

Full Length Research Paper

Fruit drying process: Analysis, modeling and simulation

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The current work presents an investigation on fruit drying system. The effect of the operating parameters on the quality of products and the efficiency of the system is studied. The method is based on a new model which was developed to study the fruit drying system performance considering equilibrium moisture content of fruit, humidity of dryer atmosphere, temperature of dryer atmosphere and air flow. The results revealed that operating parameters are highly controlling the dryer efficiency, whereas increase in the air temperature highly reduced the energy required and enhance the dryer efficiency. However, high temperature could damage the fruit, that is worsens the quality. Therefore, the air temperature plays the main role in controlling the quality of the dried fruit.

Key words: Fruit drying process, operating parameters, quality, modeling.

INTRODUCTION

Drying of crop and fruit products is an important issue for the preservation and conservation of food. Using solar drying system is becoming an attractive and alternative food preservation technique over the conventional ones. This is due to many advantages of solar drying system compared to others, that is low cost, high quality of dried products and environmentally friendly (Heredia et al., 2007; Toor and Savage, 2006; Walker and Wilhelm, 1995; Ziauddin and Liang, 1986; Shinskey, 1996; Souza, 1997). Moreover, the products are isolated from rain, storm, windborne dirt, dust, and infestation by insects, rodents and other animals. In other words, the quality of food can be preserved (Heredia et al., 2007). In Heredia et al. (2007), Toor and Savage (2006), Walker and Wilhelm (1995) and Ziauddin and Liang (1986), it has been reported that system performance highly influences the quality of the products. The performance of the solar drying system is controlled by number of physical processes such as heat and mass transfer of air (Toor and Savage, 2006). In the drying system, convection,

conduction and radiation processes take place (Souza, 1997; Simpson, 1996), while the mass transfer occurs by liquid phase transformation into gas phase (Walker and Wilhelm, 1995). Batch process represents the core of the solar drying systems (Ziauddin and Liang, 1986). One of the common used batch process controller is the proportional derivative (PD) control (Shinskey, 1996). It has been implemented in many systems (Lewicki, 2006; Cykler, 1996; Bona, 1994; Filkova and Choc, 1989). When controlling a batch fruit dehydrator, the objective is not currently one of achieving steady state operation but the determination of the end point. The end point may occur before the steady state of the process is reached. In fact, this is preferable when the costs and time of the process are to be minimised. It is possible to operate a drying process to achieve steady state. This is achieved when the dryer's conditions (fruit's equilibrium moisture content) equals the desired result. This requires significant inputs to achieve namely time and energy (Aylward and Findlay, 1979; Backhurst et al., 1974; El-Sebaili et al., 2002; McBean and McG 1976). In practice, the operation of batch dryers is to continue the evaporation until the moisture content is equal to that required, at which point the process is stopped.

Over shooting of the end point should be avoided as it

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results in loss of quality and higher energy costs. Souza looked at controller design that would allow the air temperature of the dryer to follow a maximum profile throughout the drying time (Garg and Sharma, 1990; Henderson, 1952; Unadi et al., 2002).

The drying of wood is a more complex problem that requires the rate of evaporation to be limited so as not to cause checking in the product (Simpson, 1996). Due to the extra limitation on the system, a third controller is added to the system used for batch fluidized bed dryers. This controller operates in parallel to the temperature controller. The aim of this controller is to change the temperature of the air by a set amount. The two control signals are compared and the smaller signal is passed to the plant (Shinsky, 1996). Timber dryers use inferential moisture control to determine the end point. This paper shows that better control of the process is achievable through an understanding of the following factors and their place in the dryer process; the nature of the product, the equilibrium moisture content, the temperature of the atmosphere in the dryer, the humidity of the atmosphere in the dryer and the flow of the atmosphere in the dryer. Control of the humidity in the dryer improves efficiency by only venting the system to maintain the conditions within the dryer.

DEVELOPMENT OF THE MODEL

In current design dryers, the controller of the air speed relies on the amount of the fruit loaded into the dryer. In this method, there is a design solution that removes the dependence of the air speed on the packing density of the fruit. This airflow is considered to be turbulent flow. For a fruit dryer, this would be achieved through the use of tapered ducts above the trays. The lower side of the duct contains a series of regular spaced holes 'nozzles' to direct the airflow evenly onto the drying surface (Figure 1). The volume of air flowing out of an opening in the duct is a function of the change in cross sectional area of the duct due to the taper and the size of the opening, the smaller the opening the higher the speed. The area of the nozzles sets the speed of the atmosphere over the surface of the fruit. The air speed u is a function of the dry air mass flow rate, the nozzle area and the density of the atmosphere (Equation 1):

$$u = \frac{G}{A_n d} \quad (1)$$

Where G is the mass of air flows, d is density of the atmosphere and A_n is the nozzle area.

In this case, it does not consider the dependency of the air speed and in laminar flow dryers on the cross sectional area (Equation 2).

$$\dot{x} = \frac{G}{dA_s} \quad (2)$$

Where \dot{x} is the speed of the air, A_s is a function of the cross sectional area.

Graphic user interface technique was used to ease the method of entering the data and parameters to the model (Figure 2).

Control of humidity

The humidity within the dryer can be held constant through the control of the recirculation rate. The humidity of the dryer is the sum of the percentage x ambient humidity ω_a and the complementary percentage $(1-x)$ of the outlet humidity ω_0 that is mixed together to form the humidity at the nozzles ω_n :

$$\omega_a x + \omega_0 (1-x) = \omega_n \quad (3)$$

The humidity at the outlet of the dryer will be the humidity at the nozzles plus the evaporation rate \dot{m} divided by the mass flow rate of dry air:

$$\omega_0 = \omega_n + \frac{\dot{m}}{G} \quad (4)$$

Solve Equation 3 for x :

$$x = \frac{\omega_n - \omega_0}{\omega_a - \omega_0} \quad (5)$$

Substituting Equations 4 into 5 and reducing:

$$x = \frac{-\dot{m}}{G(\omega_a - \omega_n) - \dot{m}} \quad (6)$$

The exhaust ratio x can be found from Equation 6 from the change in the mass of the fruit and the ambient humidity.

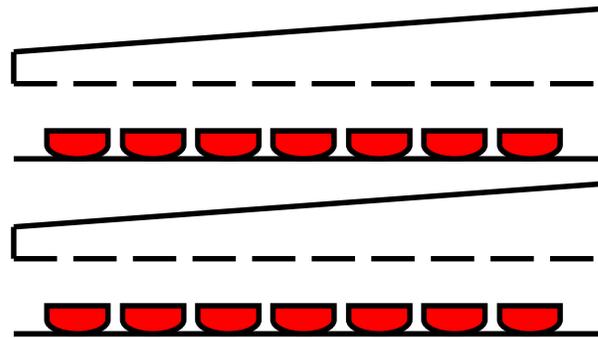
Determining the evaporation rate for the controller

In a laminar airflow dryer, the effect of each fruit acts sequentially so the rate of evaporation for the dryer \dot{m} will be:

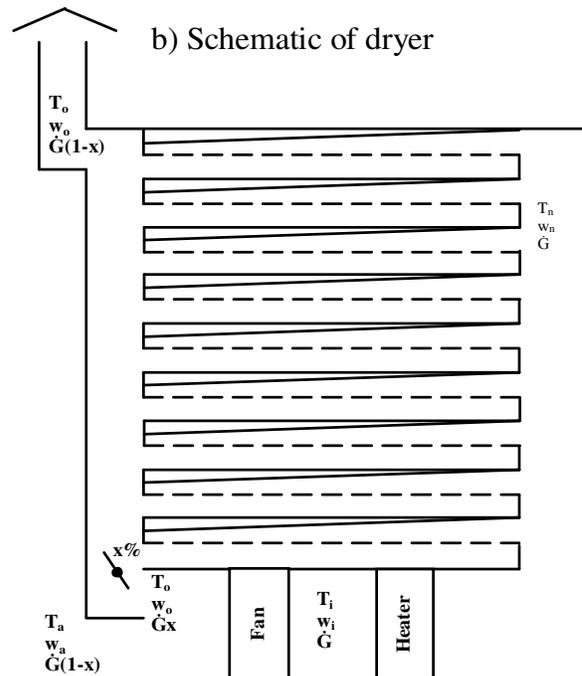
$$\dot{m} = \sum_j i \dot{m}_j \quad (7)$$

Where i is the number of fruit across the tray (normal to

a) Section through nozzle dryer



b) Schematic of dryer



c) Smaller nozzle openings, higher air speed

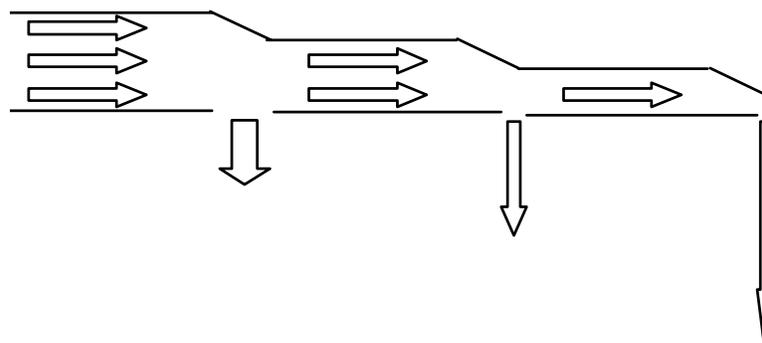


Figure 1. Schematic drawing showing the modelling of the current dryer system.

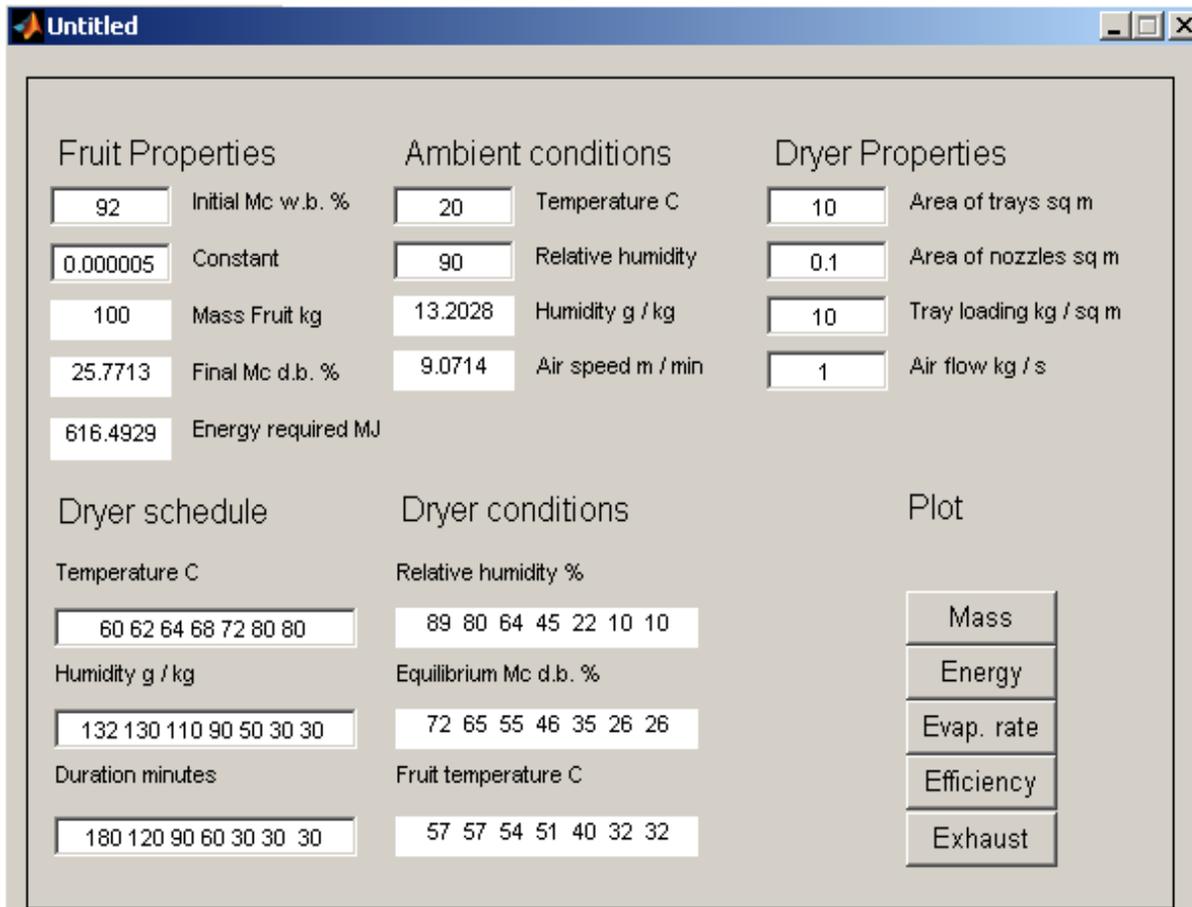


Figure 2. Window of the develop model using Matlab.

the air flow) and l is the fruit along the tray (parallel to the air flow).

The mass flow rate of the dry air will remain constant as the fan speed is fixed. The condition of the atmosphere before the fruit will have a temperature T_i and a humidity of ω_i . The rate of energy flow before the fruit can be calculated from Equation 8.

$$\dot{E} = T_a \dot{G} (c_a + \omega c_w) \quad (8)$$

The energy flowing with the atmosphere after the fruit \dot{E}_0 will be the energy flow before the fruit \dot{E}_i minus the energy flow into the fruit \dot{E}_f :

$$\dot{E}_0 = \dot{E}_i - \dot{E}_f \quad (9)$$

The energy flowing into the fruit will equal the flow of moisture from the fruit times the latent heat of vapourisation λ plus the change in temperature of the

fruit times the mass of the fruit times the heat capacitance of the fruit.

$$\dot{E}_f = \dot{m} \lambda + \dot{T}_f m c_f \quad (10)$$

By assuming that the condition of the inlet atmosphere is constant, Equation 10 will reduce to:

$$\dot{E}_f = \dot{m} \lambda \quad (11)$$

$$\lambda = 2444.4 \text{ J/g} \quad (12)$$

Where λ is the molar heat of vaporization for transition liquid to vapour.

$$\lambda = \Delta H_S - \Delta H_m$$

Where ΔH_S is the standard molar heat of sublimation at

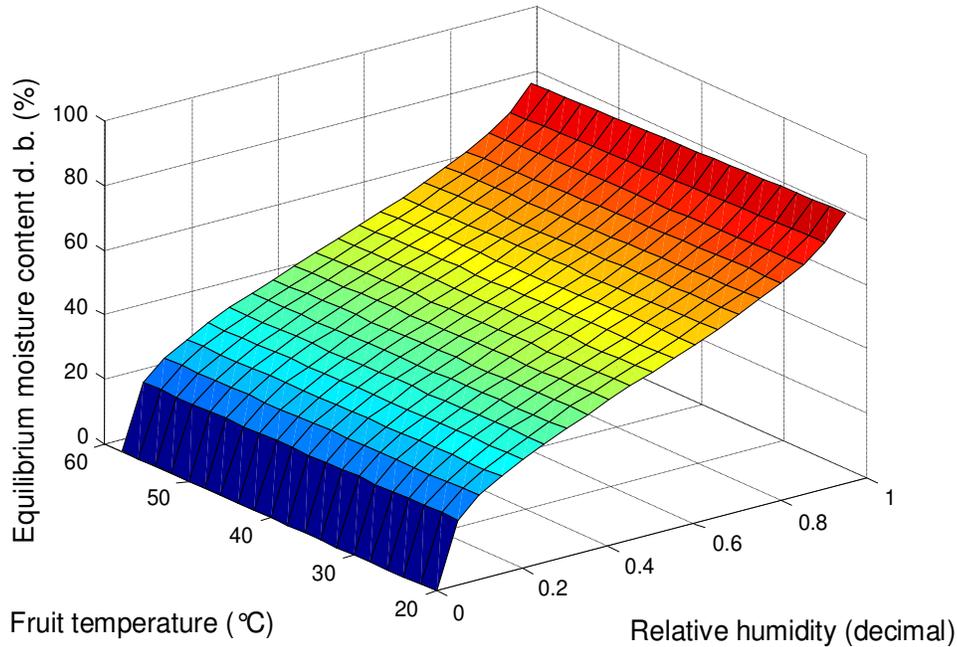


Figure 3. Henderson's equilibrium moisture content for tomatoes.

25°C for the transition solid to vapour. Where ΔH_m is the molar heat melting or fusion for the transition solid to liquid.

$$\left(\frac{50 - 6}{18}\right) \times 1000 = 2444.4 \text{ J/g}$$

The humidity after the fruit will be equal to the humidity before the fruit plus the evaporation rate divided by the mass flow rate of the dry air:

$$\omega_0 = \omega_i + \frac{\dot{m}}{\dot{G}} \tag{13}$$

The temperature of the atmosphere after the fruit will equal the energy flowing with the atmosphere divided by the mass of dry air flow rate times the heat capacitance of the atmosphere:

$$T_0 = \frac{\dot{E}_0}{\dot{G}(c_a + \omega_0 c_v)} \tag{14}$$

Substitute Equations 9 and 13 into 14:

$$T_0 = \frac{\dot{E}_i - \dot{E}_f}{\dot{G}(c_a + (\omega_i + \frac{\dot{m}}{\dot{G}})c_v)} \tag{15}$$

Substitute Equations 8 and 11 into Equation 15, it

becomes:

$$T_0 = \frac{T_i(c_a + \omega_i c_v) - \dot{m}\lambda}{c_a + (\omega_i + \frac{\dot{m}}{\dot{G}})c_v} \tag{16}$$

Solving for the evaporation rate to get:

$$\dot{m} = \frac{\dot{G}(T_i - T_0)(c_a + \omega_i c_v)}{T_0 c_v + \lambda \dot{G}} \tag{17}$$

When controlling the humidity in a laminar flow dryer, the change in mass of the fruit in the dryer can be found from the temperature change of the atmosphere with Equation 16.

Evaporation from fruit in a turbulent flow dryer will still conform to Equation 16. In a turbulent flow dryer, the rate of evaporation for the whole dryer is equal to the number of fruit times the rate of evaporation of a single fruit.

$$\dot{m} = \dot{m}_f n \tag{17}$$

When controlling the humidity in a turbulent flow dryer, the change in mass of a few fruit can be considered as a representative of the moisture content of all the fruit in the dryer. The evaporation rate in a turbulent flow dryer can be measured directly from the change in the mass of the fruit (Figure 3).

In a discreet system, the evaporation rate would be:

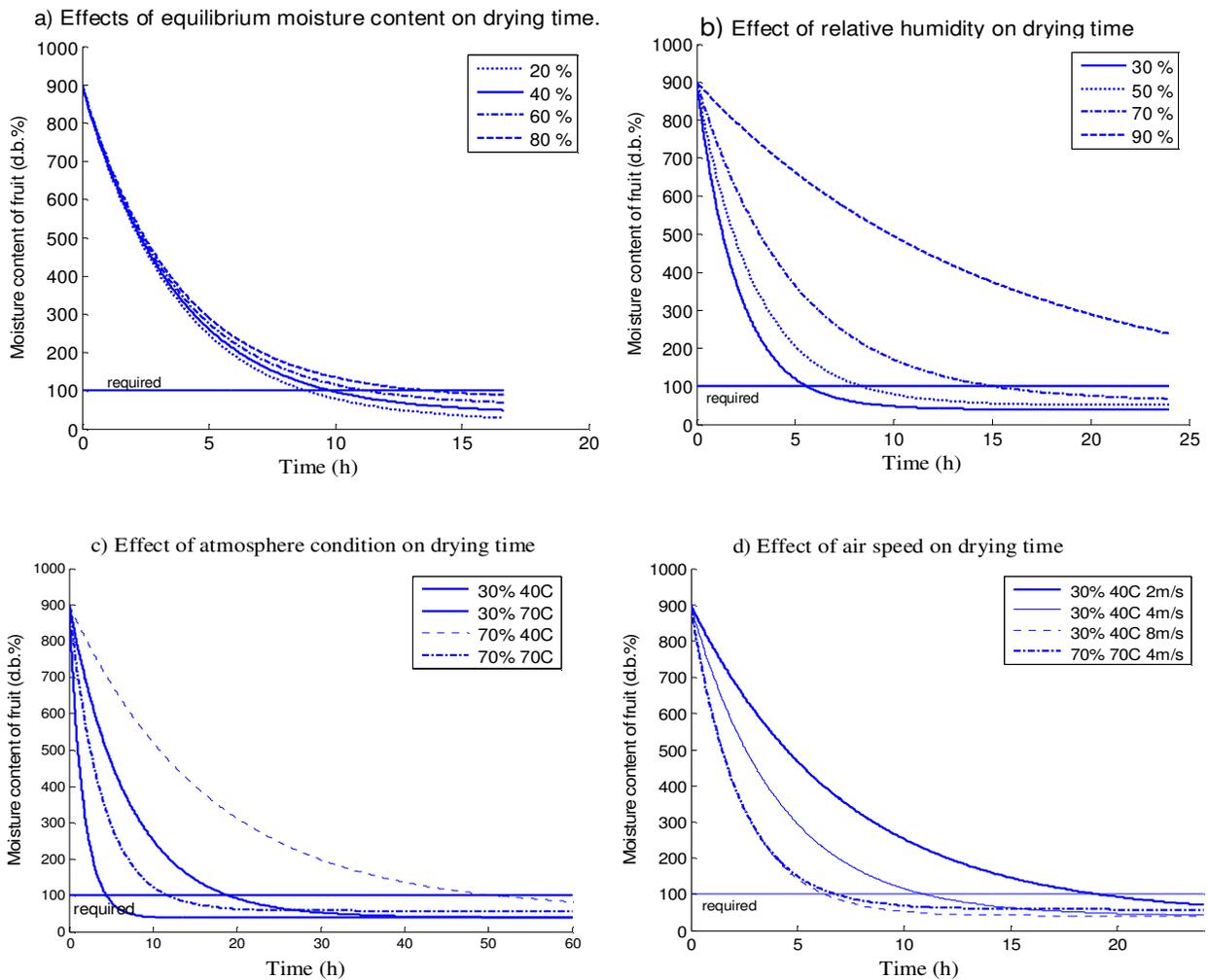


Figure 4. Effect of different parameters on the drying time.

$$\dot{m}_n = \frac{m_n - m_{(n-1)}}{\tau} \quad (18)$$

RESULTS

The results of the developed model for tomatoes drying at different conditions and parameters are presented in Figures 4 to 8.

Influence of the drying time

Effects of equilibrium moisture content on drying time are displayed in Figure 4a - d.

In Figure 4a, the influence of equilibrium moisture in drying is presented with respect to the moisture contents of the fruit. In general, reducing the equilibrium moisture

content on the model shortens the time required to reach the end point. Figure 4b shows that the relative humidity has a significant effect on the time required to dry a batch of fruit. The effect of relative humidity on drying time is pronounced. The lower the relative humidity in the dryer the faster the fruit will dry. However, the relative humidity in the dryer is dependent on the humidity of the atmosphere outside the dryer. Location of dryer currently effects the operation. Figure 4c shows the moisture content over time for four different conditions of atmosphere. The effect of a high temperature and a low humidity are obvious with the fruit drying in less than 4 h. The next fastest drying curve is from conditions of 70° and 70% humidity. Here the higher enthalpy of the atmosphere increases the rate of drying. The drying time for the conditions of 40° and 70% is over 50 h. In Figure 4d, the effect of increasing the air speed on the drying time is quite pronounced. Increasing the air speed will

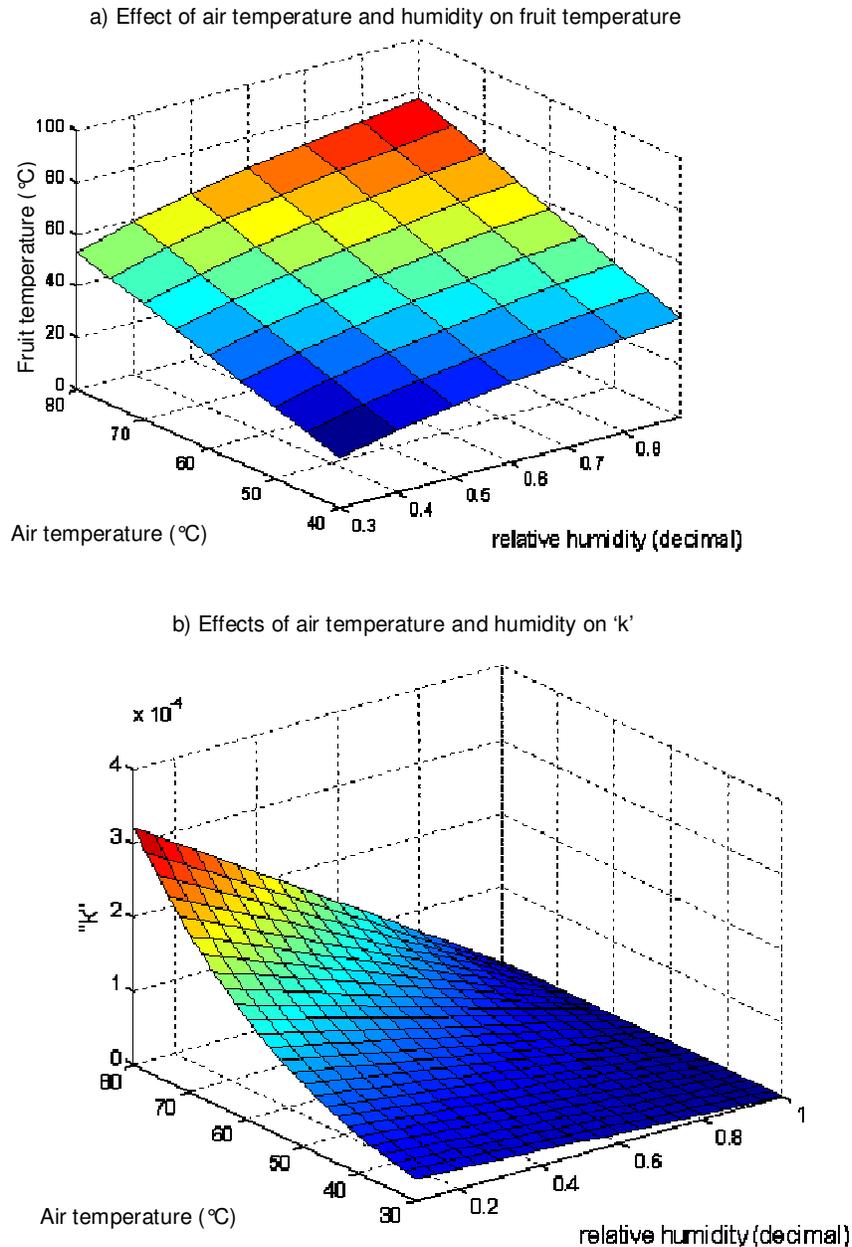


Figure 5. Effects of air temperature and humidity on fruit temperature and 'k'.

shorten the time taken to dry a given mass of fruit.

Effects of air temperature and humidity on fruit temperature

Effects of air temperature and humidity on fruit temperature and 'k' are displayed in Figure 5a and b. In Figure 5a, the influence of air temperature and humidity on fruit temperature is the higher the fruit's temperature the more thermal degradation that occurs during the

drying process. On the other hand, Figure 5b shows the effect of both air temperature and relative humidity on the value of 'k'. The effect of the atmospheric conditions on 'k' shows that the fastest rate of drying will occur when the conditions are of high temperature and low humidity.

The rate of evaporation varies from fruit to fruit dependent on the conditions at each fruit. Evenness in moisture content can only be achieved when the fruits come in to equilibrium with the atmosphere in the dryer.

The equilibrium moisture content achieved will vary dependently on the ambient humidity at the time. When

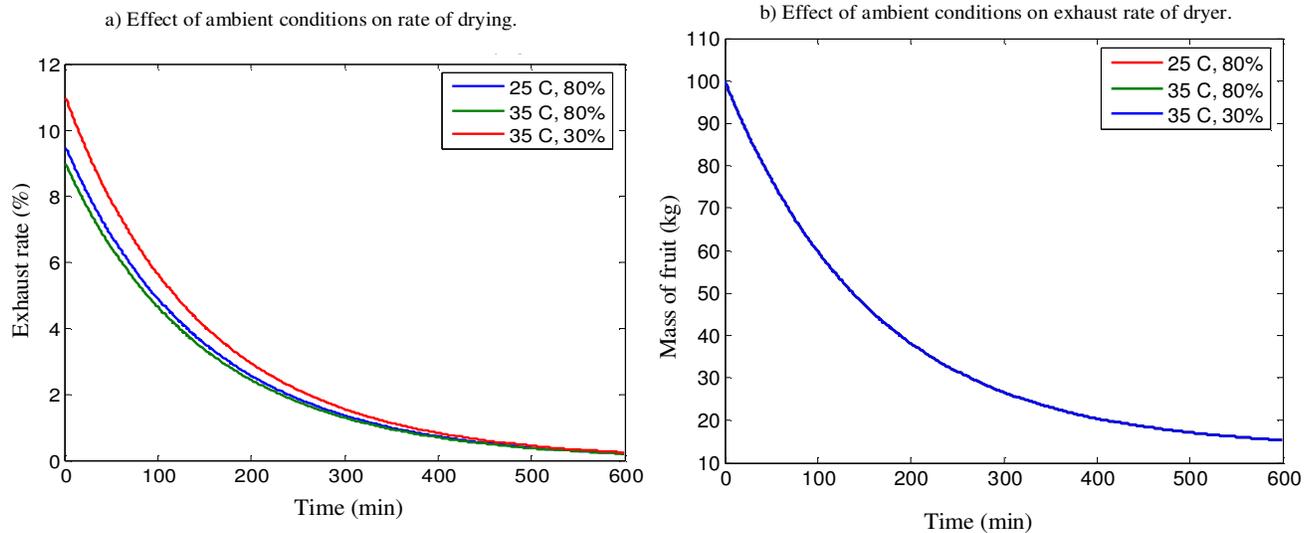


Figure 6. Effect of time on the rate of drying and exhaust rate of drying.

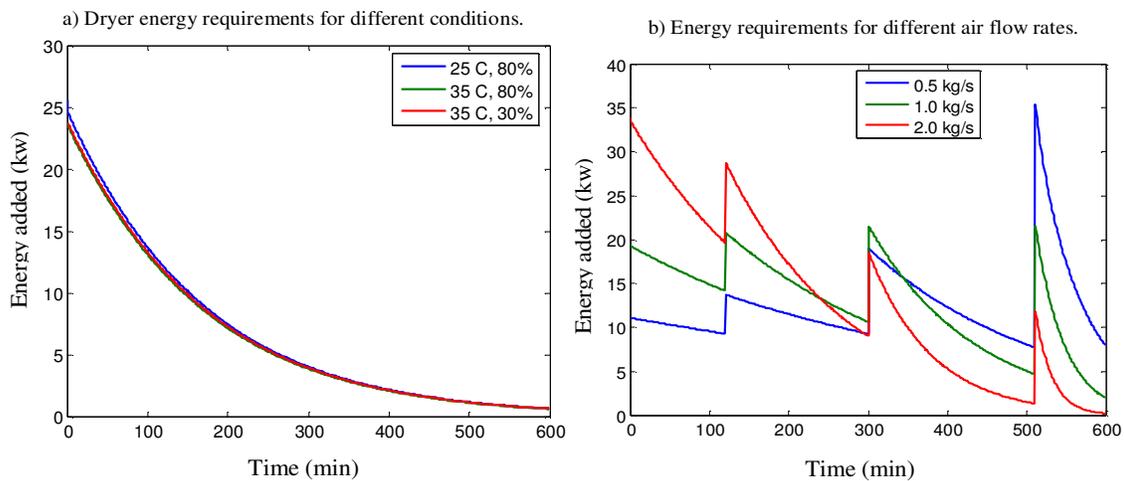


Figure 7. Effect of time on the energy required for the system.

these two factors are controlled, the variation in the drying process can be removed, the fruit dryer is operating to produce constant: batch time, quality and cost.

Effects of time on the rate of drying and exhaust rate of drying

Figure 6a and b shows the effects, the ambient conditions on the operation of the dryer. Figure 6a shows that the rate of evaporation is not affected by the ambient weather conditions outside the dryer. The fruit dries at the same rate for all three ambient conditions. This dryer is

capable of producing constant operating times regardless of the ambient conditions. It does however affect the exhaust rate as displayed in Figure 6b.

Effects of time on the energy required

Figure 7a and b shows the effect of time on the energy required. Figure 7a shows the rate of energy input required for different ambient conditions. The lower the ambient air temperature, the more energy that is required to dry the fruit. Changes in humidity of the ambient air do not affect the energy requirements of the dryer. Figure 7b shows the energy requirements for the dryer due to

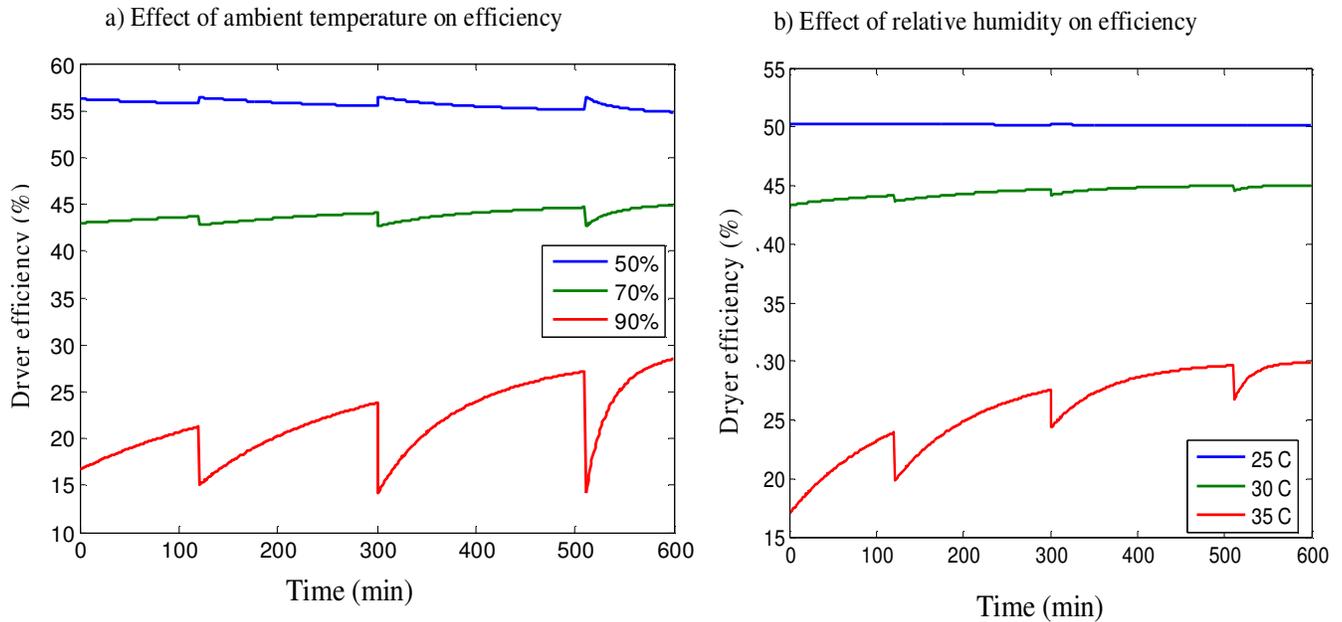


Figure 8. Effect of operating conditions on the drying efficiency.

different airflow rates. Higher airflow not only increases the energy demand of the dryer but also the range of the variation. This variation is due to the decline in evaporation as the fruit dries. This produces less change in the dryer's humidity, the exhaust closes and less energy is lost from the system.

Effects of operation conditions on the drying efficiency

Figure 8a and b shows the effect of different parameters on the efficiency of the dryer. Figure 8a shows that reducing the ambient air temperature improves the efficiency of the dryer. Although the relative humidity is held constant at 70%, the humidity of the ambient air fell with the temperature. Moreover, the lower humidity reduces the exhaust rate and thus the flow of energy out of the system is reduced. Figure 8b displays the result of variation in the relative humidity at a fixed ambient air temperature. The presented results in Figure 8b seem to contradict the results given in Figure 8a. Here, the efficiency increases as the relative humidity increase which is due to the energy that enters the dryer with the incoming ambient airflow. The higher the humidity for a given temperature the higher the energy carried by the air.

DISCUSSION

Moisture content is a critical factor of fruit quality (Heredia

et al., 2007). The current work shows temperature, humidity and speed of inlet air play important role in controlling the drying performance of the system. Such findings are in agreement with the published works in Deng et al. (2009), Amer et al. (2010) and Teeboonma et al. (2003). The current work revealed that the batch drying of tomatoes is a time intensive process. Moreover in El-Sebaili et al. (2002), it was proposed that the uncertainty in processing produces an environment in which it is difficult to run the dryer continuously without having staff present on a 24 h basis. This is confirmed by the current work, where the system can daily run twice for 4 h. According to Deng et al. (2009), Amer et al. (2010) and Teeboonma et al. (2003), the current practice is to start the dryer off at a temperature higher than that required for drying so that the maximum rate of heating can be achieved. In the current work, this problem can be overcome by closing the exhaust completely and setting the temperature relatively low. In other words, once the heating reaches the required level, the exhaust is opened and the temperature can rise. Moreover, the humidity is controlled to give a wet bulb temperature of the atmosphere equivalent to the required fruit temperature. Using the current model, the humidity of the ambient atmosphere can be controlled via air conditioning system. It should be mentioned here that the novelty of the current work is that the model can be used for different types of fruits.

In the model, there is nature of product factors which determine the type of the fruit, for example banana, apple, onion...etc.

Conclusions

- 1) Operating parameters and air conditions highly influence the dryer performance and the energy required. Increase the air speed and/or temperature highly reduced the energy required and enhance the dryer efficiency. In other words, high reduction in the cost can be achieved.
- 2) The quality of the fruit in terms of variation in moisture content is highly controlled by the dryer system temperature. However, high temperature could damage the fruit which worsens the quality. Therefore, the air temperature plays the main role in controlling the quality of the fruit. Control of the humidity in the dryer improved efficiency of the dryer by only venting the system as much as is required to maintain the conditions within the dryer.
- 3) Controlling the humidity in the dryer reduces the cost of operation. Moreover, improving the efficiency in terms of energy and time reduces the costs of the process.
- 4) Using the new model to simulate the drying system can lead to low energy consumption, high quality of products and low cost of the process. It is highly recommended to simulate the dryer before conducting laboratory experiments and/or commercializing the products.
- 5) The new model can be adopted with other dryer systems such as solar or hybrid drying systems.

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