COMPARISON OF ENERGY CONSUMPTION IN THE CONVECTIVE AND FREEZE DRYING OF RASPBERRIES

POREĐENJE UTROŠKA ENERGIJE ZA SUŠENJE MALINE KONVEKTIVNIM POSTUPKOM I SUŠENJEM ZAMRZAVANJEM

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ABSTRACT

Freeze-drying has proven to be one of the best drying processes thus far. The drying process itself lasts considerably longer than any other drying method. This paper makes a comparison of the energy consumption and time required for drying 100 kg of raspberries using lyophilization and convective drying. The calculations of energy consumption were performed for both drying methods, as well as their subsequent comparison. When calculating the energy consumption, special attention was paid to all consumers involved in the drying process (both directly and indirectly). The results obtained show that the energy consumption in the freeze-drying of raspberries was higher than that recorded in the convective drying method. The freeze-drying time was slightly more than 3 times longer than the convective drying time. Relative to the energy consumption and drying duration, the convective drying process was found to be far more efficient than the freeze-drying process.

Keywords: energy consumption, freeze-drying, lyophilization, convective drying, raspberry.

REZIME

Sušenje maline obavlja se sušenjem zamrzavanjem (liofilizacija). Dobijeni proizvod je kvalitetan. Liofilizacija je skup process. U radu upoređena je potrošnja energije i dužina trajanja procesa pri sušenju 100 kg maline postupkom sublimacionog sušenja i konvektivnog sušenja. Konvektivno sušenje obavljeno je u laboratorijskoj sušari "IVA-2" na Poljoprivrednom fakultetu u Novom Sadu. Za sušenje zamrzavanjem korišćen je laboratorijski liofilizator 2-4 LD plus, švajcarskog proizvođača Marthin Christ. Obavio se proračun potrošnje energije za oba oblika sušenja kao i njihovo poređenje. Prilikom proračuna potrošnje energije obratila se pažnja na sve potrošače uključene u process sušenja (direktno i indirektno). Obavio se proračun potrošnje energije za svaki postupak sušenja pojedinačno. Kod svakog procesa izdvojili su se glavni potrošači i izračunata je njihova potrošnja. Kod sublimacionog sušenja glavni potrošači su bili su: komora za zamrzavanje, liofilizator i vakum pumpa. Kod postupka konvektivnog sušenja ti potrošači bili su aksijalni ventilator i grejna tela tj. toplotna energija potrebna za isparavanje vlage iz maline. Takođe je utvrđena i dužina trajanja procesa sušenja. Dobijeni rezultati sušenja oba slučaja upoređeni su jedni sa drugima. Rezultati su pokazali da je potrošnja energije za process sušenja zamrzavanjem veća od procesa sušenja konvektivnom metodom. Dužina sušenja zamrzavanjem duže traje od sušenja konvektivnim postupkom.

Ključne reči: potrošnja energije, sušenje zamrzavanjem, liofilizacija, konvektivno sušenje, malina.

INTRODUCTION

Raspberries are one of the most demanding fruit crops to dry, requiring proper drying methods and time. The most common method of raspberry drying is sublimation drying (i.e. freeze-drying, lyophilization), which usually results in products of satisfactory quality. However, a major disadvantage of this drying method is the price of finished products (Ratti, C., 2001). One of the main reasons for the high price of freeze-dried products is the energy consumption in the freeze-drying process (Stamenković, Z., et al. 2016). The most significant item among the costs of dried fruit production refers to the costs of energy generating products. Moreover, the drying time is longer than in other drying processes. Conversely, the convective drying process, as one of the most commonly used methods of drying, results in products of somewhat lower quality (Sette, P. et al., 2016; Kowalski, S.J., et al., 2016). However, the drying process itself features lower energy requirements and a shorter drying time.

The purpose of this paper is to compare the energy consumption in two methods of raspberry drying, i.e. lyophilization, the most frequently used drying method at present and convective drying, the standard raspberry drying method. On the basis of the operating features of a lyophilizer and a laboratory convective dryer, owned by the Laboratory for

Biosystems Engineering at the Faculty of Agriculture in Novi Sad, the calculations of the energy consumption required for drying 100 kg of raspberries were performed. The calculations were done using the measurement values obtained and the values based on previous experience.

A comparison between the convective drying and freeze-drying of raspberries was based on the total energy input (kJ).

Nomenclature:

q (kJ)	- amount of energy
m (kg)	- mass
t (°C)	- temperature
c _p (kJ/kgK)	- specific heat
ω (kg/kg)	- moisture content in raspberries
i (kJ/kg)	- enthalpy
r (kJ/kg)	- heat of the phase change
P (kW)	- power
E (kJ)	- electric energy
Q	- amount of heat for a given mass

Greek symbols:

Δ	- difference of two parameters
τ	- time

Subscripts:

ukz	- total internal energy
w	- moisture
p	- from the liquid to the solid phase
l	- ice
sm	- dry matter
m	- raspberry
v	- water
ul	- total enthalpy
+	- temperature in the plus
-	- temperature in the minus
k	- convective drying
tz	- set temperature
iv	- evaporated water
70	- temperature
V	- fan
pu	- the total power of the pump
pl	- the lyophilizer pump 2-4 Ldplus
a2-4	- lyophilizer capacity 2-4 Ldplus
1	- first stage
2	- second stage
3	

MATERIAL AND METHOD

Raspberry fruits used in the experiment indicated a humidity of 84.6% (relative to the wet basis) and the following average sizes: 22.6 mm (length), 21.05 mm (width) and 18.32 mm (height).

The method of analysis and synthesis was applied in the research. All individual energy consumers for freeze drying and convective drying process were determined using method of analysis. The total energy consumption for both types of drying was determined by synthesis.

The following freeze-drying parameters were recorded: condenser temperature (-60 °C), absolute pressure (0.0010 mbar) and drying time (24 h). The catalog data values of the laboratory Lyophilizer 2-4 LD plus Marthin Christ were compared to the industrial data values obtained. Raspberries were frozen at a temperature of -40 °C (from an initial temperature of 20 °C) in a deep freeze chamber for 24 hours.

The convective raspberry drying was carried out using a convective dryer, i.e. in a thin immovable layer with a tapping of 2.5 kg/m², an air temperature of 50 °C and a duration of 15 hours. The air speed in front of the layer was 1 m/s.

The following energy consumers were included in the raspberry freeze-drying process:

- a cooling chamber for freezing raspberries from the initial 20 °C to -40 °C for a period of 24h,
- a vacuum pump providing and maintaining a pressure relief within the lyophilizer chamber (assuming that the pump works continuously for 24h in parallel with the lyophilizer),
- heat energy necessary for the sublimation process within the lyophilizer.

The following calculations of energy consumption were performed for all the energy consumers in the raspberry freeze-drying process:

1. Freezing chamber

A freezing chamber freezes raspberries from 20 °C to -40 °C. In order to freeze raspberries, it is necessary to take a certain amount of energy from the fruits. The heat energy that needs to be taken from raspberries can be classified as follows:

- energy needed to cool raspberries to a freezing temperature (-1,6 °C) - the first stage,
- energy needed to change the phase (from liquid to solid) - the second stage,
- energy needed to cool raspberries to a deep freeze temperature (-40 °C) - the third stage.

Equation 1 includes all the considerations noted above:

$$q_{ukz} = q_1 + q_2 + q_3$$

where

$$q_1 = 7929.36 \text{ [kJ]},$$

$$q_2 = 28170 \text{ [kJ]},$$

$$q_3 = 7191.18 \text{ [kJ]}.$$

The total internal moisture energy is equal to the sum of the energies q₁, q₂ and q₃ (1). The energy consumption equation is of the following form:

$$q_1 = m_m \cdot c_{pm} \cdot \Delta t_{12}$$

where

$$m_m = 100 \text{ [kg]},$$

$$c_{pm} = 3.671 \text{ [kJ/kgK]} \text{ i}$$

$$\Delta t_{12} = 21.6 \text{ }^\circ\text{C}$$

- third stage

The specific raspberry heat, for a temperature interval from 20 °C to -1.6 °C, was calculated using the following equation:

$$c_{pm+} = 0.837 \cdot m_{sm} + 4.187 \cdot m_w \text{ [kJ/kgK]}$$

where

$$c_{psv} = 0.837 \text{ [kJ/kgK]},$$

$$m_{sm} = 0.154 \text{ [kg}_{sv}/\text{kg}_m],$$

$$c_{pv} = 4.187 \text{ [kJ/kgK]}$$

$$m_w = 0.846 \text{ [kg}_{sv}/\text{kg}_m].$$

$$q_2 = m_m \cdot r$$

where

$$m_m = 100 \text{ [kg]} \text{ i}$$

$$r_m = 281.7 \text{ [kJ/kg]}.$$

The heat of the phase change in raspberries was calculated using the following equation:

$$r_m = r_1 \cdot 0.846$$

where

$$r_1 = 333.2 \text{ [kJ/kg]}$$

$$m_w = 0.846 \text{ [kg}_{sv}/\text{kg}_m].$$

$$q_3 = m_m \cdot c_{pm-} \cdot \Delta t_{23}$$

where

$$m_m = 100 \text{ [kg]}$$

$$c_{pm-} = 1.863 \text{ [kJ/kgK]} \text{ i}$$

$$\Delta t_{23} = 38.6 \text{ }^\circ\text{C}$$

The specific heat of raspberries, for a temperature interval from -1.6 °C to -40 °C, was calculated according to the following equation:

$$c_{pm-} = 0.837 \cdot m_a + 2.050 \cdot m_l \text{ [kJ/kgK]}$$

$$c_{psv} = 0.837 \text{ [kJ/kgK]},$$

$$m_{sv} = 0.154 \text{ [kg}_{sv}/\text{kg}_m],$$

$$c_{pl} = 2.050 \text{ [kJ/kgK]} \text{ i}$$

$$m_l = 0.846 \text{ [kg}_l/\text{kg}_m].$$

Due to the increased energy consumption, caused by the inadequate thermal insulation of the system, the degree of usefulness of the system, the air inside the chamber, etc., the final value of the total heat required to freeze 100 kg raspberry from 20 °C to -40 °C is multiplied by the arbitrary coefficient 1.2.

2. Sublimation process within the lyophilizer - freeze-drying process

Freeze-drying was performed at material temperature of -40 °C and a condenser temperature of -60 °C. The absolute pressure inside the chamber was 0.0010 mbar during the whole drying process. Considering the equilibrium moisture content of raspberries (6%), at a pressure of $p = 1$ atm and a temperature of 23 °C (Pavkov, I., et. al., 2017), the total amount of water to be evaporated for 100 kg of raspberries was 83.6 kg of moisture (Equation 8). The calculation of the removal of heat from raspberries using evaporation is expressed in the following equation:

$$m_1 = m_m \cdot \frac{\omega_1 - \omega_2}{100 - \omega_2}$$

where

$$m_m = 100 \text{ [kg]}$$

$$\omega_1 = 84,6 \text{ [%]}$$

$$\omega_2 = 6 \text{ [%]}$$

The calculation of the heat energy consumption in the sublimation process is expressed in the following equation:

$$m_{iv} = 83,6 \text{ kg moisture (in 100 kg of raspberry):}$$

$$q_{ul} = m_{iv} \cdot (r_1 + r_2) \text{ [kJ]} \text{ (Voronjec, D., et. al., 1985).}$$

where

$$r_1 = 411,6 \text{ [kJ]} \text{ (Kozić, D., et. al., 1994)}$$

$$r_2 = 2426,6 \text{ [kJ]} \text{ (Kozić, D., et. al., 1994) i}$$

$$m_{iv} = 83,6 \text{ [kg].}$$

Due to the increased energy consumption, caused by the inadequate thermal insulation of the system, the degree of usefulness of the system, the air inside the chamber, etc., the final value of the total heat required to freeze 100 kg raspberry from -40 °C to -60 °C is multiplied by the arbitrary coefficient 1.2.

3. Vacuum pump

The power of the vacuum pump for the lyophilizer 2-4 LDplus was obtained from the catalog $P_{pl} = 0.3$ kW. The power of the vacuum pump necessary for drying 100 kg of raspberry and evaporating 83.6 kg of water was calculated as follows:

$$P_{pu} = \frac{P_{pl}}{4} \cdot 83.6 \text{ kg}$$

where

$$m_{a2-4} = 4 \text{ [kg]},$$

$$m_v = 83.6 \text{ [kg]}$$

After obtaining the power P_{pu} in kW, the consumption of electrical energy (in kJ) was calculated using the following equation:

$$P_{pu} \cdot 24 \text{ h} \cdot 3600 \text{ s [kJ]}$$

When calculating the energy consumption in convective drying, the energy consumption of the dryer and heat energy fan should be taken into consideration. The following energy consumers are included in the convective drying process:

- an axial fan supplying a warm airflow for a period of 15h,
- heaters or heaters used for air heating.

The specific amount of energy required to evaporate one kilogram of water is $q_{iv} = 5,500$ kJ/kg_{iv} (Babić, M., et. al., 2005).

The calculation of energy consumption for the energy consumers in the convective drying process:

1. Power of the axial fan $P_v = 0.55$ kW

The following equation was used to determine the total amount of electrical energy consumed by the axial fan operating for 15 hours:

$$E_v = P_v \cdot 15 \text{ h} \cdot 3600 \text{ s}$$

where

$$\tau_h = 15 \text{ i}$$

$$\tau_s = 3600.$$

2. The amount of heat to evaporate one kilogram of water from raspberries is calculated via the adopted value of specific heat consumption $q_{iv} = 5,500$ kJ/kg (Babić, M., et. al., 2005).

The heat energy used to evaporate water is expressed in the following equation:

$$Q_{iv} = q_{iv} \cdot m_{iv}$$

where

$$m_{iv} = 83.6 \text{ [kg].}$$

RESULTS AND DISCUSSION

Results of the energy consumption in deep freeze-drying (lyophilization)

Table 1 gives the values of the energy consumed, the operating time of the cooling chamber, the sublimation process and the vacuum pump. Equation 1 indicates that the total heat energy to be consumed by the freezing chamber for drying 100 kg of raspberries, containing 84.6 kg of the moisture content and 15.4 kg of the dry matter, amounts to $q_{ukz} = 51,569.112$ kJ. Equation 9 indicates the heat energy needed to be taken in the sublimation process, for 83.6 kg of the moisture content, is $q_{uk} = 237,273.51$ kJ. The required vacuum pump power is expressed in Equation 3, amounting to $P_{pu} = 6.345$ kW. However, a suitable engine for generating such power was not employed so a catalog value of $P_{pu} = 7.5$ kW was used in the calculations.

Table 1. Power, operation time and energy consumption of all the consumers in the freeze-drying process

	Total hours of work per operation	Energy consumed during operation (kJ)
Cooling chamber	24	51,903.91 [kW]
Sublimation	24	237,273.51
Vacuum pump	24	648,000.00
In total:		937,177.42

Table 1 indicates that the freezing compartment must first freeze raspberries at -40°C (a process requiring 24h), which is followed by drying (resulting in the prolongation of the entire drying process). The process is prolonged for as long as the chamber needs to freeze raspberries. Figure 1 shows the diagram of all the consumers individually. The largest consumer in the freeze-drying process is a vacuum pump, while the sublimation process and the freezing compartment consume less energy. The energy required to carry out the sublimation process is the energy consumed by the capacitor. Regarding energy consumption, a compressor was also taken into account as part of the sublimation process. The largest consumer of electrical energy in the freeze-drying process is the vacuum pump, whereas the smallest consumer is the freezing chamber. The calculation used to calculate the energy consumption in the sublimation process and the freezing chamber is similar to the calculation used by other authors (D. G. Mercer 2007).

Fig. 1. Comparison of consumers' consumption in the freeze-drying of 100 kg of raspberries

Results of energy consumption in convective drying

The power required to drive the axial fan approximates to $P = 0.55$ kW (the fan of this power corresponds to a dryer for drying 100 kg of raspberry). Different forms of heating bodies and energy sources can be used for air heating. Therefore, the required amount of thermal energy for the evaporation of 1 kg of water was determined. A total of 5,500 kJ is required for the evaporation of 1 kg of water from raspberries. Consequently, a total of 459.800 kJ is required for the evaporation of 83.6 kg of water. Table 2 shows the values of consumed energy, fan operating times, fan power, and total energy consumption. Table 2 indicates that the axial fan is a small consumer of electricity. Heating bodies converting electricity into heat are large energy consumers

Table 2. Power, operation time and energy consumption of all the consumers in the convective drying process

	Total hours of work per operation	Energy consumed during operation (kJ)
Electric energy (axial fan)	15	29,700
Heat energy (heaters)	-	459,800
In total:		489,500

Comparison of the research results of the raspberry lyophilization and convective drying

The ratio of consumed energy to dry 100 kg of raspberries is shown in Table 3. The table shows the total consumption of energy for the convective drying and freeze-drying of raspberries. Moreover, it is also noteworthy that the lyophilization of 100 kg of raspberries required significantly more time than the convective drying. Figure 2 shows the ratio of consumed energy to dry 100 kg of raspberries. Figure 3 shows the ratio of the time necessary to dry the same amount of raspberries. Figure 2 indicates that the energy consumption in the lyophilization of raspberries is approximately 1.91 times higher than the energy required for a convective drying method.

Table 3. Energy consumption and duration of the convective drying and lyophilization of raspberries

	Total hours of work per operation	Energy consumed during operation (kJ)
Lyophilization	48	937,177.4
Convective drying	15	489,500.0

Fig. 2. Energy used for drying 100 kg of raspberries

Fig. 3. Total time required for drying 100 kg of raspberries

Both dryers, as well as their additional equipment, were connected to the electrical network. The vacuum pump was marked as the largest individual energy consumer, whereas the axial fan was found to be the smallest consumer of electricity. The freeze-drying process itself consumes larger amounts of electrical energy than the convective drying process. The main reasons for high freeze-drying energy requirements are found in the longer drying time and energy requirements of additional equipment. Moreover, the drying process itself is more complex than the convective drying process.

Notwithstanding the high energy consumption, sublimation drying (lyophilization) has advantages over convective drying with regard to the product quality, which is crucial to meet the consumer demands. However, some products such as raspberry powder do not indicate a significant decrease in quality after convective drying, whereas the energy consumption is considerably lower. Moreover, high investment costs in the construction of the lyophilization plant should also be taken into account.

CONCLUSION

Based on the results obtained, it is evident that the energy consumption in freeze-drying (lyophilization) is 1.91 times higher than in the convective drying method. The time required for freeze-drying is 3.2 times longer than the time needed for convective drying. The largest energy consumer in freeze-drying is a vacuum pump, whereas the smallest consumer is a cooling chamber. In convective drying, the largest energy consumers are heating bodies, consuming about 10 times as much energy as it is used to drive an axial fan. However, energy consumption is not crucial in selecting the drying process, but the quality finished products. The sublimation drying process results in products of higher quality than those produced in the convective drying process.

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