CHARACTERISATION OF INDUSTRIAL TOMATO BY-PRODUCTS FROM INFRARED DRYING PROCESS

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Abstract

The thin-layer infrared drying behaviour of industrial tomato residues, peels and seeds, was experimentally investigated in the temperature range from 100ºC to 160ºC. Using a non-linear regression (Marquart’s method) together with a multiple regression analysis, a mathematical model for the thin-layer infrared drying process of industrial tomato residues was proposed. The average values for the diffusivity coefficients at each temperature were obtained using Fick’s second law of diffusion. The temperature dependence of the effective diffusivity coefficient was described following an Arrhenius-type relationship. Activation energy for the moisture diffusion was determined as 22.23 kJ/mol.

Keywords: Tomato residue; Infrared drying; Moisture-ratio models; Statistical test; Activation energy

1. Introduction

The cultivation of tomato (Solanum lycopersicum) is widespread throughout the world. In particular, 90% of world output is produced in the northern hemisphere (Mediterranean area, California and China). Although tomato is cultivated in more than one hundred countries, both for fresh consumption and for industrial processing, the top ten producers account for more than 80% of world output: United States, China, Italy, Iran, Turkey, Spain, Brazil, Portugal, Greece and Chile. The total world production exceeded 125 million tons in 2006 [4], thus representing one of the most relevant crops in terms of employment and wealth generation.

The industrial processing of tomato leads to a great variety of output products. Some of the most relevant are the following: concentrated tomato products, either as puree or paste depending on the percentage of natural soluble solids; pizza sauce, from peels and seeds; tomato powder, as dehydrated concentrated tomato; peeled tomato, either whole or diced; ketchup, tomato sauce seasoned with vinegar, sugar, salt and some spices, etc. The residue used in the experiments performed in the present work consists of tomato seed and peel wastes from industrial processing, and represents between 3% and 5% (in weight) of fresh product. These by-products, as most of organic vegetable solid residues, are mainly used for livestock feed production –primarily cattle and sheep–, or are otherwise dumped in controlled landfills. Those residues have a high moisture content, which leads to some storage difficulties. This way, fast consumption is advised in order to prevent fermentation processes (which are
favoured by high temperatures during the industrial processing period). Also, important costs are derived from transport of wastes with significant moisture content, thus impeding their reasonable use. In order to overcome such problems, a thermal drying process of industrial tomato residues (ITR) is highly recommended.

The most widely used commercial drying plants for numerous industrial agrifood by-products are convective-type dryers, in which heat is transferred to the product by means of hot gases. Examples of this type of dryer are drum dryers, belt dryers and fluidised bed dryers. Nevertheless, most of these technologies can be optimised in terms of energy consumption, operating safety, drying process control and environmental impact through emissions, fossil mass or biomass combustion used as energy supply for the drying plant. Biomass drying via hot air or hot gases leads to low energy efficiency and lengthy drying time during falling rate period. Because of the low thermal conductivity of biomass materials in this period, heat transfer of product during conventional heating is limited.

Bringing all this into account, we introduce in this work the infrared (IR) drying technique applied to ITR, in order to achieve an increase of the effective thermal processing. IR drying is based on the action of infrared wavelength radiation from a source, which interacts with the internal structure of the sample and thus increases its temperature and favours the evaporation of its moisture content. IR drying technique is particularly valid for products with significant moisture content, for which long wave radiation (over 3 μm) is almost totally absorbed by moisture, while dry material is highly permeable to such radiation. IR heating presents some advantages with respect to conventional drying: decreasing drying time, high energy efficiency and lower air flow through the sample product.

IR drying has been investigated as a potential method for the drying of numerous foodstuffs, including fruit, vegetables and grains, and of some derived subproducts, as described in the works on the IR drying of carrot [10], of potato [1], of onion [9] and of wet olive husk [7]. The falling rate period appeared as the most relevant variable in all those studies, and Fick’s Law of diffusion was used to describe the drying process. In particular, empirical and semi-theoretical models -which consider only the external resistance to moisture transfer between product and air- are the most widely used.

The aim of the present experimental work was to investigate the thin-layer infrared drying behaviour of ITR at drying temperatures 100°C, 120°C, 140°C and 160°C. For such purpose, the mathematical modelling of drying curves is used to determine the moisture diffusivity as a function of moisture content, and also to evaluate the activation energy of ITR.

2. Experimental procedure

The samples of fresh ITR were obtained from a local tomato industry located in the province of Badajoz. Tomato peels and seeds showed an initial moisture content (236.70±0.5)% by weight (dry basis).

The samples were uniformly arranged on the tray as a thin layer (Fig. 1). Sample size was kept constant (20.61 g) for each experiment, with 0.70 cm sample thickness. Drying temperature was programmed as 100°C, 120°C, 140°C and 160°C for each experiment. Moisture loss was recorder at 30 s intervals during the drying process in order to determine the drying curves. The drying process was continued until no moisture content was recorded. Samples were thus completely dried in order to carry out the mathematical modelling of kinetics of the drying process. Nevertheless, for practical purposes, if the final product is intended for the manufacture of pellets, the final moisture content should not be lower than that of
equilibrium. Moisture content was calculated using the equation: \( M = \frac{(W_0 - W) - W_1}{W_1} \), where \( M \) is the moisture content (g water/g dry matter), \( W_0 \) is initial weight of sample (g), \( W \) is the amount of evaporated moisture (g) and \( W_1 \) is dry matter content of sample (g).

![Image](image.png)

**Figure 1.** Moisture analyzer

The values for the moisture content obtained were converted into the moisture ratio, \( MR \). The dimensionless moisture ratio can be calculated using the following equation [5]: \( MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \). However, the moisture ratio was simplified to \( M_t / M_0 \), where \( M_t \) and \( M_0 \) are the moisture content at any given time and the initial moisture content, respectively, since in IR drying, samples may be dried as much as dry matter content.

The coefficient of determination \( (r^2) \), reduced chi-square \( (\chi^2) \), root mean square error \( (RMSE) \) and sum of residuals were calculated for each model in order to test their accuracy in reproducing the experimental data. The higher values of the coefficient of determination \( (r^2) \) and the lower values of the reduced chi-square \( (\chi^2) \), RMSE and sum of residuals were chosen for goodness of fit [6], [2]. These parameters can be calculated as:

\[
\chi^2 = \frac{\sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i})^2}{N - p} \quad (1)
\]

\[
RMSE = \left[ \frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{exp,i})^2 \right]^{1/2} \quad (2)
\]

\[
\text{residuals} = \sum_{i=1}^{N} (MR_{exp,i} - MR_{pre,i}) \quad (3)
\]

where \( MR_{exp,i} \) is the experimental moisture ratio, \( MR_{pre,i} \) the predicted moisture ratio, \( N \) the number of data points and \( p \) the number of constants in the regression model.

**3. Results and discussion**

Changes in the moisture ratio with time during infrared drying of ITR are shown in Fig.2. It can be observed that moisture ratio decreases exponentially with drying time, that no constant rate drying period is found in these curves, and also that all the processes are seen to occur in
the falling rate period. As expected, the total drying time showed a substantial reduction as drying temperature was increased. At four different temperatures (100°C, 120°C, 140°C and 160°C) such values for the time period were determined as 99.5 min, 55 min, 44 min and 35 min, respectively (final moisture content 5.26% in weight in dry basis).

The drying rate, DR, is expressed as the amount of the evaporated moisture over time (g water/ g dry matter s). Values for DR were calculated as $DR = (M_{i + \Delta t} - M_t) / \Delta t$.

Fig.3 shows the drying rate versus drying time and the variations of drying rate with moisture content of the ITR samples at drying temperatures 100°C, 120°C, 140°C and 160°C. Drying rate decreases continuously with time and also with decreasing moisture content. After an initial period of sample heating, the drying rate reached its maximum value, and afterwards the product dried itself in the falling rate period. The water evaporation process took place initially at the surface of the ITR samples, but it begins to be less important as the drying time goes by. The moisture diffusion process progressively becomes the most important factor.

Figure 2. Drying curves of RIT at different temperatures.

Figure 3. Speed of drying compared to the moisture content of RIT at different temperatures.
Table 1 lists some models of drying vegetables, fruits and agricultural products, with their mathematical equations, where a, b and c are empirical constants, k is the drying rate constant and t the drying time. Table 2 shows the values of the coefficients used to test some of the models, where n is a positive number and e is an empirical constant. Nonlinear regression techniques was used to obtain the different constants for each model.

**Table 1.** Some drying models and their respective expressions

<table>
<thead>
<tr>
<th>Nº</th>
<th>Model</th>
<th>Analytical expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Modificado de Page-I</td>
<td>MR = exp(-(k*t)^n)</td>
</tr>
<tr>
<td>2</td>
<td>Logarítmico</td>
<td>MR = a exp(-kt)+c</td>
</tr>
<tr>
<td>3</td>
<td>Midilli</td>
<td>MR = a exp(-kt^n) + bt</td>
</tr>
<tr>
<td>4</td>
<td>Aproximación de la difusión</td>
<td>MR = a exp(-kt) + (1-a) exp(-ktb)</td>
</tr>
<tr>
<td>5</td>
<td>Difusión de Fick simplificado</td>
<td>MR = a exp(-c (t / L^2))</td>
</tr>
</tbody>
</table>
In this paper it is analyzed a wide range of drying curves for describing thin layer drying curves at different temperatures. The Midilli model was found to show the most adequate behaviour, with values of $r^2$ over 0.9997 along the whole temperature range, $\chi^2$ between 5.3309 x $10^{-6}$ and 2.0747 x $10^{-6}$ and RMSE between 0.00251 and 0.00443. The residuals of this model varied from -0.00001 to 0.00097.

The fitting procedure indicated that the results obtained with the Midilli model might be used to model the IR drying behaviour of ITR, but failed to reproduce the influence of drying temperature. The values of the constants and coefficients of the Midilli model were regressed against those of drying temperature using a multiple regression technique. The multiple combinations of all parameters that resulted in the highest value for $r^2$ were included in the selected model.

Based on the multiple regression analysis, the following equation was proposed to evaluate the moisture ratio of ITR for the drying time and the drying temperatures considered in the experiments:

$$\text{Table 2. Coefficients of the previous drying models.}$$

<table>
<thead>
<tr>
<th>Nº</th>
<th>$T^\circ$</th>
<th>Models constants</th>
<th>$r^2$</th>
<th>$\chi^2$</th>
<th>RMSE</th>
<th>Suma de los residuales</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100°C</td>
<td>$a=0.00035319$, $y=1.1932981$</td>
<td>0.9915</td>
<td>6.6146 x 10^{-4}</td>
<td>0.02560</td>
<td>-1.45299</td>
</tr>
<tr>
<td></td>
<td>120°C</td>
<td>$a=0.00060806$, $y=1.2528442$</td>
<td>0.9916</td>
<td>6.9148 x 10^{-4}</td>
<td>0.02607</td>
<td>-0.76401</td>
</tr>
<tr>
<td></td>
<td>140°C</td>
<td>$a=0.00077419$, $y=1.2518549$</td>
<td>0.9926</td>
<td>6.2489 x 10^{-4}</td>
<td>0.02474</td>
<td>-0.56053</td>
</tr>
<tr>
<td></td>
<td>160°C</td>
<td>$a=0.00093120$, $y=1.3231262$</td>
<td>0.9923</td>
<td>6.7816 x 10^{-4}</td>
<td>0.02570</td>
<td>-0.41674</td>
</tr>
<tr>
<td>2</td>
<td>100°C</td>
<td>$a=1.2607776$, $c=-0.2770623$, $k=0.00022511$</td>
<td>0.9997</td>
<td>2.0768 x 10^{-4}</td>
<td>0.00452</td>
<td>-0.00000</td>
</tr>
<tr>
<td></td>
<td>120°C</td>
<td>$a=1.3624521$, $c=-0.3656689$, $k=0.00035805$</td>
<td>0.9997</td>
<td>1.7889 x 10^{-4}</td>
<td>0.00417</td>
<td>0.00000</td>
</tr>
<tr>
<td></td>
<td>140°C</td>
<td>$a=1.3111636$, $c=-0.3053866$, $k=0.00049266$</td>
<td>0.9997</td>
<td>2.5134 x 10^{-4}</td>
<td>0.00493</td>
<td>0.00000</td>
</tr>
<tr>
<td></td>
<td>160°C</td>
<td>$a=1.4493959$, $c=-0.4322513$, $k=0.00052743$</td>
<td>0.9996</td>
<td>2.7047 x 10^{-4}</td>
<td>0.00509</td>
<td>0.00000</td>
</tr>
<tr>
<td>3</td>
<td>100°C</td>
<td>$a=1.0033400$, $b=-0.000028988$, $n=0.9282856$, $k=0.0004704$</td>
<td>0.9999</td>
<td>5.3309 x 10^{-6}</td>
<td>0.00228</td>
<td>-0.00097</td>
</tr>
<tr>
<td></td>
<td>120°C</td>
<td>$a=1.0116795$, $b=-0.00061340$, $n=0.9420742$, $k=0.0008723$</td>
<td>0.9999</td>
<td>6.5179 x 10^{-6}</td>
<td>0.00251</td>
<td>-0.00020</td>
</tr>
<tr>
<td></td>
<td>140°C</td>
<td>$a=1.0192737$, $b=-0.000066536$, $n=0.9530249$, $k=0.0008269$</td>
<td>0.9998</td>
<td>1.3663 x 10^{-5}</td>
<td>0.00362</td>
<td>-0.00001</td>
</tr>
<tr>
<td></td>
<td>160°C</td>
<td>$a=1.0236663$, $b=-0.000099754$, $n=0.9821009$, $k=0.0007600$</td>
<td>0.9997</td>
<td>2.0747 x 10^{-5}</td>
<td>0.00443</td>
<td>0.00028</td>
</tr>
<tr>
<td>4</td>
<td>100°C</td>
<td>$a=1.6691186$, $b=0.3522094$, $k=0.00020564$</td>
<td>0.9993</td>
<td>5.4378 x 10^{-5}</td>
<td>0.00732</td>
<td>-0.44741</td>
</tr>
<tr>
<td></td>
<td>120°C</td>
<td>$a=6.65180657$, $b=0.8151380$, $k=0.00023787$</td>
<td>0.9996</td>
<td>2.6673 x 10^{-5}</td>
<td>0.00510</td>
<td>-0.06490</td>
</tr>
<tr>
<td></td>
<td>140°C</td>
<td>$a=3.24554663$, $b=0.6433201$, $k=0.00034763$</td>
<td>0.9996</td>
<td>3.3330 x 10^{-5}</td>
<td>0.00568</td>
<td>0.00649</td>
</tr>
<tr>
<td></td>
<td>160°C</td>
<td>$a=7.18767011$, $b=0.7892166$, $k=0.00031108$</td>
<td>0.9993</td>
<td>5.4579 x 10^{-5}</td>
<td>0.00724</td>
<td>0.10985</td>
</tr>
<tr>
<td>5</td>
<td>100°C</td>
<td>$a=1.04852691$, $c=0.000000018521$</td>
<td>0.9835</td>
<td>1.2890 x 10^{-5}</td>
<td>0.03574</td>
<td>-1.58553</td>
</tr>
<tr>
<td></td>
<td>120°C</td>
<td>$a=1.06749603$, $c=0.000000032480$</td>
<td>0.9803</td>
<td>1.6206 x 10^{-5}</td>
<td>0.03992</td>
<td>-0.90593</td>
</tr>
<tr>
<td></td>
<td>140°C</td>
<td>$a=1.07273987$, $c=0.000000041641$</td>
<td>0.9822</td>
<td>1.4992 x 10^{-5}</td>
<td>0.03832</td>
<td>-0.75210</td>
</tr>
<tr>
<td></td>
<td>160°C</td>
<td>$a=1.09192729$, $c=0.000000050903$</td>
<td>0.9777</td>
<td>1.9659 x 10^{-5}</td>
<td>0.04375</td>
<td>-0.61460</td>
</tr>
</tbody>
</table>
This model can be used to perform an accurate estimate of the moisture ratio of ITR at any time during the drying process along the whole temperature range considered in the experiments. In the effort to find a single expression for the temperature range studied, the inclusion of the dependence of Midilli’s model variables with temperature provides a good approximation to the real drying process kinetics.

The analytical solution of the diffusion equation assuming an uniform initial moisture distribution, with simplifying the movement of moisture by diffusion, a negligible volume reduction, diffusion coefficients and constant temperature, can be expressed as [3]:

\[
MR = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp \left( -\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L^2} \right)
\]  

(5)

where \(D_{eff}\) is the effective diffusivity (m²/s), \(L\) is the half-thickness of slab (m) if drying from both sides, or the thickness of slab (m) if drying from a single side, and \(n\) the number of terms taken into consideration.

For long drying periods, \(MR<0.6\), the equation can be simplified to the first term of the series [8]. Therefore, assuming the effective diffusivity not to depend on the moisture content of the sample, one can take natural logarithms of both sides in Eq.(14) to end up with the following expression:

\[
\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L^2}
\]  

(6)

The diffusion coefficient for each drying temperature can be calculated by substituting the experimental data in the previous equation. In practice, such coefficient was determined by plotting experimental data in terms of \(\ln(MR)\) versus drying time. If it is represented the \(\ln(MR)\) of the equation number 6 versus drying time we get a line with a slope that represents the measure of the diffusivity.

The correlation between drying conditions and the measured values of the effective diffusivity can be expressed by an Arrhenius type equation, such as:

\[
D_{eff} = D_o \exp \left( -\frac{E_a}{RT} \right)
\]  

(7)

where \(D_{eff,avg}\) is the average effective moisture diffusivity (m²/s), \(D_o\) the pre-exponential factor of the Arrhenius equation (m²/s), \(E_a\) the activation energy of the moisture diffusion (kJ/mol), \(T\) the absolute temperature (K) of air and \(R\) the universal gas constant (8.3143 kJ/kmol K).

Taking natural logarithms, equation (7) can be linearized as:

\[
\ln D_{eff} = \ln D_o - \frac{E_a}{R} \frac{1}{T}
\]  

(8)

In order to obtain the magnitudes of the coefficients of the previous equation, values of \(\ln(D_{eff})\) were plotted versus \(T^{-1}\). The activation energy was calculated from the slope of the
straight line (Ea/R), while the intercept equals ln(D0), Fig.4. The final value was found to be 22.23 kJ/mol, where the Arrhenius factor D0 was 7.254 x 10^-6 m²/s.

4. Conclusions

The mathematical modelling of the thin-layer infrared drying process of industrial tomato residues was developed in this work, using a nonlinear regression (Marquart’s) method. The Midilli model was found to combine accuracy and analytical simplicity, and might thus be considered to reproduce adequately the change of moisture ratio with drying time at temperatures from 100°C to 160°C, with values of r² over 0.9997 within the whole temperature range.

The values for the average effective moisture diffusivity varied from 5.179 x 10^-9 m²/s to 1.429 x 10^-8 m²/s for the above-mentioned temperature range, according to the increasing behaviour of effective diffusivity with temperature. Besides, temperature dependence of the diffusivity coefficients was described by an Arrhenius-type relationship. Finally, the activation energy for moisture diffusion was found to be 22.23 kJ/mol.

References


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