Volume and hydrodynamic characteristics of the product layer

Kh. Nuriddinov*, *I.S.* Khasanov, *Zh.Zh.* Kuchkorov and *O.Kh.* Nuriddinov

Bukhara Institute of Natural Resources Management of the National Research University of Tashkent Institute of Irrigation and Agricultural Mechanization Engineers

Abstract. The paper deals with the determination and study of the drying rate. The authors believe that it is necessary to present the curves for changing the mass of the product and time, to take into account the possible ranges of changes in the parameters of the coolant. In addition, the paper discusses the actual speeds of airflow around the product, the required drying modes will become known owing to the knowledge of the features of the drying process. In this regard, the authors of the paper consider the volumetric and hydrodynamic characteristics of the product layer. The purpose of the study was to determine the area of the free section in the layer of products, the speed of air movement, the pressure loss in the layer. The results of computational and experimental studies have shown the possibility of determining the true speed of drying of various products.

1 Introduction

The issues of ensuring the required drying modes need the knowledge of the features of the drying process in each case for each material.

When solving the problem, it is necessary to take into account the possible ranges of changes in the parameters of the coolant, which are due to both the features of the dried technology of the product and the type of draught plant.

For a combined solar-thermal dryer, these requirements are formulated as follows: ensuring minimal energy costs while maximizing the performance of a combined dryer to a convective thermal dryer.

These features of the problem also determine the features of the study of various drying parameters, namely, the drying process occurs in the range of temperatures, humidity and air speeds carried out in solar dryers.

Solving the problems of optimizing the drying mode requires knowledge of the actual speeds of drying products, the speeds of air movement in the layer of products, the loss of air pressure in the layer. To determine the indicated parameters of the product layer, computational and experimental studies were carried out.

The purpose of the study was to determine the area of the free section in the layer of products, the speed of air movement, the pressure loss in the layer.

These characteristics were determined on the basis of a calculated experimental study of the dependence of the air velocity in the chamber on the characteristics of the product layer: loading and the number of shelves with products, the study of the volumetric characteristics of the product.

2 Materials and methods

The layout of the shelves with products in the chamber and their overall dimensions are shown in Figure 1 (a). Research results for Shevargani grapes (fruit weight is m_{grapes} = 3…3.7 gr, volume is V_{grapes} = 1.7…2.9 cm^3, average density is P_{grapes} = 1.5 g/cm^3, load per shelf is 4…4.5 kg) are shown in Figure 1 (b).

Based on these data, we determine the cross-sectional area SC in the product layer.

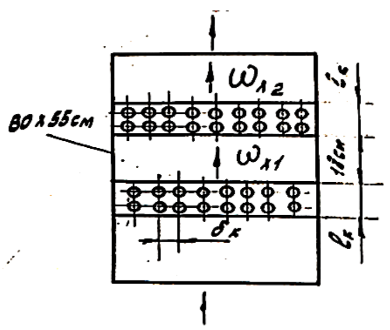
Let us first consider the case when one shelf is loaded with the product in the chamber. When solving the problem, we make the following assumptions:

- the free section of the layer is a system of smooth parallel cylindrical channels with an effective diameter and a length equal to the thickness of the product layer;
- the real shape of the products is replaced by a spherical shape with equal volume and weight;
- the local resistances in the chamber are neglect.

Taking into account the indicated assumptions, we have the following system of equations.

The volume flow in the chamber L is equal to the total volume flow of air in the channels.

* Corresponding author: tiiame@exat.uz


(a)

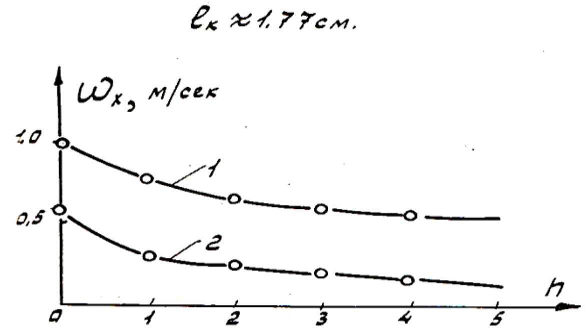

(b)

Fig. 1. (a) Scheme of shelf position; (b) Dependence of the air velocity in the chamber on the number of shelves (n) with the product: 1 is full and 2 is low ventilation (type VO10-U2.34 W).

$$L = \omega \cdot S = \omega_K \cdot S_K \cdot n, \quad (1)$$

where ω is the air speed in the chamber with a cross S section ω is the air speed in a separate channel, the cross-section S_K, n and the number of channels in the layer.

The pressure loss ΔP in the channel is determined by the formula [2]:

$$\Delta P = \lambda \frac{l_K}{d_K} \cdot \rho \frac{\omega_K^2}{2}, \quad (2)$$

where λ is the coefficient of friction resistance; ρ is the density of air; d_K is the diameter of the channel.

The λ-factor can be determined by well-known formulas, depending on the channel geometry and the Reynolds number [3]. Taking into account the above assumptions, we can also write that the total volume of channels in the layer of the dried product is equal to:

$$V_{K\Sigma} = S_K \cdot l_K \cdot n. \quad (3)$$

The total pressure drop in the layer can be determined by the formula [4]:

$$\Delta P_\Sigma = K(L_0^2 - L^2), \quad (4)$$

where K is the coefficient of the fan curve; L_0 is the volume of air flow in the empty chamber, m^3/h; L is the volume flow of air in the loaded chamber [4–8].

When the channels are connected in parallel, the pressure drop in each channel is constant and equal to the total pressure drop in the product layer [9].

Based on fan characteristics (N = 0.034 kW, η = 0.48) of the measured air flow in an empty chamber L_0 = 0.33 m^3/s we have the initial pressure P = 50 Pa, from which it follows that the coefficient of the fan flow curve K is equal to:

$$K = \frac{P}{L_0^2} = \frac{50\text{pa}}{1188\text{m}^2/\text{h}} = 3.54 \cdot 10^{-5}\text{pa.s/m}^3.$$

For one product layer (see Figure 1, b) we have L · S 3600 = 926 m^3/h and from (1.4) it follows that the total air pressure drop in the product layer is equal to:

$$P_\Sigma = 3.54 \cdot 10^{-5}\left(1.41 \cdot 10^6 - 0.857 \cdot 10^6\right) = 19.1 \text{ pa}.$$

Let us now determine the free volume of the layer $V_K\Sigma$. The layout of grapes in the layer, taking into account the assumptions made above, is shown in Figure 2, including the dimensions of the chamber section, the height of the layer [10–13].

At the beginning, we consider one layer of grapes and determine the area of the free section. Figure 2 shows that the free sectional area is equal to:

$$S_{K\Sigma} = S_{\text{cross}} - S_{pr}, \quad (5)$$

where S_{cros} is the total cross-sectional area of the shelf, equal to the cross-sectional area of the chamber, $S_{K\Sigma} = a \cdot b$, S_{pr} is the cross-sectional area of the shelf occupied by grapes [14–17].

From the layout of the product in the layer (Figure 2), we can write that:

$$S_{\text{pr}} = S_{\text{r}} \cdot m_a \cdot m_b, \quad (6)$$

where the cross-sectional area of an individual product is (r is an effective radius of the product, $r = \sqrt{\frac{3 \cdot V}{4\pi}}$, where V is the average volume of one product; 3 is the number of product units along the width (a) and (b) of the chamber.

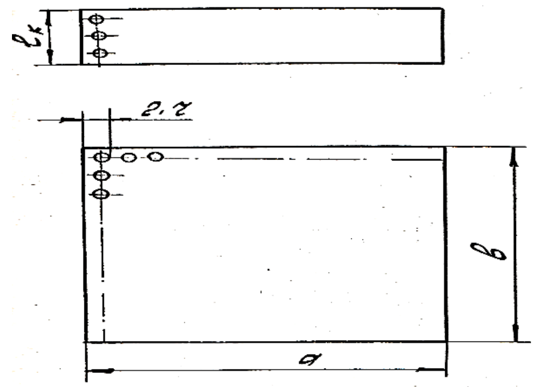


Fig. 2. Determination of the free volume in the product layer.

It follows that $m_a = \frac{a}{2r}$, $m_B = \frac{B}{2r}$ or

$$S_{K\Sigma} = a \cdot b - \pi r^2 \cdot \frac{a}{2r} \cdot \frac{B}{2r} = a \cdot b \cdot (1 - \frac{\pi}{4}). \quad (7)$$

From (8) it follows that the area of the free section of the layer is independent of the absolute radius of the fruit and is 21.5% of the section of the chamber [18].

Let us now determine the volume of the free section $S_{K\Sigma} = a \cdot b$. By S_{pr} analogy with the method for determining the free section, we have:

$$V_{K\Sigma} = V_l \cdot V_{pr},$$

where V_l is the total volume of the layer $V_l = a \cdot b \cdot l$, V_{pr} is the volume occupied by the product in the layer.

It is known that $V_{pr} = V_r \cdot m_a \cdot m_b \cdot m_l$, or $V_l = \frac{4}{3}\pi r^3$ allows obtaining

$$V_{K\Sigma} = V_l - V_{pr} = a \cdot b \cdot l(1 - \frac{\pi}{6}). \quad (8)$$

3 Computational study

Based on it, it follows that the volume occupied by the product in the layer, V_{pr}, and hence also the free volume $V_{K\Sigma}$ do not depend on the size of an individual product and amount to 52.3% and 47.6% of the total volume of the layer, respectively. Knowing the total weight of the product and its density, we can determine the volume occupied by the product:

$$V_{pr} = \frac{P_{pr}}{P} = \frac{4500\text{g}}{1.5\text{g/cm}^3} = 3000\text{cm}^3.$$

The effective length (thickness) of the product layer, as follows from (8), is equal to:

$$l = \frac{V_{pr} \cdot 6}{\pi \cdot a \cdot b} 1.74\text{cm}.$$

The total volume of the layer V_{sl} is equal to: $a \cdot b \cdot l$ = 60 cm · 55 cm · 1.74 cm = 5279 cm^3 and a free volume $V_{K\Sigma}$ is equal to:

$$V_{K\Sigma} = a \cdot b \cdot l(1 - \frac{\pi}{6}) = 5729.5 \cdot (1 - 0.4764) = 2729 \text{ cm}^3.$$

On the other hand, we can write that:

$$V_{K\Sigma} = S_K \cdot l_K \cdot n. \quad (9)$$

From (1) and (9) it is possible to determine the speed of air movement in the channel ω_K:

$$\omega_K = \frac{\omega \cdot S_K}{V_{K\Sigma}} \cdot l_K. \quad (10)$$

The analysis shows that expression (1.10) is more applicable when we have several product layers on one shelf. In the case when we have one layer of the product, it is more correct to find the speed of movement of the product along the free section $S_{K\Sigma}$ [19–21].

Substituted in (1) the value of $S_K \cdot n$ equal to $S_{K\Sigma}$, we get:

$$\omega_K = \frac{\omega \cdot S}{S_{K\Sigma}} = \frac{\omega \cdot a \cdot b}{a \cdot b \cdot (1 - \frac{\pi}{4})} = \frac{\omega}{(1 - \frac{\pi}{4})}. \quad (11)$$

From (11) it follows that, regardless of the dimensions, there is a constancy of the ratio of velocities in the chamber and channel for the case of one product layer. At W = 0.78 m/s (one layer), we get:

$$\omega_K = 0.78 \cdot 0.215 = 3.63 \text{ m/s}.$$

From geometric relationships, we can also determine the effective channel diameter and the number of channels in the layer n.

From Figure 2 it follows that the total number of channels in one layer of the product is equal.

$$n = n_1 + n_2 + n_3 + \\ +2\left((m-1) + (n-1)\right) + (m-1)(n-1). \quad (12)$$

As follows from Figure 2, we have three types of channels (n_1, n_2, n_3) whose areas are related as 1: 2:4. For m, n 30, it follows from (12) that neglecting channels like n_1 and n_2 will introduce an error not exceeding 1.5–2%. Thus:

$$n = (m-1)(n-1); \quad (13)$$

$$S_K = \frac{S_{K\Sigma}}{n} = \frac{a \cdot b \cdot (1 - \frac{\pi}{4})}{(m-1)(n-1)}. \quad (14)$$

Substituting instead of m and n their values $\left(m = \frac{a}{2r}, \quad n = \frac{B}{2r}\right)$ and taking into account $S_K = \frac{\pi d_K^2}{4}$, we get:

$$d_K \cong d_{pr} \cdot 2\sqrt{\frac{(1 - \frac{\pi}{4})}{\pi}} = 0.522 \cdot d_{pr} \cdot \sqrt{2}. \quad (15)$$

If determined by the formula $d_K = \frac{4S_K}{U}$, S_K is the area and U is the premium channel. Then:

$$d_K = 0.217 \cdot d_{pr}.$$

Substituting the values into (2.37) and (2.39) d_{pr} = 1.6 cm, a = 60 cm, B = 55 cm we get:

$$n = \left(\frac{a}{d_{pr}} - 1\right)\left(\frac{B}{d_{pr}} - 1\right) = 1218.$$

If according to the formula $d_{eq} = \frac{4S_K}{U}$ is transformed to $d_{eq} = 0.271 \cdot d_{pr}$

d_K = 0.522 · 1.6 = 0.592 cm, d_{KE} = 0.271 · 1.6 = 0.434 cm

Based on the obtained data, the pressure drop P in the layer can be calculated from (15) [22].

The equation (16) includes the friction coefficient λ, the value of which, depending on the number Re, is equal to:

$$\lambda = \frac{0.3164}{\text{Re}^{0.25}},$$

$$\text{Re} > 3 \cdot 10^3 \ldots 1 \cdot 10^5$$

$$\lambda = \frac{64}{\text{Re}}, \quad \text{at Re} < 3 \cdot 10^3 \quad (16)$$

for the obtained values at kinematic humidity.

For the received values ω_K and d_K at kinematic humidity of air $V = 19 \cdot 10^{-6}$ mg/s, the Re number is:

$$\text{Re} = \frac{0.592 \cdot 10^{-2} \cdot 3.63}{19 \cdot 10^{-6}} = 1131.$$

Assuming that the free section consists of cylindrical channels and supplying the obtained values of the parameters in (2), we obtain:

$$\Delta P = \lambda \cdot \frac{l_K}{d_K} \cdot P \frac{\omega_K^2}{2} = 1.3 \text{ Pa}$$

For d_{KE_1} $\Delta P = 2.42$ Pa.

This differs significantly from the experimental values; hence it follows that the resistance in the free section of the layer is local [23].

In the first approximation, the air passes from the chamber with a cross-sectional area S through the diaphragm with an area Sg and then again through a chamber with an area *S*.

Since there are expressions in the literature only for a separate aperture, we will assume that the areas S and S_g represent the total area of the chamber S and the free section ($S_{k\Sigma}$) or take into account [3]:

$$\xi_M = \xi_{cm}\left(\frac{S_{K\Sigma}}{\varepsilon \cdot S}\right) + K\left(\frac{S}{\varepsilon \cdot S_{K\Sigma}} - 1\right)^2. \quad (17)$$

In the first approximation in (17), it is assumed that: $\xi_{cm} = 0$; K ≈ 1, or considering $\frac{S}{S_{K\Sigma}} = \frac{1}{0.215}$;

$$\xi_{cm} = \left(\frac{1}{0.215 \cdot 0.616} - 1\right)^2 \cong 43.$$

The pressure drop with local resistances is generally equal to:

$$\Delta P = \xi_M \cdot \rho \frac{\omega^2}{2} \quad (18)$$

Substituting into (2.42) the values ρ = 1.2 kg/m^3, ω = 0.78 m/s, we get $\Delta P = 15.7$ Pa. This value is experimental $\Delta P = 19$ Pa). The error is mainly due to the fact that in the calculation it is assumed that the products are located in one layer [24].

Let us now determine from the condition of the balance of air flow in the chamber and layer (1) the effective velocity of air movement in the channels to:

$$\omega_K = \frac{\omega \cdot S}{S_k \cdot n} = \frac{0.78 \cdot 3300 \cdot 4}{1218 \cdot 3.14 \cdot 0.592^2} = 3.8 \text{ m/s},$$

$$d_{KE} + 0.217 \cdot d_{pr} = 0.434 \text{ cm};$$

$$\omega_{KE} = 14.3 \text{ m/s}.$$

The value ω = 3.8 m/s characterizes the average speed in the channel, and ω_{KE} is the maximum speed in the smallest section.

It follows that the number Re in the layer has a value from 2400 to 3200, i.e., the nature of air movement in the channels can be considered close to laminar.

And finally, the total surface area of the product layer is equal to:

$$S_{pp} = 4\pi r_{pr}^2 \cdot \frac{P}{m_{pr}} = 4\pi\left(\frac{3V_{pr}}{4\pi}\right) \cdot \frac{2}{3} \cdot \frac{P}{m_{pr}} \approx 11200 \text{ cm}^2$$

The obtained parameters make it possible to determine the true drying rates of the product in one layer of the product, which is usually the case in practice.

Let us now consider the case when there are two shelves with products in the chamber: ω_{KE} = 0.65 m/s.

Total pressure drop – $\Delta P = 1.4$ cm.

$$\Delta P_2 = K\left(L_0^2 - L_2^2\right)$$

$$K = 3.54 \cdot 10^{-5}\, pa \cdot \text{ m}^3/\text{s}; L_0 = S \cdot 3600 = 1113 \text{ m}^3/\text{s};$$

$$\Delta P \cong 28.8 \text{ pa}.$$

If we consider the resistance in each local layer, then the calculated value of ∇P_{2p} is equal to:

$$\nabla P_{2p} = 2 \cdot \xi_M \cdot \rho \frac{\omega_2^2}{2} = 21.8 \text{ pa}.$$

Calculations and experiments, taking into account the accepted assumptions, coincide (an error in determining the speed of 0.1 m/s leads to an error in determining P of 33%).

For three layers: (ω_3 = 0.62 m/s):

$$P_{3E} = K\left(L_0^2 - L_3^2\right) = 3.54 \cdot 10^{-5}\left(1.41 \cdot 10^6 - 736.6^2\right) = 30.7 \text{ pa}$$

and the calculated value P_3 (P_{3p}) is:

$$\Delta P_{3p} = 3 \cdot \xi_M \cdot P \frac{\omega_3^2}{2} = 29.75 \text{ pa}.$$

For four shelves from graph ω_4 = 0.58 m/s, or

$$\Delta P_3 = K\left(L_0^2 - L_4^2\right) = 3.54 \cdot 10^{-5}\left(1.41 \cdot 10^6 - 689^2\right) = 33 \text{ pa}.$$

The calculated value of p is:

$$\Delta P_p = 4 \cdot \xi_M \cdot P \frac{\omega_4^2}{2} = 4.34 \cdot 1.2 \frac{0.336}{2} = 34.7 \text{ pa}.$$

For five layers: (ω_5 = 0.54 m/s), or:

$$\Delta P_3 = K\left(L_0^2 - L_5^2\right) = 3.54 \cdot 10^{-5}\left(1.41 \cdot 10^6 - 641.5^2\right) = 35.34 \text{ pa}.$$

$$\Delta P_p = 5 \cdot \xi_M \cdot P \frac{\omega_5^2}{2} = 5.34 \cdot 1.2 \frac{0.54^2}{2} = 37.6 \text{ pa}.$$

The speed of air movement in one layer of the product, as shown above, does not depend on the size of the product, with the formulas for local resistances; we will assume that formula (11).

4 Conclusion

The results of computational and experimental studies have shown the possibility of determining the true speed of drying of various products, as well as determining the necessary number of shelves with products, using the obtained dependencies for hydraulic and thermal calculation of dryers [25].

The results of computational and experimental studies have shown the possibility of determining the true speed of drying of various products, as well as determining the necessary number of shelves with products, using the obtained dependencies for hydraulic and thermal calculation of dryers.

In particular, for all the studied products there is a clear boundary between the drying periods, it is shown that with an increase in the drying temperature, the boundary of the first period comes at a higher humidity, it is also obtained that the absolute rate of drying of the products remains practically constant throughout the entire drying process.

The dependences obtained are presented in a form convenient for practical use as a function of the temperature of the drying agent.

References

1. Kh. Nuriddinov, *Development and research of a combined helium dryer for fruit and vegetable products* (PhD thesis) (Tashkent, 1994)
2. M.A. Mikheev, I.M. Mikheeva, *Fundamentals of Heat Transfer* (Energy, Moscow, 1973)
3. *Heat engineering and heat power engineering*, Kn. 2 (Energoavtomitizdat, Moscow, 1988)
4. M.P. Kalinushki, *Pumps and Fans* (Vysshaya shkola, Moscow, 1987)
5. Kh. Nuriddinov, Zh. Kuchkarov, Ch. Normamatov, A. Zhuraev, O. Nuriddinov, Thermal regime during convective drying of products, Exact Sci.: Natural Sci. J. (Kemerovo) 6–11 (2019)
6. I.V. Lakomov, Yu.M. Pomogaev, The principles of energy-saving drying technology, Bull. of Voronezh State Agrar. Univ. **1 (48)**, 70 (2016)
7. A.A. Garyaev, *Optimization of energy-saving schemes for convective drying installations for thermolabile materials* (PhD Thesis) (Moscow, 2011)
8. D.S. Kashmensky, Drying of agricultural products using heat pumps WEB-Conference, *Proc. of First Int. Sci. Readings dedicated to the 105th anniversary of academician A.V. Lykov* (Moscow, National Res. Univ. MPEI, 22–23 September, 2015)
9. A. Gariaev, The use of heat exchangers and heat pumps to save energy when drying materials *Proc. of First Int. Sci. Readings dedicated to the 105th anniversary of academician A.V. Lykov* (Moscow, National Res. Univ. MPEI, 22–23 September, 2015), pp. 343–347
10. A.S. Ginzburg, *Calculation and Design of Drying Plants for the Food Industry*, Textbook for Universities (Agropromizdat, Moscow, 1985)
11. S.P. Rudobashta, *Heat Engineering* (Kolos, Moscow, 2010)
12. V.I. Konovalov, E.V. Romanova, N.T. Gatapova, Drying with heat pumps in the chemical industry: possibilities and experimental techniques, *Bull. of TSTU* **17(1)**, 153 (2011)
13. N.S. Kholmirzaev, V.D. Kim, B.E. Khairiddinov, Thermal balance of a solar air heater with recuperative heat exchanger, Solar Technol. **3** (2005)
14. V.I. Mushtaev, *Drying of Dispersed Materials* (Khimiya, Moscow, 1988)
15. R.I. Shazzo, V.M. Shlyahovetsky, *Low-temperature Drying of Food Products in Conditioned Air* (Kolos, Moscow, 1994)
16. N.M. Nazarova, T.D. Zhuraev, M.R. Nazarov, Energy saving recirculating solar dryer with recuperative heat exchanger, *New Materials and Solar Technologies*, Proc. of Int. Sci. Conf. (Tashken, Uzbekistan, May 20–21, 2021)
17. O.F. Safarov, D.Sh. Bazarbaeva, F. Sulaimonov, Exergy analysis of a solar dryer with a heat pump, Heliotekhnika **3**, 47–55 (2003)
18. O.F. Safarov, O.S. Komilov, M.F. Radzhabov, O.R. Abdurakhmonov, An exergy analysis of a heat pump drying plant with a solar collector as a low-grade heat source, Solar Technol. **1**, 46–51 (2009)
19. S.K. Kakhkharov, M.R. Nazarov, H.O. Zhuraev, O.S. Kakhkharov, *Combined solar dryer*, Patent for invention, no. UZIAP 05746 (Tashkent)
20. G.G. Umarov, Sh.M. Mirziyoev, O.N. Yusupbekov, *Heli drying of agricultural products* (Fan, Tashkent, 1999)
21. O. Rakhmatov, On the issue of thermal optimization of the operating mode of a solar-fuel drying unit of a convective type, Bull. of Altai State Agrar. Univ. **1(135)**, 132–136 (2016)
22. A.N. Juraev, S.J. Imomov, S.S. Orziev, Application of energy and resource engineering software in cotton fields, IOP Conf. Ser.: Earth and Environ. Sci. **868**, 012067 (2021)
23. F.U. Juraev, I.N. Ibodov, A.J. Juraev, D.K. Najimov, L.B. Isoyeva, Development of procedures for corn varieties irrigation as main crops, IOP Conf. Ser.: Earth and Environ. Sci. **868**, 012089 (2021)
24. F. Juraev, G. Karimov, Mathematical model of water absorption area in intensive garden irrigation from the ground, E3S Web of Conf. **264**, 01044 (2021)
25. F. Juraev, Y. Rajabov, N. Farmonov, A. Joraev, Development of technology and equipment for improving the reclamation state of saline soils, E3S Web of Conf. **264**, 04018 (2021)