

Analysis of energy consumption during convective drying of fruits and berries

Igor Korotkiy¹, Evgeniy Neverov^{1,*}, Ludmila Lifentseva¹, and Alexandr Raschepkin¹

¹Kemerovo State University, 6, Krasnaya Str., Kemerovo, 650000, Russia

Abstract. The work is dedicated to the calculation of energy costs for the realization of the process of convective drying of fruits and berries in a suspended layer. The energy consumption for the fan drive for organizing the air flow, providing the phenomenon of fluidization of fruits and berries, as well as the costs for supplying heat to the dehydration object have been calculated. The energy consumption was determined for various options of energy supply: using a heat pump and due to the operation of thermoelectric heaters (TEH). It is found that the largest proportion of the energy consumption for air circulation organization. It has been established that from the energy point of view, of all the investigated freons, the refrigerant R410 is the most efficient, the total energy consumption for dehydration of 1 kg of irgi berries with it is 7102 kJ, for honeysuckle - 9765 kJ / kg, for lingonberry - 7989 kJ / kg. Comparative analysis revealed that the use of a heat pump installation of convective drying fruits and berries in the fluidized bed reduces the power consumption by an average of 13% in comparison with drying by using heaters to heat the coolant.

1 Introduction

This work is devoted to the analysis of energy costs when using a heat pump in the processes of convective drying of fruits and berries.[1] The use of energy-efficient plants and technologies for processing food raw materials allows to reduce this cost item, and hence the cost of the product, which is an important factor for increasing the competitiveness of manufacturing enterprises.

The use of low-temperature technologies in drying processes makes it possible to one way or another to reduce energy consumption and shorten the dehydration time. Quite a lot of domestic works are devoted to the comparative analysis of energy costs when using certain methods of dehydration.[2,3] Most of the works show that modern innovative drying equipment can achieve high results in terms of energy savings through the use of heat pumps and refrigeration units. This work is devoted to the analysis of energy costs when using a heat pump in the processes of convective drying of fruits and berries. Some background information on the technological regimes adopted on the basis of studies conducted earlier.[4, 5, 6]

* Corresponding author: neverov42@mail.ru

2 Materials and methods

To calculate the energy consumption for the operation of a heat pump during convective drying of fruits and berries in a suspended layer, first of all, it is necessary to determine the thermal load on the condenser of the refrigerating machine.

Let's consider the calculation using the example of irgi. The duration of convective drying of irgi at 50 ° C is 8 hours. According to the results of the studies presented in Chapter 5, during this time it is possible to remove 70% of the mass of raw materials. We define the amount of moisture removed in the average for 1 hour

$$m_v = \frac{0,7 \cdot m}{\tau} = \frac{0,7 \cdot 1}{8} = 0,086 \text{ kg / h} \quad (1)$$

where m is the initial mass of the product, kg; τ - drying time, hour.

The amount of heat input required to evaporate the above amount of moisture can be found as follows:

$$q_u = m_v \cdot r_u = 0,086 \cdot 2382 = 204,85 \text{ kJ / hour} \quad (2)$$

where r_u is the specific heat of evaporation (vaporization) of water, at a temperature of 50 °C, $r_u = 2382 \text{ kJ / hour}$.

However, in addition to the heat removed from the berry, it is also necessary to take into account heat losses to the environment and heat inflows to the evaporator. Based on the calculated data, we will accept the above heat losses $q_p = 450 \text{ kJ / h}$. These heat losses were calculated taking into account the loading of the working chamber of 10 kg. With respect to 1 kg of product, specific heat losses will be respectively 45 kJ / h Then the total load on the heat pump condenser is determined by the sum of the heat loads:

$$Q_k = q_u \cdot q_n = 204,85 + 45 = 249,85 \text{ kJ / hour} \quad (3)$$

The diagram and cycle of the heat pump installation are shown in fig. 1.

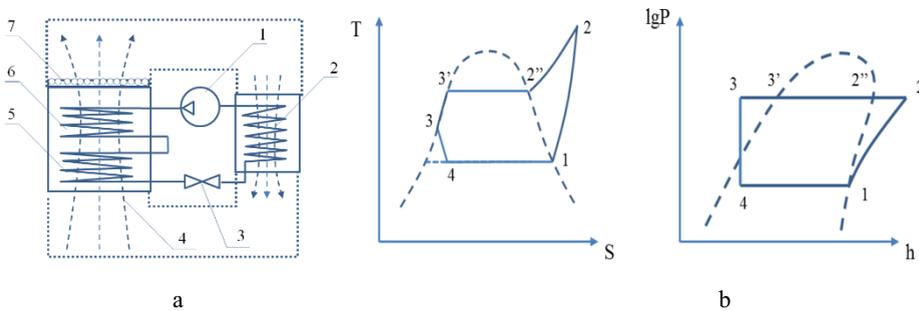


Fig. 1. Scheme (a) and cycle (b) of the heat pump installation. In fig. 1a: 1 - compressor; 2 - evaporator; 3 - throttle device; 4 - coolant (air); 5 - capacitor; 6 - pre-capacitor; 7 - product. In fig. 1b: 1-2 - compression of refrigerant vapors; 2-3 - refrigerant condensation; 3'-3 - hypothermia; 3-4 - throttling of the liquid refrigerant; 4-1 - boiling refrigerant in the evaporator.

Taking the final temperature difference in the evaporator $\Delta t_u = t_{u2} - t_1 = 1 - 4 = -3^\circ \text{ C}$, we calculate the evaporation temperature:

$$\Delta t_1 = t_{u2} - t_u = 1 + 3 = 4^\circ \text{C} \quad (4)$$

At a given evaporation temperature, the air leaving the evaporator will have a temperature of 12 ° C and a relative humidity of about 10%, which ensures the most

effective drying process, therefore, using a lower evaporator temperature is impractical, which is confirmed by the data from the graph in Fig.

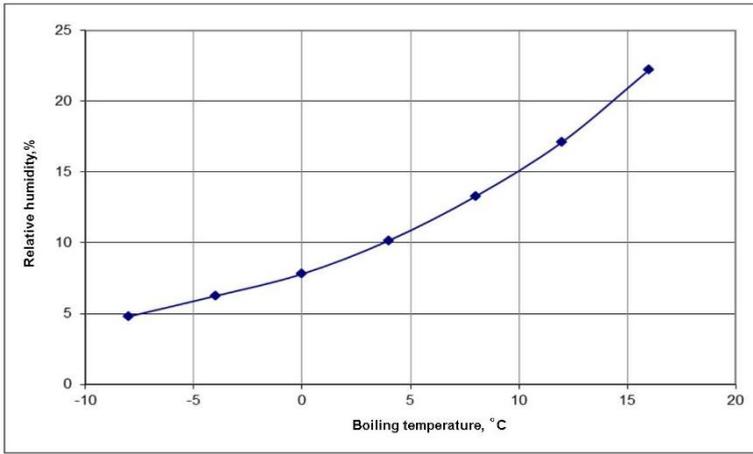


Fig. 2. Dependences of the relative humidity of the air leaving the evaporator on the boiling point of the refrigerant.

Based on the selected convective drying modes, the condensation temperature should be 50 °C. We accept the temperature difference in the condenser 5°C.

Using the T-S diagram for refrigerant R134A, determine the cycle set points (Table. 1).

Table 1. Parameters of the cycle points of the heat pump installation.

№ points	t, °C	P, MPa	h, kJ/kg
1	4	0.9	426
2	72	3.04	459
2''	50	3.04	430
3'	50	3.04	292
3	35	3.04	260
4	4	0.9	260

We accept the internal adiabatic efficiency of the compressor $\eta_{li}=0,8$. Determine the inner workings of the compressor:

$$l_i = h_{2''} - h_1 = 422 - 400 = 22 \text{ kJ} \quad (5)$$

The specific heat load of the evaporator will be calculated as follows:

$$q_0 = h_1 - h_4 = 400 - 247 = 153 \text{ kJ/kg} \quad (6)$$

Next, we determine the specific thermal load of the capacitor.

$$q_k = h_{2''} - h_{3'} = 422 - 271 = 151 \text{ kJ/kg} \quad (7)$$

Find the specific heat load of the pre-capacitor.

$$q_{pc} = h_{3'} - h_3 = 271 - 247 = 24 \text{ kJ/kg} \quad (8)$$

The energy balance in this case can be represented as follows.

$$q = l_i + q_0 = q_k + q_{pc} = 175 \text{ kJ/kg} \quad (9)$$

We calculate the mass flow rate of the refrigerant.

$$G = \frac{Q_k}{q_k + q_{pc}} = \frac{249,85}{151+24} = 1,42 \text{ kg/h} \quad (10)$$

The volumetric capacity of the compressor is determined as follows:

$$V_1 = \frac{G \cdot v_1}{\lambda} = \frac{1,42 \cdot 0,061}{0,82} = 0,104 \text{ m}^3 / \text{h} \quad (11)$$

where v_1 is the specific volume of the working substance sucked in by the compressor; λ - compressor delivery ratio, $\lambda = f(p_{hg}/p_{bc})$. Here p_{hg} - pressure to which the process of compression of the working substance in the compressor is carried out; p_{bc} - pressure of the working substance entering directly into the working cavity of the compressor.

We determine the power spent on overcoming friction and driving auxiliary devices using the empirical formula:

$$N_f = p_{if} + V_1 = 75 \cdot 10^3 = 7,83 \text{ kJ} \quad (12)$$

where $p_{if} = (40 \div 90) \cdot 10^3 \text{ Pa}$ - friction pressure.

Next, we find the indicated compressor power:

$$N_i = \frac{G \cdot l_i}{\eta_i} = \frac{1,42 \cdot 22}{0,8} = 39,26 \text{ kJ} \quad (13)$$

where η_i - compressor indicator efficiency.

Then the capacity of the chiller N_e (kJ), which must be provided for organizing the convective drying process is determined as follows.

$$N_e = N_i + N_f = 39,26 + 7,83 = 47,09 \text{ kJ} \quad (14)$$

In addition to the above power, it is also necessary to take into account the energy consumption for organizing air movement..

Determine the volume of air required to dry 1 kg of product using the following formula:

$$V_c = 3600 \cdot \omega \cdot F_c \cdot \tau = 3600 \cdot 4 \cdot 0,176 \cdot 8 = 20275 \text{ m}^3 \quad (15)$$

where ω - air speed, m / s (we accept 4 m / s [4]); F_c - air duct cross-sectional area, m^2 ; τ - drying time, hour.

Determine the Archimedes number by the formula:

$$Ar = \frac{g \cdot d_e \cdot (\rho_{pr} - \rho_b)}{v_b^2 \cdot \rho_b} = \frac{9,8 \cdot 0,012^3 \cdot (1011 - 1,1)}{0,0000179 \cdot 1,1} = 48523200 \quad (16)$$

The porosity of the fluidization layer will be calculated by the formula:

$$\varepsilon = \left(\frac{18Re + 0,36Re^2}{Ar} \right)^{0,21} = \left(\frac{18 \cdot 0,0264 + 0,36 \cdot 0,0264^2}{48523200} \right)^{0,21} = 0,855 \quad (17)$$

We calculate the height of the fluidization layer of the product.

$$H_f = H_0 \left(\frac{1 - \varepsilon_0}{1 - \varepsilon} \right) = 0,012 \left(\frac{1 - 0,303}{1 - 0,855} \right) = 0,058 \text{ m}^2 \quad (18)$$

Where H_0 - height of the bulk layer of the product, m; ε_0 - bulk layer porosity.

Determine the aerodynamic resistance of the fluidization layer using the following formula:

$$\Delta P_f = 1,67 \left(Re \frac{H_f}{d_e} \right)^{0,2} \cdot \frac{G_p}{F_p} = 1,67 \left(0,0264 \frac{0,058}{0,012} \right)^{0,2} \cdot \frac{1}{0,157} = 7,04 \text{ Pa} \quad (19)$$

where G_p – product weight (accepted $G_p = 1 \text{ kg}$); F_p – area occupied by the product on the grid, m^2 .

Next, we find the aerodynamic resistance of the supporting grid with cells of size $3 \times 3 \text{ mm}$ and free cross-section for air passage $E = 0,308$.

$$\Delta P_p = 13,72 \cdot \omega^2 - 43,12 \cdot \omega + 119,36 = 13,72 \cdot 4^2 - 43,12 \cdot 4 + 119,36 = 166,4 \text{ Pa} \quad (20)$$

Determine the aerodynamic resistance of the finned section of the air cooler:

$$\Delta P_b = 1,35 \cdot A \cdot \text{Re}^{-0,24} \cdot \rho_b \cdot \omega^2 = 1,35 \cdot 1,2 \cdot 0,0264^{-0,24} \cdot 1,1 \cdot 4^2 = 68,2 \text{ Pa} \quad (21)$$

where A – coefficient taking into account the design features of the air cooler. The total value of aerodynamic resistance to air movement in the circulation ring of the air cooler can be found from the following equation:

$$\Delta P = (\Delta P_f + \Delta P_p + \Delta P_b) \alpha = (7,04 + 166,4 + 68,21) \cdot 1,1 = 265,8 \text{ Pa} \quad (22)$$

where $\alpha = 1,1$ – coefficient of resistance to air movement due to friction.

Based on the above calculations, you can determine the energy required to circulate the required amount of air at the required speed.

$$L_b = \frac{V_b \cdot \Delta P}{\eta_b} = \frac{20275 \cdot 265,8}{0,76} = 7091,2 \text{ kJ} \quad (23)$$

where η_b – Fan efficiency, for centrifugal fans the efficiency is approximately $\eta_b = 0,76$.

Thus, the total energy consumption for dehydration of 1 kg of berries will be equal to:

$$E = L_b + N_e = 7091,2 + 47,09 = 7138 \text{ kJ/kg} \quad (24)$$

Energy consumption for refrigerants R407 and R410 was calculated in a similar way. The calculation results are summarized in table. 2.

Table 2. Point settings cycle heat pump installation.

Refrigerant	G. kg/h	P ₀	P _κ	E. kJ/kg
R134A	1.42	0.9	3.04	7138
R407	1.52	0.56	2.32	7129
R410	1.47	0.9	3.04	7102

3 Results and Discussion

Thus, from the energy point of view, of all the investigated freons, the most effective refrigerant is R410, the total energy consumption for dehydration of 1 kg of irrigated berries is 7102 kJ. For the rest of the studied berries, the average energy consumption is:

- for honeysuckle – 9765 kJ/kg;
- for lingonberry - 7989 kJ/kg;
- for black currant - 17755 kJ/kg;
- for sea buckthorn – 12428 kJ/kg.

It should be noted that the largest share is made up of energy costs for organizing air circulation, therefore, the above energy costs will differ significantly due to different drying times.

To compare the efficiency of using a heat pump instead of heating elements, the energy consumption for convective drying was also calculated in the case of using heating elements for heating air. The power required to organize air heating due to heating elements was determined by the following:

$$N_{\text{ten}} = \frac{Q}{\eta} \cdot k_n \quad (25)$$

where Q – the required amount of heat to organize the drying process, kJ/h; η – Efficiency of heating elements; k_n – coefficient taking into account heat loss to the environment.

4 Conclusion

Total costs consisted of costs for heating and air heating elements on air circulation organization costs.

In fig. 3 shows graphs comparing energy consumption for convective drying of berries using heating elements and using a heat pump.

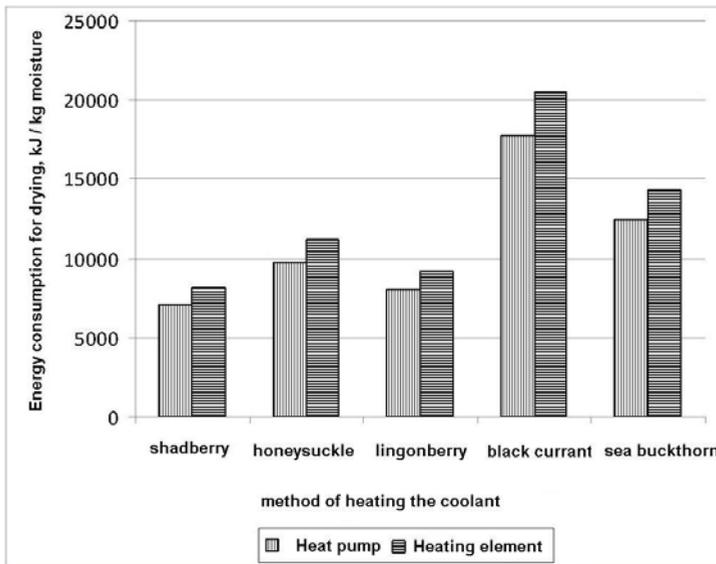


Fig. 3. Comparison of energy consumption for convective drying of fruits and berries using different methods of heat supply.

Comparative analysis shows that the use of a heat pump in a unit for convective drying of fruits and berries in a suspended layer can reduce energy consumption by an average of 13% compared to drying when using heating elements for heating the coolant. Thus, from the point of view of energy costs, the efficiency of using a heat pump for organizing the process of drying fruits and berries has been proven.

Acknowledgment

The main authors are very grateful to the student of the Kemerovo State University Radzhaboi Rustamov, for his help in translating the article into English.

References

1. A. Gariaev, *Optimization of energy-saving schemes for convective drying installations for thermolabile materials* (2011)
2. A. Shevtsov et al., *Izvestiya VUZov. Food Technology* **4**, 88-92 (2012)
3. I.Korotkij et al., *Izvestiya VUZov. Food Technology* **5-6**, 341-342 (2014)
4. N. Myasisheva, *Technique and technology of food production* **3**, 36-40 (2013)

5. I. Korotkij et al., Technique and technology of food production **4**, 91-97 (2014)
6. R. Barykin et al., Voronezh State University of Engineering Technologies Bulletin **1(59)**, 47-50 (2014)
7. L. Vlazneva, *Creation of healthy food products with a functional focus based on fruits and berries* (2011)
8. E. Gorobtsov, Bulletin of KrasGAU **10**, 235-239 (2013)
9. I. Bakin et al., Vesnik KrasGAU **6**, 159-162 (2015)
10. G. Maslennikova, *Materials of the IV All-Russian conference of students, graduate students and young scientists "Food and human health"*, 122-123 (2011)
11. A. Rashepkin et al., Technique and technology of food production **1(32)**, 101-105 (2014)
12. L. Ratnikova et al., Bulletin of the Siberian University of Consumer Cooperatives **1(2)**, 96-100 (2012)
13. V. Filippov et al., Scientific journal NRU ITMO **2(16)** (2013)
14. A. Shevcov et al., Proceedings of universities, Food technology **4**, 88-92 (2012)
15. Y. Ryakhovsky et al., Finance. Economy. Strategy. Series "Innovative Economy: Human Dimension" **4**, 18–20 (2013)