Досліджено гідродинаміку фільтрування газового потоку крізь сформований шар цукатів. Встановлена залежність коефіцієнту гідравлічного опору шару цукатів від числа Рейнольдса. Узагальнення експериментальних даних дає змогу застосовувати залежність Дарсі-Вейсбаха для прогнозування втрат тиску в шарі цукатів залежно від методу формування шару. Це є важливим для чисельного моделювання перебігу тепло-масообмінних процесів під час їх висушування

Ключові слова: цукат, формування шару, рівняння Дарсі-Вейсбаха, еквівалентний діаметр, питома поверхня

Исследована гидродинамика фильтрации газового потока через сформированный слой цукатов. Выведена зависимость коэффициента гидравлического сопротивления слоя цукатов от числа Рейнольдса. Обобщение экспериментальных данных позволяет использовать зависимость Дарси-Вейсбаха для прогнозирования потерь давления в слое цукатов в зависимости от метода формирования слоя. Это необходимо для числового моделирования протекания тепло-масообменных процессов при сушке

Ключевые слова: цукат, формирование слоя, уравнение Дарси-Вейсбаха, эквивалентный диаметр, удельная поверхность

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SELECTION OF OPTIMAL METHOD OF FORMING A LAYER OF CANDIED FRUITS DURING FILTRATION DRYING

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1. Introduction

One of the priority directions of development of food industry of Ukraine is the production of candied fruits. This product is useful for the human body due to availability of mineral salts, microelements, pectins, and vitamins. At present, main attention in the production of candied fruits is paid to the processes of saturation of raw materials with sugar and its subsequent drying, as well as to examination of physical and chemical composition of the finished product. The most prolonged and energy-consuming stage of the production of candied fruits is drying. Ukraine is an energy-dependent state, that is why theoretical and experimental research aimed at reducing energy consumption is promising. In addition, cuts in energy consumption positively influence the cost of the finished product and its sales market.

The most common ways of drying chaotically formed layer of candied fruits are convective, sublimation and combined. Chaotic formation of the layer of candied fruits on the working surface of drying equipment is the simplest in terms of its loading, but it negatively affects thermal mass exchange processes. Raw materials for the production of candied fruits are in the form of cylinders, cubes, disks. During chaotic formation of the layer, the total surface of evaporation decreases due to the contact of particles with each other; as a result, the time of drying increases. Of interest are the studies of influence of the method of formation of the layer of candied fruits on the working surface of drying equipment on the intensity of drying. It is known that hydrodynamics of the process of washing the candied fruits particles with thermal agent determines the thickness of hydraulic, thermal and mass exchanging boundary layer. Thus, the processes of heat exchange occur by thermal conductivity while mass exchange – by molecular diffusion. The thickness of the boundary layer of the steam-gas mixture determines the speed of development of these processes. Reducing the thickness of the boundary layer intensifies its heat and mass exchange. Increasing the speed of motion of the gas medium relative to solid surface leads to the decrease of the indicated boundary layers; however, the growth in speed leads in turn to the growth in pressure losses and, accordingly, to the growth in energy costs in general. Therefore, experimental and theoretical studies of hydrodynamics of gas flow motion through the formed layer of candied fruits are a relevant task.

2. Literature review and problem statement

Authors [1, 2] examined physical-chemical composition and organoleptic properties of candied fruits from different varieties of pumpkin and argue that convective drying allows maintaining natural coloring and taste of the finished product. However, this process is long-lasting over time (it may take 8–48 hours). Research into industrial drying of pumpkin raw material and preservation of antioxidant properties of the finished product is the subject of work [3]. The author notes that technological parameters of the process definitely influence quality, i. e., the drying is necessary to be carried out under mild temperature modes that also leads to the increase in the period of drying. This is explained by a minor driving force of the process of heat transfer and, accordingly, evaporation of moisture. In addition, characteristic for convective drying is a small contact area of the particles' surface with thermal agent, as a result of disordered arrangement of particles in the drying area.

Sublimation drying method, according to authors [4, 5], makes it possible to obtain a dried product of higher quality, in comparison to the convective one, but with slightly worse organoleptic properties. However, the high cost of implementing such a process prevents common use of this method in industrial production. Research into effect of pumpkin particles' dimensions and drying modes temperature on duration of the process and quality of the final product is presented in [6]. This paper demonstrates that rising temperature of the gas flow leads to reducing the time of drying, however, quality of the dried product somewhat worsens.

The combined method of drying, in particular convective-radiation [7] and convective-microwave [8], according to authors, allows reducing energy expenses, compared to the sublimation one. However, they observed somewhat worse quality indicators of the dried product.

Authors [9, 10] examined the influence of technological parameters on the quality of the finished product and ways of cutting candied pumpkin using a metal matrix in the form of a cylinder with a diameter of 10–15 mm or a cube with an edge of 10–15 mm.

Theoretical analysis of manufacturing candied fruits from vegetable raw materials is presented in [11]. The authors argue that the particles for the candied fruits must be cut into slices or bits of rectangular shape of size 8–20 mm. Along with this, in paper [12], for the candied potato, the particles are cut into circles with a diameter of 30 mm, thickness of 20–40 mm. For the melons and gourds they form irregularly shaped particles of size 20–40 mm [13].

The implementation of the processes of drying in all cases is carried out in a stationary layer in closed drying chambers and the raw material is chaotically placed on the tiered sieves. Drying of vegetable raw materials can be performed in belt driers (single and multi-tiered) with microwave chambers or steam heating elements [14]. The drying product is loaded also chaotically on the belts, «in bulk».

Given analysis of the literature sources, we see that the methods of drying proposed by authors take place in a stationary layer in one or many tiers. The formation of particles occurs in different ways and the formation of layer happens chaotically. Other methods of forming layers with any method of drying of candied fruits are not considered in the scientific literature. It is obvious that uneven filling of drying plants with particles of food thermolabile substance leads to its uneven drying and, as a consequence, increases duration of the process and deteriorates quality of the finished product.

The formation of a layer of candied fruits in the drying zone should provide for developed specific surface, low hydraulic resistance, and small equivalent diameter of channels between the particles. Thanks to such arrangement of particles in a layer, it is possible to reduce the volume of dryer, to increase the contact area of the outer surface of the particle with thermal agent and, as a consequence, to cut energy costs.

According to authors [15], during filtration drying, the resistance of layer of material, through which thermal agent is filtered, determines energy costs of the process. That is, hydrodynamic processes in a layer significantly influence the course of heat mass exchanging processes. The formation of a layer with maximum possible specific surface and the same equivalent diameter over entire height will reduce hydraulic resistance of the layer. However, in the case of drying polydisperse materials, such uniformity is impossible to achieve. Only the layer, systematically formed out of particles of the same size and shape, will make it possible to reduce hydraulic resistance.

The designs, which focus on experimental studies of problems of hydrodynamics are fairly well covered in the scientific literature. The research into fluid motion through the cubic, semi-cubic, trapezoidal, parabolic channels [16] prove significant influence of the shape of channel, washing perimeter, and equivalent diameter on the consumption and speed of fluid. It was proven that the cubic section has the lowest hydraulic resistance, which reduces energy expenses for the process.

Literature [17] describes experimental study of the process of hydrodynamics of mixing two streams in the channels of variable section. The temperature, speed and pressure of the streams are registered. It is proved that the magnitudes of velocity of gases and heat flow significantly increase with the decrease in the width of the channel. This leads to intensification of heat exchanging processes. Along with this, the existing methods of research of hydrodynamics [16–17] do not consider the motion of gas medium through the formed layer of particles of regular shape.

So the filtration method of drying appears to be interesting, the essence of which lies in the filtration of gas flow in the direction of «stationary layer of candied fruits – perforated partition". This method in the production of candied fruits is not considered in the scientific literature. Its advantage is, first of all, a large area of contact of the candied fruits particles with thermal agent and large coefficients of heat and mass release due to the fact that the speed of filtration of gas flow is significantly larger than during the convective drying method. This approach to the methods of the formation of a layer of candied fruits and solution to the problems of hydrodynamics during filtration of gas flow through the formed layer of candied fruits has both practical and theoretical interest.

3. The purpose and objectives of the study

The aim of the work was to explore hydrodynamics of filtration of gas flow through the formed layer of candied fruits, to determine the dependency of coefficient of hydraulic resistance on the Reynolds number and to compare the estimated values with experimental ones.

To achieve the set goal, the following tasks are to be solved:

– to determine experimentally the main characteristics of the formed layer of candied fruits (specific layer surface, equivalent diameters of channels between the particles and porosity of the layer for particles of the set dimensions);

– to explore experimentally the change in hydraulic resistance from the fictitious speed of filtration of the gas flow through the formed layer of candied fruits;

– to define dependency of coefficient of hydraulic resistance on the Reynolds number;

– to compare the theoretically calculated losses of pressure in the formed layer of candied fruits based on the Darcy-Weisbach dependency with experimental values.

4. Materials and methods of study of the formation of a layer from particles of candied fruits on the hydrodynamic processes during the filtration drying

4. 1. The studied materials and equipment used in the experiment

The object of research was the particles of similar size of cylindrical shape (height of 20 mm and diameter of 10 mm) from pumpkin of the variety «Stofuntovka Vassma», grown in the Western regions of Ukraine. The particles were loaded in the container of cylindrical shape (Fig. 1).

Container for the examination of hydrodynamics consisted of four sections with height of 30 mm. In between the sections, when needed, we installed perforated bottoms. The pressure drop in the layer of material was registered by the differential manometer OKSI 1D. The limit of the instrument readings is dilution from 1 to 1000 Pa. The sensitivity of the device – 1 Pa. The country of origin is China. Consumption of gas flow was registered by the flowmeter of standard model PM-II, model RM-02-0,016ZhUZ. The country of origin is Russia (Arzamasky Instrument–building Plant).

Terms of the experiment and description of the equipment used is described in more detail in [18].

4. 2. Methodology of experimental research into the filtration of gas flow through the formed layer of candied fruits

Preparation of the raw material was carried out according to the following stages: the pumpkin was peeled off, the membrane removed; using the matrix, we formed particles of cylindrical shape of similar size (height of 20 mm and diameter of 10 mm) and made a layer of them by four different methods in a container, as shown in Fig. 1.

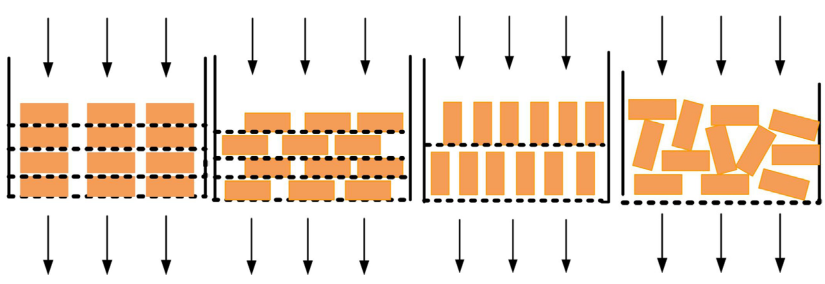

Fig. 1. Methods of forming a layer of candied fruits: *a* — method I of arranging candied fruits horizontally "one on one"; *b* — method II of arranging candied fruits horizontally "with blocking the channels"; *c* — method III method of arranging candied fruits vertically "with blocking the channels"; *d* — method IV of arranging candied fruits "chaotically"

The experiment on the hydrodynamics of stationary layer of particles from pumpkin was conducted by various heights of the layer. Each height in the case of the four methods was formed with the same number of particles. The container was put on the receiver. A vacuum pump was turned on and by means of a regulating valve we set a different rate of gas flow through the layer. Gas flow under the influence of pressures drop was filtered in the direction "pumpkin layer – perforated partition" (Fig. 1). The magnitude of rate was determined by the readings of flowmeter and losses of pressure by the readings of differential manometer.

The methodology of conducting experimental research into hydrodynamics of the formed layer of candied fruits is described in more detail in paper [18].

5. Results of experimental research into hydrodynamics of the motion of gas flow through the layer of candied fruits, formed by four different methods

Dependencies of the pressure losses in the layer of candied fruits, arranged according to methods I–IV (Fig. 1) on the fictitious speed of gas flow for different heights are shown in Fig. 2.

Fig. 2, *a* demonstrates that pressure losses in the layer of candied fruits of height 20 mm at the speed of gas flow of 2 m/s, arranged according to method I, was 145 Pa; with the increase in height, pressure losses grew and amounted for the layer of height 40 mm – 155 Pa, 60 mm – 175 Pa. The obtained results are logical and do not contradict basic provisions of theory of hydrodynamics of a stationary layer. There is a slight growth of hydraulic resistance observed when increasing the height (Fig. 2, *a*; curves 1–3). This phenomenon is explained by the fact that the equivalent diameter of channels between the particles of candied fruits is large enough. This method of arrangement enables the thermal agent to blow out the outer surface of particles, as can be seen from Fig. 1, *a*.

The experimentally determined values of porosity (ε, m^3/m^3), specific surface (a, m^2/m^3) and equivalent diameter (d_e, m) of the layer for methods I–IV are presented in Table 1.

The second method of arrangement, as can be seen from Fig. 1, *b*, enables the thermal agent to blow over a larger surface of the particles. However, the losses of pressure in the layer of candied fruits, arranged by the second method, are larger in comparison with the first method. Fig. 2 demonstrates that resistance of the layer of height 20 mm at the speed of gas flow of 2 m/s equals 210 Pa, resistance of the layer of height 40 mm – slightly exceeding 400 Pa, resistance of the layer of height 60 mm – 550 Pa. This is due to the fact that the equivalent diameter of channels between the particles of candied fruits is smaller and specific surface of the layer is larger in comparison to the first method of arrangement (Table 1).

The third method of arrangement, as can be seen from Fig. 1, *c*, enables the thermal agent to blow over even larger surface of the particles in comparison with the first two methods. The losses of pressure in the layer of height 20 mm at the speed of gas flow of 2 m/s are approximately equal to 250 Pa. The losses of pressure in the layer of height 40 mm – 500 Pa, the losses of pressure in the layer of height 60 mm – 700 Pa (Fig. 2, *c*). Resistance of the layer is lower in comparison with the two previous methods. As we can see from Table 1, under conditions of this method of arrangement, equivalent diameter of the layer is smaller while specific surface is larger in comparison with the first two methods.

Table 1

Characteristics of layer of candied fruits, formed by different methods

Characteristics of layer	method I	method II	method III	method IV
ε, m^3/m^3	0.23	0.23	0.23	0.1
a, m^2/m^3	178,5	244	277	172
d_e, m	0,005	0,004	0,003	0,002

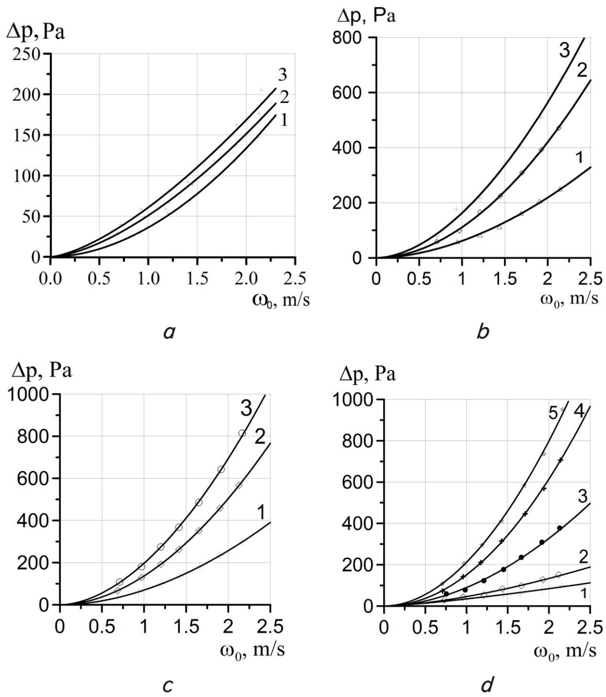

Fig. 2. Dependency of pressure losses in the layer of candied fruits, arranged according to the four methods, on the fictitious speed of gas flow for different heights H: *a* — method I (1 — 20 mm; 2 — 40 mm; 3 — 60 mm); *b* — method II (1 — 20 mm; 2 — 40 mm; 3 — 60 mm); *c* — method III (1 — 40 mm; 2 — 80 mm; 3 — 120 mm); *d* — method IV (1 — 20 mm; 2 — 40 mm; 3 — 60 mm; 4 — 80 mm; 5 — 100 mm)

Pressure losses in the layer of candied fruits according to the fourth method of arrangement are the lowest (Fig. 2, *d*). This is explained by the fact that during the chaotic arrangement of the particles, there are «stagnant» zones in the layer, through which thermal agent practically does not come through, and those zones, through which, by the path of least resistance, the bulk of gas flow passes along wide channels. This character of motion justifies disproportionate growth of hydraulic resistance at increasing the height of the layer (Fig. 2, *d*; curve 1–4). According to Table 1, the values of equivalent diameter and specific surface are the lowest compared with the previous methods.

6. Discussion of results of research into hydrodynamics of the motion of gas flow through the layer of candied fruits, formed by four different methods

To generalize the results of research into hydrodynamics, we conducted comparison of the values of hydraulic resistance of the layers of candied fruits, formed by the four above-mentioned methods under conditions of equal height of the layer, which contained the same number of pumpkin particles. For a uniform distribution of gas flow on the plane of container, we chose the height H=0.04 m (the container contained 56 particles at such height). The curves for comparison are shown in Fig. 3.

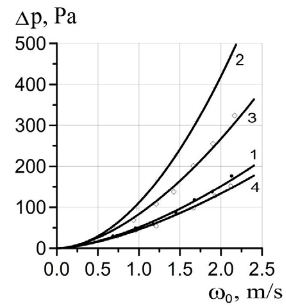

Fig. 3. Dependency of pressure loss in the layer of candied fruits, arranged according to the four methods, on the fictitious speed of gas flow (H=0.04 m (56 particles)): 1 — method I; 2 — method II; 3 — method III; 4 — method IV

As we can see from Fig. 3, the lowest resistance is demonstrated by the layer, formed according to the fourth method, the largest resistance – by the layer, formed according to the second method.

For theoretical calculation of hydraulic resistance of the layer of candied fruits, let us use the Darcy-Weisbach equation, which, according to literary sources [19], is widely used in practice for a stationary layer formed by particles of regular shape.

We decided to summarise results of dependency of the change in hydraulic resistance of the layer of candied fruits on the speed of gas flow and geometric parameters of the layer by the following method.

Hydraulic resistance coefficient can be defined based on the experimental data from the Darcy-Weisbach equation, presenting it in the form:

$$\lambda = 2 \cdot \frac{d_e}{H_e} \cdot \frac{\Delta p}{\rho \cdot \omega^2} \text{ or } \lambda = 2 \cdot \frac{d_e}{H_e} \cdot Eu,$$

where Δp is the hydraulic resistance of a stationary layer of dispersion material; λ is the coefficient of hydraulic resistance of a stationary layer of dispersion material; H_e is the equivalent length of channels in a layer of material, m; (H_e=1.5·H); H is the height of a layer of material, m; ρ is the density of gas flow, kg/m^3; ω is the actual speed of gas flow, m/s; ω=ω0/ε; ω0 is the fictitious speed of gas flow, m/s; Eu is the Euler's criterion.

Using experimental data on the losses of pressure (Δp) and the actual speed of gas flow (ω), we determined the coefficient of resistance (λ).

The Reynolds criterion was determined from the dependency presented in [19] for the case of internal problem of hydrodynamics.

$$Re_e = \frac{\omega \cdot d_e \cdot \rho}{\mu},$$

where μ is the viscosity of gas flow, Pa·s.

Graphical dependencies of the coefficient of resistance λ on the Reynolds criteria Re are shown in Fig. 4.

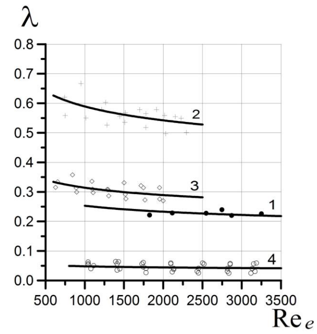

Fig. 4. Dependency of the coefficient of resistance λ on the number Re during motion of gas flow through the layer of candied fruits arranged according to the four methods: H=0.04 m, 56 particles: 1 – method I; 2 – method II; 3 – method III; 4 – method IV

In the technical literature, the coefficient of hydraulic resistance is represented as a function of the Reynolds number in the form:

$$\lambda = \frac{A}{Re^n},$$

where A and n are the coefficients determined experimentally. That is why the experimentally determined values of the coefficient of resistance of the formed layers of candied fruits were approximated by power dependence. The approximation was performed using the graphic-program complex Grapher 10. Received equations for the calculation of the coefficient of hydraulic resistance and the losses of pressure in a stationary layer of candied fruits, formed by different methods, are shown in Table 2.

Table 2

Equation for calculating the coefficient of hydraulic resistance and the losses of pressure in a stationary layer of candied fruits, formed by different methods

Parameter	method I	method II	method III	method IV
λ	$0.58/Re^{0.12}$	$1.35/Re^{0.12}$	$0.72/Re^{0.12}$	$0.11/Re^{0.12}$
Δp, Pa	$\frac{0.58}{Re^{0.12}} \cdot \frac{H_e}{d_e} \cdot \frac{\rho \cdot \omega^2}{2}$	$\frac{1.35}{Re^{0.12}} \cdot \frac{H_e}{d_e} \cdot \frac{\rho \cdot \omega^2}{2}$	$\frac{0.72}{Re^{0.12}} \cdot \frac{H_e}{d_e} \cdot \frac{\rho \cdot \omega^2}{2}$	$\frac{0.11}{Re^{0.12}} \cdot \frac{H_e}{d_e} \cdot \frac{\rho \cdot \omega^2}{2}$

Thus, the equations obtained by generalization of experimental data (Table 2) enable us to theoretically determine the coefficient of resistance λ and to predict the losses of pressure in a stationary layer of candied fruits by different methods of its formation.

Table 2 also displays equations that enable to determine theoretically hydraulic resistance (Δr, Pa) of the layer of candied fruits, formed in a certain way, during the filtration of gas flow in the direction of "layer of material – perforated partition". The experimental and theoretically calculated data agree with each other (Fig. 5), and maximum relative error between the experimentally obtained and the estimated values does not exceed 10 %, therefore, they may be recommended for practical calculation of drying equipment.

The limits of using equations that are given in Table 2: particle height 20 mm, particle diameter 10 mm, layer height 20–120 mm, Re<4000.

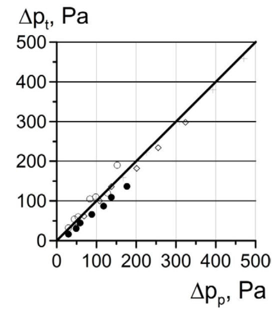

Fig. 5. Correlation dependency between the experimental and the calculated values of hydraulic resistance of the layer of candied fruits, arranged according to the four methods for the height: H=0.04 m (56 particles)

When analyzing the results of experimental and theoretical research, one can draw the following conclusions. Despite the fact that hydraulic resistance of the layer, formed by method IV is the lowest (Fig. 3, Table 2), this method of arrangement is "chaotic", from which it follows that separate areas of the layer will be "stagnant", i. e., will not be blown over by thermal agent while a principal amount of gas flow will pass through other zones. Specific surface (a, m^2/m^3) of the layer formed by this method is the smallest (Table 2). Thus, with this method of arrangement, drying will be long-lasting and uneven.

Optimal method of formation of the package is the method of arranging the candied fruits vertically "with blocking the channels" (method III) as shown in Fig. 1, *c*. This may be stated based on considerations that the average specific surface (a, m^2/m^3) of the layer formed by this method is the largest (Table 2). Hydraulic resistance of the layer is lower in comparison with methods I–II (Fig. 3, Table 2). That is why the contact of gas flow with the layer of candied fruits will be the best and energy expenses are low due to low hydraulic resistance.

The magnitude of actual speed (under conditions of constant rate of gas flow) will be the larger, the smaller is equivalent diameter between the particles. With the growth of real speed, the value of heat release coefficient α increases; the thickness of the boundary layer decreases and, as a consequence, the process of filtration drying largely intensifies due to a significant amount of heat, which is transferred from gas flow to a wet particle.

Therefore, method III of the formation of the layer (Fig. 1, *c*) will provide low hydraulic resistance, intensity and reduction in the time of drying, and, as a consequence, reduction in capital expenditures for the process. We can also argue that the received estimated dependencies are important both for numerical simulation of the course of thermal mass exchanging process during drying and for practical calculations.

7. Conclusions

1. We determined characteristics of the layer of candied fruits formed by different methods, particularly: porosity (ε, m^3/m^3), specific surface (a, m^2/m^3), equivalent diameter of channel between the particles (d_e, m).

2. Based on generalizations of experimental data, through their approximation with power function, we obtained estimated dependencies, for the calculation of coefficient of hydraulic resistance and losses of pressure in the layer of candied fruits formed by different methods.

3. The obtained theoretical dependencies agree well with experimental data and are important for the prediction of kinetics of the filtration drying with regard to energy costs of the process. In particular, the expediency of forming a layer with the method of arranging the particles of candied fruits vertically "with blocking the channels". This allows providing for minimum pressure losses in a stationary layer and intensifying the thermal mass exchanging process when drying candied fruits.

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