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Exergy analyses of onion drying by convection: Influence of dryer parameters on its performance

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Abstract

This research work is concerned in the exergy analysis of the continuous-convection drying of onion. The influence of temperature and air flow rate was studied in terms of exergy parameters. The energy and exergy balances were carried out taking into account the onion drying chamber. Its behaviour was analysed based on exergy efficiency, exergy loss rate, exergetic improvement potential rate and sustainability index.

The exergy loss rates increase with the temperature and air flow rate augmentation. Exergy loss rate is augmented at higher drying air temperatures and flow rates because the overall heat transfer coefficient increase. On the other hand, the exergy efficiency increases with the air flow rate augmentation. This behavior is due to the energy utilization was improved because the most amount of supplied energy was utilized for the moisture evaporation. However, the exergy efficiency decreases with the temperature augmentation due to the free moisture is less, then, the moisture begins diffusing from the internal structure to the surface. The exergetic improvement potential rate values show that the onion drying process presents a high potential to improve the exergy efficiency. The sustainability index of the drying chamber varied from 1.9 to 5.1. To reduce the environmental impact of the process, the parameters must be modified in order to ameliorate the exergy efficiency of the process.

Keywords: onion drying; exergy analysis; exergetic improvement potential rate; sustainability index.

1. Introduction

Thermodynamics plays an important role to analyses the energy efficiency of industrial processes. The used energy through a process is important and its utilization optimization is substantial considering the environmental and economic aspects. Through exergy analysis is possible to identify potential savings taking into account the operating conditions. Exergy is defined as the maximum work quantity produced from a matter flow, heat or work during the equilibrium is reached with the environment taken as reference. The exergy analysis is also a useful methodology to establish strategies in the design and operation of industrial processes when the energy use must be optimized. In recent years, exergy analysis has been widely used to evaluate the thermal systems performance.

The energy balance is the traditional approach to evaluate various energy conversion processes. The energy balance, the first law of thermodynamics, allows to calculate heat losses, but does not provide information about the optimal energy transformation.

This objective can be reached in the exergy analysis, due to the second law of thermodynamics establishes that all the input energy in the system cannot be transformed into useful work. In this analysis, the first and second law of thermodynamics are used. The exergy is not subject for conservation law, but the exergy is consumed or destroyed due to irreversibilities in any process (Terehovics et al., 2017).

On the other hand, considering the drying process, the objective is to use the minimum amount of energy to obtain the maximum moisture removal and to achieve the desired product conditions (Fudholi et al., 2014). This process is widely used in various industries such as the food, chemical, wood, biotechnology, polymer, ceramics, pharmaceutical and bio-energy industries, consuming the large amount of energy. It is generally used to remove moisture or liquid from a wet solid, converting them to the vapor state. In most drying operations, the water is evaporated liquid and, air is normally used as a purge gas. Due to the high prices and shortage of energy, environmental concerns and decreasing fossil-fuel recourses, the optimum application of energy and the energy consumption management methods are very important for the enterprise sustainability.

Boulemtafes-Boukadoum and Benzaoui (2011) carried out an energy and exergy analysis of solar drying process of mint. They used an indirect type, passive dryer without extra energy and discontinuously operating. These researchers quantified the solar energy received by a solar heater and available for drying, using the energy analysis. The energy losses during the drying process were estimated through the exergy. Rabha et al. (2017) realized energy and exergy analyses of the solar drying processes of ghost chilli pepper and ginger, using a forced convection solar tunnel dryer integrated with a shell and tube based latent heat storage module. They concluded that the thermal efficiencies of the first and the second solar air heaters varied between 22.10% and 40.24% and 9.64% and 19.50%, respectively. When the ghost chilli was dried, the average exergy efficiency of the drying chamber was equal to 63%, and it was equal to 47%, while the ginger was dried. The high exergy efficiency was recorded in the last few hours of the drying operation of the consecutive drying days.

Brasil Maia et al. (2017) carried out a thermodynamic analysis of the drying process of bananas in a small-scale solar updraft tower. They proposed a model based on the first and second laws of thermodynamics, using the ambient conditions and airflow parameters data obtained in the experimental prototype. They concluded that the incident solar radiation plays an important role on the drying process of bananas, the higher the solar radiation, the higher the exergy rates.

Azadbakht et al. (2017) analysed the energy and exergy loss in the drying of eggplant using a fluidized bed dryer. They investigated the effects of temperature, flow rate of drying air, and sample size on energy consumption and exergy losses. Their results showed that the minimum energy consumption and exergy losses occurred at a diameter of 13 mm, air flow rate of 3 m s-1, and temperature of 313K. The results demonstrated that higher temperature, air flow rate, and eggplant samples' lesser diameter increased energy consumption.

The objective of this study is to present energy and exergy analyses of onion drying at different conditions of air temperature and air flow rate considering a continuous-

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convection process. The proposed model does not include properties related to the particles of the material to be dried, in this case, onions. The studied system is the drying chamber, considered a black box.

2. Methodology

In this work, the drying air parameters influence, as temperature and air flow rate, in an onion drying system, was studied, using the exergy analysis. A thermodynamic model was proposed based upon the mass, energy and exergy balances, considering the onion drying chamber. The exergy performance based on exergy efficiency, exergy loss, exergetic improvement potential and sustainability index, were analysed. The drying chamber production was considered equal to 1 kg of onion/s. Drying conditions were selected for different combinations of drying air parameters including temperature (323, 333, 343 and 353 K) and flow rate (0.5, 1 and 2ms^{-1}); the initial humidity of the air was set as 0.01 kg water/kg dry air. Taking into account the onion, its initial temperature is considered equal to 298 K and its initial and final water mass fractions equal to 0.89 and 0.05, respectively.

In order to write balances equations for the different components of the drying chamber, the following assumptions have been made:

The heat capacity of wall material of drying chamber is neglected.

There is no stratification in air temperature of drying chamber.

The absorptivity and heat capacity of enclosed air is neglected.

2.1. Energy balance

Considering the input and output energy flows through the system, the energy balance Equation can be written as follows (Smith et al., 2007):

$$Q = m_{dp} \cdot \widehat{H}_{dp} + m_{ma} \cdot \widehat{H}_{ma} + m_{wo} \cdot \widehat{H}_{wo} - m_{da} \cdot \widehat{H}_{da} - m_{wp} \cdot \widehat{H}_{wp} - m_{wi} \cdot \widehat{H}_{wi} \qquad (1)$$

Where Q, is the heat transferred to or from the walls of the drying chamber, in this case adiabatic conditions were considered so it takes the value zero. $\widehat{H}$ is the enthalpic content per mass unit of each stream, expressed in kJ kg, and m is the mass flow rate of each stream, expressed in kg/s. The subscripts *dp, ma, da, wi* and *wo* correspond to the properties of dry product, humid air, dry air, contained water in the input product and water contained to the output product, respectively.

2.2. Entropy balance

The general entropy balance can be expressed by (Smith et al., 2007):

$$S_{gen} = \sum m_{in} \cdot S_{in} - \sum m_{out} \cdot S_{out} \pm \sum \frac{Q_i}{T_0} \tag{2}$$

Where *Sgen* is the generated entropy in the process expressed in kJ/K, m_{in} and m_{out} are the mass flows of the input and output flows expressed in kg/s, correspondingly. S_{in} and S_{out}, are the entropies of the input and output flows, respectively, expressed in kJ/kg K, T_o is the temperature of the environment equal to and 298 K Q_i is the transferred heat through the walls of the drying chamber expressed in kJ. The negative sign in the last term denotes the heat transferred to the control volume, and the positive sign denotes the heat transferred from the control volume, in this case the dryer.

2.3. Exergy balance

The exergy losses in the drying chamber are associated with the exergy losses with the air left by the dryer and, the exergy losses from the walls with the heat loss and the exergy losses in the product. The exergy balance was developed based on the general form of the exergy flow Equation for steady-state systems. The effect of kinetic and potential energies was considered negligible. In the drying chamber, the work is equal to cero. Therefore, the transfer of exergy due to the transfer of work is zero, too. Analogous to the energy balance, the balance of exergy to the system is (Moran et al., 2011):

$$m_{dp} \cdot \varepsilon_{dp} + m_{ma} \cdot \varepsilon_{ma} + m_{wo} \cdot \varepsilon_{wo} = m_{da} \cdot \varepsilon_{da} + m_{wp} \cdot \varepsilon_{wp} + m_{wi} \cdot \varepsilon_{wi} + \varepsilon_q + \varepsilon_d \tag{3}$$

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Where *m* is the mass flow expressed in kg/s, the subscripts *dp* indicate dry product, *ma,* (moist air) humid air, *wo* output humidity, *da* dry air or inlet air, *wp,* humid product and *wi,* input humidity.

Where ε_d is the destroyed exergy and ε_q is the exergy associated with heat losses in kJ/s. ε_q can be expressed by:

$$\varepsilon_q = \sum \left(1 - \frac{T_0}{T}\right) Q \tag{4}$$

Where T_0 and T are the environment and system temperatures, respectively. The destroyed exergy due to irreversibilities is calculated as:

$$\varepsilon_d = T_0 \cdot S_{gen} \tag{5}$$

The difference in the input and output exergy flows of the drying chamber is equal to the sum of the thermal exergy loss and the destroyed exergy due to irreversibility. The exergy flow of a stream in stationary flow is given by:

$$\dot{\varepsilon} = \dot{m}\left[Cp(T - T_0) - T_0\left\{Cpln\left(\frac{T}{T_0}\right) - Rln\left(\frac{P}{P_0}\right)\right\}\right] \tag{6}$$

Where $\dot{\varepsilon}$ is the flow exergy (kJ/s), $\dot{m}$ is the mass flow (kg/s), *Cp* is the flow specific heat (kJ/kg K), R is the gases constant, T_0 and P_0 are the reference temperature and pressure considered as 298K and 1 atm, respectively, T and P are the flow temperature and pressure.

The change in pressure between the inlet and outlet dryer flows is negligible. So, the Equation (6) can be written as:

$$\dot{\varepsilon} = \dot{m}Cp\left[(T - T_0) - T_0 ln\left(\frac{T}{T_0}\right)\right] \tag{7}$$

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Taking into account the moisture content of the drying air, its exergy is expressed as a function of the conditions at the inlet or outlet dryer flows such as:

$$\varepsilon_{da} = Cp_{da} \cdot (T - T_0) - T_0 \left[Cp_{da} ln \left(\frac{T}{T_0} \right) \right] + T_0 \left[Rln \left(\frac{1+1.6078 \cdot \omega_0}{1+1.6078 \cdot \omega} \right) + 1.6078 \omega Rln \left(\frac{\omega}{\omega_0} \right) \right] \tag{8}$$

Where Cpda is the specific heat of the drying air (kJ/kg K), ω is the specific humidity (kg water/kg dry air), ω_0 is the reference humidity (0.009 kg water/kg dry air). Its relationship with the relative humidity content of the air (φ) is:

$$\omega = 0.622 \cdot \frac{\varphi \cdot P_{vs}}{P - P_{vs}} \tag{9}$$

Where p_{vs} is the saturated vapor pressure at the flow temperature and P is the air pressure. The specific heat of the drying air is calculated as (Corzo et al., 2008):

$$Cp_{da} = \frac{1.004 + 1.88 \cdot \omega}{1000} \tag{10}$$

The physical exergy of the wet product can be expressed as:

$$\varepsilon_p = (H - H^0) - T_0(S - S^0) = \left[H_p(T, P) - H_p(T_0, P_0) \right] - T_0 \left[S_p(T, P) - S_p(T_0, P_0) \right] \tag{11}$$

T_0 and P_0 are the temperature and pressure of environmental state taken as a reference, respectively. The temperature and pressure are equal to 298K and 1 atm, respectively.

$$(H - H^0) = \int_{T_0}^{T} Cp \, dT = Cp \cdot (T - T_0) \tag{11}$$

$$(S - S^0) = \int_{T_0}^{T} \frac{Cp}{T} dT = Cp \cdot ln \left(\frac{T}{T_0} \right) \tag{12}$$

Where Cp is the onion specific heat (kJ/kg K), $(H - H^0)$ y $(S - S^0)$ are the enthalpy and entropy changes, respectively. These changes are taken between the flow temperature and pressure conditions, and those that they correspond to the environment state.

The onion specific heat as a function of moisture content is given by (Rapusas and Driscoll, 1995):

$$Cp = 1.84 + 2.34 \cdot w \tag{13}$$

Where w is the water mass fraction in the onion.

The exergy losses in the drying chamber are calculated as (Corzo et al., 2008):

$$\varepsilon_{loss} = \varepsilon_{in} - \varepsilon_{out} = \sum \varepsilon_L = \sum \varepsilon_i - \sum \varepsilon_o \tag{14}$$

Where ε_{loss} is the total lost exergy (kJ/s), ε_i is the exergy associated with the input flows at the drying chamber and ε_o is the exergy associated with the output flows.

The exergy efficiency is defined as the ratio of the used exergy in the product drying and the exergy of the drying air supplied to the system.

$$\eta_{\varepsilon x} = \frac{Exergy\ inflow - Exergy\ loss}{Exergy\ inflow} = \frac{\varepsilon_i - \varepsilon_L}{\varepsilon_i} = 1 - \frac{\varepsilon_L}{\varepsilon_i} \tag{15}$$

Where $\eta_{\varepsilon x}$ is the is the exergy efficiency. The optimal values of this parameter for a system or process are obviously reached when the exergy losses are minimized. The concept of exergetic improvement potential (IP) is commonly used to analyse different processes or economy sectors. IP is given by (Fudholi et al., 2014):

$$IP = (1 - \eta_{\varepsilon x})\varepsilon_L \tag{16}$$

The exergy sustainability is based on the exergy analysis, and it is defined as the relation between the input exergy and the exergy losses of the system. This index allows to

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obtain information about the process influence on the environment, and it is considered an important evaluation parameter (Açıkkalp and Caner, 2015). The exergetic sustainability index is calculated as:

$$SI = \frac{1}{1-\eta_{\varepsilon x}} \tag{17}$$

The exergetic sustainability index is a function of the relationship between residual exergy and exergy efficiency. The environmental impact factor decreases if the exergetic sustainability index increases (Dincer et al. 2014).

3. Results and Discussion

The calculation basis was equal to 1 kg of onion/s. Different temperatures and flow rate of drying air were considered: 323, 333, 343 and 353 K and 0.5, 1 and 2 ms^{-1}, respectively. The exergy loss rate associated with the onion drying process increases with temperature and the air flow rate (Figure 1). The highest values of these rates are reached at air flow rate equal to 2 ms^{-1} and temperature equal to 353 K. The losses rate value is 218.89 kJs^{-1}, representing 28.6% of the total inlet exergy at the drying chamber. It is important taking into account that one of the thermodynamic inefficiencies of these systems is the exergy loss from the drying chamber to the environment. With the temperature and flow rate increase, the input exergy to the drying chamber growths, and then, a large amount of the input exergy come out without being used in water evaporation contained in the onion. Additionally, exergy loss rate is augmented at higher drying air temperatures and flow rates because the overall heat transfer coefficient increase (Dincer and Sahin, 2017). Corzo et al. (2008), Azadbakht et al. (2017) and Nazghelichi (2010) obtained analogous observations.

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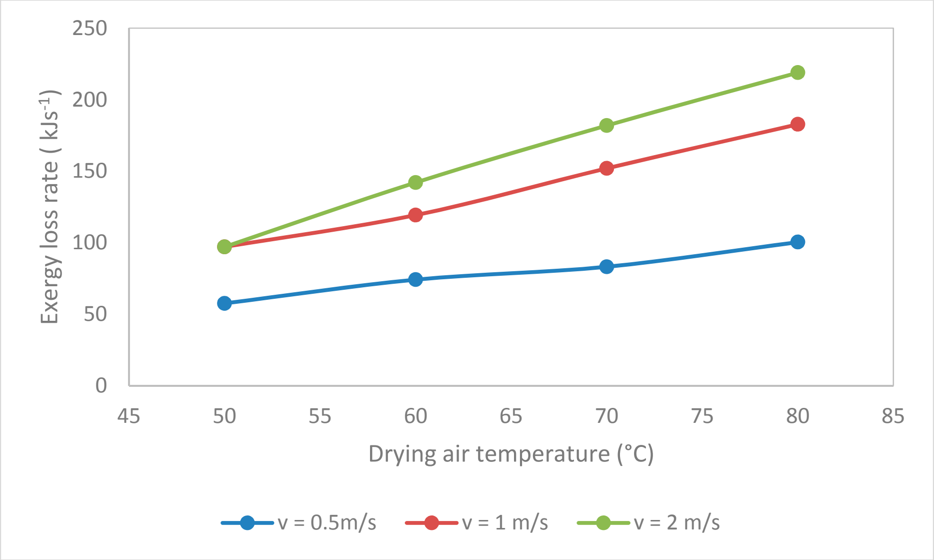

Figure 1. Exergy loss rate variation with the temperature and air flow rate.

Figure 2 shows the exergy efficiency variation of the drying chamber with the analysed variables. As it can be observed, the exergy efficiency increases with the air flow rate augmentation. Aghbashlo et al. (2008) obtained similar results. The energy utilization was increased due to the most amount of supplied energy was utilized for the moisture evaporation. Heat loss augmented when the flow rate increased, probably because a growth in the overall heat transfer coefficient. However, these losses are very small comparing with the effect of the inlet enthalpy on heat and mass transfer, causing a high energy utilization. In addition, at higher air velocities, there is an increase in the output exergy comparing with the input air exergy. So, the exergy efficiency is equal to 50.6, 54.9 and 73.0% for a temperature of 333K and air flow rate equal to 0.5, 1 and 2ms^{-1}, respectively; demonstrating that the convective drying is a process moderately poor, considering the exergy efficiency.

The exergy efficiency of the process decreased by the increase in the inlet drying air temperature. Similar results were obtained by Rabha et al. (2017), Ozgener and Ozgener (2009), Khanali et al. (2013) and Aghbashlo et al. (2012). However, other authors (Ranjbaran and Zare, 2013, Aghbashlo et al. 2008a) observed that the exergy efficiency increases with the temperature augmentation; this can be due to moisture saturated surface for which more heat is utilized to evaporate the free moisture.

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However, when this moisture is less, the moisture begins diffusing from the internal structure to the surface (Rabha et al., 2017)[x].

According to the proposed model, for a drying air temperature and air flow rate equal to 323K and 2 ms^{-1}, respectively, the calculated exergy efficiency was 80.7%. Aghbashlo et al. (2008) obtained values close to 87% and the values obtained for Khanali et al. , 2013 varied between 65% and 74%, approximately. For a drying temperature equal to 343K, the exergy efficiency was about 73%, and these researchers found values about 67%.

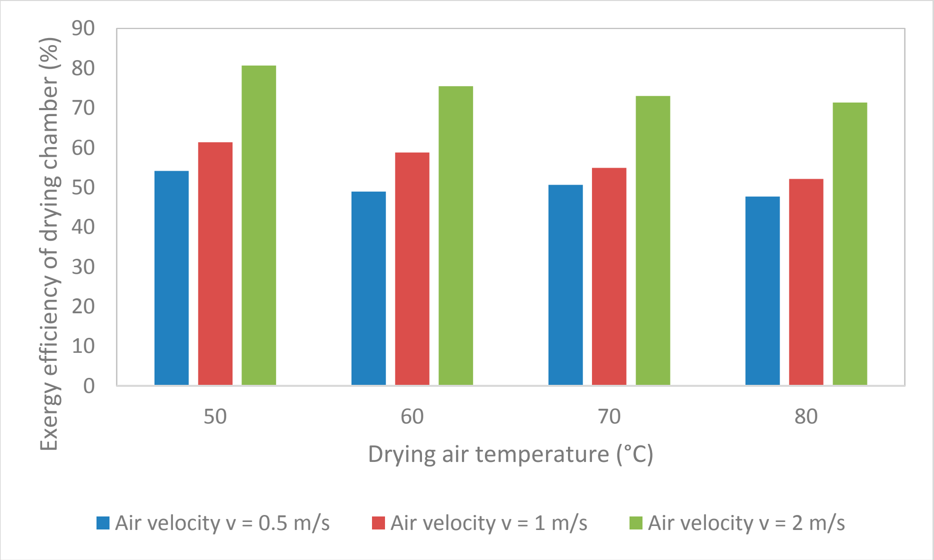

Figure 2. Exergy efficiency of the drying chamber. Variation with the temperature and air flow rate.

Figure 3 shows the variation of exergetic improvement potential rate in the onion drying chamber with temperature and air flow rate. Their values vary from 18.7 to 87.4 kJs^{-1}. The exergetic improvement potential rate, under studied operative conditions, vary from 21-29.9% of the total input exergy. These values show that the onion drying process presents a high potential to improve the exergy efficiency. Its value increases when the temperature and air flow rate growth, similar results were found by Kuzgunkaya and Hepbasli, (2007) by Icier, et al. (2010). So, the growth in exergy destruction caused in augmented exergetic improvement potential rate of this process.

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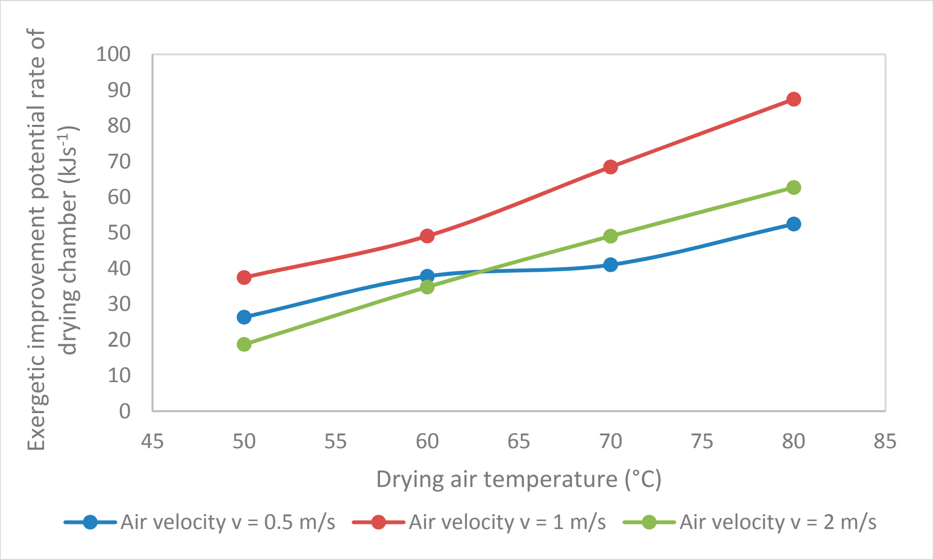

Figure 3. Exergetic improvement potential rate. Variation with the temperature and air flow rate.

The effect of temperature and air flow rate on the sustainability index of the onion drying chamber can be seen in Figure 4. At higher exergy efficiency values, the sustainability index increases and the environmental impact will be lower. The sustainability index varies from 1.9 to 5.1 under studied operating conditions. Its value increase with the air flow rate augmentation, however, it diminishes with the temperature increase. The influences of these parameters on the sustainability index and exergy efficiency drying chamber are similar. Therefore, in order to reduce the environmental impact, the exergy efficiency should be improved.

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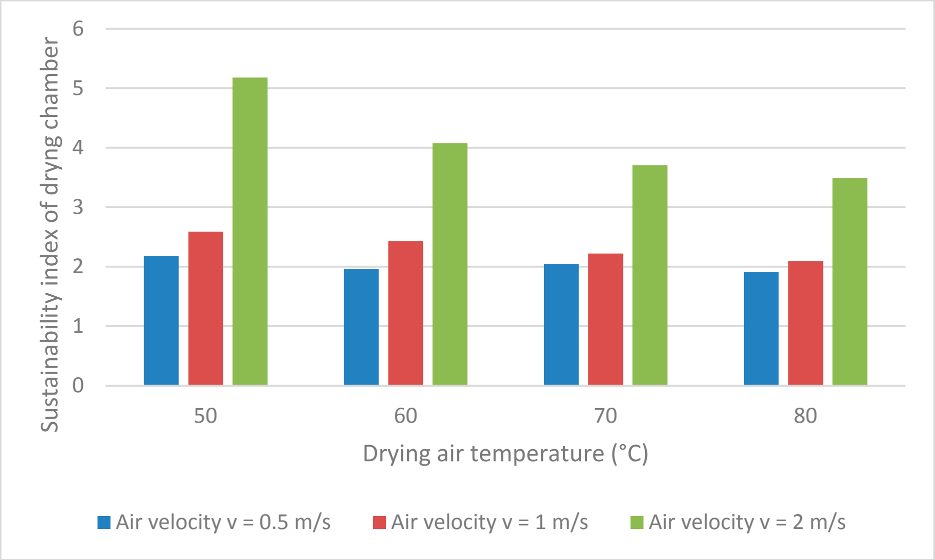

Figure 4. Sustainability index of drying chamber. Variation with the temperature and air flow rate.

Conclusion

The drying air parameters influence, in an onion drying system, was studied in terms of exergy parameters. The temperature and air flow rate were considered in order to carry out this analysis. A thermodynamic model was proposed based upon the matter, energy and exergy balances taking into account the onion drying chamber. The chamber behavior was analysed based on exergy efficiency, exergy loss rate, exergetic improvement potential rate and sustainability index.

The exergy loss rates increase with the temperature and air flow rate augmentation. The minimum value is 57.5 kJ/s at 50 °C and 0.5 m/s.

The exergy efficiency increases with the air flow rate augmentation and decreases with the temperature. The maximum value to this parameter was obtained at 323K and 2 m/s being equal to 80.6%.

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The exergetic improvement potential rate, under studied operative conditions, vary from 21-29.9% of the total input exergy.

The sustainability index of the drying chamber varied from 1.9 to 5.1. To reduce the environmental impact of the process, the parameters must be modified in order to ameliorate the exergy efficiency of the drying process.

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