QUANTITATIVE ASSESSMENT OF THE IMPROVEMENT OF THE DRYING PROCESS BY INCREASING THE TURBULENCE LEVEL

by

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Original scientific paper
https://doi.org/10.2298/TSCI170509189C

The drying process of vegetable species is a widely used technique for food conservation. The process requires large amounts of energy and it is responsible for the emission of pollutants to the environment. Therefore, many investigations have been made in order to improve the energy aspects of the process. It is very common that the effect of temperature and drying air mass-flow rate on the drying process are included in research but the effect of the turbulence level has not been studied yet. In this paper, the effect of the drying air turbulence level, temperature and mass-flow rate in the drying time, efficiency and energy consumption involved in the drying process of three types of chilies are studied. Under the conditions studied the turbulence level is the most influential factor in the drying process, followed by drying temperature. Also, the energy invested in increasing the turbulence level is very advantageous.

Key words: *drying process, specific energy consumption, capsicum annum, energy saving.*

Introduction

Dehydration is an important preservation process which reduces water activity through the decrease of water content, avoiding deterioration and contamination during long storage periods. Also, food quality is preserved.

In Mexico, chili consumption is widespread, with a per capita consumption of 0.56 kg [1]. Also, according to the Mexico's Agri-food and Fisheries Information Service (SIAP), Mexico is the biggest exporter of green chili in the world and the sixth largest one of dry chili. The U.S., Japan, Germany, Canada and the UK are some of the main customers of dry chili [2].

The drying process is very useful in the food industry but demands high energy consumption. Therefore, it is very important to conduct research which can make this process more efficient and less energy demanding. Such is the case of the work presented by Hernandez *et al.* [3] who achieved a 18% reduction in energy consumption of the drying process of coffee in a Guardiola type dryer by implementing a mathematical model of the dryer.

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There are many studies in the literature describing the drying process of various agricultural products, for example agave [4], pistachio [5], apple [6, 7], giant pumpkin [8], castor seed oil [9], carrot [10], strawberry [11], south cherry [12], and plants [13]. All these studies agree that the temperature, mass-flow and relative humidity of the drying air are the most important factors in the process. These studies also have in common that the amount of air entering the drying chamber is changed, as a consequence, the drying air speed and turbulence level are also changed.

The description and analysis of multiple devices that study the drying process can also be found in the literature, for example, Passos *et al.*, [14] present a device that is able to record a decrease in the volume of the sample after time passed. Tzempelikos *et al.* [15] designed, built and tested a prototype that was able to work in closed loop or open cycle, Ghasemkhani *et al.* [6] added a heat exchanger to increase the second law efficiency of the dryer, Zdanski *et al.* [16] analyzed, by means of CFD, a wood dryer with multiple channels and recommended that the length of the main feed channel did not exceed a certain extent.

Also, there are many studies related specifically to Capsicum Annum. Table 1 shows the considered variables in some recent studies on the drying process of chili.

Table 1. Some recent works on the drying process of red chili.

Reference	Temperature	Mass-flow rate	Relative humidity	Other considerations	Turbulence
Zhen-Zhen *et al.* [17]	Yes	No	No	Sun, convective and infrared drying	No
Lechtanska, *et al.* [18]	Yes	Yes	No	Infrared and microwave drying	No
Onat *et al.* [19]	Yes	Yes	No	Influence of geometrical shape	No
Pal *et al.* [20]	Yes	Yes	Yes	Heat pump drying	No
Veras *et al.* [21]	Yes	Yes	No	Freezing and convective drying	No
Vega *et al.* [22]	Yes	Yes	No	Var. Hungarion	No
Scala *et al.* [23]	Yes	No	No	Quality aspects	No
Vega *et al.* [24]	Yes	Yes	No	Var. Lamuyo	No

As a general rule, the drying time diminishes when the drying air velocity (and therefore turbulence level) is increased. Increasing the drying air temperature also decreases the drying time. The energy required for the drying process is directly proportional to the temperature and mass-flow rate of the drying air. On the other hand, the turbulence level can be increased with only a small fraction of the energy used to raise the temperature of the inlet air. Due to this, it is important to assess the effect of the turbulence level in the drying process.

After searching, no studies of independent evaluations of the effect off the turbulence level inside the drying chamber, as well as the amount of air entering the drying chamber were found. In this paper, the effects of the turbulence level, drying air temperature and mass-flow rate in the drying process of three different types of Capsicum Annum L. is studied.

Methodology

The convective dryer

The effects of temperature, mass-flow rate and turbulence level present within the drying chamber are evaluated separately in this paper. To this end, a prototype of a convective dryer was designed and built. The uniformity of the temperature within the chamber was previously studied [25]. The dryer is provided with a 2.4 W fan inside the drying chamber, which, when energized increases the turbulence level within the drying chamber and the coefficients of heat transfer and convection mass. During the experiments, a hot cable anemometer was introduced into the drying chamber, next to the samples to be dried. The anemometer recorded a velocity of 0 m/s when the internal fan was off (low turbulence level) and an average velocity of 0.046 m/s when the internal fan was on. Another anemometer showed no variation of the velocity at the inlet of the dryer which means that the mass-flow rate was kept constant while the velocity (and the turbulence level) around the chili samples changed.

The electrical and electronic component's description is given:

Air-flow sensor. The air-flow sensor is a hot wire anemometer Amprobe model TMA20HW. This sensor provides a durable and stable accuracy of 0.1% for precise air-flow measurements.

Current sensor. As part of the study of chili, it is important to measure the current that flows over the electric resistance heater. One sensor Allegro model ACS712 was implemented to measure the current. The sensor is located between the 120 V driver and the electric resistance.

DAQ Cards. The system has two acquisition cards (National Instruments USB 6009 and MCC USB-TEMP TC Series) for analog/digital data conversion. In this study, the sampling time of the cards is set as 100 ms.

Electric resistance heater. The electric resistance is able to heat the dryer chamber up to 100 °C which is fed with 120 V. It has a total resistance of 15 Ohm and is installed inside the diffuser.

Fans. The system has two fans which are fed with 12 V. The two small fans are located inside the dryer to introduce (air-flow fan) and move air inside the chamber (turbulence fan). Each fan is controlled using pulse-width modulation (PWM).

Humidity sensors. The system has three humidity sensors. The SHT15 sensors are used both to measure temperature and humidity simultaneously. The sensors are located inside the diffuser, chamber and output tube. Table 1 shows the technical information of humidity sensors.

Load cell. The system has one s-beam load cell FUTEK model LSB300 to measure the weight of the chilies. A proportional controller was used in order to control the temperature. This controller is selected because it reduces the steady state error between the desired temperature and the actual temperature [26].

The prototype is able to perform the following functions:

– control the intake air speed and temperature,
– monitor the relative humidity at the inlet and outlet of the dryer,
– record the weight variation of the sample over time, and
– separate the effect of air mass-flow rate and turbulence level within the drying chamber.

Materials

Three different types of *Capsicum Annuum* L. were used during the experiments. These three different variations of *Capsicum Annuum* L. are Puya, Mulato, and Mirasol. These types of chilies are available in the market in fresh produce from June to September, but they are consumed all year around in dry form. They are used for a wide variety of Mexican dishes. The chilies were purchased at the local market. The samples were cooled to 3 °C and allowed to reach room temperature before each test. To determine dry weight of each type of pepper, the samples were exposed to a temperature of 105 °C until the weight showed no change at an interval of one hour. The experiments were carried out until the moisture ratio (MR) reached a value of 0.1. Table 2 shows the initial and final humidity of the samples.

Table 2. Humidity characteristics of the samples.

Type of chili	Initial moisture d.b [g water kg^{-1}]	Initial moisture wet basis [–]	Final moisture	Evaporated moisture [kg]
Puya	3.51	0.7783	0.07877	0.8328
Mirasol	7.26	0.897	0.08884	0.948
Mulato	6.102	0.8591	0.08581	0.9289

The three types of *Capsicum Annuum* L. are about 0.15 m long and they are shown in fig. 1. The skin thickness is 0.002 m for the Puya and Mirasol chilies and 0.004 m for the Mulato chili.

Figure 1. Puya, Mirasol, and Mulato chilies

For every type of chili, eight different experiments were performed and repeated twice. Approximately 1.2 kg of chilies were used in each experiment. The drying conditions for each experiment are shown in tab. 3. The mass-flow rate was calculated by multiplying velocity times area times density. The velocity was measured with a hot wire anemometer. The inlet area was 0.01 m^2. The density was calculated for a location at 2100 m over sea level, at 20 ºC.

Table 3. Drying conditions used during experimentation

Run no.	Temperature [ºC]	Mass-flow [kgs^{-1}]	Turbulence level	Run no.	Temperature [ºC]	Mass-flow [kgs^{-1}]	Turbulence level
1	65	4.8 e^{-3}	Low	5	65	4.8 e^{-3}	High
2	75	4.8 e^{-3}	Low	6	75	4.8 e^{-3}	High
3	65	6.3 e^{-3}	Low	7	65	6.3 e^{-3}	High
4	75	6.3 e^{-3}	Low	8	75	6.3 e^{-3}	High

In this study, the drying process is characterized by means of three parameters drying time, thermal efficiency and specific energy consumption (SEC).

The thermal efficiency of a process is defined as the ratio between the desired output and the required input [27]. For the drying process of a vegetable the desired output is the removal of moisture and the required input is the energy consumed by the dryer. The energy required to remove moisture from the product can be calculated with the equation:

$$E_{EV} = (m_0 - m_f)h_{fg} \tag{1}$$

where E_{EV} is the energy required to evaporate the water contained in the product to be dried.

The energy used to carry out the drying process is:

$$E = E_R + E_{V1} + E_{V2} \tag{2}$$

Equation (2) includes the energy consumed by the electric resistances and the two fans.

This way, the efficiency of the drying process, η, is calculated:

$$\eta = \frac{E_{EV}}{E} \tag{3}$$

The SEC is defined as the ratio of the amount of energy supplied to the dryer to the mass of evaporated water:

$$SEC = \frac{E}{m_0 - m_f} \tag{4}$$

The MR of chilies are expressed by eq. (5). In this study, the mass change data obtained in drying experiments were converted into the MR. The elapsed time for the samples to reach a MR value of 0.05 is the drying time:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{5}$$

Results

Drying curves

Figure 2 shows the MR as function of time for all the experiments carried out. For Puya and Marisol chilies, the drying curves with high turbulence fall faster than those eith low turbulence. For Mulato Chili, the drying curves with high temperature fall faster than those with low temperature. For the three types of chilies, the curves with different mass-flow rates are very similar.

Drying time

The effect of the temperature in the drying time is calculated by comparing the drying time of the four experiments performed at 75 °C with the four experiments performed at 65 °C. The same occurs for the turbulence level and air mass-flow rate. The effect of the temperature, turbulence level and air mass-flow rate in the drying time of the three different types of chili is shown in fig. 3. In this figure, each column represents the average of four experiments having the same value of one variable. Figure 3 shows that increasing temperature and turbulence level caused a decrease in drying time. On the other hand, increasing air mass-flow rate caused only a small decrease in drying time.

For Puya and Mirasol chilies the turbulence level caused a larger reduction in drying time (249 and 320 minutes, respectively). The increase in temperature caused a decrease of 122 and 163 minutes in the drying time for the Puya and Mirasol chilies, respectively. This means that the turbulence level inside the drying chamber is the most influential factor in drying time of the chilies used.

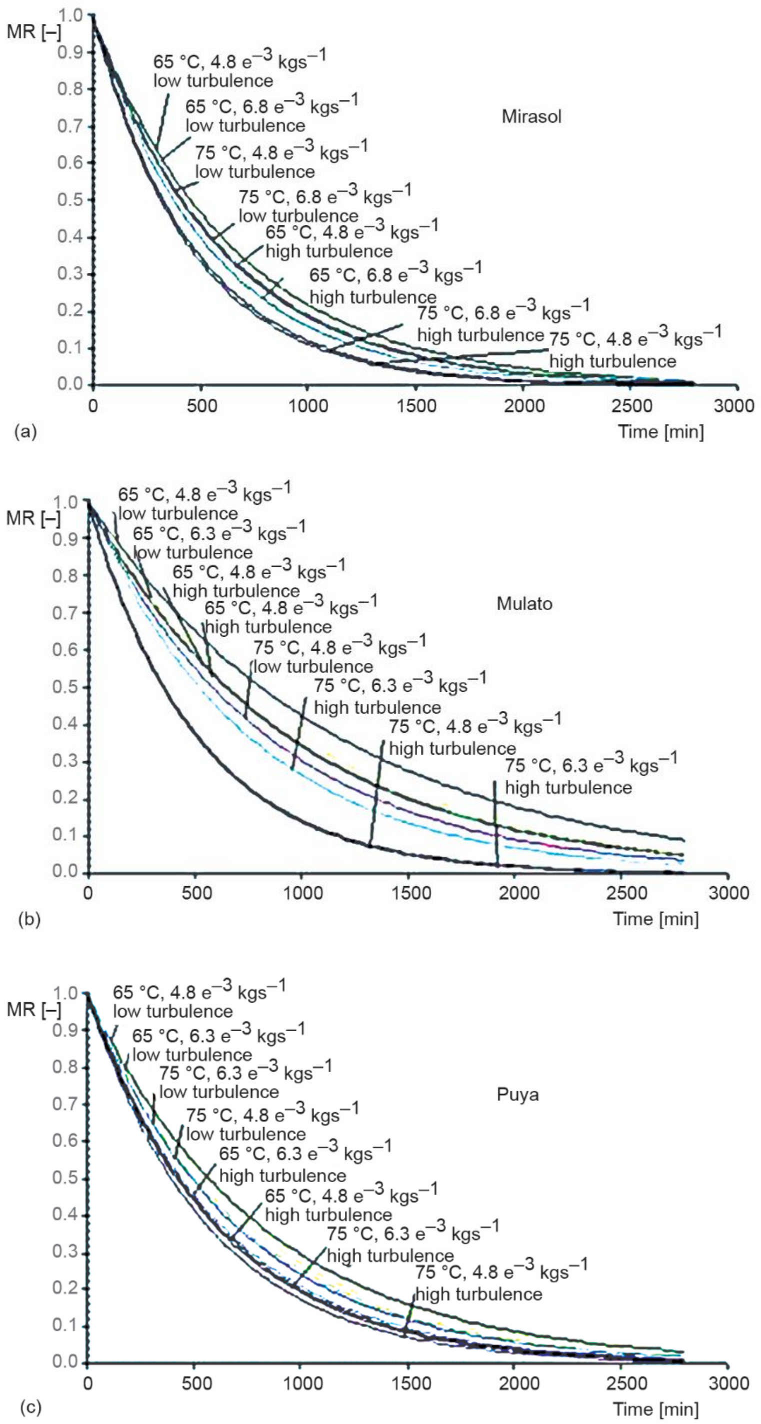

Figure 2. Drying curves

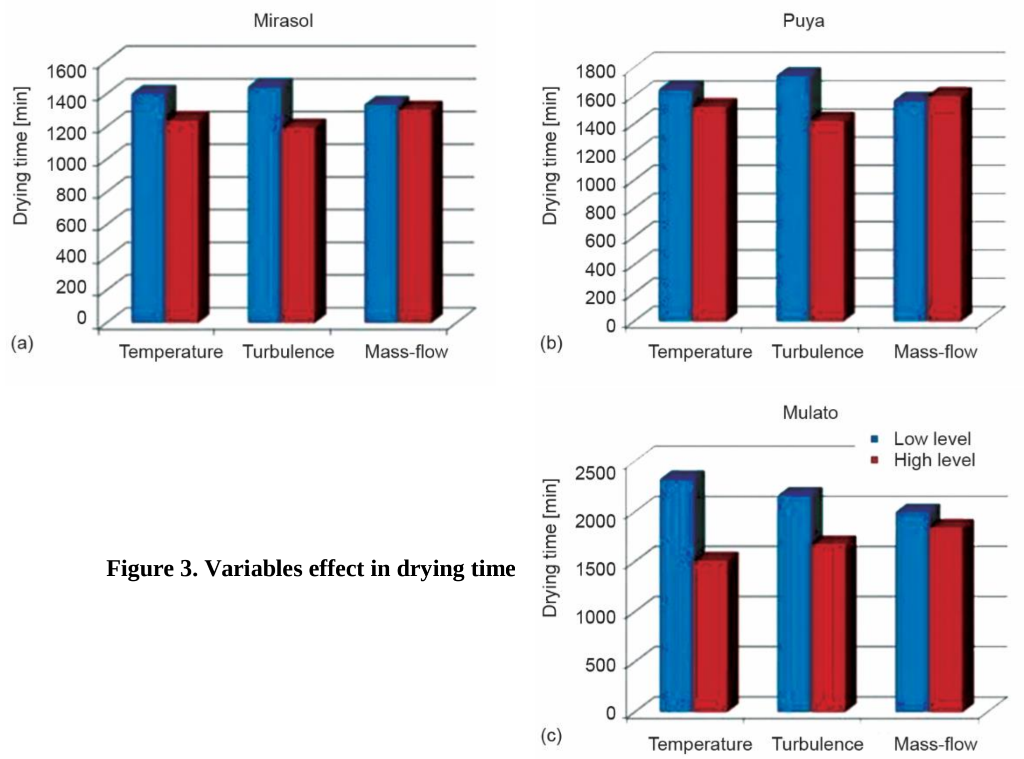

Figure 3. Variables effect in drying time

Temperature is the most important variable in the drying time of Mulato chili, since it caused the largest reduction in drying time (814 min), followed by the turbulence level (486 min).

References shown in tab. 1 state that temperature is the most important factor for drying time which is different from the results for the Mirasol and Puya chilies. A wider range of temperature was considered and the turbulence level was not modified directly.

The reduction in drying time caused by the increase of the mass-flow rate of the drying air is a 50 minute average for the three types of chilies. The effect of the air mass-flow rate is small compared to the temperature and turbulence level. The amount of air that enters, when the low level is used is enough to carry out the drying process without a significant increase in the relative humidity.

The interactions between temperature, mass-flow rate and turbulence might be important in the drying process. The turbulence-temperature interaction graph is shown in fig. 4(a) where the * point was determined by the response average of the experiments with a low turbulence level and 65 ºC. The other dots in fig. 4(a) can be calculated in a similar manner. Parallel or near parallel lines are indicators of little or no interaction with this type of diagram. The two lines corresponding to 65 °C and 75 °C are nearly parallel, indicating that the effect of this interaction is small and regardless of the temperature used, the drying time is always less when the fan is on. Similar results are obtained for Puya and Mulato chilies.

This result is important because the energy needed to increase the turbulence level (2.4 W in this study) is only a small fraction of the energy needed to raise the temperature of the inlet gases, although it should be noted that the energy necessary for the fan should be of the highest quality (mechanical work). While the energy required for rising the temperature of the inlet gases may come from a source of lower quality (burned gases, solar energy).

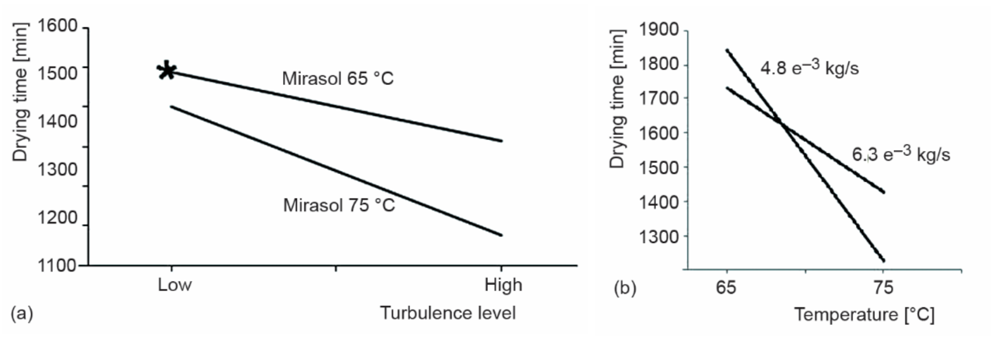

Figure 4. Effect of the interaction between variables on the drying time

If a solar dryer is designed, it would be convenient to have a space for a photocell to energize the fan placed inside the drying chamber.

The effect of the interaction between temperature and mass-flow rate can be assessed in a similar manner. Figure 4(b) shows the interaction between temperature and air mass-flow rate for the average of the three types of chilies. The effect of temperature is more important when the air mass-flow rate is small for the three types of chilies. The reduction of drying time caused by increasing the temperature from 65 °C to 75 °C is bigger when the air mass-flow rate is smaller than when the air mass-flow rate is higher.

In order to quantify the interaction effect, a coded value is assigned to each variable value, –1 for the low level and 1 for the high level. The coded value of an interaction is generated by simply multiplying appropriate values from the interacting factors.

For example, in run No. 2, the temperature has a high level, mass-flow rate, and turbulence has a low level. The coded values are 1, –1, and –1, respectively. The interaction between temperature and mass-flow rate has a coded value of –1 and the interaction between mass-flow rate and turbulence has a coded value of 1. An average value for the drying time can be calculated for all the experiments by the –1 or 1 value of every interaction. The difference between these two values is the interaction effect.

Figure 5 compares the effect of factors and their interactions. The turbulence level is the most important factor followed by temperature for Mirasol and Puya chilies. For Mulato chili temperature is the most important factor, followed by the turbulence level. The interaction between the turbulence level and the temperature appears as the third most important effect for Mirasol and Mulato chilies. Turbulence and temperature are the variables governing the drying time in this experiment.

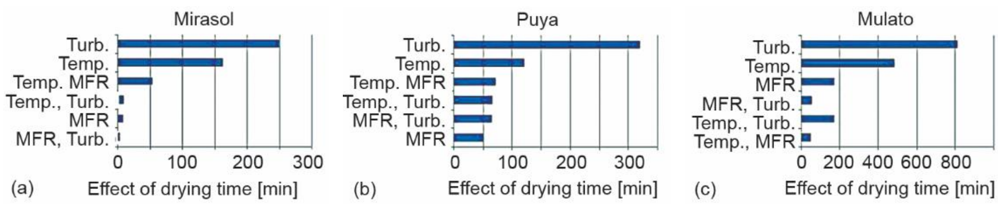

Figure 5. Effect of the interactions and variables on drying time

There were no noticeable differences in the quality of the products that were dried under the different conditions used in this study.

Efficiency and specific energy consumption:

The reduction of drying time does not always mean a reduction in the energy used to carry out the process, especially when the reduction is achieved by increasing temperature. As a consequence, the efficiency of the drying process is not increased by the mere fact of reducing the drying time. Figure 6(a) shows the effect of temperature, mass-flow rate and turbulence level on efficiency.

It is observed that the increased air mass-flow rate causes a decrease in the efficiency of the drying process of the three types of chili. When the input speed is increased, the energy consumed increases linearly while the drying time changes very little.

The turbulence level and mass-flow rate have different effects. By increasing the turbulence level the efficiency of the drying process also gets increased. The reduction of drying time and the small increase in energy consumption are the causes of the increase in efficiency.

The increase in the temperature of the drying air causes a reduction in the efficiency of the drying process for Mirasol and Puya chilies. The same increase causes an increase in efficiency for Mulato chili. The reduction of drying time caused by the increase in temperature is big enough to compensate for the increase of energy demanded to reach a higher temperature.

The effect of the variables on the SEC is contrary to the effect that it has on the efficiency, as shown in fig. 6(b). This is because the energy consumed is the denominator of the efficiency and the SEC is in the denominator. In average, SEC rises 3.1% when temperature changes from 65 ºC to 75 ºC, 11.9% when the mass-flow rate of air is increased, but, when the turbulence level changes from the low to the high level, SEC decreases 7.49%.

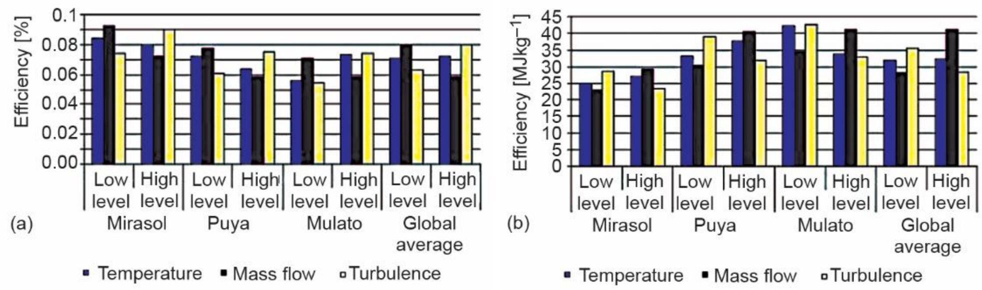

Figure 6. Effect of the temperature, mass-flow rate and turbulence level on efficiency and SEC

The calculations done to quantify the interaction effects on drying time are repeated for efficiency and SEC. The calculations results are shown in fig. 7(a) for efficiency and in fig. 7(b) for SEC. From this figures it is observed that the effect of interactions are small. This

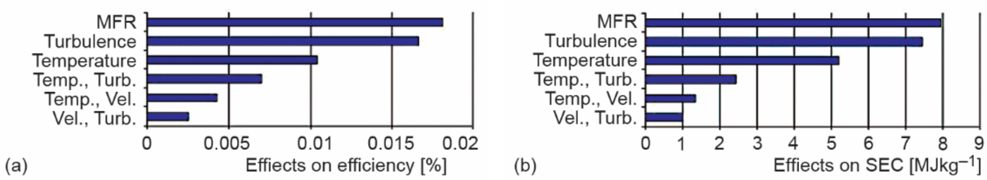

Figure 7. Effect of the variables and their interactions in efficiency

means that the increased power consumption caused by the increase in temperature and inlet air speed, along with the decrease in drying time caused by the increase of turbulence level govern the efficiency and SEC of the drying process of the three types of chili.

Conclusions

The drying process of Puya and Mirasol peppers show several similarities, for example, the turbulence level is the most influential factor for the drying time, followed by the temperature.

Likewise, the increase in the temperature and mass-flow rate of the drying air cause a decrease in process efficiency and an increase in the specific energy consumption, also, the most influential factor for the efficiency and specific energy consumption is the speed of the drying air, followed by turbulence level. So, it is advisable to reduce the air mass-flow rate and promote turbulence within the drying chamber.

The drying temperature and the turbulence level are the most influential factors in the drying time, process efficiency and the specific energy consumption of chile Mulato followed by the interaction of these two factors, therefore, the high temperature and high turbulence level are recommended for the drying process of this type of chilli. Also, the low level for inlet mass-flow rate is recommended since the high level causes reduced efficiency, increases cost and does not cause a reduction in the drying time.

The increase in the turbulence level causes a decrease in drying time and specific energy consumption and an increase in the efficiency of the drying process of the three types of chilli considered in this study.

Acknowledgment

The authors thanks CONACYT and the state government of Zacatecas for the support in the development of this research.

Nomenclature

E – total energy used for the drying process, [kJ]
E_{EV} – energy required to evaporate the water contained in the product to be dried, [kJ]
E_R – energy consumed by the electric resistances, [kJ]
E_{V1} – energy consumed by the fan drawing air into the dryer, [kJ]
E_{V2} – energy consumed by the fan placed inside the drying chamber, [kJ]
h_{fg} – latent vaporization heat of the water, [kJkg^{-1}]
M – moisture content, [–]
m – mass of the sample, [kg]

Acronyms

MFR – mass-flow rate [kgs^{-1}]
MR – moisture ratio, [–]
SEC – specific energy consumption, [–]

Greek symbol

η – efficiency, [–]

Subscripts

0 – initial
e – equilibrium
f – final
t – at time t

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Paper submitted: May 9, 2017
Paper revised: August 8, 2017
Paper accepted: August 25, 2017

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