Modelling the Drying Kinetics of Pineapple Slices in a Tray Dryer
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ABSTRACT
This study aimed the development of a simulation model of the pineapple slices drying process validating it by means of the comparison between the simulated and experimental results. There was used a fixed bed (tray) dryer with a 373 W Fan and supplied with complementary energy for the drying air by means of electric resistances. For the drying process there was used the temperatures of 60, 65 and 70 °C and air velocities of 0.50; 0.75 and 1.00 m s\textsuperscript{-1}. The model proposed by Thompson et al.\cite{15} implemented to simulate the drying of pineapple slices, showed accuracy satisfactory to simulate the process, it can be used to provide the time and the conditions of drying.

Keywords: Pre-treatment, dehydration, Ananas comosus, simulation

INTRODUCTION
Several models were proposed to predict the behaviour of the drying of agricultural products, by these to be presented as an important tool for the professional area\cite{14}. To describe the drying process in the period of decreasing rate, theoretical, semi-empirical, and empirical models are frequently used. These models are normally based in the phenomenon of heat and mass transfer. Empirical and semi-empirical models are based in the Newton`s low, for cooling, applied to the transfer of mass. When applying the law, it is assumed-that the conditions are isotherms and that the resistance to the transfer of humidity is confined to the surface\cite{2}.

The establishment of curves of hygroscopic equilibrium is important to define limits of dehydration of the product, estimate the changes of humidity under specific condition of temperature and relative humidity of the environment and to define the moisture contents conducive to the activity beginning of agents that will cause the deterioration of the product. In the pineapple case, it is important to highlight that the conditions of appropriate drying and storage are essential to maintain the quality of the product due to the activity initiation of agents that will cause the deterioration of the product. In the case of the pineapple, it is important to highlight that the appropriate drying and storage conditions are essential to maintain the quality of the product due to its high water activity.

Studies on the handling of humidity on the inside of grains submitted to drying process, revealed that the transport of humidity occurs by diffusion of liquid or dissemination of vapour or, still, by combining these mechanisms, predominantly one or another during the drying process. However, Fortes & Okos\cite{5} stated that, in a given stage of drying, the movement of humidity is determined, basically, by diffusion of liquid. In accordance with Nicoleti\cite{12}, the main factors that affect the drying rate are the physical properties of the product, the geometric arrangement of the product in respect of the heat transfer area, the physical properties of the drying process environment and the drying equipment characteristic. The aforementioned factors, which most influences the drying rate is the nature of the raw material, including the chemistry and physics constitution of the cells walls.

Among the problems encountered during the drying process the complexity of the composition and structure of the food and more specifically the coefficients for the transfer of heat and mass, as well as the thermodynamic properties of the feeding stuff. These properties are in function of temperature and humidity, and so that the differential equation resulting from the new system makes it not linear and can only be solved by numerical methods.

Various researchers used mathematical models to describe the drying process of biological materials: Jesek et.al\cite{9} obtained results that enabled designing a two-parameter model of carrot drying. Their results also provide reliable parameters for dryer construction. Fioreze & Morini\cite{4} used the model of Thompson for yam...
drying. Planinic et al.\textsuperscript{[13]} used Peleg’s Model in drying and rehydration of carrots. Janjai et al.\textsuperscript{[8]}, used a two-dimensional finite element model to simulate moisture diffusion in mango fruit during drying. These authors also developed a computer program in Compaq Visual FORTRAN version 6.5 was developed to simulate the finite element model and concluded that it satisfactorily predicted the moisture diffusion during drying. The Fick model was used by Togrul & Pehlivan\textsuperscript{[16]} to predict the drying of grape, peach, fig and plum; Hawlader et al.\textsuperscript{[6]} for tomatoes and Babalis & Velessiotis\textsuperscript{[2]} for figs. Whereas the product conditions is during the drying process, it was aimed with this work to implement a simulation model to predict the drying of pineapple slices, validating it by means of comparing both simulated and experimental results;

**MATERIALS & METHODS**

The work was carried out in the Laboratory of pre-processing and storage of vegetable products from the Department of Agricultural Engineering, Universidade Federal de Viçosa (UFV). In the drying process were used pineapple fruits (\textit{Ananas comosus}), Perola variety with initial moisture content of 86 % in wet basis. The drying kinetics model was implemented based on the one proposed by Thompson \textit{et al.}\textsuperscript{[15]}. In that model, it was used, as artificie, dividing the drying process in several sub processes. The bed of product was considered as formed by several layers of pineapple-reduced thickness slices, placed on each other. Variations in conditions of air and slice, for each layer, were calculated based on small increments of time.

In Figure 1 is shown a diagram illustrating how changes occurred considered in the simulation of drying a reduced thickness layer, which comprises a bed of the product to be dried. When the air passes through the layer, during a given time interval, a certain quantity of water of the product is evaporated, turning to the air. In the intervening period, the air temperature decreases, as a consequence of the transfer of sensitive heat of the air for heating the pineapple, and the partial latent heat supplied by the product water evaporation. The quantity of water lost by the product is calculated by means of an empirical thin layer drying equation. Final temperatures of the air and the pineapple, consistent with the evaporative cooling, are obtained by means of the balance of energy.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Schematic drawing of changes arising from the drying process thin layer during a time interval $\Delta T$.}
\end{figure}

In the development of the model, the following assumptions were taken:

a) drying a thin layer of the product can be described by an equation obtained empirically
b) the temperature of slice equals the air temperature that involves it, after the balance of energy, which take into account the cooling from the product water evaporation and of the temperatures of slices and air;

c) the slices balance moisture content depends on the temperature and relative humidity of air in the surrounds; the enthalpy of vaporization of the water in slices is constant;

d) The product specific enthalpy depends on the moisture content.
To model the drying of the pineapple slices layer, were used the procedures proposed by Souza et al.\textsuperscript{[14]}. The following steps were implemented: humidity balance calculation between the air and the product; the product humidity balance calculation; equivalent time calculation; the product humidity ratio calculation; the product and the air final temperatures calculation; checking the consistency of the final temperature and exit air mixture ratio values.

For the calculation of the equilibrium temperature between the air and the product, was considered only the exchange of sensitive heat. For this determination, was necessary the following energy balance (Equation 1).

\[
0.24 \cdot T_0 + W_0 \cdot \left(588 + 0.45 \cdot T_0\right) + C_p \cdot R \cdot (1 + U) \cdot T_{st} = 0.24 \cdot T_e + W_0 \cdot \left(588 + 0.45 \cdot T_e\right) + C_p \cdot R \cdot (1 + U) \cdot T_{se}
\]

Where:
- \(T_0\) = Air temperature at the entrance of the layer of the product °C
- \(W_0\) = Mixture ratio in air entry of the layer of the product, kg of water vapour per kg of dry air
- \(T_{st}\) = Product temperature at time \(t\), in equilibrium with the air, °C
- \(T_{se}\) = Product temperature when it is in equilibrium with air, °C
- \(U\) = Product Moisture content of the product at time \(t\), decimal in dry basis.
- \(C_p\) = Specific enthalpy of pineapple, kJ kg\(^{-1}\) °C\(^{-1}\), and
- \(R\) = Mass ratio of dry matter of product layer and dry air in the time interval \(\Delta t\), kg.kg\(^{-1}\).

Specific enthalpy of pineapple was obtained from Mohsenin\textsuperscript{[11]} as being of 3.6844kJ.kg\(^{-1}\).°C\(^{-1}\). The equilibrium temperature between the drying air and the product was determined by Thompson et al.\textsuperscript{[15]}. To calculate the product equilibrium moisture content it was necessary to determine primarily the air relative humidity. For this, was used the equation proposed by Brooker et al.\textsuperscript{[3]}, Vapour pressure of saturated air was determined using the equation, presented by Standard ASAE D271.2\textsuperscript{[1]}. For the calculation of moisture content in the equilibrium state was used the GAB model, with the parameters for pineapple, obtained by Nicoleti\textsuperscript{[12]}.

Fruits of pineapple (\textit{Ananas comosus}), variety pearl, were selected given the commercial standards of quality. The fruits pre-washing with drinking water were performed immersing then in chlorinated water in a concentration of 10ppm of chlorine, during ten minutes. The pineapples were cut and then sliced at approximately 0.01m and these were cut in halves. After cutting, the moisture content of the product was determined, in a lab oven according to the Analytical Standards of the Instituto Adolfo Lutz\textsuperscript{[7]}.

A fixed bed (tray) dryer was used, with automatic control of the drying air temperature, composed of a fan (372.85 Watts), electric resistances (7500W) and tray with diameter of 0.335 m. The speed of the outlet air in the dryer was monitored by means of a thermo anemometer and the mass of the product was measured, in a digital scale, with centesimal precision, at intervals of thirty minutes. The air was moved perpendicularly to the direction of the tray. The moisture of the pineapple was reduced, by means of drying with heated and forced air movement until a final moisture content of approximately 20 % wet basis.

Drying air temperatures used were 60, 65 and 70°C and the drying air speed 0.5, 0.75 and 1.00 m.s\(^{-1}\). Three drying processes were used for each treatment.

To evaluate the differences between the results simulated and experimentally obtained, the relative average error and the determination and variation coefficients were used.

**RESULTS & DISCUSSION**

Some examples of the pineapple drying simulation curves, using the implemented model, as well as the points obtained experimentally and the correspondence between the same, are presented in Figures 2 to 11. The rates of drying, under the conditions of this experiment, were all approximately constant, indicating that the results obtained are limited to this stage of the drying process. In general, we can find that the results simulated were higher than experimental ones, with the relative average error varying between 2.62 and 11.33% and the determination coefficients close to 0.99. The behaviour of the curves of simulated data represents the curve of experimental data within the tolerable and acceptable errors limits in engineering process, considering the conditions under which was conducted the experiment, although with a slight tendency to underestimation.
These facts show that the simulation model developed is consistent, which could be used in the simulation of drying pineapple in fixed bed. The relative error average observed 7.3% is lower than 20% found by Mata & Dantas[10] and 10.9% found by Souza et al.[14], with these authors consider the errors obtained in their models as satisfactory.

Figure 2. Moisture content observed (a) and simulated results in relation to time in pineapple drying at the temperature of 70°C and air velocity of 1.0 m.s⁻¹(b).

Figure 3. Moisture content observed (a) and simulated results in relation to time in pineapple drying at the temperature of 70°C and air velocity of 0.75 m.s⁻¹(b).

Figure 4. Moisture content observed (a) and simulated results in relation to time in pineapple drying at the temperature of 65°C and air velocity of 1.0 m.s⁻¹(b).
Figure 5. Moisture content observed (a) and simulated results in relation to time in pineapple drying at the temperature of 60°C and air velocity of 1.0 m.s⁻¹ (b).

Figure 6. Moisture content observed (a) and simulated results in relation to time in pineapple drying at the temperature of 60°C and air velocity of 0.75 m.s⁻¹ (b).

Figure 7. Moisture content observed (a) and simulated results in relation to time in pineapple drying at the temperature of 60°C and air velocity of 0.50 m.s⁻¹ (b).

CONCLUSION
The mathematical model implemented for drying pineapple slices, using fixed bed dryer, showed to be viable, presented satisfactory accuracy and can be considered valid to simulate the drying of pineapple, under the conditions of this experiment. Deserving, however, more detailed studies and, mainly for lower moisture contents.
REFERENCES