air temperature of 100 °C and 1.45 m/s.

A fourth-order polynomial fit has been used to understand the trend of η_x because the evaporation rate data shows experimental noise. The polynomial equation was found to fit the best the experimental data is:

$$\eta_x = -2\times10^{-10}t^4 + 7\times10^{-8}t^3 - 1\times10^{-5}t^2 + 0.0006t + 0.0015 \quad (17)$$

The efficiency variation trend is directly related to the drying rate curves of tomato. The maximum value of the efficiency curve corresponds to the maximum value that can be observed within drying rate curves. This maximum value represents the stage when the available energy is efficiently used in the removal of moisture content. As the drying rate decreases, the available energy begins to be less used. This can also be deduced by observing, in a complementary way, Fig. 10.

It must be taken into account that hot air drying is the one that has, among all the other drying methods, the highest exergy losses due to the hot air outlet, little exergy is introduced during the process to the solid to be dried and there are a few losses in the walls of the dryer due to its size even when it is insulated. It also influences that the dryer is experimental and the sample to be dried is small compared to the dimensions of the dryer.

Analysing the conditions and the dryer with the theory, it is found that increasing the mass flow of the solid decreases the exergy. Increasing the mass flow of the inlet air does not significantly affect the exergy, therefore the optimal flow must be used and calculated to increase the exergy efficiency. The exergy increases by increasing the mass of the solid to be dried, as this experiment was carried out with an experimental dryer, in which very large air flows are usually used with respect to the water to be evaporated, low exergy efficiency values emerged. However, in the design of an industrial dryer, an appropriate relationship between the flow of air and the water to be evaporated must be considered for better use of the available energy. Increasing the temperature of the incoming drying air decreases the exergy as more energy is used to heat the incoming air.

4. CONCLUSIONS

Drying kinetics of tomato (*Lycopersicon esculentum* Miller) was investigated in a laboratory tunnel dryer at a constant air velocity of 1.45 m/s and temperatures of 100, 115, and 130 °C. Tomato did not observe a constant drying rate period under the experimental conditions employed and showed only a falling drying rate period, such as most food products. Further, a non-linear regression procedure was used to determine the characteristic drying curve. The enthalpy variation of the gas increased as the inlet gas temperature increase. It was observed that at the 40 minutes of the drying process, the outlet gas enthalpy reached a maximum value that is very close to the inlet value and remained constant until the end of the process. This behaviour is due to the reduction of the total enthalpy within the system, or in other words, the reduction of the effective heat transfer of the hot airflow to the tomato. Also, the outlet entropy exhibits a significant increase that is not only due to the temperature variation but also to the increase of the water vapour phase within the hot airflow. The maximum value of the exergy efficiency curve corresponds to the maximum value observed within drying rate curves. This maximum value represents the stage when the available energy is efficiently used in moisture removal. As the drying rate decreases the available energy is started to be less employed. The exergetic efficiency was directly dependent on the evaporation flux and since convective drying is less efficient than other types of dryers, therefore the exergetic efficiency likely has relatively low values.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interests regarding the publication of this article.

NOTATION

A_s	Drying area	(m^2)
c_p	Specific heat	(kJ kg^{-1} K^{-1})
E_x	Exergy	(kW)
f	Relative drying rate	(-)
h	Enthalpy	(kJ)
m	Mass	(kg)
$\dot{m}$	Mass flow	(kg s^{-1})
N_v	Drying rate	(kg m^{-2} s^{-1})
N_w	Drying rate at constant rate period	(kg m^{-2} s^{-1})
$\dot{Q}$	Heat flow	(kJ s^{-1})
s	Entropy	(kW)
t	Time	(s)
T	Temperature	(K)
V	Volume	(m^3)
w	Humidity ratio	(-)
X	Solid moisture content, dry basis	(kg kg^{-1})

Greek Letters

λ	Latent heat of vaporisation	(J kg^{-1})
ϕ	Characteristic moisture content	(-)
η_x	Exergy efficiency	(-)

Subscripts

c	Critical	o	Outlet
eq	Equilibrium	s	Solid
g	Gas	∞	Ambient
i	Inlet	0	Initial
L	Loss		

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