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Full Length Research Paper

Energy and exergy analysis of fluidized bed drying of chickpea and bean

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Nowadays, drying process has taken an important role in food and agricultural production fields. Drying process is necessary to prepare the products for consumption and storage. There are various drying process techniques, point from the technological and process technique. Fluidized bed drying is usually preferred, because of high heat and mass transfer coefficient. In this work, fluidized bed was used in the experiments. The scope of this work is the exergy and energy analysis of fluidized bed drying of bean and chickpea. Drying process was employed at different temperatures and velocities for both products. Exergy analysis was accomplished to determine the type and magnitude of exergy losses during the drying process by applying the second law of thermodynamics. As a result, the parameters that affected the exergy efficiency were determined. As the exergy efficiency is evaluated, it can be seen that it is proportional to drying air temperature and velocity. Also, it was found that the efficiency for the same drying air temperature (47.1°C), is between 56 to 65% for bean and it is between 45 to 62% for chickpea.

Key words: Exergy and energy analysis, fluidized bed drying, drying.

INTRODUCTION

In the beginning of 1930s and 1940s, resulting from the wide range of researches and developments, the determination of the advantages of fluidized beds in the solid-gas contact required applications that increased the importance of fluidized beds. At first, for the production of petrol and petrol based products, a catalytic separator with fluidized bed was developed. Today, fluidized beds are used worldwide for different processes in different industries. Because of their high capacity of heat transfer and the ability of easy control, fluidized bed systems were widely used in combustion processes. Later, it is thought to be useful for the drying of different materials and researches have been made according to this aim.

The main principle of fluidized bed drying is to keep the solid particles stable by sending the air through the product materials so fast that the air can withstand the gravitational force. The drying air passes through the materials which are in granule form. The gas velocity must be decided very carefully. Since the contact between the powder or granule form material and the fluidization gas is very effective, in the same manner, the heat transfer between drying air and particles is very powerful. With this method, it is possible to dry the materials without the disadvantage of large temperature differences. For the evaluation of the systems in the view of thermodynamics, the exergy analysis which is the combination of the first and the second laws of thermodynamics is generally preferred.

Below, it is mentioned shortly about works in which energy and exergy analyses were applied to fluidized bed drying processes in the literature.

Midilli and Küçük (2001) have researched the energy and exergy analyses of the drying process of unpeeled and peeled pistachios by using cabinet dryer with solar

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energy. By using the first law of thermodynamics, energy usage ratio and the amount of energy which was gained from solar collectors were calculated. By using the second law of themodynamics, the amount of exergy losses during the drying process were determined. Syahrul et al. (2002) have studied on the thermodynamic modeling of the drying of humid particles in fluidized bed. The velocity of fluidization, the effects of hydrodynamic and thermodynamic conditions which were at inlet air temperature and the energy and exergy efficiencies based on the amount of the first humidity were analyzed. In the experiments, corn and wheat were used. For wheat, it was found that the inlet air temperature has a powerful effect on the thermodynamic efficiency, whereas for corn, it was found that the increase in air temperature do not lead an increase in efficiency. At the end of the research, it was seen that the energy and exergy efficiencies are higher at the particles which have large amount of first humidity under the effect of variable air velocity. Dinçer and Şahin (2003) carried out a studied on a new thermodynamic model for drying process including exergy term. Exergy efficiencies were identified as a function of heat and mass transfer. They investigated exergy differences between the inlet and outlet particle, the weight of the particle, the humidity of the drying air and sampling and confirming of applicability of the drying model which exists at different air temperatures. In conclusion, what was trying to be done in this research was not only verifying the usability of exergy analysis while evaluating the drying process thermodynamically, but also realizing their performance and efficiencies. Akpınar (2004) has applied the energy and exergy analysis to the process of drying of pepper slices at three different temperatures (55, 60, 70°C) with air velocity of 1.5 m/s in conventional drier. To calculate the energy usage ratio, energy analysis was employed and to calculate the exergy losses during the drying process, exergy analysis was employed. Akpınar et al. (2004) studied on the energy and exergy analysis of single layer drying process of potato slices in cyclone type drier. Potato slices were dried between 10 to 12 h at 60 to 80°C drying air temperature with 10 to 20% relative humidity and 1 to 1.5 m/s air velocity. For potato slices in the first tray, it has been determined that more energy was consumed in comparison to potato slices in the second tray. It has been finalized that the energy usage ratio of the first tray was higher than the second one and the first tray consisted of lower usable energy during the drying process because of the higher exergy losses. Çolak and Hepbaşlı (2007) by using the exergy analysis, they evaluated the performance of green olive in the single layer drier. The drying process took part at four different air temperatures (40, 50, 60, 70°C) and 15% relative humidity. They obtained the maximum exergy efficiency at 70°C and at the same time the drying air mass flow rate of between 0.015 and 0.0004 kg/s. Corzo et al. (2007) examined the energy and exergy analysis of single layer drying process of coroba palm slices at three different air temperatures (71, 82 and 93°C) and 0.82 to 1.12 m/s air velocities. They investigated the effects of the inlet air temperature and velocity on the energy and exergy. While the efficiency of exergy is becoming lower, with the increase of drying time both energy usage and energy usage ratio are becoming higher. The exergy inlet and outlet at 71 to 93°C drying temperature and air velocity of 0.82 to 1.18 m/s was found as 0.33 to 0.87 kJ/s and 0.25 to 0.75 kJ/s. At the same air velocity and temperature, exergy loss and exergy efficiency was found to be 0.005 to 0.01 kJ/s and 0.97 to 0.80 kJ/s, respectively. Martin et al. (2008) by using the exergy methodology and the mixture of biomass and low quality coal, studied to prove the technical applicability of the combustion within the bubble fluidized bed. Mass, energy and exergy balances were applied to a plant by experiments at nine different conditions. The exergy losses and exergy efficiency were determined by these experiments and the cost of irreversibilities was calculated. Nazghelichi et al. (2010) investigated the energy and exergy analyses of fluidized bed drying of carrot cubes. They studied the effects of drying variables on energy utilization, energy utilization ratio, exergy loss and exergy efficiency. They found that the energy utilization and energy utilization ratio was varying between 0.105 to 1.949 kJ/s and 0.074 to 0.486, respectively. They showed that small particles, deep beds and high inlet air temperatures increased energy utilization, energy utilization ratio, and exergy loss due to high value of heat and mass transfer.

In this study, agriculture products such as bean and chickpea were dried. By using the energy and exergy equations to the drying chamber, inlet, outlet, consumed for the mass transfer and disappeared exergies were theoretically calculated and their effects on the exergy efficiency were determined.

MATERIALS AND METHODS

Experimental study

A laboratory scaled experimental set up has been constructed for the drying of grain products. The schematic representation of this set up has been shown in Figure 1. The set consists of two heaters, a fan, a frequency invertor, air pipe, a perforated plate, a fluidized bed body, five thermocouple, two temperature and humidity sensor, a pitot-static tube, three pressure difference gauge, electric board, other fittings and insulation materials.

Some pre-experiments had been made before making the fluidized bed drying experiment. These are summarized as the determination of minimum fluidization velocity of bean and chickpea and the calibration of pitot-tube.

For the calibration of pitot-tube, the rotation of the fan motor was changed by using the invertor and the air velocity in the fluidized bed was determined by using both anemometer and pitot-tube.

For the determination of the materials' minimum fluidization

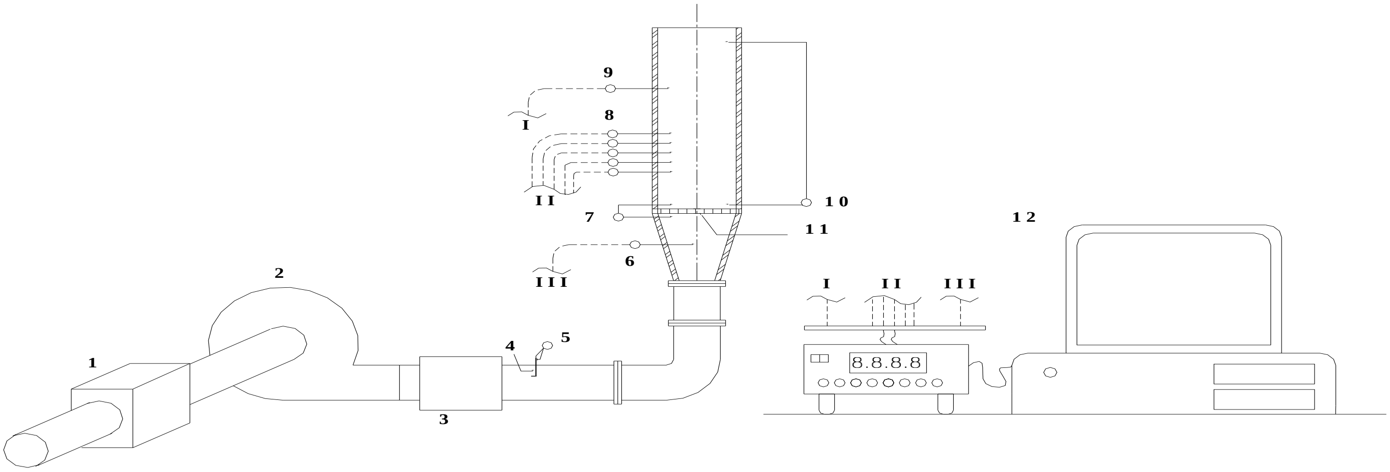

Figure 1. The schematic representation of fluidized bed experimental set up. (1: Preheater, 2: Fan, 3: Last heater, 4: Pitot-static tube, 5-7-10: Pressure cell, 6-9: Humidity sensor, 8: Temperature sensors, 11: Perforated plate, 12: Data collector system and computer).

velocity, 5 mm diameter and 700 g bean and 6 mm diameter and 700 g chickpea were placed into the fluidized bed at different times. After this, the rotation of the fan motor was changed by the invertor and the pressure difference of the fluidized bed for 5, 10, 15, 20, 25, 30, 35, 40, 45, 50 Hz was read and compared to the fluidized bed air velocity. Pressure difference increases with air velocity at the beginning but later at a specified point the pressure difference tends to decrease.

At this point, the pressure difference of fluidized bed is equal to the product's weight. The velocity at this point is called the minimum fluidization velocity. For bean, the fluidization velocity was determined as 3.68 m/s and for chickpea as 4.59 m/s. Our experiments took place slightly above this velocity.

To prepare the experimental setup, the system was set to work, however the bed was empty, about 1 to 2 h to ensure the system was balanced. After the required conditions (constant temperature) were achieved, the materials were put into the system. The humidity of the samples were pre-humidified by water, and were measured at the time period of 5, 10, 20, 30, 40, 50, 60, 70, 80 and 90 min. The agriculture products were subjected to the experiments at different temperature and humidity values and the temperature distribution in fluidized bed, the outlet temperature of air, the variation of air humidity and how the drying properties of materials change at different conditions were obtained as the result of the experiments.

Energy and exergy analysis

Researchers utilized the first law of thermodynamics for many years to evaluate the processes in which energy is used. Especially, because of the excessive energy sources and the lack of demand to these sources kept away the researchers from evaluating the irreversibilities in the systems. However, the increase in the population of the world and the demand to the energy sources force the researchers to use the energy more efficiently.

The first law of thermodynamics is related to the quantity of energy. It emphasizes that energy cannot be created or destroyed. However, the first law of thermodynamics is inadequate for evaluating the processes on its own and because of this reason, researchers applied new techniques. The most effective technique is the exergy analysis for evaluating the processes. During a phase change, the energy quality gets lower and entropy is produced. Now, by using exergy analysis, we can consider these important concepts.

First law analysis: Energy usage

The goal in this part of the work is to find the behaviour of drying air and the change in energy with the help of first law of thermodynamics. It was assumed that the flow is steady-state. The mass-energy model which was used during the examination process can be seen in Figure 2.

The conservation of mass for dry air

$$\sum \dot{m}_{hi} = \sum \dot{m}_{ho} \qquad (1)$$

The conservation of mass for humidity

$$\sum (\dot{m}_{ni} + \dot{m}_{mn}) = \sum \dot{m}_{no} \text{ or}$$

$$\sum (\dot{m}_{hi}.w_i + \dot{m}_{mn}) = \sum \dot{m}_{hi}.w_o \qquad (2)$$

The conservation of energy

$$\dot{Q} - \dot{W} = \sum \dot{m}_o \left(h_o + \frac{V_o^2}{2} \right) - \sum \dot{m}_i \left(h_i + \frac{V_i^2}{2} \right) \qquad (3)$$

Only, the kinetic energy change in fan was considered. The enthalpy and the relative humidity of dry air were found with

$$\phi = \frac{w.P}{(0.622 + w).P_{sv@T}} \qquad (4)$$

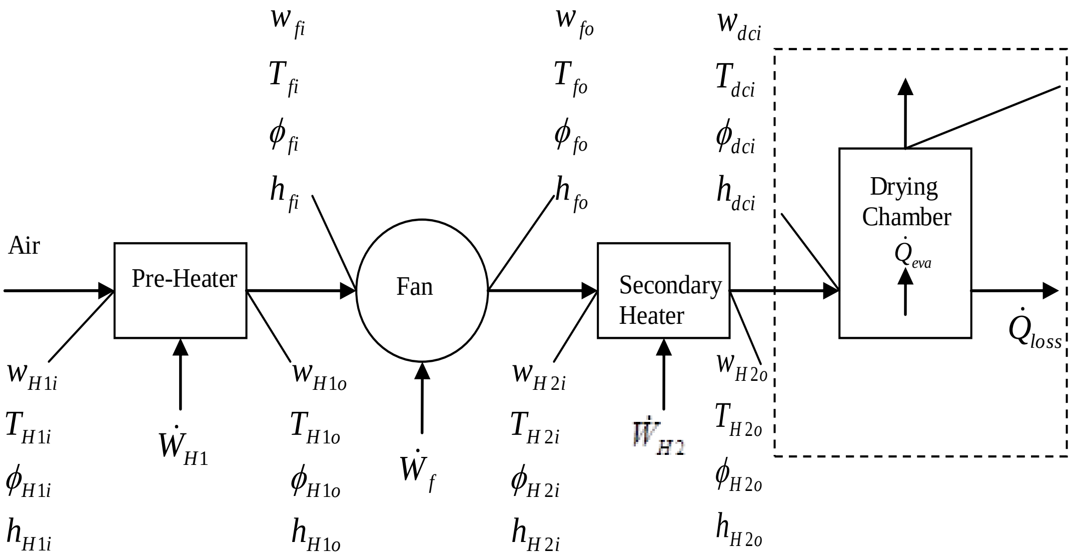

Figure 2. The mass-energy model for drying experiment. (w, T, ϕ and h are specific humidity, temperature, relative humidity and enthalpy of air, respectively. H_1 and H_2 are heater, f_i and f_o are fan inlet and outlet, dc_i and dc_o are drying chamber inlet and outlet, respectively. $\dot{W}$ is the rate of work, $\dot{Q}_{eva}$ is thermal power obtained from evaporation and $\dot{Q}_{loss}$ is thermal power loss).

w denotes the specific humidity, P atmospheric pressure, $P_{sv@T}$ saturated vapor pressure of dry air. The dry air enthalpy was found with

$$h = c_{p_{da}}.T + w.h_{sv@T} \tag{5}$$

$c_{p_{da}}$ is specific heat, T is temperature of dry air and $h_{sv@T}$ is the enthalpy of saturated vapor.

Determination of fan outlet conditions

The Equation (5) was used to determine the fan outlet enthalpy.

$$\dot{Q} + \dot{W}_f = \sum \dot{m}_{da}\left[\left(h_{fo} - h_{fi}\right) + \left(\frac{V_{fo}^{\ 2} - V_{fi}^{\ 2}}{2*1000}\right)\right] \tag{6}$$

In Equation (6), since there is no heat transfer, $\dot{Q}$=0 and ignoring the V_{fi}

$$h_{fo} = \left[\left(\dot{W}_f - \frac{V_{fo}^{\ 2}}{2*1000}\right)\left(\frac{1}{\dot{m}_{da}}\right)\right] + h_{fi} \tag{7}$$

h_{fi} is fan inlet enthalpy, h_{fo} is fan outlet enthalpy of air; V_{fi} is fan inlet velocity, V_{fo} is fan outlet velocity of air, $\dot{W}_f$ is the power of fan and $\dot{m}_{da}$ is the mass flow rate of dry air.

Determination of heater inlet and outlet conditions

To determine the heater inlet and outlet conditions, the heat losses in the connection pipes between fan and heaters were ignored.

$$\begin{aligned} w_{H1o} &= w_{fi} \\ T_{H1o} &= T_{fi} \\ \phi_{H1o} &= \phi_{fi} \\ h_{H1o} &= h_{fi} \end{aligned} \qquad \begin{aligned} w_{H2i} &= w_{fo} \\ T_{H2i} &= T_{fo} \\ \phi_{H2i} &= \phi_{fo} \\ h_{H2i} &= h_{fo} \end{aligned} \tag{8}$$

w, T, ϕ and *h* are specific humidity, temperature, relative humidity and enthalpy of air, respectively. H_i and H_o are heater inlet and outlet, respectively. The usable energy obtained from heater was found from

$$\dot{Q}_{usable} = \dot{m}_{da} c_{p_{da}} \left(T_{Hi} - T_{Ho}\right) \tag{9}$$

Determination of drying chamber inlet conditions

For determining the drying chamber inlet conditions, the inlet air temperature and inlet air humidity needs to be identified. Because of the thermal losses between heater inlet and outlet, it is strongly emphasized that the heater outlet conditions are not equal to the drying chamber inlet conditions. The heat loss in pipes between the heater and the drying chamber was found from

$$\dot{Q}_{loss} = \dot{m}_{da} c_{p_{da}} \left(T_{dci} - T_{H2o} \right) \tag{10}$$

The relative humidity at the outlet of drying chamber

$$w_{dco} = w_{dci} + \frac{\dot{m}_{mn}}{\dot{m}_{da}} \tag{11}$$

w_{dco} and w_{dci} are specific heats at the outlet and inlet of the drying chamber, respectively. $\dot{m}_{mn}$ is the mass flow rate of the wet product. The thermal energy which was used for the drying process was found from

$$\dot{Q}_{dc} = \dot{m}_{da} . \left(h_{dci@T} - h_{dco@T} \right) \tag{12}$$

The energy usage ratio during the drying process was found from (Akpınar, 2004)

$$EUR_{dc} = \frac{\dot{m}_{da.} \left(h_{dci@T} - h_{dco@T} \right)}{\dot{m}_{da.} . c_{p_{da}} \left(T_{dci} - T_{Hi} \right)} \tag{13}$$

Determination of drying chamber flow conditions

For the flow in smooth surface pipes, if the Reynolds Number is lower than 2300, then the flow is assumed to be laminar, if it is higher than 10^4, then the flow is assumed to be turbulent.

$$\mathrm{Re}_d = \frac{V.d}{\nu} \quad \text{(Radial systems)} \tag{14}$$

To calculate the convection coefficient in pipe flow, Reynolds and Nusselt Nember were employed. During our experiments, Re_d number was found betwen 2.10^4 – 2.10^6. According to these results, we can say that our flow is fully developed turbulent flow. For circular pipes, the Nusselt Number in fully developed turbulent flow can be found (Incropera and Dewitt, 1996) from

$$Nu_d = \frac{\alpha . d}{\lambda} = 0{,}023 . \mathrm{Re}_d^{4/5} . \mathrm{Pr}^n \tag{15}$$

λ is the conduction coefficient of the fluid, α is heat convection coefficient of air, d is the diameter of drying chamber, and Pr is the Prandtl Number of air (For heating n=0.4, for cooling n=0.3)

Second law analysis: Exergy analysis

The exergy losses between drying chamber inlet and outlet were calculated according to the concept of exergy analysis. The main aim of exergy analysis for drying chamber is to determine the exergy values at the dead state and the exergy variations during the process. For open systems, regardless of the temperature and pressure, the exergy equation for unit mass is

$$e = \left(h - h_\infty \right) - T_\infty \left(s - s_\infty \right) \quad \text{(Çengel and Boles, 1999)} \tag{16}$$

∞ denotes the dead state. The kinetic, potential and chemical exergy values are ignored. Then, the total exergy equation is

$$\dot{E}x = \dot{m}_{da} \left[(h - h_\infty) - T_\infty (s - s_\infty) \right] \tag{17}$$

For the enthalpy change of air

$$\Delta h = c_{p_{da}} (T - T_\infty) \tag{18}$$

With the assumption of constant c_p, the entropy variation during a phase change is

$$\Delta S = S_2 - S_1 = \int_1^2 \left(\frac{\delta Q}{T} \right)_{\mathrm{int}.rev.} \tag{19}$$

If the drying air is assumed to be ideal gas

$$s - s_\infty = c_p \ln \frac{T}{T_\infty} - R \ln \frac{P}{P_\infty} \tag{20}$$

With ignoring the pressure variation, if the Equations (18) and (20) can be rewritten in Equation (17), then the exergy change

$$\dot{E}x = \dot{m}_{da} c_{p_{da}} \left[\left(T - T_\infty \right) - T_\infty \ln \frac{T}{T_\infty} \right] \tag{21}$$

The inlet and outlet exergies were determined according to the drying chamber inlet and outlet temperatures as shown below. [$T_\infty = T_o$ (ambient temperature)]. The enthalpy of air at the drying chamber inlet

$$\dot{E}x_{dci} = \dot{m}_{da} c_{p_{da}} \left[\left(T_{dci} - T_\infty \right) - T_\infty \ln \frac{T_{dci}}{T_\infty} \right] \tag{22}$$

The enthalpy of air at the drying chamber outlet

$$\dot{E}x_{dco} = \dot{m}_{da} c_{p_{da}} \left[\left(T_{dco} - T_\infty \right) - T_\infty \ln \frac{T_{dco}}{T_\infty} \right] \tag{23}$$

With the assumption of steady-state flow, the exergy balance can be written as follows; (Syahrul et. al., 2002; Çolak and Hepbaşlı, 2007)

$$\sum \left(1 - \frac{T_\infty}{T_{so}} \right) \dot{Q}_{so} - \dot{W} + \sum_i \dot{E}x - \sum_o \dot{E}x - \dot{E}x_Y = 0 \tag{24}$$

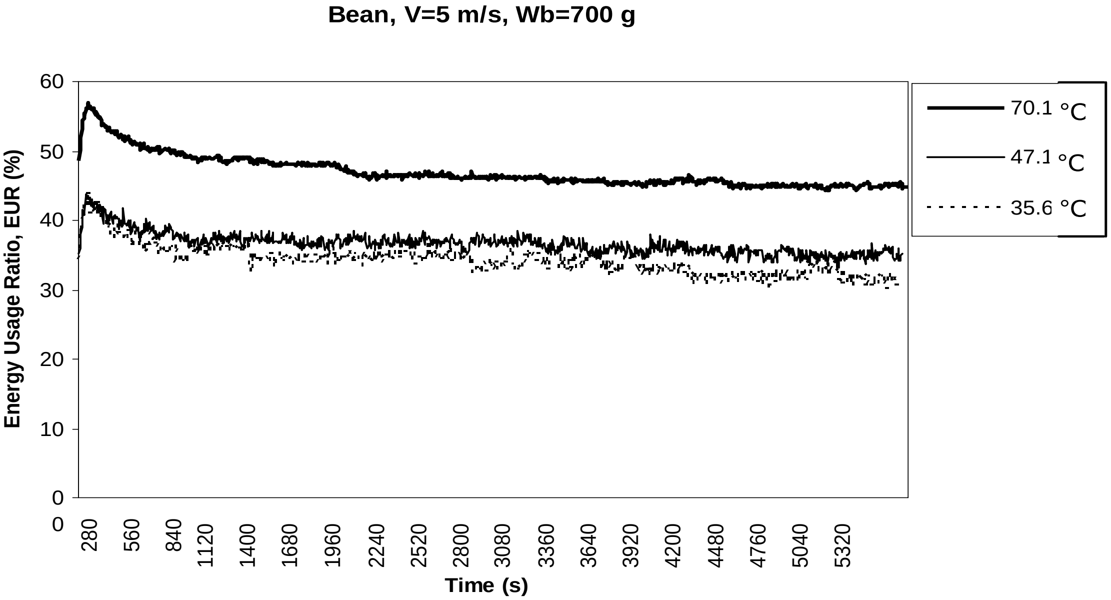

Figure 3. The change of energy usage ratio as a function of time with respect to the temperature at drying air velocity of 5 m/s.

$\dot{Q}_{so}$ is the heat transfer between the system and the thermal energy source, T_{so} is the temperature of the thermal energy source. Since, there was no heat input or output to or from the system, these terms were ignored too. In addition, since, there was no work interaction within the system, then $\dot{W}$ = 0. Lastly, $\dot{E}x_Y$ denotes the exergy loss (irreversibilities).

For the whole system, Equation (24) becomes

$\sum$ Exergy Loss (irreversibilities) = $\sum$ Exergy inlet - $\sum$ Exergy outlet

$$\sum \dot{E}x_Y = \sum \dot{E}x_{dci} - \sum \dot{E}x_{dco} \tag{25}$$

The equations of the exergy loss because of the heat transfer to the ambient ($\dot{E}x_{loss}$) and the exergy loss because of the mass transfer of the evaporating humidity in the drying chamber are as follows

$$\dot{E}x_{loss} = \left[1 - \frac{T_\infty}{T_s}\right]\dot{Q}_{thermal} \tag{26}$$

The heat transfer from drying chamber to the ambient is

$$\dot{Q}_{thermal} = \frac{T_{\infty 1} - T_{\infty 2}}{\dfrac{1}{2\pi r_1 L \lambda_1} + \dfrac{\ln\left({}^{r_2}\!/\!_{r_1}\right)}{2\pi k L} + \dfrac{1}{2\pi r_2 L \lambda_2}} \tag{27}$$

The exergy which arises because of the mass transfer of evaporated humidity

$$\dot{E}x_{eva} = \left[1 - \frac{T_\infty}{T_{ave}}\right]\dot{Q}_{eva} \tag{28}$$

T_{ave} is the product's average temperature, $\dot{Q}_{eva}$ is the heat transfer because of the evaporation.

$$\dot{Q}_{eva} = \dot{m}_n h_{fg} \tag{29}$$

$\dot{m}_n$ is the mass flow rate of the humidity in the air, h_{fg} is the latent heat of the water which is evaporating. In conclusion, exergy efficiency is

Exergy Efficiency = (Input Exergy – Exergy Loss) / Input Exergy

$$\eta_{Ex} = 1 - \frac{\dot{E}x_Y}{\dot{E}x_{dci}} \tag{30}$$

RESULTS

Bean

The results of the drying process in fluidized bed for 700 g bean which belongs to Konya city in Turkey at ambient temperatures between 11.9 to 14.9°C, drying air temperature between 35.6 to 70.1°C, and air velocity between 5 to 6.2 m/s are are shown in Figures 3 and 4.

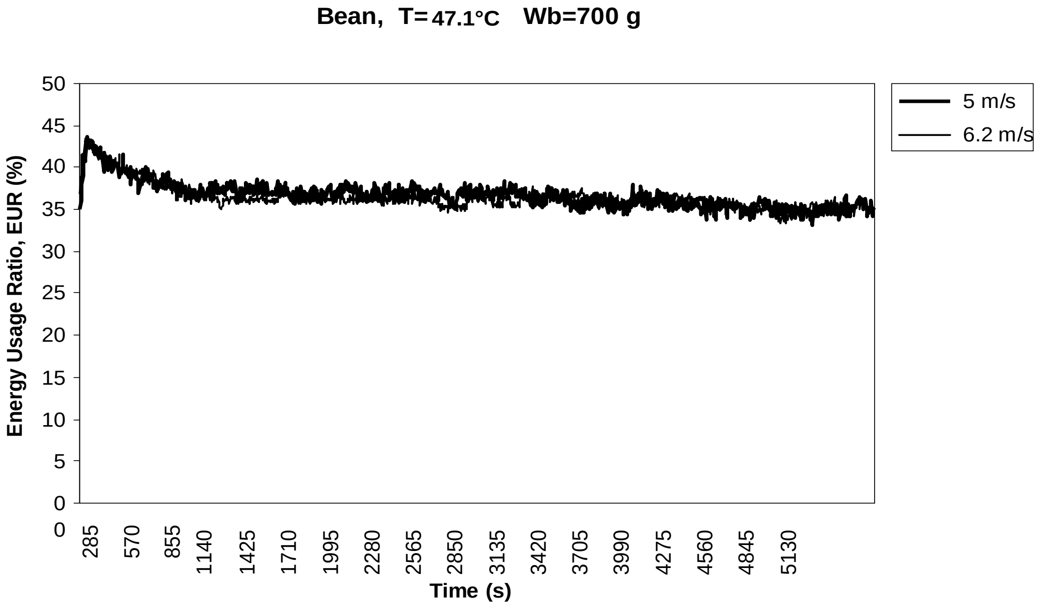

Figure 4. The change of energy usage ratio as a function of time with respect to the velocity with drying air temperature of 47.1°C.

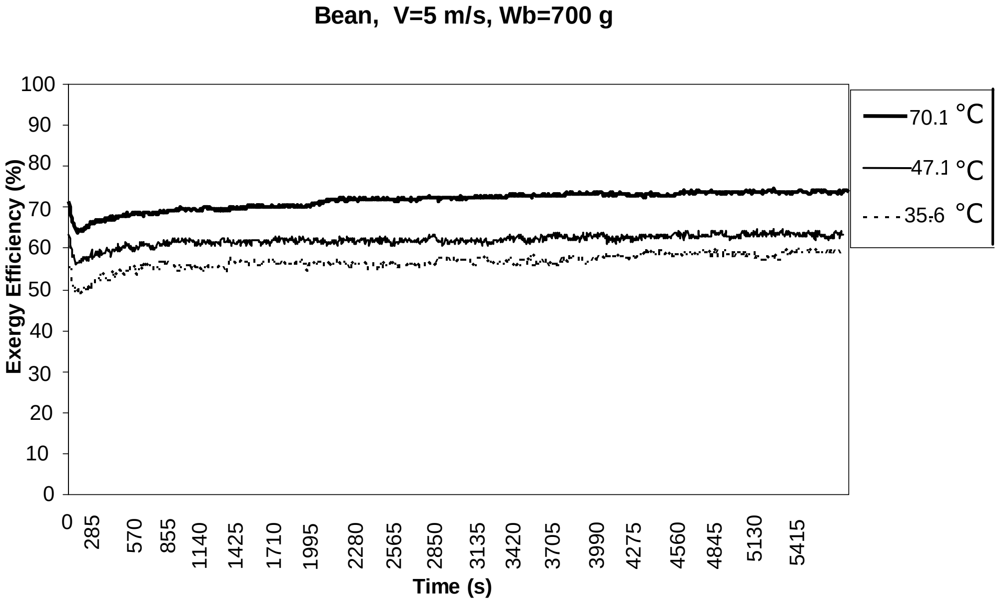

Figure 5. The change of exergy efficiency as a function of time with respect to the temperature at drying air velocity of 5 m/s.

To see how the exergy efficiency changes with drying air temperature and velocity, one can examine the Figures 5 and 6.

In Figure 7, it can be seen how the irreversibilities can change according to the drying air temperature.

Chickpea

The results of the drying process in fluidized bed for 700 g chickpea at ambient temperatures between 13.2 to 15°C, drying air temperature between 36.1 to 60.1°C, and

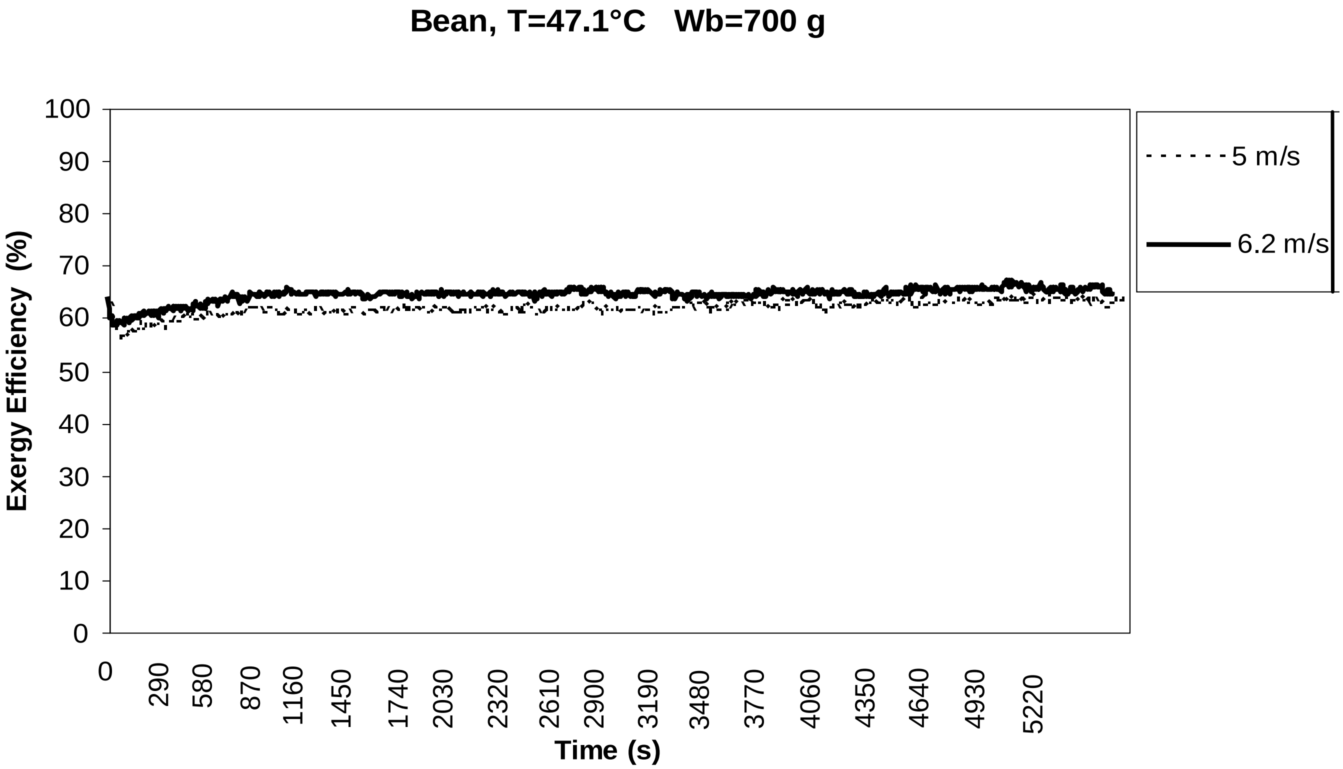

Figure 6. The change of exergy efficiency as a function of time with respect to the velocity with drying air temperature of 47.1°C.

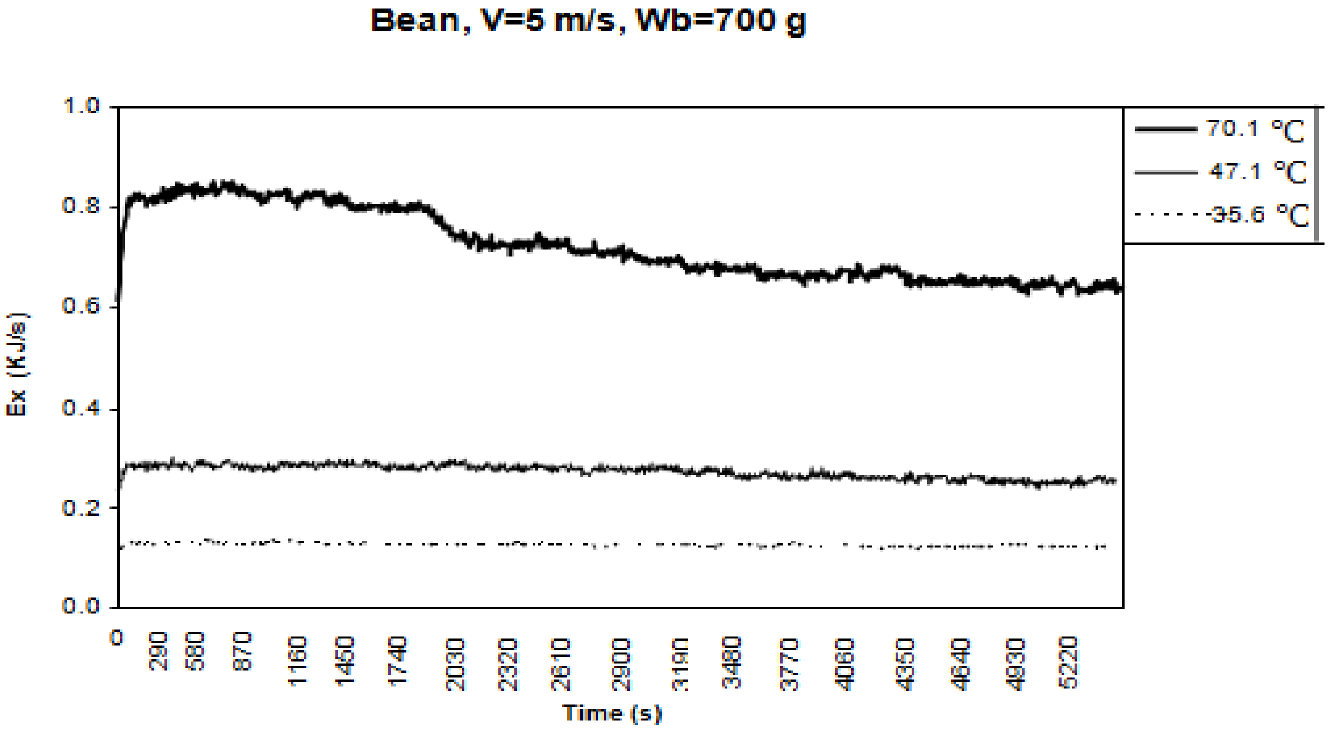

Figure 7. The change of exergy ($\dot{E}x_Y$) as a function of time with respect to the temperature at the drying air velocity of 5 m/s.

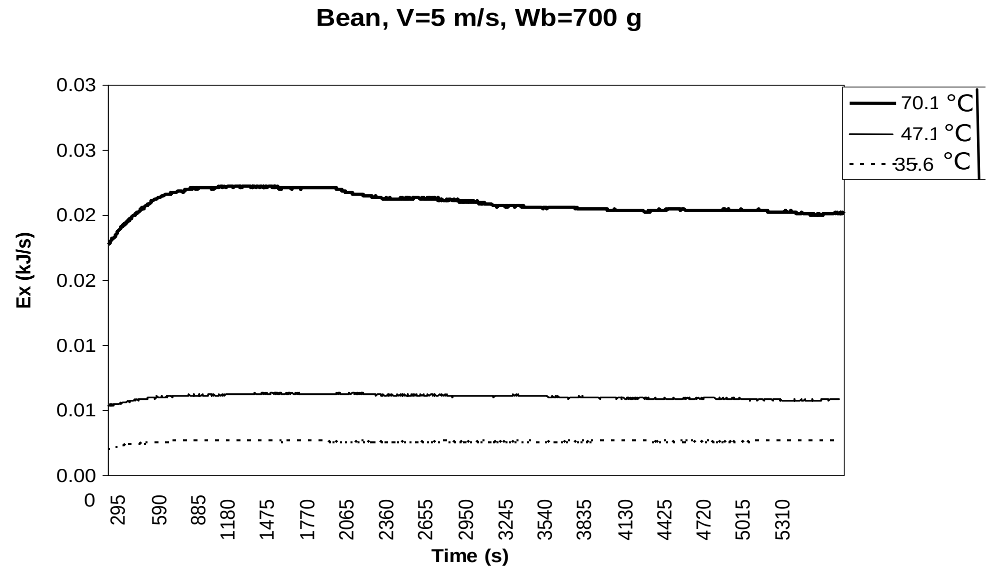

Figure 8. The change of exergy loss as a function of time with respect to the velocity at drying air velocity of 5 m/s due to the heat transfer to the ambient.

air velocity between 5.4 to 6.3 m/s are shown in Figure 10 to 14.

DISCUSSION

Bean

As Figure 3 is evaluated, it can be seen that the energy usage ratio increases with temperature. For the three conditions, the increase in drying air inlet temperature leads to an increase in energy usage ratio, whereas the ambient temperatures are nearly the same. The reason for that is explained at the beginning of the drying process, because of the heat and mass transfer between the product and the drying air, leads to a decrease in the outlet temperature. But later on, since the product temperature becomes higher, these temperatures get closer. As can be seen from Figure 4, the change of energy usage ratio is nearly the same at the same drying air temperature even though the velocity increases. The reason of the increase at the beginning is the decrease in outlet temperature because of the mass and heat transfer. In Figure 5, it can be seen that the exergy efficiency increases with temperature. The reason for that is the increase in temperature that leads to an increase in Ex_{eva} value. Figure 6 shows that the exergy efficiency changes linearly with the drying air velocity. In Figure 7, it can be seen that the irreversibilities can change according to the drying air temperature. The increase in temperature increases the parameters such as mass and heat transfer, frictions which are the reasons of exergy loss. In Figure 8, it is determined that the exergy loss which is due to the heat transfer to the ambient is proportional to the air temperature of the bed.

It was determined that the exergy of air at the drying chamber inlet is between 0.638 to 0.759 kJs^{-1}, at the drying chamber outlet it is between 0.368 to 0.467 kJs^{-1}. At the same time, which factors are mainly responsible for the irreversibilities were determined. These factors are shown schematically in Figure 9.

Chickpea

As a result of the experiments and calculations which were done for chickpea, it was seen that the exergy efficiency, exergy loss according to the fluidized bed air temperature and velocity are similar to that of bean. The little differences is explained as following: it was determined that the exergy of air at the drying chamber inlet is between 1.257 to 1.619 kJs^{-1}, at the drying chamber outlet it is between 0.71 to 0.996 kJs^{-1}. In Figure 14, the drying chamber exergy balance is shown schematically.

Conclusions

As a result of the experimental evaluation and exergy analysis of fluidized bed drying of bean and chickpea, the

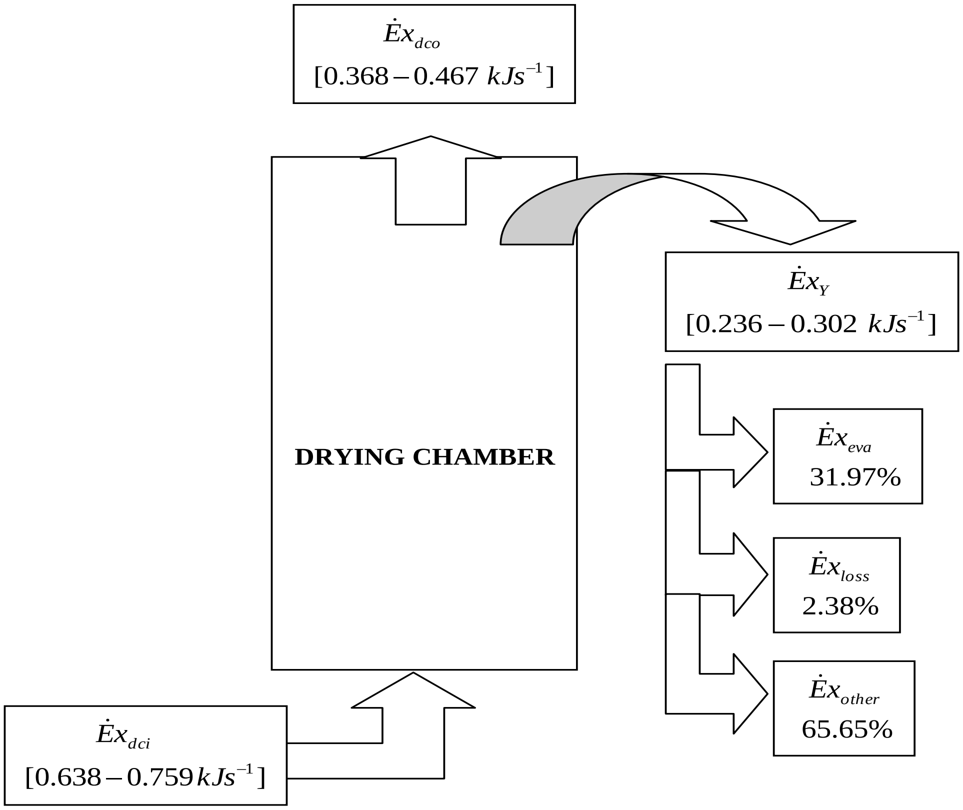

Figure 9. The schematic representation of exergy balance for bean at the conditions of 47.1 ^{0}C drying air temperatureand 5 m/s drying air velocity.

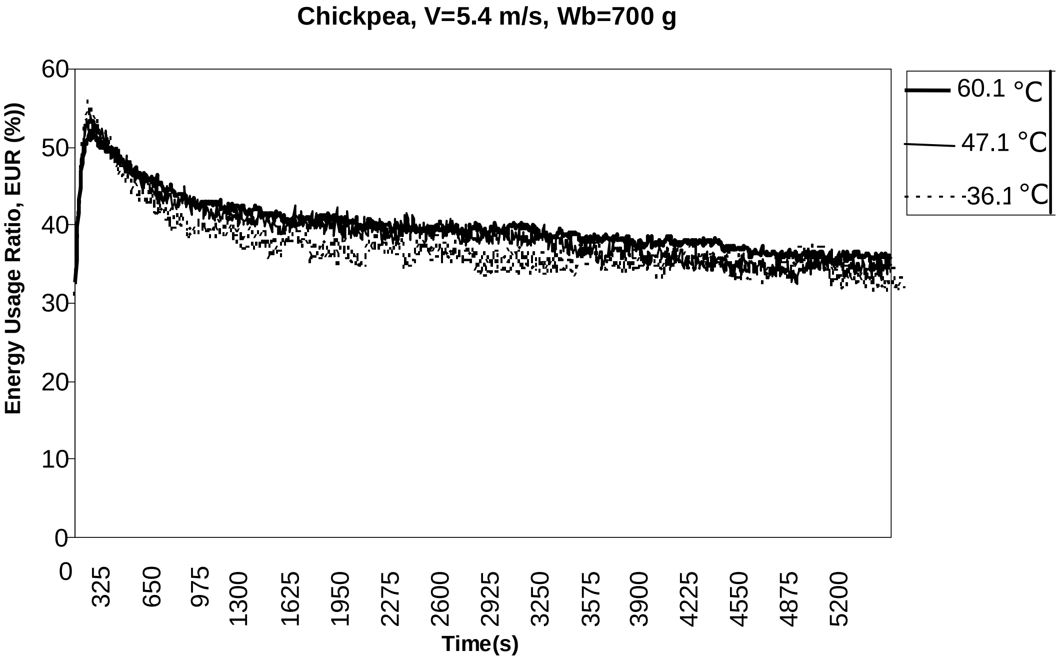

Figure 10. The change of energy usage ratio as a function of time according to the temperature at drying air velocity of 5.4 m/s.

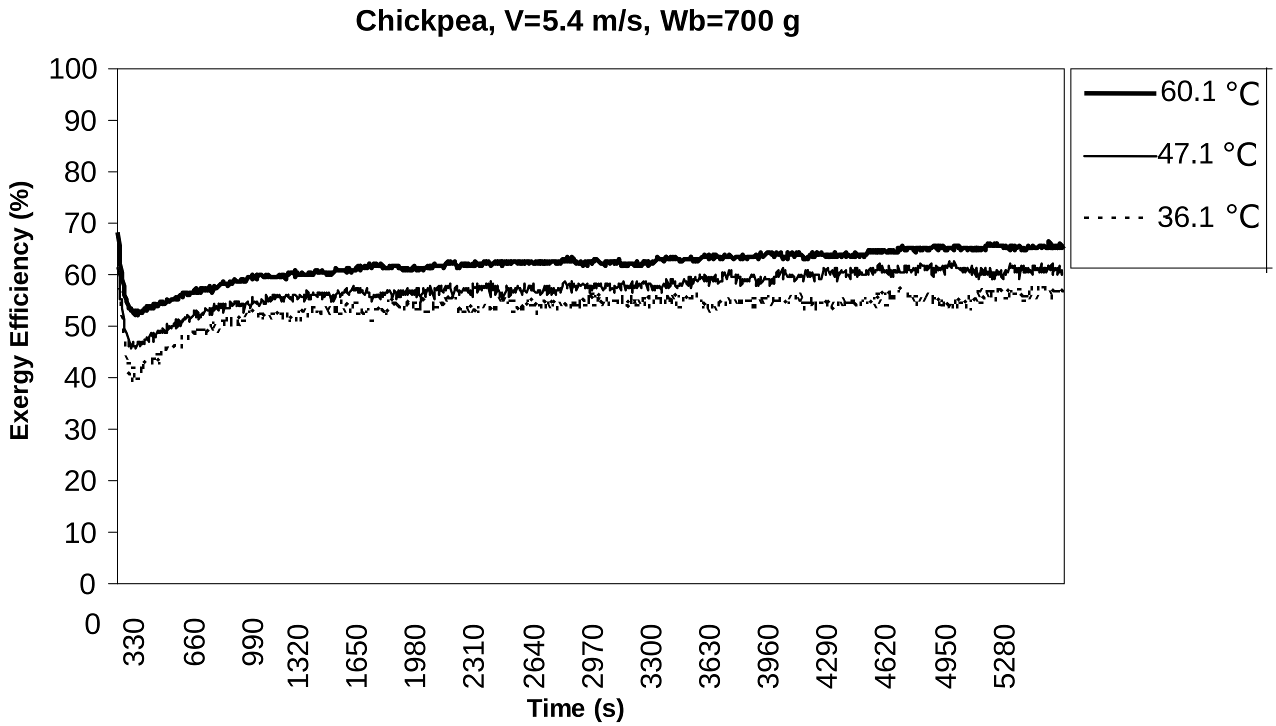

Figure 11. The change of exergy efficiency as a function of time according to the temperature at drying velocity of 5.4 m/s.

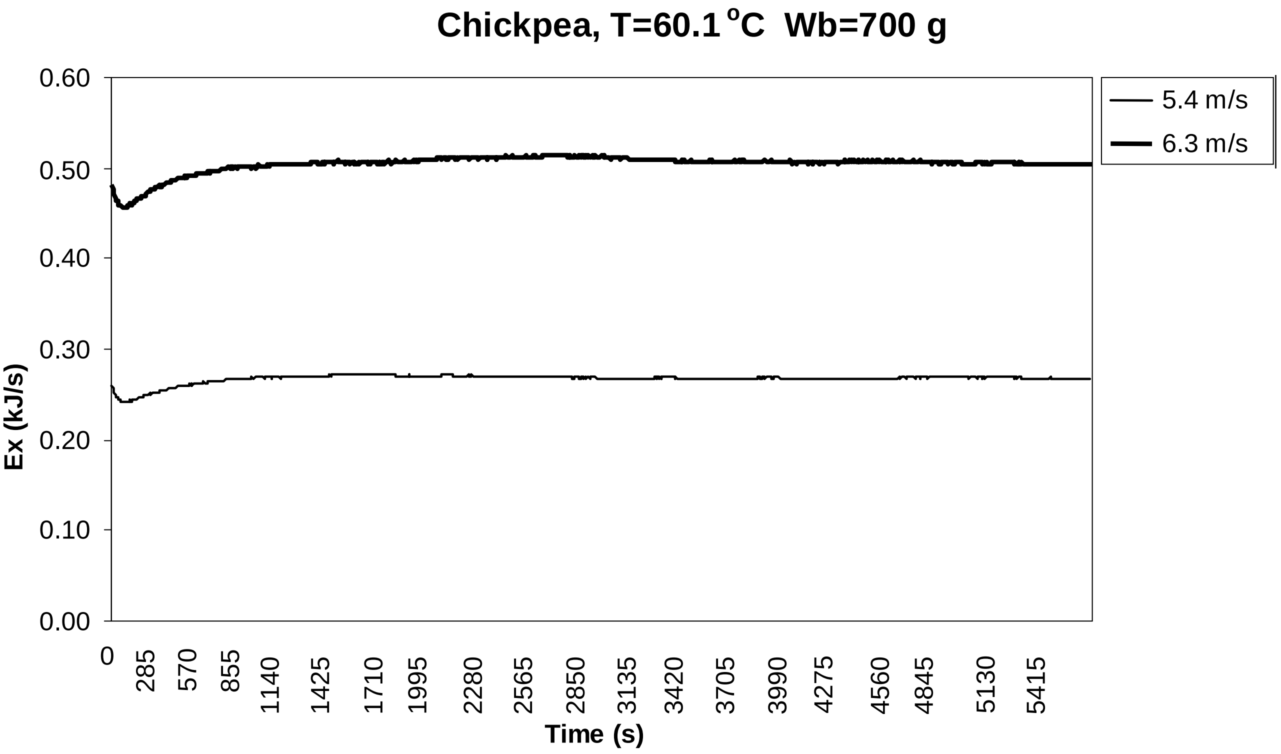

Figure 12. The change of exergy loss due to the evaporation as a function of time according to the velocity at drying air temperature of 60.1°C.

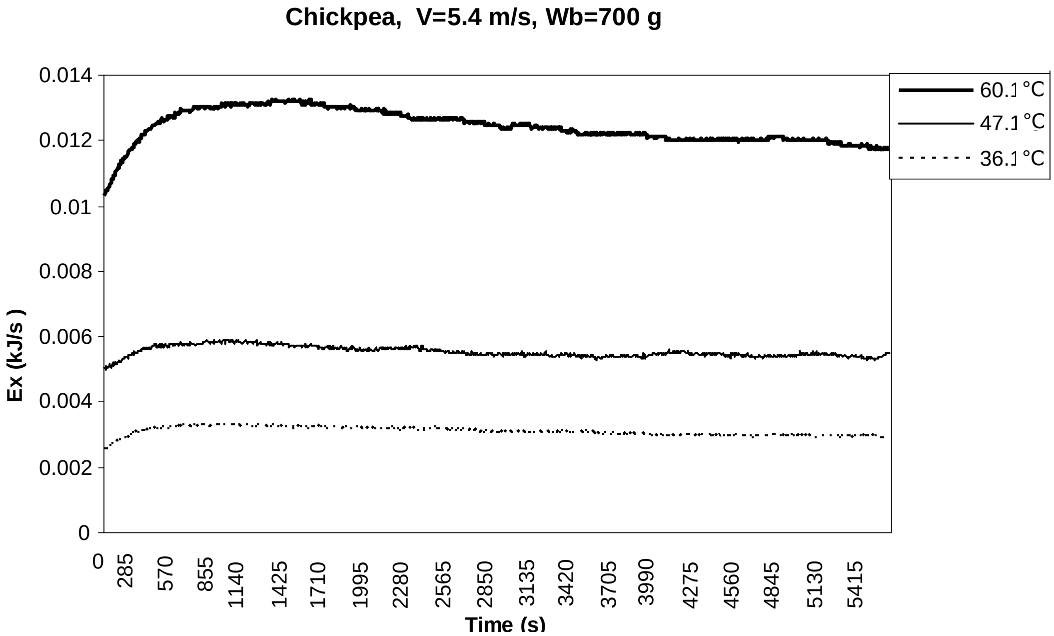

Figure 13. The change of exergy loss due to the heat transfer to the ambient as a function of time according to the temperature at drying air velocity of 5.4 m/s.

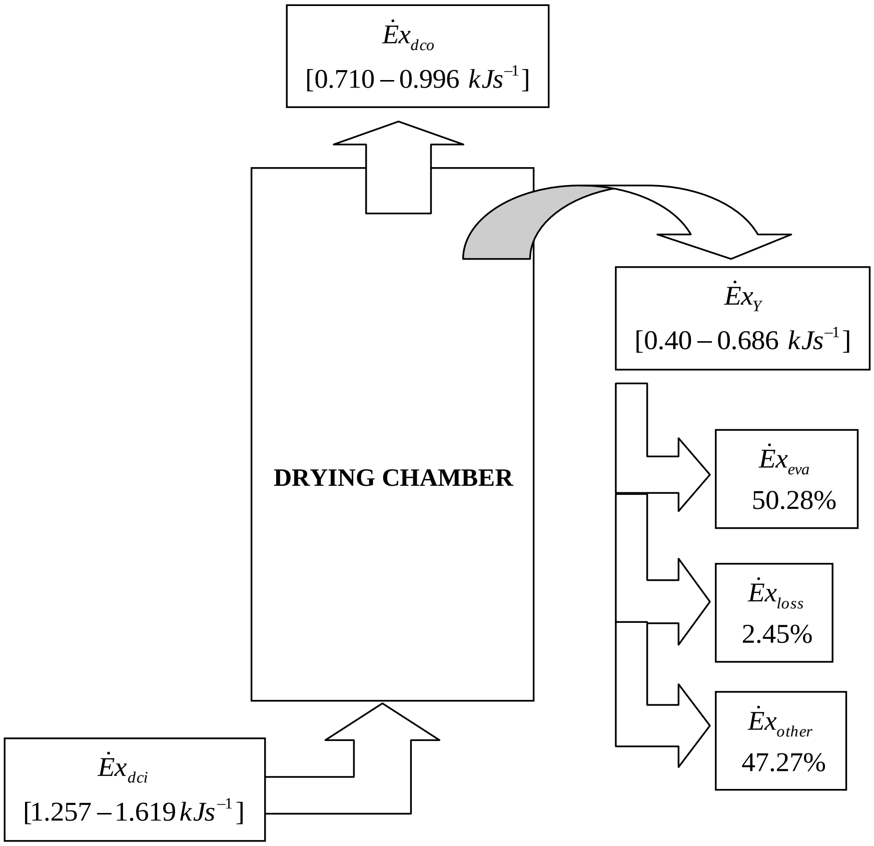

Figure 14. The schematic representation of drying chamber exergy balance at drying air velocity of 47.1°C and drying air velocity of 5.4 m/s for chickpea.

following conclusions have been reached. It has been determined that the drying velocity increases with drying air temperature, whereas the increase in drying air velocity can not affect the process strongly. It has also been shown that, energy usage ratio increases with both drying air temperature and velocity.

It has been seen that in drying chamber, the exergy loss due to the mass transfer which is the result of the evaporation of humidity, is proportional to the drying air temperature and velocity. In additon, the exergy loss due to the heat transfer to the ambient from drying chamber increases with drying air temperature, whereas the drying air velocity has a little effect on this sitution.

As the exergy efficiency is evaluated, it can be seen that it is proportional to drying air temperature and velocity. Also, it was found that the efficiency for the same drying air temperature (47.1°C), is between 56 to 65% for bean and it is between 45 to 62% for chickpea. The difference in efficiencies is because of the bean drying is more slower than chickpea drying.

If the exergy analysis is evaluated completely, it can be seen that the exergy loss due to the irreversibilities such as friction is more higher than the exergy loss due to the evaporation and heat loss. It has been determined that, the exergy quantity entering the drying chamber decreased about 43% for bean and 53% for chickpea. However, the amount of exergy consumed for evaporation for both products, since the amount of exergy entering the drying chamber was lower in chickpea experiments, the exergy efficiency for chickpea was found higher.

Abbreviations: $\dot{m}$, Mass flow rate $(kg.s^{-1})$; w, specific humidity $(g.g^{-1})$; $\dot{Q}$, heat transfer rate $(kJ.s^{-1})$; $\dot{W}$, power $(kJ.s^{-1})$; V, velocity $(m.s^{-1})$; ϕ, relative humidity; T, temperature (K); T_s, boundary layer temperature (K); T_∞, ambient temperature, dead state (K); h, specific enthalpy $(kJ.kg^{-1})$; h_{fg}, latent heat of evaporating water $(kJ.kg_{water}^{-1})$; c_p, constant pressure specific heat $(kJ.kg^{-1}.K^{-1})$; d, drying chamber diameter (m); r, drying chamber radius (m); g, gravitational acceleration $(m.s^{-2})$; u, specific internal energy $(kJ.kg^{-1})$; s, specific entropy $(kJ.kg^{-1}.K^{-1})$; ***Re,*** Reynolds Number; ***Nu,*** Nusselt Number; ***Pr,*** Prandtl Number; ν, kinematic viscosity $(m^2.s^{-1})$; λ, thermal conductivity $(\mathrm{W.m^{-1}.K^{-1}})$; α, convection coefficient $(W.m^{-2}.K^{-1})$; **P,** pressure (Pa); $\dot{E}x$, exergy $(kJ.s^{-1})$; ***EUR,*** energy usage ratio; ***Eva,*** evaporation; ***Va,*** vanish; ***İ,*** inlet; ***O,*** outlet; ***Hu,*** humidity; ***Ma,*** material; ***Mh,*** material humidity; **H,** heater; ***Sv,*** saturated vapor; ***Da,*** dry air; ***F,*** fan; ***Dc,*** drying chamber; ***L,*** loss; ***So,*** source.

REFERENCES

Akpınar EK (2004). Energy and Exergy Analyses of Drying of Red Peppers Slices in a Convective Type Dryer. Sci. Direct PII:S0735-1933(04)00133-2.

Akpınar EK, Midilli A, Biçer Y (2004). Energy and exergy of patato drying process via cyclone type dryer. Energy Conserv. Manage. 46:2530-2552.

Corzo O, Bracho N, Vasquez A, Pereira A (2007). Energy and exergy analysis of thin layer drying of coroba slices. J. Food Eng. 86:151-161.

Çengel YA, Boles MA (1999). Thermodynamics: An Engineering Approach. McGraw Hill.

Çolak N, Hepbaşlı A (2007). Performance analysis of drying of gren olive in a tray dryer. J. Food Eng. 80:1188-1193.

Dinçer I, Şahin AZ (2003). A new model for thermodynamic analysis of a drying process. Int. J. Heat Mass Transf. 47:645-652.

Incropera FP, Dewitt DP (1996). Fundamentals of Heat and Mass Transfer, Wıley, 4th edition.

Martin C, Miguel A, Villamanan CR, Chamorro JO, Cabanillas A, Segovia JJ (2008). Low-grade and biomass co-combustion on fluidized bed: Exergy analysis. Energy 31:330-344.

Midilli A, Küçük H (2001). Energy and exergy analyses of solar drying process of pistachio. Energy 28(2003):539-556.

Syahrul S, Dinçer I, Hamdullahpur F (2002). Thermodynamic modeling of fluidized bed drying of moist particles. Int. J. Therm. Sci. 42:691-701.

Nazghelichi T, Kianmehr MH, Aghbashlo M (2010). Thermodynamic analysis of fluidized bed drying of carrot cubes. Energy 35:4679-4684.