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Specific Energy Consumption of Onion Slices During Hot-air Convection, Infrared Radiation and Combined Infrared-Convection Drying

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ABSTRACT

Total energy requirement and specific energy consumption for drying of onion slices were evaluated using various drying methods including hot-air convection, infrared radiation and hot air convection-infrared combination drying. Onion slices with initial moisture content of 7.31 g water/g dry solids, were dried to a final moisture content of 0.07 g water/g dry solids. Energy and specific energy consumption under the different drying conditions of the onion slices were compared. In particular, the experiments were carried out in convective dryer at three air temperature levels of 50, 60 and 70 ^{o}C and three air velocity levels of 0.5, 1.0 and 2.0 m/s. Experiments in the infrared dryer were done at three air velocity of 0.5, 0.7 and 1.0 m/s. For combination of infrared and hot-air convection drying, there were three air temperature levels of 40, 50 and 60 ^{o}C and three air velocity levels 0.5, 0.7 and 1 m/s while the infrared intensity was set at 0.15, 0.20 and 0.30 W/cm^2. Results of data analysis showed that the lowest and highest energy consumption levels in drying onion slices were associated with the hot air convection-infrared combination (IR-HA) and convection (HA) dryers, respectively. Specific energy consumption in the hot air dryer showed a downward trend with increasing air temperature and an upward trend with increasing air velocity. In infrared (IR) drying, it was observed that increasing the air velocity increases the drying time and consequently the amount of energy consumed. However, a reduction in energy IR-HA was noted with increasing infrared intensities under combination drying relative to infrared drying alone. Therefore, IR-HA drying of onion slices proved to have the lowest specific energy consumption and therefore the most efficient.

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INTRODUCTION

Onion (*Allium cepa* L.) has been widely used even in ancient times as seasonings, for medical uses and as foods. In current times, onion is an important vegetable to serve as ingredients in dishes, as toppings on burgers, in seasonings, as chip coatings, and in a variety of other food products including ramen noodles and canned foods (Parveen Kumar *et al*. 2006). The demand for dried onions has increased and it is therefore necessary that an efficient and effective method of dehydrating this product be developed. Onion is semi-perishable and has a short storage life. Dehydration is one of the simplest ways to improve the shelf-life of fruits and vegetables by reducing the moisture content (Das *et al*. 2001). Dehydration operations are important steps in food processing industry that involves a process of moisture removal due to simultaneous heat and mass transfer. Drying provides cheaper transportation cost and smaller space demand during storage (Kalbasi 2003 and Sharma *et al*. 2005).

Dehydrated onion has become a standard food ingredient in a wide range of food products (Mazza and LeMaguer 1980) such as ketchup, soups, salad dressings, sausage and meat products, potato chips, crackers, and many other convenience foods (Kaymak-Ertekin and Gedik 2005). Direct solar drying as a conventional and traditional approach is strongly questioned due to numerous problems such as contaminations, dusts, damages caused by insects, birds and precipitations. As a consequence, industrial dryers have been developed in order to eliminate most of these problems (Kostaropoulos and Saravacos 1995).

Hot air convection drying is one of the oldest techniques and the most commonly used methods of food drying. Over 85% of industrial dryers use convective hot air systems to drive the evaporation process from the food. Convective drying is accomplished when the heated air is brought into contact with the wet material to be dried to accelerate heat and mass transfer (Zlatanović *et al*. 2013). The major disadvantages of hot air drying are

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low energy efficiency and lengthy drying time during the falling rate period which causes low thermal conductivity. Subsequently, heat transfer in food products during conventional heating is limited (Doymaz 2004; Nowak and Lewicki 2004 and Pan *et al.* 2008). The problems associated with hot air convective dryers have encouraged researchers to investigate other technologies such as infrared, microwave and vacuum drying of agricultural products.

Infrared radiation heating offers many advantages over conventional hot air drying. When infrared radiation is used to heat or dry moist materials, the radiation impinges the exposed material and penetrates it and then the energy of radiation converts into heat (Hebbar and Rostagi 2001). Since a material is heated intensely, the temperature gradient is small. Therefore, energy consumption in infrared drying process is relatively low. Introduced energy is transferred from the heating element to the product surface without heating the surrounding air (Jones 1992). The use of infrared radiation technology in dehydrating foods has several advantages. These may include decreased drying time, high energy efficiency, high quality of finished products, uniform temperature in the product while drying, and a reduced necessity for air flow across the product (Celma *et al.* 2009, Nowak and Lewicki 2004, Shi *et al.* 2008 and Baysal *et al.* 2003). The major influencing parameters in infrared radiation drying are air velocity and intensity of radiation (Wang 2002).

Application of combined electromagnetic radiation and hot air heating is considered to be more efficient over radiation or hot air heating alone as it gives the synergistic effect. Datta and Ni (2002) reported the application of combined infrared, microwave and hot air heating of food materials. Energy and quality aspects were studied during combined far infrared and convective drying of barley (Afzal *et al*. 1999). A laboratory scale batch dryer was used for this purpose. The total energy required for the IR-HA mode drying was reduced by nearly 245% when compared with HA drying at 70 ^{o}C. The IR-HA drying provides the synergistic effect, resulting in an efficient drying process. The convective flow of air removes the moisture from the surface, besides lowering its temperature, which results in increased mass transfer (Kocabiyik and Tezer, 2009 and Wanyo *et al.* 2011). An advantage of using combined convective-infrared heat transfer method is that due to radiation heat transfer, the dried product has a higher quality, and the drying time is shorter compared to HA or IR drying alone, while energy consumption is reduced (Meeso *et al*. 2008 and Hebber *et al*. 2004).

Although considerable data exists in the literature regarding the specific energy consumption for drying of various agricultural commodities such as mulberry (Akbulut and Durmus, 2010), garlic cloves (Sharma and Prasad, 2006), pistachios (Midilli and Kucuk, 2003), longan (Tippayawong *et al.* 2008), nettle leaves (Alibas, 2007), carrot slices (Aghabashlo *et al.* 2008), red pepper (Akpinar, 2004), potato (Akpinar *et al.* 2005), porous media (Prommas *et al*., 2010) and carrot cubes (Nazghelichi *et al*., 2010), little information is available on the evaluation and comparison of total energy consumption and specific energy consumption in drying of onion slices using different drying methods.

The objectives of this study were to evaluate and compare the specific energy consumption during the drying of onion slices under three drying methods: (1) hot-air convection drying (HA), (2) infrared drying (IR) and (3) combined infrared radiation and hot air convection (IR-HA) drying.

MATERIALS AND METHODS

1.1. Materials:

The fresh onions (Allium cepa L.) of the white variety were used in the present study. They were procured in bulk from the local market and then stored in a refrigerator that was maintained at 4 ^{o}C and 60 % relative humidity. The onions were hand peeled, cut into slices of approximately 5 ±0.1 mm thickness using a sharp stainless steel knife. Three measurements were made on each slice for its thickness, using a verniercaliper and the corresponding average values were considered and those slices that did not meet the requirements were removed.

1.2. Drying equipment:

The schematic views of the experimental convection hot-air dryer (HA) used in this study is shown in Fig (1-A). The dryer consisted of three basic units; a fan that provided the desired drying air velocity, a heating unit coupled with an air temperature control system, and the drying chamber.

The experimental dryer with the infrared radiation heaters (IR) is shown in Fig. (1-B). The tube type infrared heaters were electrically powered and were installed in the drying chamber as show while ambient air could be blown across the chamber using a fan.

The IR-HA dryer is shown in Fig. (1-C). The three components of the dryer are the drying chamber having a tube type infrared emitters and hot air heaters. The air velocity was regulated with the help of an air control valve placed in the air supply line to the drying chamber.

Air was forced through the dryers using a centrifugal blower and the velocity of air was controlled by use of an air control valve in all dryers. The air velocity inside the drying chamber was measured at a position just above drying tray surface using a hot wire anemometer (Testo 405 V1). Air was heated as it passed through two spiral type electrical heaters that had a heating capacity of 1.5 kW each. The air temperature was measured using T-type thermocouples (Testo 925) connected to a data logger measuring to an accuracy of ±1°C.

1.3. Drying procedure:

The initial moisture content of fresh onion was measured by drying a 20 g sample in an oven set at 105 ^oC for 24 hours and was expressed in g water/g dry matter (AOAC 1990). The initial moisture content of the onion sample varied between 7.30 and 5.99 g water/g dry matter.

The dryers were run without the sample for about 30 minutes in order to reach set conditions before each drying experiment. The drying conditions were as follows:

1) HA: The dryer was operated at three temperature levels of 50, 60 or 70 ^oC and three air velocity levels of 0.5, 1 or 2 m/s.

2) IR: the dryer was set at infrared radiation intensities of 0.15, 0.20 or 0.30 W/cm^2 and three air velocities of 0.5, 0.7 or 1.0 m/s were applied at 25 ±1^oC, ambient air temperature (no heating).

3) IR-HA: The experiments were performed at three levels of radiation intensity 0.15, 0.20 or 0.30 W/cm^2 and three air temperature levels of 40, 50 or 60 ^oC at three air velocity levels of 0.5, 0.7 or 1 m/s.

Drying runs at each experimental setting of infrared intensity, air temperature and air flow velocity were repeated three time and the average values were recorded. The runs performed in this study are presented in Table 1.

After dryer preparation and its adjustment for desired conditions according to the experimental plan, a 500 g mass of onion slices was placed in the drying chamber in a single layer. Every 15 minutes throughout the drying period, the mass of the drying onions was measured using a digital electronic balance (METTLER PM30, Germany) having an accuracy of ± 0.01g. The drying was continued until the moisture content of onion slices was reduced to approximately 0.07 g water/g dry matter.

1.4. Specific energy consumption:

The total energy consumption was defined as the sum of the electrical energy consumed during drying process and included the energy used to drive the fan, and energy for heating the air. In the infrared dryer, the total energy consumption is the sum of energy consumed by the infrared heater and the ventilator fan that is used in moving the air. The amount of energy consumed in the IR-HA dryer is obtained from the sum of the energies used to heat the air, drive the fan and in the infrared heater elements. This energy was measured using a digital electric counter (Kaan, type 101) with 0.01 kWh precision.

The specific energy consumption was estimated, in all of the three dryers by considering the total energy supplied to dry onion slices from initial moisture content of about 7.30 kg water/kg dry matter to the desired moisture content of approximately 0.07 kg water/kg dry matter. The specific energy consumption (SEC) of onion slices during drying at different drying methods was expressed in MJ/kg of water evaporated, and calculated according to Eq.1 (Tarhn *et al*. 2010):

$$\mathrm{SEC} = \frac{\text{Total energy supplied in drying process ,MJ}}{\text{Amount of water removed durin g drying ,kg}} \qquad (1)$$

RESULTS AND DISCUSSION

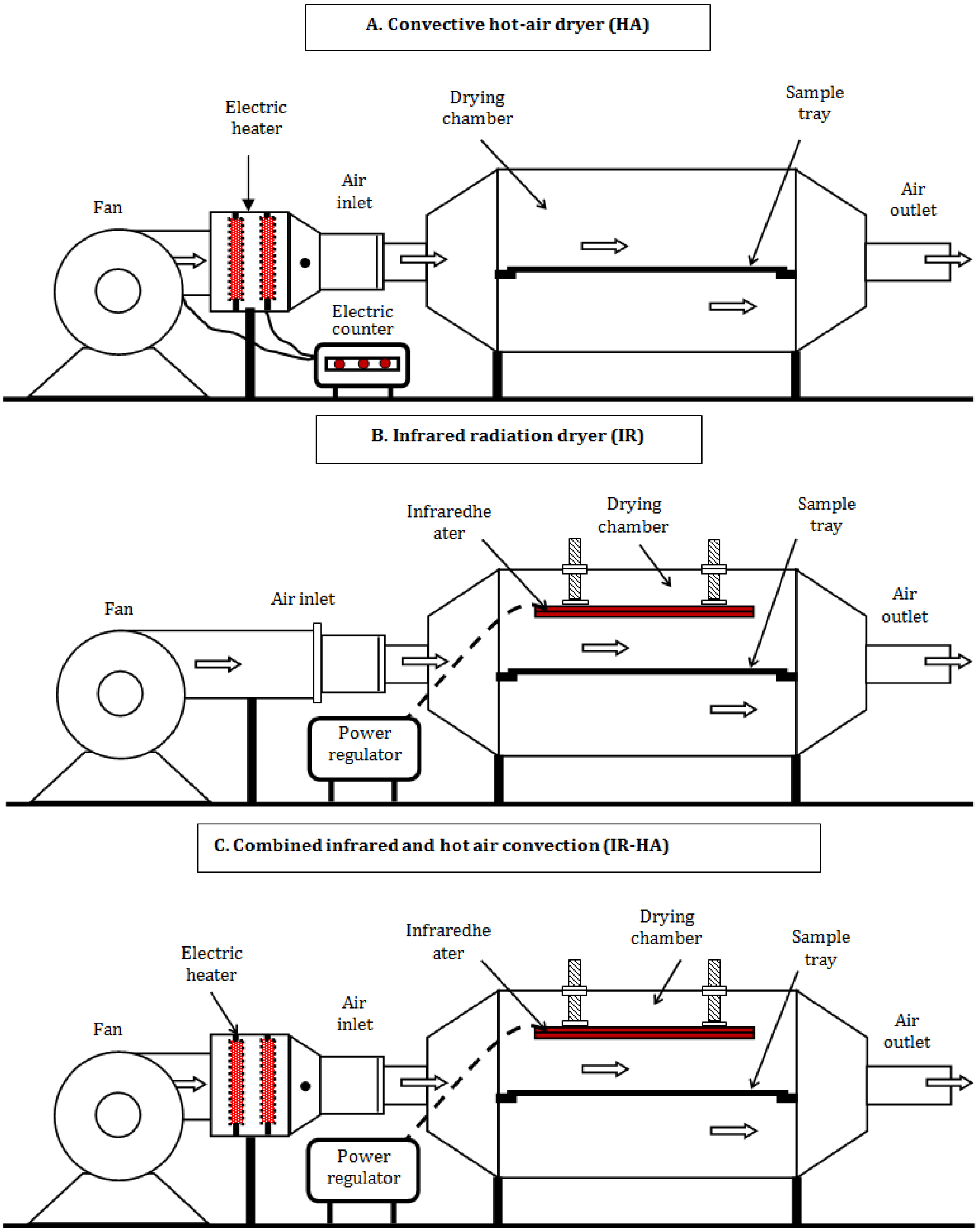
2.1. Hot air convection drying (HA):

The specific energy consumption under HA drying conditions is presented in Fig. 2. It is evident from Fig. 2 that the specific energy consumption when drying onion slices in the HA dryer decreased with increase in air temperature at constant air velocity while it increased with air velocity at constant air temperature. The minimum value of specific energy consumption for drying of onion slices was observed at 70 ^oC and 0.5 m/s air velocity and was 43.34 MJ/kg of water evaporated. The maximum specific energy consumption value was 84.68 MJ/kg and was observed at an air temperature 50 ^oC and 2.0 m/s air velocity. The SEC values are comparable to the value of 64 MJ/kg determined by Jindarat *et al*. (2011) for hot air drying at 70^oC. Sharma and Prasad (2006) found values that ranged from 140-215 MJ/kg while drying garlic and their values showed a decreasing trend with increase in air temperature within the range of 40 to 70^oC although the SEC values are decidedly higher. It is clearly depicted that drying at higher air velocities results in higher energy consumption. It can also be seen that specific energy consumption decreased with air temperature, which implies that the dryer is more efficient when operating at the lower air temperature (EL-Mesery and Mwithiga 2012 and Aghbashlo *et al*. 2008).

Multiple regression analysis was used to determine the relationship between air velocity, air temperature and specific energy consumption. The polynomial regression equation and the associated coefficient of determination (R2) are shown in Eq. 2.

$$SEC = 165.72 + 24.36\, V - 3.22\, T - 9.13\, V2 + 0.017\, T2 + 0.24\, V.\, T \qquad R^2 = 0.993 \qquad (2)$$

where, T is drying air temperature (^oC) and V is air velocity (m/s).



A. Convective hot-air dryer (HA)

B. Infrared radiation dryer (IR)

C. Combined infrared and hot air convection (IR-HA)

Fig. 1: Schematic diagram of the experimental dryers.

2.2. Infrared radiation drying (IR):

Fig. 3 represents the SEC inside an IR dryer at different infrared radiation intensities and air velocities. The lowest specific energy consumption is 7.81 MJ/kg and was obtained at a radiation intensity of 0.30 W/cm2 and air velocity of 0.5 m/s. The maximum specific energy consumption was 20.73 MJ/kg obtained at 0.15 W/cm2 and 1.0 m/s. A reduction in (SEC) was observed with increase of radiation intensity and decrease in air velocity. The increase in specific energy consumption with air velocity can be attributed to the cooling of the sample's surface by the passing air inside the drying chamber resulting in total heat loss to the drying chamber. Also, increasing infrared intensity, causes an increase in sample temperature and evaporation rate and a decrease in drying time and the specific energy for drying of onion slices (Das *et al*. 2004 and Ruiz Celma *et al*. 2009).

Kocabiyik and Tezer (2009) used three levels of infrared radiation intensity (300, 400 and 500 W) and at air velocities (1.0, 1.5 and 2.0 m/s) for drying of carrot in an infrared dryer, and found that the specific energy consumption values varied between 12.22 and 14.58 MJ/kg evaporated water for all the drying conditions.

Table 1: Processing conditions adopted during drying of onion slices.

Run	Drying methods	Drying air temperature, ^oC	Drying air velocity, m/s	Infrared intensity, W/cm^2
1	HA	50	0.5	-----
2		60	0.5	-----
3		70	0.5	-----
4		50	1.0	-----
5		60	1.0	-----
6		70	1.0	-----
7		50	2	-----
8		60	2	-----
9		70	2	-----
10	IR	-----	0.5	0.15
11		-----	0.5	0.2
12		-----	0.5	0.3
13		-----	0.7	0.15
14		-----	0.7	0.2
15		-----	0.7	0.3
16		-----	1.0	0.15
17		-----	1.0	0.2
18		-----	1.0	0.3
19	IR-HA	40	0.5	0.2
20		40	0.5	0.3
21		40	0.5	0.15
22		50	0.5	0.2
23		50	0.5	0.3
24		50	0.5	0.15
25		60	0.5	0.2
26		60	0.5	0.3
27		60	0.5	0.15
28		40	0.7	0.2
29		40	0.7	0.3
30		40	0.7	0.15
31		50	0.7	0.2
32		50	0.7	0.3
33		50	0.7	0.15
34		60	0.7	0.2
35		60	0.7	0.3
36		60	0.7	0.15
37		40	1.0	0.2
38		40	1.0	0.3
39		40	1.0	0.15
40		50	1.0	0.2
41		50	1.0	0.3
42		50	1.0	0.15
43		60	1.0	0.2
44		60	1.0	0.3
45		60	1.0	0.15

Using multiple regression analysis, a relationship was established between specific energy consumption, intensity of infrared radiation and air velocity. The relevant equation and coefficient of determination are present in Eq. 3.

$$SEC = 27.62 - 151.41\ V + 0.64\ IR + 290.66\ V2 + 12.47\ IR2 - 26.89\ V.\ IR \quad R^2 = 0.996 \quad (3)$$

Where, IR is the intensity of infrared radiation (W/cm^2) and V is air velocity (m/s).

2.3. Combined infrared and hot air convection drying (IR-HA):

Figures 4-6 show the SEC for the drying of onion slices in an (IR-HA) dryer at various air velocities. It is clear that the SEC decreases with increase in both radiation intensity and air temperature. The SEC, at a fixed air velocity of 0.5 m/s, decreased with increasing infrared radiation intensity. This was also true for the other air velocity levels (0.7 and 1.0 m/s). This phenomenon is due to the increase in the intensity of radiation and the subsequent increased temperature of the onion slices. Thus, the temperature gradient of the product surface layer or underlying slices is increased, and as a result, the rate of moisture evaporation increases. Therefore, the required SEC decreases. As seen from Figs. 4-6 it can be observed that the SEC increases with increase in air velocity from 0.5 to 1 m/s. This increase in SEC due to an increase in air velocity can be associated with increased cooling of the sample surface at higher air velocities which causes moisture evaporation to decrease, consequently increasing the drying time. Similar trends have been observed by several researchers (Afzal and abe 1998; Jaturonglumlert and Kiatsiriroat 2010 and Sharma *et al*. 2005). Comparison of the SEC, at three air velocity levels, indicates that the lowest SEC occurring at 0.5 m/s air velocity, 0.30 W/cm^2 infrared intensity, and 60 ^{o}C air temperature, was 3.78 MJ/kg and the highest value occurred at an air velocity of 1.0 m/s, radiation intensity of 0.15 W/cm^2, and air temperature 40 oC was 22.07 MJ/kg. Multiple regression analysis of specific energy consumption, as a function of air temperature and intensity of the infrared radiation was performed and a relationship was obtained for each air velocity (Figs. 4-6). For 0.5 m/s this relationship is given by Eq. 4 while that for an air velocity of 0.7 and 1.0 m/s are presented by Eq. 5 and Eq.6, respectively.

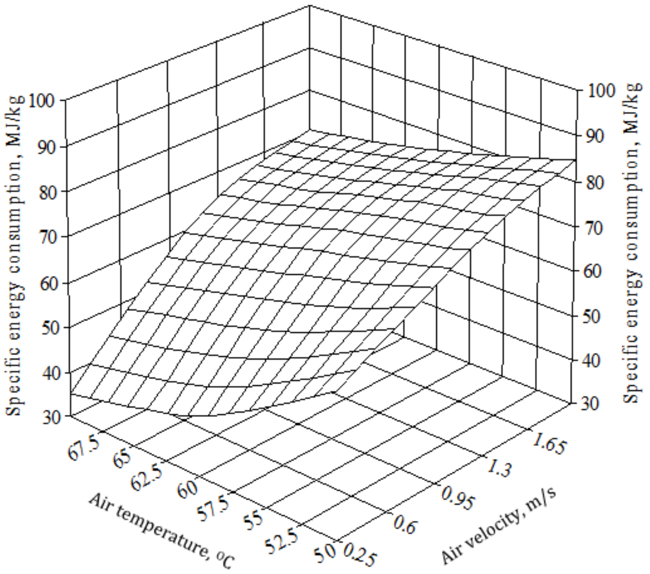


Fig. 2: Interaction effect of temperature and air velocity on the specific energy consumption for hot air convection drying of onion slices.

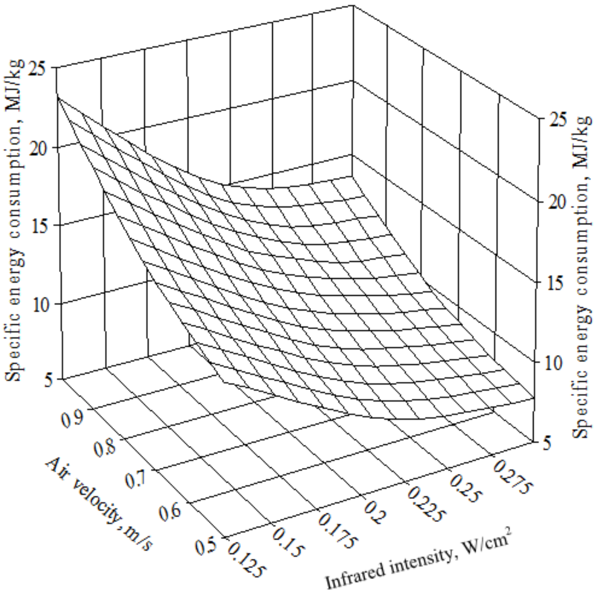


Fig. 3: Variation of infrared radiation intensity and air velocity with the specific energy consumption when drying onion slices.

$SEC = 19.13 - 14.45\ IR - 0.19\ T + 8.86\ IR2 - 4.18\ T2 - 0.014\ IR.T$ $R2 = 0.998$ (4)
$SEC = 23.42 - 39.32\ IR - 0.03\ T + 11.18\ IR2 - 0.003\ T2 + 0.39\ IR.\ T$ $R2 = 0.994$ (5)
$SEC = 48.67 - 54.21\ IR - 0.61\ T + 69.15\ IR2 + 0.003\ T2 - 0.092\ IR.T$ $R2 = 0.994$ (6)
where IR is infrared radiation intensity (W/cm2) and T is drying air temperature (oC).

Based on the findings obtained for each of the three drying methods (HA, IR and HA-IR) for drying onion slices, the lowest SEC values obtained under these drying conditions (air temperature, air velocity and infrared intensity) investigated were compared in Fig. 7. The lowest amounts of specific energy were observed in the (IR-HA) dryer while the highest amount was recorded while drying in the (HA) dryer.

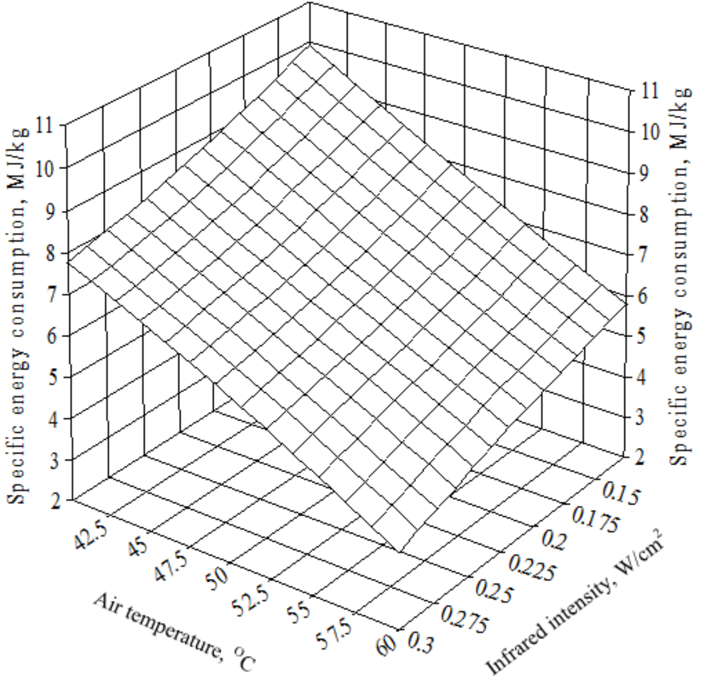


Fig. 4: The influence of infrared radiation intensity and air temperature on specific energy consumption when drying onion slices in combined infrared and hot air convection dryer at air velocity 0.5 m/s.

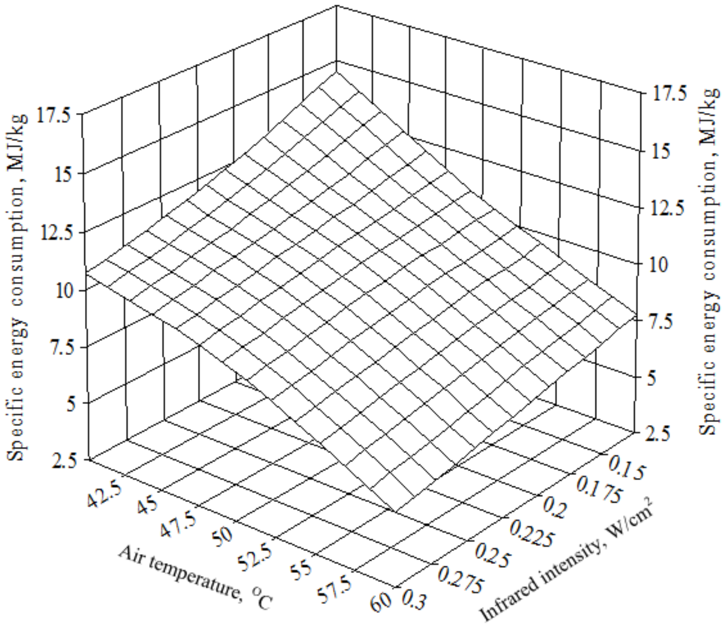


Fig. 5: Variation of infrared radiation intensity and air temperature on specific energy consumption when drying onion slices in combined infrared and hot air convection dryer at air velocity 0.7 m/s.

The direct heating of the onion slices by the infrared radiation, which driving the moisture to the surface, combined with the hot air, which readily absorbs and carries the moisture away from the surface, ensures that limitations to the rate of drying are not due to convective removal. Other researchers who had observed a reduction in specific energy consumption when drying products under a combined mode of heating include Afzal *et al*. (1999), Sharma and Prasad (2006), Meeso *et al*. (2008) and Wanyo *et al*. (2011).

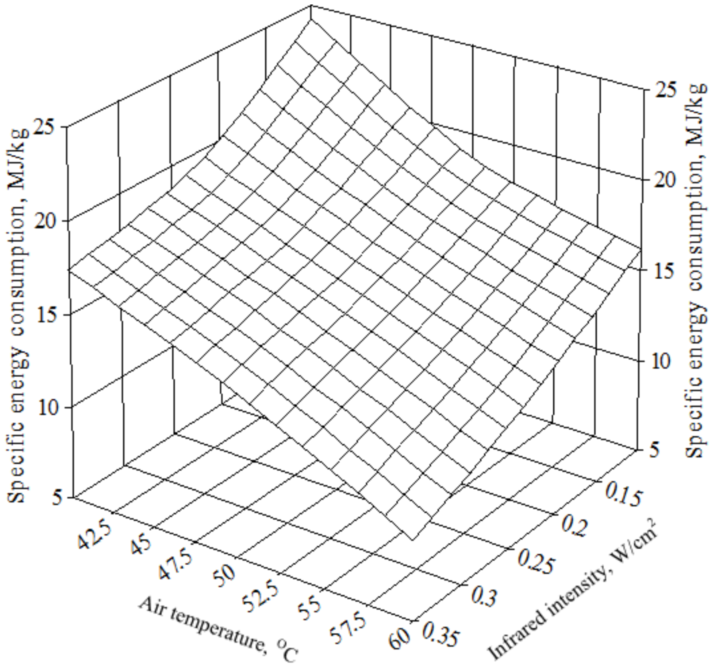


Fig. 6: The influence of infrared radiation intensity and air temperature on specific energy consumption for combined infrared and hot air convection drying of onion slices at air velocity 1.0 m/s.

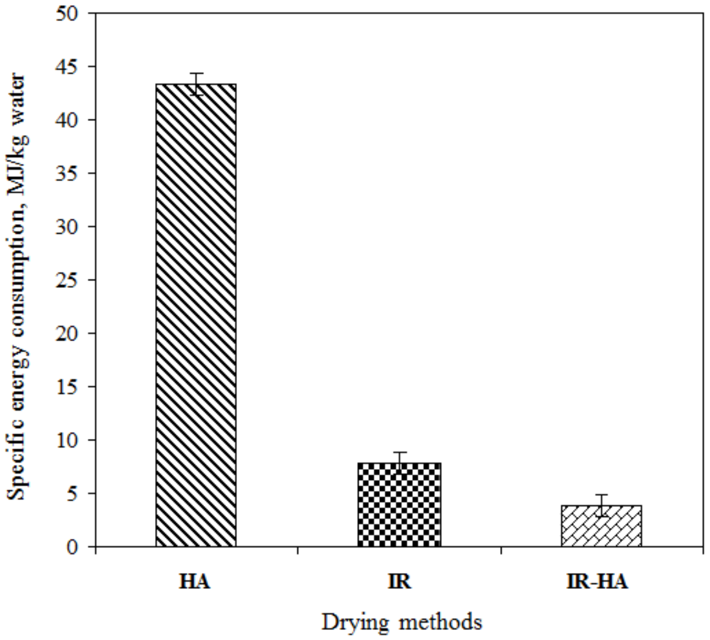


Fig. 7: Specific energy consumption during the drying of onion slices under different drying methods.

3. Conclusion:

This study was conducted to evaluate specific energy consumption in various dryers including hot-air convection, infrared drying, and combined infrared-hot air convection drying. Tests were conducted using onion slices under various experimental conditions as follows. Results of data analysis showed that the lowest and highest specific energy consumption levels in drying onion slices were associated with hot air convection and combined infrared and hot air convection dryer, respectively. Specific energy consumption in the hot air drying decreases with increase in air temperature but increases with increase in air velocity. In drying onion using infrared radiation it was observed that increased air velocity increases drying time and consequently the amount of consumed energy. Conversely, specific energy consumption decreased with increasing radiation intensity. Using a combination of hot air and infrared drying decreased energy consumption relatively when compared to either infrared drying alone or hot air drying. Combined infrared and hot air convection drying of onion slices proved to have the lowest specific energy consumption.

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