Turkish Journal of Science & Technology
16(1), 85-95, 2021

Energy and Exergy Analysis of Drying Behavior for a Fish

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(Geliş/Received: 05/01/2021; Kabul/Accepted: 28/01/2021)

Abstract: The drying of rainbow trout in a square cross-sectional drier is examined to analyze the system in terms of energy and exergy by considering a thin-layer drying approach. In the experiments, the inlet velocity of air was kept to be constant at 1.5 m/s while varying the temperature of inlet air of 38, 46, and 53 °C with relative moisture ranged from 28 to 43 percent. In the beginning, the moisture content of specimen (fish) on wet basis was found to be around 75 %. Fish with an average weight of 200 grams were used in the experiments. The energy analysis on the consumed energy for the drying process was performed by considering the energy balance. Moreover, the exergy analysis was actualized by considering the second law of thermodynamics to identify the efficiency of the device and the magnitude of energy losses. At the beginning of the drying, the energy consumption was high on account of the large moisture content and decreased with decreasing moisture content. The exergy for inflow and outflow was observed to be increased with increasing the air temperature used for the drying process. Furthermore, it was observed that the lower temperature of the drying air, the lower exergy losses for the entire drying period in the range of 0-900 minutes.

Key words: Energy, Exergy analysis, Convective dryer, Drying, Fish drying.

Bir Balık için Kuruma Davranışının Enerji ve Ekserji Analizi

Öz: Bu çalışma, kare-kesitli bir kurutucuda kurutulan gökkuşağı alabalığının ince tabaka kurutma işleminin enerji ve ekserji analizini ele almaktadır. Deneyler, 1.5 m/s giriş havası hızında, ancak 38, 46 ve 53 °C' lik farklı giriş hava sıcaklığında yüzde 28-43 bağıl nem aralığında gerçekleştirilmiştir. Başlangıçta yaş temele (w.b.) göre nem içeriği % 75 olarak belirlenmiş ve balıklar için uygun olan seviyeye düşürmeyi amaçlanmıştır. Deneylerde, ortalama 200 gram ağırlığına sahip balıklar kullanılmıştır. Termodinamiğin birinci kanunu kullanılarak kurutma işlemi sırasında kullanılan enerji dikkate alınarak analiz yapılmıştır. Ayrıca termodinamiğin ikinci yasası uygulanarak sistemin tipi ve ekserji kayıplarının büyüklüğü ile kurutma işlemi sırasında ekserji verimliliğini belirlemek için ekserji analizi yapılmıştır. Yüksek nem içeriğinden dolayı kurutma işleminin başlangıcında enerji kullanımının yüksek olduğu ve azalan nem içeriği ile düştüğü görülmüştür. Ekserji girişi ve çıkışı, artan kurutma hava sıcaklığı ile artar. Ayrıca en düşük ekserji kayıplarının tüm kurutma süresi boyunca en düşük kurutma hava sıcaklığında gerçekleştiği ve en yüksek ekserji kayıplarının 0-900 dakika kuruma süresi aralığında en yüksek kurutma sıcaklığıyla meydana geldiği görülmüştür. Ancak en yüksek ekserji verimi en yüksek kurutma havası sıcaklığında elde edilmiştir.

Anahtar kelimeler: Enerji, Ekserji analizi, Taşınımlı kurutucu, Kurutma, Balık kurutma.

1. Introduction

Preservation of the agricultural and animal nutrients by drying has been known in the early ages. This preservation technique can be implemented in several kinds of food. To consume fish later, the fish have to be preserved by some preservation method such as drying since fish must be consumed within a short period of time. Fish and other food items are, the most of time, required to be dried in closed areas since those nutrients can be protected from the harm of insects, dust, and rain. Thereby, it can be considered that drying nutrients in closed areas is healthier than under the sun in open areas [1-4].

The available energy in a system at various stages can be determined by the exergy analysis. The exergy method offers valuable information in designing a system to choose the required component configuration and operation procedure. The knowledge of the application of exergy analysis is far more effective in evaluating the

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configuration, running costs, and energy conservation [5]. In this respect, it is possible to list the works of some studies as follows. Prommas et al. [6] studied energy and exergy analysis in the drying porous media to determine a suitable size and drying conditions. They suggested that the effects of energy and energy analysis can be applied to determine the effects of porosity and grain size in different drying processes of porous materials. Akpinar et al. [7] studied the drying of potato slices in a cyclone type dryer and examined the energy and exergy. They pointed out that the 1 st tray in which the available energy was less used during the single-layer drying method acts as an exergy loser. In another study, Akpinar [8] examined the drying of red pepper slices using exergy and energy analysis. The exergies for inflow, outflow, and thus losses were observed to be increased while the rising temperature of the air used in the drying process. Dincer and Sahin [9] developed a new model for the exergy analysis for a drying process by using the first and the second law of thermodynamics. Corzo et al. [10] dried cordoba slices at various temperatures and velocities of air and the energy and exergy analysis was performed for the thin-layer drying process. In energy and energy research, Boulemtafes-Boukadoum and Benzaoui [11] conducted a research about the drying of mint in the solar drier. The drying of pumpkin slices in cyclone dryers was examined by Akpinar et al. [12]. Aghbashlo et al. [13] performed a study about the microencapsulation drying process for fish oil by performing an energy and exergy analysis. The drying of green olives in a tray drier was investigated by Colak and Hepbasli [14] using the method of exergy analysis at various air temperatures and constant air humidity of 15 percent. It was reported that the performance values for the exergy were varied in the range of 68.65-91.79 percent for the considered drying air temperatures while varying flow rates between 0.01 kg/s-0.015 kg/s. In addition, there have recently been encountered some investigations related to energy and exergy analysis of drying some products in the solar collectors in the literature [15,16].

Today, energy consumption is increasing at the same rate in parallel with the increase in the human population. Researchers are constantly doing research to reduce energy consumption in every espect of life. Thereby, it is very important to execute an exergy analysis besides energy use for drying processes. Furthermore, there have been few studies related to drying of fish in the tunnel drier in terms of energy and exergy analysis in the related literature. It is considered that the data obtained in the present study are crucial for researchers who will study on this subject and in this respect, the present investigation can make some contributions to the literature about drying of fish and drying systems. Therefore, the aim in the present paper is to examine the energy and exergy analysis of the thin-layer drying process of a kind of fish in a tunnel drier of the square cross-section at different inlet air temperatures. Methods for increasing the energy efficiency in the present dryer can be implemented to dry other products in the same drier.

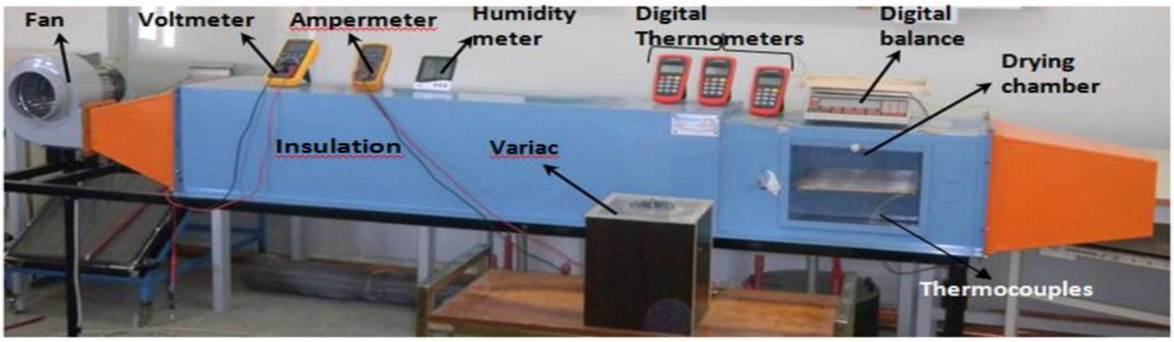
2. Material and Procedure

2.1 Material

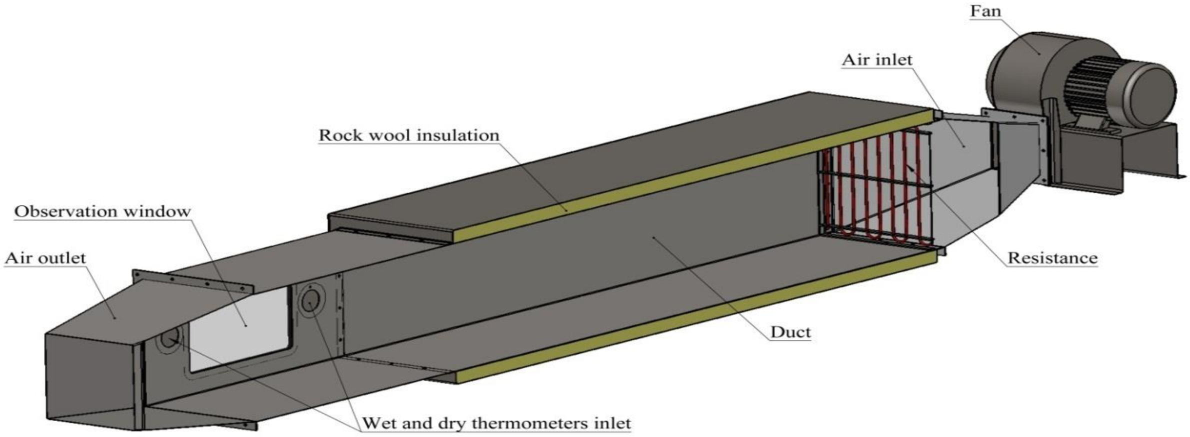
The fish used in the experiments were obtained from fresh waters (Keban dam) in Elazig in Turkey. The samples used in the experiments were chosen to be about the same size, an average weight of 200 grams, in order to obtain the accurate experimental results.

2.2. Experimental set-up

The set-up of the drier system for the present study is represented in Figure 1. As can be seen in the figure, a 375 W electric fan, drying chamber, heater resistance, and some instruments for measuring some variables such as temperature, weight, etc. are the main parts of this drier. The heating system consists of an electric heater which is mounted in the duct (maximum power of 1000 W). The heater power control regulates the drying chamber temperature. The fan velocity control unit regulates the inlet airflow rate. The drying duct of the square cross-section was made of a sheet of st-52 steel and has a length of 2000 mm, a width of 300 mm, a height of 300 mm, and a drying chamber length of 590 mm as well. The instruments used for temperature measurement are three K-type thermocouple numbers that can be operated manually with a two-channel digital thermometer (CHY, 806 AW, with the accuracy of ±0.1°C). A digital anemometer (RAM DT-619, m/s - range: 0.4 - 3 m/s, precision: 3 percent) measures the air velocity lasting from inside the device. A digital balance (Avery Berkel, Model CC061) registers the amount of moisture loss at an interval of 10 minutes during the drying process and those data were used to calculate the rate of moisture removal. The digital balance with the range in between 0 and 6000 g having the accuracy of ±0.1g was used to record weigh losses of samples. The power consumed by the heater was measured by the Wattmeter connected to the electrical supply side of the heater.



a)



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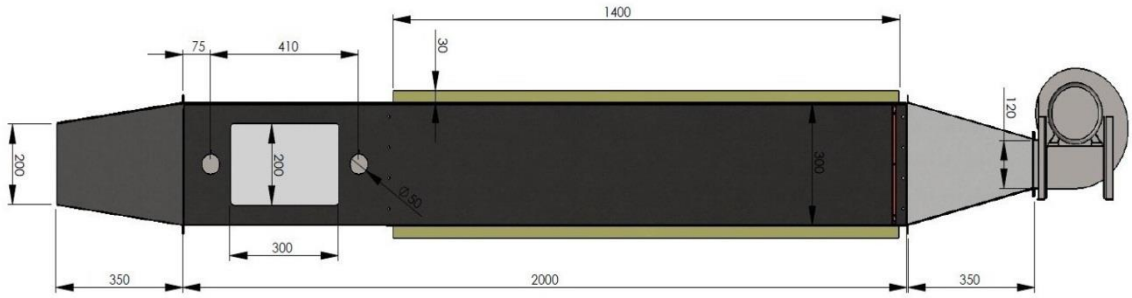

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Figure 1. Experimental set up: a) experimental set-up, b) the schematic presentation of the experimental set-up, c) the dimensions of the experimental set-up.

2.3. The mathematical formulation for drying curves

According to wet basis (w.b.), the moisture content is carried out with the following equation [17].

$$M_{wb} = \frac{M_w}{M_i} \tag{1}$$

Where, M_{wb} is moisture content, $M_{i,}$ the weight of fish at the beginning, $M_{W,}$ the amount of water. Equation (2) is the differential form of the drying velocity.

$$\lim_{\Delta t \to 0}\left(\frac{M_{t+\Delta t} - M_t}{\Delta t}\right) = -\frac{dM}{dt} \tag{2}$$

Here, $M_{t,}$ and $M_{t+\Delta t}$, stand for the weight of the sample (rainbow trout) at the time of t and t+Δt, respectively and dM/dt drying rate.

3. Analysis

A single-layer drying approach for energy and exergy analysis proposed by Midilli and Kucuk [5] was implemented in the present research study. The single-layer drying process is known to be a steady-flow process in the drying system in which the first and second thermodynamic laws are used to analyze the system.

3.1. The first law analysis

Energy analysis for drying of the fish in the tray dryer was applied to find the amount of energy and parameters of the single-layer drying using the first law of thermodynamics. In this process, steady-state conditions for conservation of mass and energy can be used to model air conditioning processes [5]. The following equations are usually used to determine the mass, the energy, the relative humidity, and the enthalpy and energy analysis for the single-layer drying processes [5, 18]:

Equation (3) states that the mass conservation for the drying process.

$$\sum \dot{m}_{dai} = \sum \dot{m}_{dao} \tag{3}$$

In this equation, $\dot{m}_{dai}$ and $\dot{m}_{dao}$ stand for mass flow rates of the inlet and outlet flows in the drier, respectively. Equation (3) with a little detail can be written as follows. In other words, the mass conservation for the drying air process can be expressed with Equation (4) also.

$$\sum (\dot{m}_{wi} + \dot{m}_{mp}) = \sum \dot{m}_{wo} \quad \text{or,} \quad \sum (\dot{m}_{dai} w_i + \dot{m}_{mp}) = \sum \dot{m}_{dai} w_o \tag{4}$$

In this equation, $\dot{m}_{mp}$ stands for the mass flow of moisture of the product, and $\dot{m}_{wi}$ and $\dot{m}_{wo}$ denote the mass flow rates of humidity of the inlet and the outlet air flows, respectively. w_i and w_o represent specific humidity for the inlet and the outlet flows, respectively.
Equation (5) represents energy conservation for the system at hand.

$$\dot{Q} - \dot{W} = \sum \dot{m}_{dao}\left(h_o + \frac{V_o^2}{2}\right) - \sum \dot{m}_{dai}\left(h_i + \frac{V_i^2}{2}\right) \tag{5}$$

In this equation h shows enthalpy; v, air rate; Q, heat; $\dot{W}$, work.
The relative humidity of the air used for the drying process can be found from Equation (6).

$$\phi = \frac{\omega P}{(0.622 + \omega) P_{sat@T}} \tag{6}$$

The potential and kinetic energy can be ignored in the entire drying process except for the fan's kinetic energy. Equations (7) - (9) were used for the calculation of the enthalpy of drying air while calculating the energy and exergy for the system.

$$h = c_{pda}T + wh_{sat@T} \tag{7}$$

The following equation is used to calculate the fan outlet enthalpy [19] in the present study.

$$h_{fo} = \left[\left(\dot{W}_f - \frac{V_{fo}^2}{2*1000}\right)\left(\frac{1}{\dot{m}_{da}}\right)\right] + h_{fi} \tag{8}$$

$h_{fi,}$ and h_{fo}, characterize enthalpies for the drying air at the inlet and the outlet of the fan, respectively. $\dot{W}_f$, fan energy, V_{fo} is the velocity of drying air at the fan outlet and $\dot{m}_{da}$, the air mass flow rate. By taking into account the enthalpy and dry-bulb temperature, Akpinar [7] used Eq. (8) to find the relative and specific humidity of the drying air at the outlet of the ventilator. The heater's inlet conditions and the outlet conditions of the fan are taken to be equal to one another in the calculations. As a convection heat source, the useful energy obtained from the heater described in Equation (9) enters the drying chamber.

$$\dot{Q}_u = \dot{m}_{da}c_{pda}(T_{ho} - T_{hi}) \tag{9}$$

Here, T_{ho} and T_{hi} are temperatures of outlet and inlet air flows in the heating portion, respectively. In the drying chamber, the inlet conditions were determined according to the drying air humidity and temperatures. For the drying air, the mass flow rate was calculated by considering the inlet conditions. The specific humidity of outlet flow at the drying chamber is determined using Equation (10) [6].

$$w_{pbo} = w_{pbi} + \frac{\dot{m}_{wp}}{\dot{m}_{da}} \tag{10}$$

In this equation, while $\dot{m}_{wp}$ shows the mass flow rate of the removed moisture, $\dot{w}_{pbi}$ and w_{pbo} stand for the specific humidity at the inlet and outlet of the chamber, respectively. Equation (11) is used to calculate the heat consumed for the humidification process in the drying chamber.

$$\dot{Q}_{pb} = \dot{m}_{da}\,(h_{pbi@T} - h_{pbo@T}) \tag{11}$$

3.2. The second law analysis

The thermal systems are usually analyzed using the second law of thermodynamics in terms of evaluation of exergy. In a system, the exergy can be taken into account as measuring of the available energy at various points. Exergy can be considered as an indicator of quality or energy grade that can be lost in the system in which the energy is consumed for processes. It is known that some of the energy that enters a thermal system by any means of energy sources is lost in the system on account of irreversibility. The available energy in a thermal system or the lost energy and thus, the efficiency of the system can be determined using the second law analysis. While performing the exergy analysis of the chamber, it was assumed that the steady-state condition at each point is valid. Energy consumption for the process at hand was determined by using an energy balance that is expressed as follows [20]. Equation (12) is utilized to perform the exergy balance.

$$Exergy = (u - u_\infty) - T_\infty(s - s_\infty) + \frac{P_\infty}{J}(v - v_\infty) + \frac{V^2}{2gJ} + (z - z_\infty)\frac{g}{g_c J}$$

Internal energy entropy work momentum gravity (12)

$$+ \textstyle\sum_c(\mu_c - \mu_\infty)N_c + E_i A_i F_i(3T^4 - T_\infty^4 - 4T_\infty T^3) + \cdots$$

Chemical radiation emission

Here the reference conditions are shown by the subscript ∞. Only some terms shown in Equation (12) are used to perform the exergy analyses for many systems because the available energy source can be magnetic fields, electric current flow, and material diffusion flow. One common simplification can be made by substituting enthalpy for PV terms and the internal energy into Eq. (12). The gravity and momentum terms are commonly disregarded in Eq. (12) during the evaluation of exergy. The further simplification can be done in Eq. (12) by ignoring pressure changes in the system by virtue of $v \approx v_\infty$. Therefore, Eq. (12) reduces to the following equation [18]:

$$Exergy = \bar{c}_p \left[(T - T_\infty) - T_\infty \ln \frac{T}{T_\infty} \right] \tag{13}$$

Eq. (13) can be used for the calculation of exergies for the inflow and outflow by taking into account of the inlet and outlet temperatures in the drying chamber. Thereby, the loss of exergy was calculated using Eq. (14).

$$\sum Ex_L = \sum Ex_i - \sum Ex_o = \bar{c}_{p_{da}} \left[(T_{dci} - T_{dco}) - T_\infty \ln \frac{T_{dci}}{T_{dco}} \right. \tag{14}$$

The exergy for inlet airflow in the drying chamber is determined from the following equation:

$$Ex_{dci} = Ex_{pbi} = \bar{c}_{p_{da}} \left[(T_{dci} - T_\infty) - T_\infty \ln \frac{T_{dci}}{T_\infty} \right] \tag{15}$$

The exergy for outlet airflow in the drying chamber is obtained from the following equation:

$$Ex_{dco} = Ex_{pbo} = \bar{c}_{p_{da}} \left[(T_{dco} - T_\infty) - T_\infty \ln \frac{T_{dco}}{T_\infty} \right] \tag{16}$$

The exergy efficiency can be defined as the ratio of the exergy of the product to that of the inlet flow in the drying chamber.

$$Exergy\ Efficiency = \frac{Exergy\ inflow - Exergy\ loss}{Exergy\ inflow} \tag{17}$$

When splitting operation is done, Eq. (17) becomes as follows:

$$\eta_{Ex} = 1 - \frac{Ex_L}{Ex_i}, \text{ or } \eta_{Ex} = \frac{Ex_o}{Ex_i} \tag{18}$$

4. Results and Discussion

4.1. Energy and Exergy Analysis

The rainbow trout fish was dried at the constant inlet air velocity of 1.5 m/s and various inlet air temperatures (38, 46, and 53 °C) in a tray dryer of cross-sectional area to actualize the energy and exergy analyses using a thin-layer drying approach and determine optimum conditions for the drier. In the present work, the magnitudes of energy consumption and exergy losses, the exergy of inlet flow and the outlet flow, and the efficiency of exergy were calculated depending on the drying time. Moreover, the rate of removed moisture of fish samples was depicted as a function of temperature. As mentioned previously, the adequate data concerning the drying behavior of the rainbow trout do not exist in the related literature. For this reason, the experimental results obtained from the present study are crucial for future investigations about the subject.

The moisture content depending on the drying rate for various inlet air temperatures (T = 38, 46, 53 °C) at the constant velocity (V=1.5 m/s) of the inlet air is illustrated in Figure 2. The maximum rate for the drying process takes place at the beginning of the drying process in which fish samples have the highest moisture contents as evidenced in the figure.

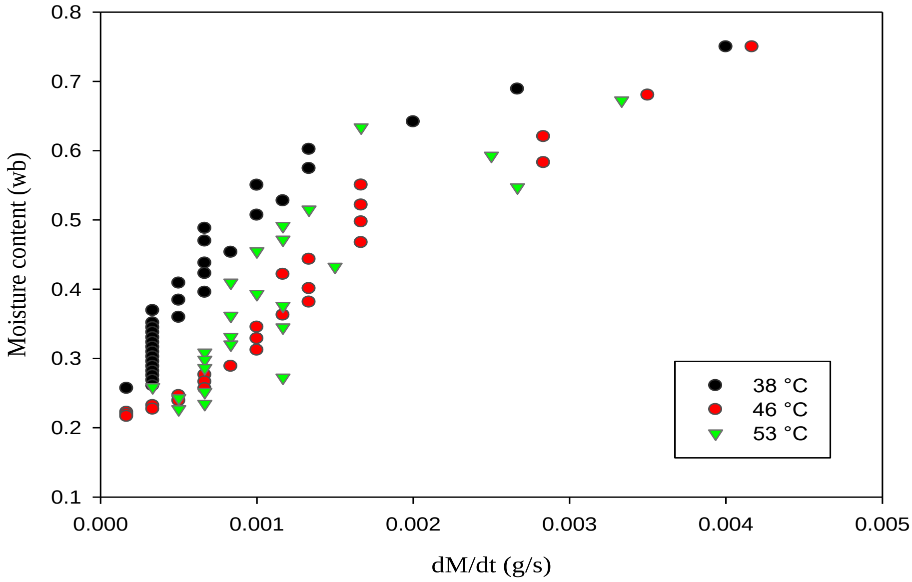

Figure 2. The moisture content depending on the drying rate for various inlet air temperatures at the constant inlet air velocity of (V=1.5 m/s).

Although it is not seen in Figure 2, both the moisture content of the specimen and drying rate reduces with increasing drying time. Figure 2 illustrates the relationship between moisture content and drying rate. Figure 3 illustrates the variations of energy utilization with the drying time for different inlet temperatures of 38, 46, and 53 °C at the constant velocity (1.5 m/s) of the drying air. The figure indicates that the use of energy by heater was large and becoming larger at the first stages of the drying process by virtue of the large amount of moisture content of the specimens, but it is observed that it lessens fast with increasing drying time on account of the low moisture content of the fish specimens at the ends of the drying. The use of the energy for drying processes varied depending drying temperatures and those were determined to be, respectively, between 0.0925-0.8480 kW, 0.2104-0.9770 kW and 0.1324-1.0297 for the drying carried out at 38 °C, 46 °C and 53 °C and at the constant velocity of 1.5 m/s. The figure shows that the lowest energy utilization occurs at the largest drying air temperature (53 °C) and the drying time in a range of 200 – 1200 min.

Changes of input and output exergy as a function of the drying time for various inlet temperatures (T = 38, 46, and 53 °C) at a constant velocity (V=1.5 m/s) of the inlet air are shown in Figure 4. The ambient air temperatures (T_∞) were measured to be 26.1 °C, 26.4 °C and 26.8 °C for drying air temperatures of 38 °C, 46 °C, and 53 °C, respectively. By considering the ambient and inlet temperatures, Eq. (15) was used to evaluate the exergy for inlet flow. On the other hand, the exergy for outlet flow was obtained from Eq. (16) with the use of the ambient and outlet temperatures. As expected when inlet temperature increased, the exergy for inlet flow increased. The exergy for inlet flow in the drying chamber changed between 0.2321-1.0893 kJ/kg depending on the temperatures of inlet air. Exergy for outlet flow was observed to be increased with increasing drying air temperatures and the values for those were found to be between 0.0679-0.2321 kJ/kg at 38 °C, 0.2803-0.5352 kJ/kg at 46 °C, 0.5936-1.0295 kJ/kg at 53 °C. These temperature values are the drying air temperatures. The exergy for inlet and outlet flows increases with increasing drying air temperature and the lowest energy losses take place at the lowest drying air temperature at present operation temperatures as proved in Figure 4. The data illustrated in Figure 4 are qualitatively in agreement with the results given in Figure 4 at the Ref. [8] in which different material was dried. During the experiments, sometimes the inlet temperature could change slightly due to voltage fluctuations. However, this negligible fluctuation was ignored and the inlet temperatures were taken to be the constant in the calculations.

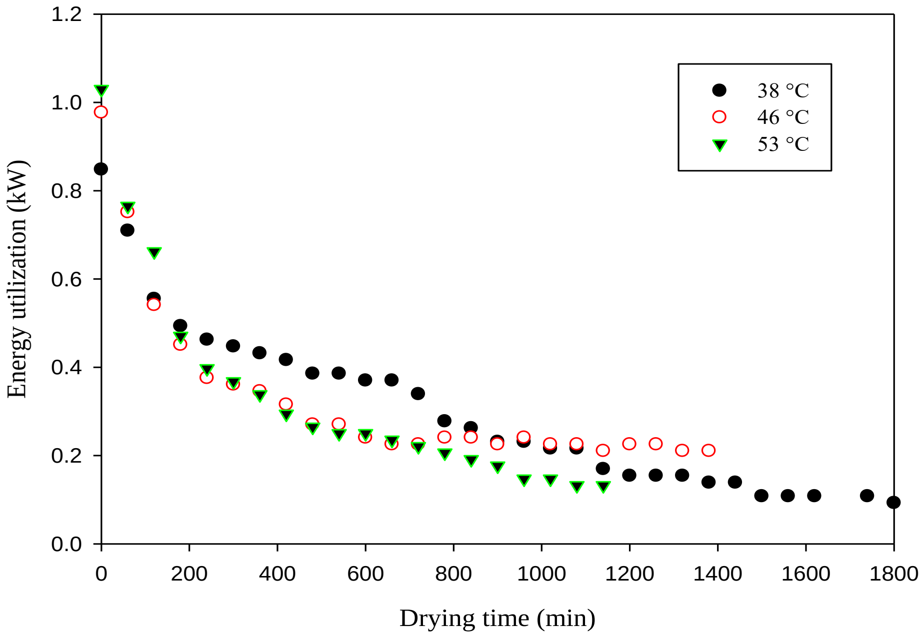

Figure 3. Changes of energy use as a function of drying time for various temperatures of the inlet air at the constant velocity (V=1.5 m/s).

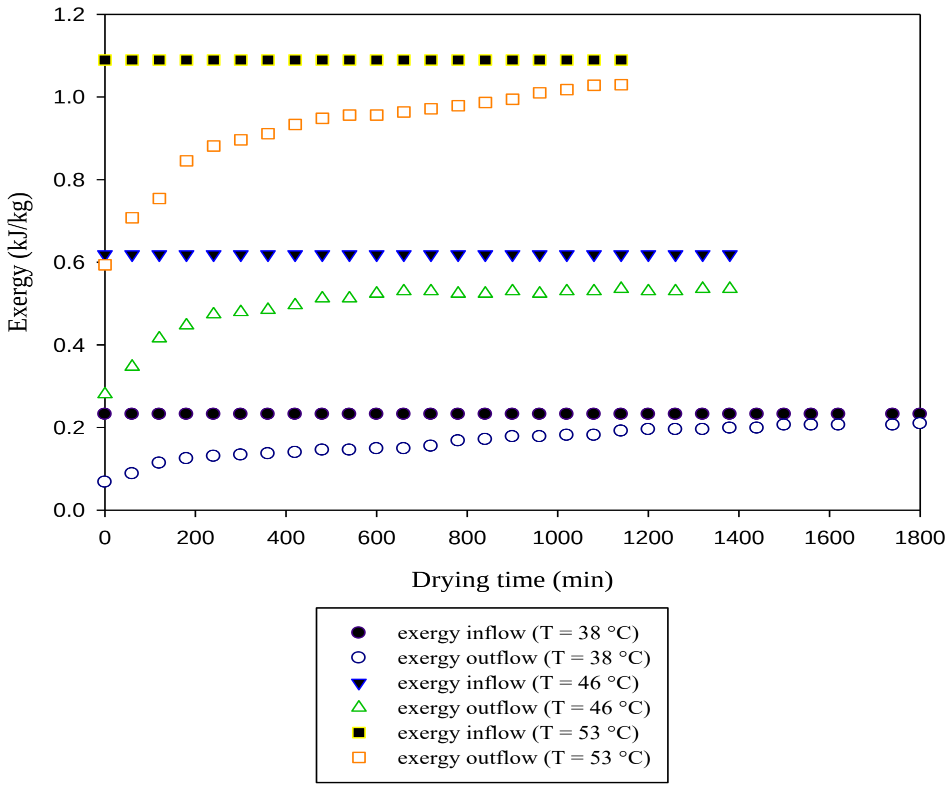

Figure 4. Changes of exergy depending on the drying time for various inlet temperatures in the drying chamber at the constant inlet velocity (V=1.5 m/s).

Figure 5 demonstrates the changes of exergy losses as a function of drying time for various values of inlet temperatures (T = 38, 46, and 53 °C) at the constant velocity of 1.5 m/s. The figure indicates that the larger temperature of inlet air temperature causes larger exergy losses. Exergy losses at each drying temperature were calculated from Eq. (14) and found to be in ranges of 0.0225-0.1642 kJ/kg at 38 °C, 0.0837-0.3386 kJ/kg at 46 °C, 0.0598-0.4957 kJ/kg at 53 °C. The figure points out that the lowest exergy losses occur at the lowest drying air temperature and the largest exergy losses happen at the highest drying temperature (53 °C) at drying time in a range of 0 – 900 min. In this context, Figure 6 agrees with Figure 5. Figure 6 illustrates the changes in exergy efficiency as a function of the drying time for various inlet temperatures (T = 38, 46, 53 °C) at constant velocity (V=1.5 m/s). The exergy efficiency increases with drying time as evidence in Figure 6. For the drying chamber, the exergy efficiencies were obtained in ranges of 29.27-94.50 % for various air temperatures at the constant velocity. As can be seen from the figure the efficiency of exergy increases with an increase in the drying air temperature. So, the highest exergy efficiency was obtained at the largest drying air temperature. Also, during the drying processes, interior temperatures of products were calculated to be between 22.5-33.5 °C at 38 °C, 24.5-40.5 °C at 46 °C, and 23-46 °C at 53 °C. As mentioned previously 38 °C, 46 °C and 53 °C are the drying air temperatures.

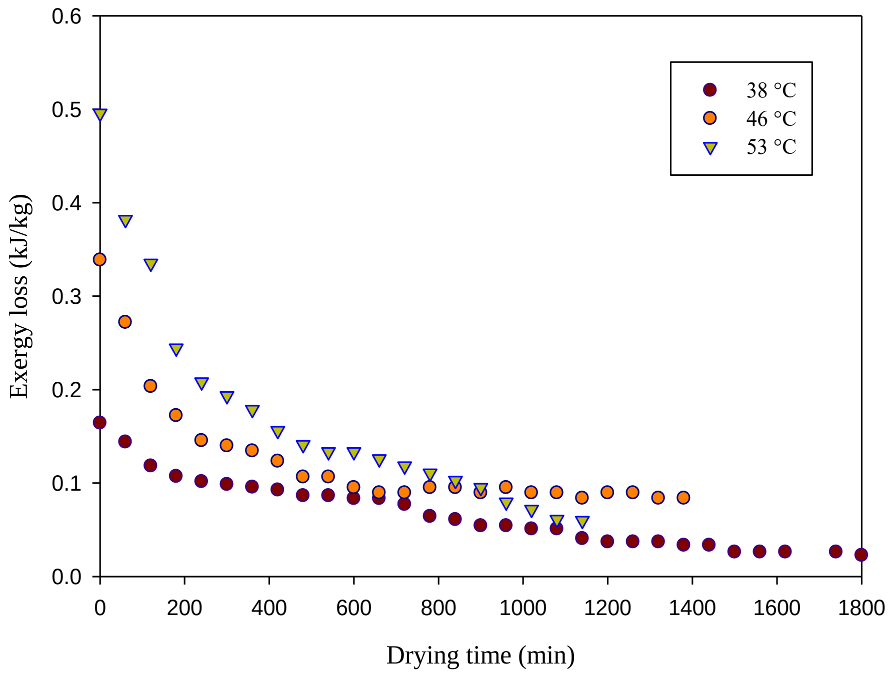

Figure 5. Changes of exergy losses in the drying chamber as a function of drying time for inlet temperatures at the constant velocity (V=1.5 m/s).

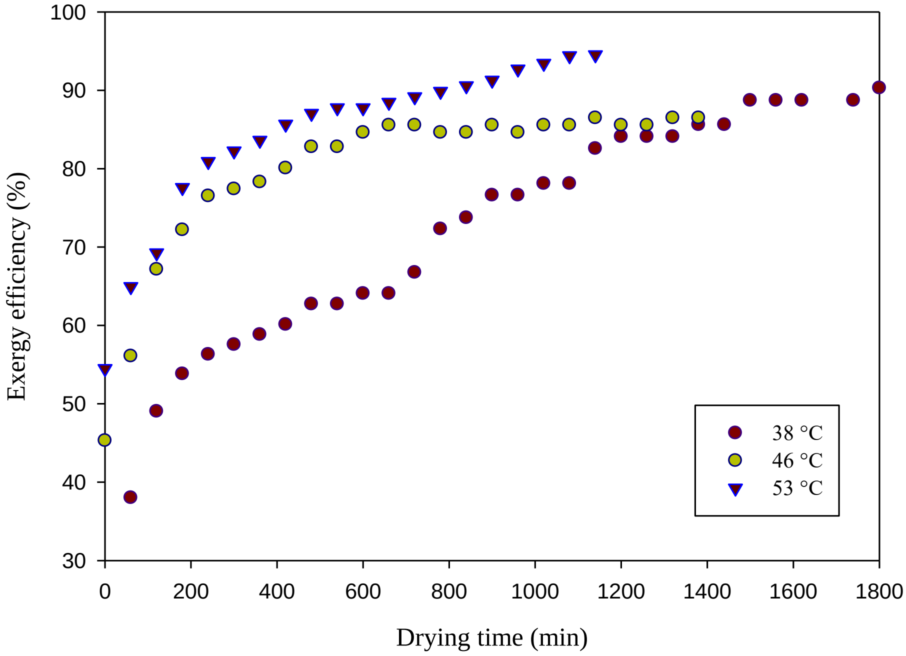

Figure 6. Changes of exergy efficiency in the drying chamber as a function of drying time for various inlet temperatures at the constant velocity (V=1.5 m/s).

4.2. Uncertainty for Experimental Study

It is expected that some errors can be occurred during the experimental study on account of instruments used in measuring effective parameters, electronic oscillations, and unknown causes, etc. The following equation [21] can be used for analysing errors that happened during performing experiments.

$$W_x = [(x_1)^2 + (x_2)^2 + \ldots\ldots\ldots\ldots\ldots\ldots + (x_\infty)^2]^{1/2} \quad (19)$$

Table 1. Uncertainties for the parameters measured in the present work.

Parameter	Unit	Total error
The temperature	°C	±0.07
The inlet velocity	m/s	±0.025
Mass for moisture	g	±0.1
The moisture content in dimensionless form	min	±0.2
Moisture loss	min	±0.17

As can be seen from Table 1 total error of the measured parameters is quite low.

5. Conclusions

In the present study, drying of fish samples in the tray dryer of cross-sectional area has examined by performing energy and exergy analysis using the thin layer drying approach. The effects of drying temperatures namely the inlet air temperature at the constant air velocity on the drying process were examined using the first and second law of thermodynamics. It is noticed that the surface of the samples does not change with the variation of inlet air temperature considered here.

The present study may lead to the following conclusions.

- While the inlet airflow exergies depending on drying air and ambient temperatures were found to be between 0.2321 - 1.0893 kJ/kg, those for outlet flow were obtained to be between 0.0679-0.2321 kJ/kg at 38 °C, 0.2803-0.5352 kJ/kg at 46 °C and 0.5936-1.0295 kJ/kg at 53 °C.
- The efficiency of exergy depending on the inlet air temperature (38, 46, and 53 °C) varied from 29.27 to 94.5% at a constant air velocity of 1.5 m/s.
- The largest use of energy was observed to be occurred at the first stages of the drying owing to the large moisture content of the specimen and decreased according to decreasing moisture content that lessens with drying time.
- Although the lowest exergy losses were observed to be taken place at the lowest drying air temperatures, the largest exergy efficiency was found at the highest drying air temperature at the considered operation temperatures.
- The exergy losses as a function of air temperature (38, 46, and 53 °C) were found to be in the range of 0.0225-0.4957 kJ/kg at the constant air velocity of 1.5 m/s.
- It was observed that the use of energy at all considered drying air temperatures reduced with an increase in the drying time.
- It can be said that the moisture content is almost proportional to the drying rate.

It can be suggested that to get a higher exergy efficiency and lower exergy loss, some parts of the experimental set-up can be improved.

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