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EXERGY CALCULATION OF THREE-PHASE FLUIDIZED BED APPARATUS FOR SEPARATION OF "SOLID-SOLID" SYSTEM

Kudrat Karimov [1*], Asatilla Karabayev[1], Taxir Nurmatov[1] and Mirolim Abdullayev[1]

[1]Tashkent State Technical University, University st., 2, 100095, Tashkent, Uzbekistan
kudrat_kf@list.ru

Annotation. Energy efficiency of the apparatus for processing root crops and tuber crops, operating on the basis of the three-phase fluidized bed (TPFB) process, has been evaluated. The exergy method of thermodynamic analysis was applied. The criterion for evaluating the effectiveness of the apparatus characterizes it only from the view point of hydrodynamics.
Key words Three-phase fluidized bed (TPFB); energy efficiency; flow of matter; oscillatory velocity; exergy.
注解。 对基于三相流化床 **(TPFB)** 工艺的块根作物和块茎作物加工设备的能源效率进行了评估。 应用热力学分析的火用方法。 评估设备有效性的标准仅从流体动力学的角度对其进行表征。
关键词三相流化床（**TPFB**）；**能源效率;** **物**质流动；**振**荡速度；**火用。**

Nomenclature

G – discharge, kg/s; E – exergy, J/s; D – exergy losses, J/s; p – pressure, Pa; s – entropy, J/(moles K); T – absolute temperature, K; u – specific internal energy; v – specific volume; η – coefficient of performance (c.o.p.).
Indexes: ‘ – inlet; “ – outlet; am – ambient medium.

1. Relevance of the problem

Vegetable production on a global scale has doubled compared to the last decade and amounts to 1150 million tons, a large share of which is occupied by root and tuber crops. The leaders in this area are China (580.7 million tons), India (121.0 million tons), USA (34.7 million tons), Turkey (28.3 million tons), Iran (23.7 million. tons), Egypt (19.6 million tons). This trend contributes to the focus of scientific research on improving the quality of processed products to a level corresponding to consumption standards, ongoing research work is aimed at improving existing technologies for processing vegetables and fruits with the development of new efficient processes and devices. Today, all over the world, an urgent task is modern methods and methods for processing root and tuber crops in order to obtain food powders, efficient and rational use of local raw materials with minimal losses, intensification of processes and apparatus for cleaning and washing with minimal energy consumption

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About the authors：Kudrat Karimov

Email: kudrat_kf@list.ru

for pumping coolants. Therefore, carrying out research work on carrying out several processes in one installation with minimal energy consumption, creating non-traditional highly efficient mobile technologies for processing raw materials, ensuring the competitiveness of products, reducing their cost and consumption of raw materials is an urgent problem. In Uzbekistan, the main attention is paid to large-scale scientific research aimed at creating a high level of scientific work on the development of the food industry, in particular, the creation of new compact mobile technologies that include efficient processes and apparatus for the complete processing of domestic raw materials with minimal loss of raw materials and valuable components to obtain food semi-finished product. At the same time, it is necessary to further deepen scientific research on the effective use of local raw materials to obtain high-quality products. The strategy of actions for the further development of the Republic of Uzbekistan provides for the following tasks: “The rise of industry by transferring it to a qualitatively new level, to further intensifying the production of finished products based on the deep processing of local raw materials, mastering the production of new types of products and technologies. ”In this regard, scientific research on the creation of new highly efficient, energy- and resource-saving processes and devices in the technology of complete processing of root and tuber crops with the production of high-quality semi-finished products is of great importance.

2. Experimental data for the exergy calculation

In [2, 3], a scientific and theoretical substantiation of the feasibility and prospects for the use of TPFB in the effective processing of root and tuber crops was carried out. A description of the experimental setup for studying the process of separation of the "pulp-skin" mixture of processed objects is given. The created installation allows to carry out experimental studies in a wide range of regime parameters: equivalent diameter d_e, water and air flow rate V_w and V_{air}, water and air velocity w_wu w_{air}, shape factor Ф, ratio of gas and liquid phases G : L. A technique has been developed for conducting experiments on the separation of a heterogeneous mixture "solid – solid body" of various root and tuber crops, as well as a method for processing experimental data on the separation of a mixture of "pulp-skin", taking into account the hydraulic losses of the process and the physical and mechanical properties of processing objects. An analysis of the indicators characterizing the values of the forces of separation F of the skin peeled from the surface of the pulp by the method of instantaneous pressure release (MIPR) indicates that for various root crops and tuber crops this is $F = 0{,}3 \div 3$N. It has been established that the ratio of the cross-sectional areas of a large ellipsoidal hole to a smaller one $F_l/F_s = 0{,}4 \div 1{,}33$ creates a flat stream jet with oscillating motion. The values of the angle of internal friction of the objects of processing for the automation of the unloading process are determined, which vary in the range $\chi = 5 \div 25^{o}$. Experimental studies were carried out in the following range of changes: geometric dimensions of thin plates of skins of root crops and tuber crops from $2{,}5 \times 3$ to 50×50mm; thickness $\delta = 0{,}1 \div 0{,}25$mm. To measure the hydraulic resistance of a layer of solid heterogeneous systems in the water distribution chamber, there are branch pipes under the grate and in the upper part of the body for connecting the MMN-240 micromanometer. The water velocity varied in the range $w_w = 0{,}001 \div 0{,}05$ m/s, and the air velocity $w_{air} = 0{,}004 \div 0{,}095$ m/s. This helps to increase the degree of separation of the "pulp-skin" mixture and save water and energy for its pumping. In [2], the results of experimental studies on the study and intensification of the separation process of the "pulp-skin" mixture are presented. In the process of cleaning root and tuber crops MIPR, after relieving pressure during automatic unloading of the mixture into the collector, the peeled thin film of the skin sticks back to the peeled pulp, which is caused by the action of adhesive forces. Moreover, the relationship between the pulp and the skin is significant and requires their experimental determination.

Figure 1 shows the results of experimental studies on the size of sticky pieces of skin on the force of separation F for various roots and tubers. The intensity of particle sticking to solid surfaces can be estimated from the sticking force [2].

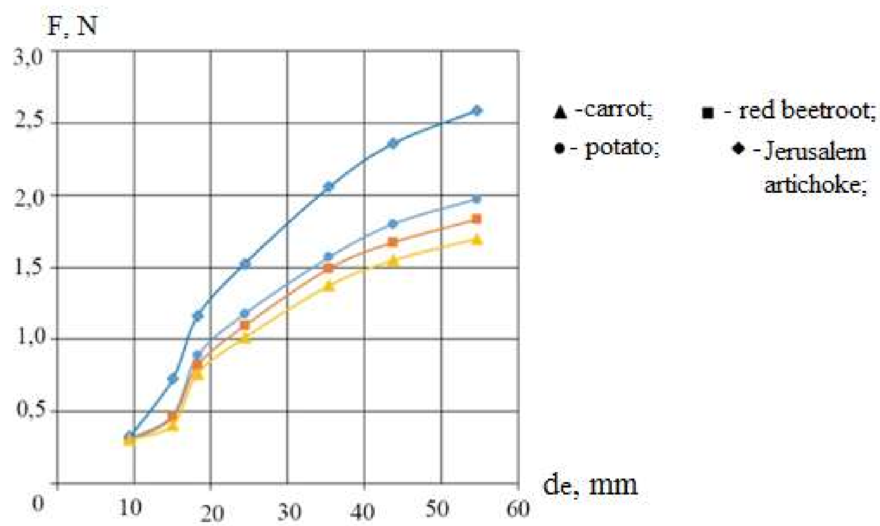

Fig.1. Dependence of the peel force on the equivalent diameter of the peel pieces in a three-phase fluidization .

Analysis of the results of studies, shown as a function $F = f(d_e)$, shows the ascending nature of the dependence of the force of separation from the surface of the skin pieces. As can be seen from the graph, the greatest effort to separate the skin from the pulp is required for the skin of Jerusalem artichoke, and the smallest force for carrots. A significant influence of the sticking surface on the force of separation is seen in the example of washing off the peel of Jerusalem artichoke. Thus, in a three-phase fluidized bed, a force of $F = 0{,}32$N is required to tear off a skin of $2{,}5 \times 4{,}5$ mm from the pulp, for a piece of 20×25mm the required force is $F = 1{,}52$ N, and, respectively, for a skin of 50x50 mm$-F = 2{,}59$N. To overcome the forces of adhesion of the adhered peel to the pulp, a gas distribution grid design has been developed that provides an oscillating velocity of the gas-liquid layer outflow. This grating has ellipsoid holes with a small cross section located at the vertices of a regular hexagon, in the center of which there is a hole with a large cross section. In order to obtain flat jets, an ellipsoid shape of the holes was chosen, which also provides a pressure gradient. This arrangement of holes allows for variable speed. As a result, an oscillating regime of the gas-liquid flow occurs, which ensures the capture and removal of the skin. The dependences of the hydraulic resistance of a sectioned grate on the flow velocity are studied for various values of the free section φ and the angle of inclination γ. It has been established that with an increase in the angle of inclination of the grating from 5 to 25 °, the hydraulic resistance increases by a factor of 1.4. With an increase in the flow velocity to $w = 8$m/s, the increase in hydraulic resistance in the case of a sectioned grate will be more than 7 times [2, 3].

Summarizing the experimental data on the hydraulic resistance of dry gratings with different proportions of the free section $\varphi$and the angle of inclination γ, the calculation formula (1) is derived, which describes the experimental data with a change in air speed $w = 0{,}1 \div 25$m/s, the fraction of the free section $\gamma = 0{,}2 \div 0{,}7$ and the angle of inclination of the grating $\gamma = 0 \div 25$ about accuracy ±7.7%:

$$\Delta P_{dr} = 9{,}53 \cdot 10^{-4} \cdot \frac{\rho w^2}{2} \cdot \varphi^{-0{,}46} \gamma^{0{,}2} \quad (1)$$

One of the main indicators of fluidized beds in the $G{:}\,L$ and $G{:}\,L{:}\,S$ systems is the hydraulic resistance. The total hydraulic resistance of two and three-phase fluidized beds is determined by the well-known formula $\Delta P = \Delta P_{dr} + \Delta P_l + \Delta P_{l.c} + \Delta P_\sigma$.

Experimental data on the influence of the layer height $H$of the processing object on the hydraulic resistance ΔP_l for various root and tuber crops have been determined. It has been established that the value of hydraulic resistance ΔP_l from the height of the layer of Jerusalem artichoke tubers is $\Delta P_l =$ 162 Pa, carrot $\Delta P_l = 185$ Pa, red beet $\Delta P_l = 250$ Pa, potato $\Delta P_l = 275$ Pa, and for sugar beet $\Delta P_l =$ 440 Pa. It was found that with an increase in the layer thickness, the H value of hydraulic resistance ΔP_l increases from 160 to 440 Pa with an increase in the height of the material layer from 40 to 100 mm. At the same time, the porosity of the layer ε, depending on the object of processing, varied from $\varepsilon = 0{,}37$ to 0,45. Experimental data on the effect of the equivalent diameter d_e of the lattice holes on the hydraulic resistance ΔP_σdue to surface tension at water temperature $t = 10 \div 30$ºC showed that with an increase in the diameter of the hole from 3 to 10.55 mm, the resistance decreases by 3.5 times, and the water temperature has practically no effect.

Experimental studies on the use of TPFB to separate the skin from the pulp purified by MIPR gave a very interesting result. Studies have shown that a heterogeneous mixture, consisting of components with sharply different densities, separates at relatively low speeds and flow rates of the liquid and gas phases in order to separate the skin from the peeled pulp. It has been established that the use of TPFB for the separation of a solid inhomogeneous system "pulp-skin" is more efficient than a two-phase one, i.e. by 13-78% depending on the equivalent diameter. Comparison of data on the speed of the start of fluidization in two-phase and three-phase systems showed a decrease in numerical values $Re$of 1.3 ÷ 2.0. Such an effect is explained by the effective effect of the gas jet on an irregularly shaped body. The fractional composition of the skin pieces, expressed in terms of particle size distribution, is shown in Fig. 2. To study the process of entrainment of solid particles from an inhomogeneous mixture "solid body−solid body", experimental studies were carried out with purified MIPR Jerusalem artichoke (potatoes, carrots, sugar and red beets) with a change in the equivalent diameter $d_e = 1 \div 8$mm, flow rate $w = 1 \div 300$mm/s, ratio $G\colon L = (0.05 \div 0.25)$: [2].

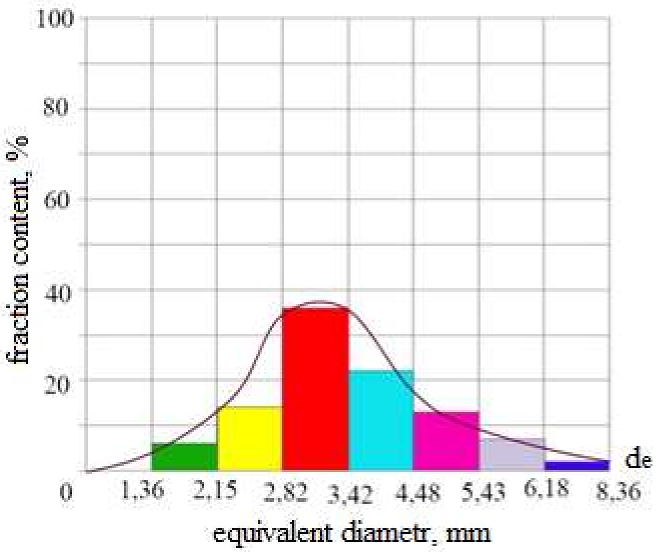

Fig.2. Particle size distribution curve for skin pieces

It is known that to calculate the entrainment rate of solids from a fluidized bed, the formula of Prof. Todes O.M. can be applied. On fig. 3 shows the dependence of the Reynolds criterion Re from the Archimedes criterion Ar in the form of a functional dependence $Re = f(Ar)$ on various distribution grids in two and three-phase systems. As can be seen from the figure, the dependence Re from Ar has a smoothly ascending form [2, 3].

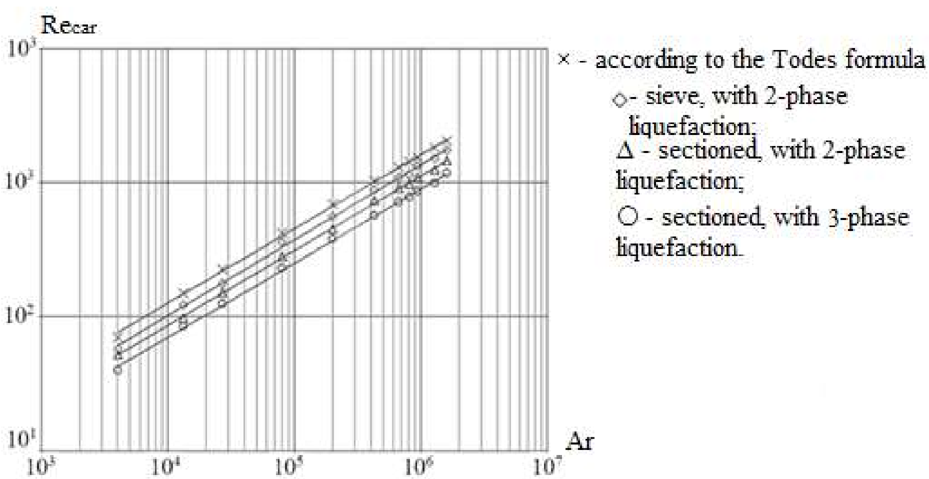

Fig.3. The dependence of the entrainment rate of irregularly shaped bodies on Arduring liquefaction on various grates

Experiments have shown that using three-phase fluidization to separate a solid inhomogeneous "pulp-skin" system, it is possible to achieve a process efficiency of 17÷32% compared to a sectioned grate in a two-phase one and 43-55% compared to a two-phase one on a grate with round holes. Often, carryover from the fluidized bed is, in most cases, an undesirable, negative phenomenon. However, in our case, when separating an inhomogeneous "solid body-solid body" system, this drawback is a positive phenomenon and makes a significant contribution to the complete, 100% separation of the mixture into components. By summarizing the experimental data on the rate of the start of fluidization of an inhomogeneous mixture "pulp-skin" in TPFB, the following formula was obtained for calculating Re_{fb}:

$$Re_{fb} = \frac{Ar}{4300+10{,}6\sqrt{Ar}} \tag{2}$$

The error of formula (2) for calculating Re_{fb} irregularly shaped bodies in the form of pieces of root skins in a three-phase fluidized bed does not exceed ±15%.

By summarizing the experimental data on the rate of removal of the skin from the inhomogeneous mixture "pulp-skin" in TPFB, the following formula was obtained for calculating Re_{rem}:

$$Re_{rem} = \frac{Ar}{18+1{,}177\sqrt{Ar}} \tag{3}$$

The error of formula (3) for calculating the entrainment rate of irregularly shaped bodies in the form of pieces of skin of root and tuber crops in a three-phase fluidized bed does not exceed ±5%.

The zone of the fluidized bed narrows somewhat with increasing particle diameter, but nevertheless it exists in a rather wide range of numbers Re, i.e. different by an order of magnitude or more. Three-phase fluidized bed has a number of advantages:

– firstly, the process of separating an inhomogeneous mixture "solid body-solid body" proceeds at relatively low velocities of both liquid and gas phases;
– secondly, there is a complete (100%) separation of the "solid body-solid body" mixture;
– thirdly, the process of sedimentation of solid particles of pollution in the form of sand, clay, etc.;
– fourthly, along with the separation of a heterogeneous mixture, the process of washing the raw pulp of root and tuber crops simultaneously proceeds;
– fifthly, often carryover from the fluidized bed in most cases is an undesirable, negative phenomenon. However, in our case, when separating an inhomogeneous "solid body-solid body" system, this drawback is a positive phenomenon and makes a significant contribution to the complete, 100% separation of the mixture into components.

3. Scheme of TPFB separation model

Today, great attention has been paid to creation of the modern methods of processing agricultural products, rational and efficient use of local raw materials with minimal losses. So, Nurmukhamedov H.S. et al. created [1] the method for processing root crops and tuber crops with TPFB. The pulp and skin of root crops and tuber crops, peeled by the method of instant pressure release, are simultaneously separated, washed, and deposited in one apparatus. Separation of the mixture "pulp-skin", washing of pulp, sedimentation of dirt are carried out by fluidization with water and oscillating the air flow. Nurmukhamedov H.S. et al. developed [2, 3] the physical model (Fig.4) of the method for separating a solid inhomogeneous mixture in a three-phase fluidized bed, explaining the mechanism of effective and complete separation of a non-homogeneous system "solid-solid", consisting of:

a) loading of the object processing;

b) setting the optimal ratio G:L (gas: liquid) and the entrainment mode;

c) rinsing the skin from the pulp of root and tuber crops;

d) unloading the washed pulp.

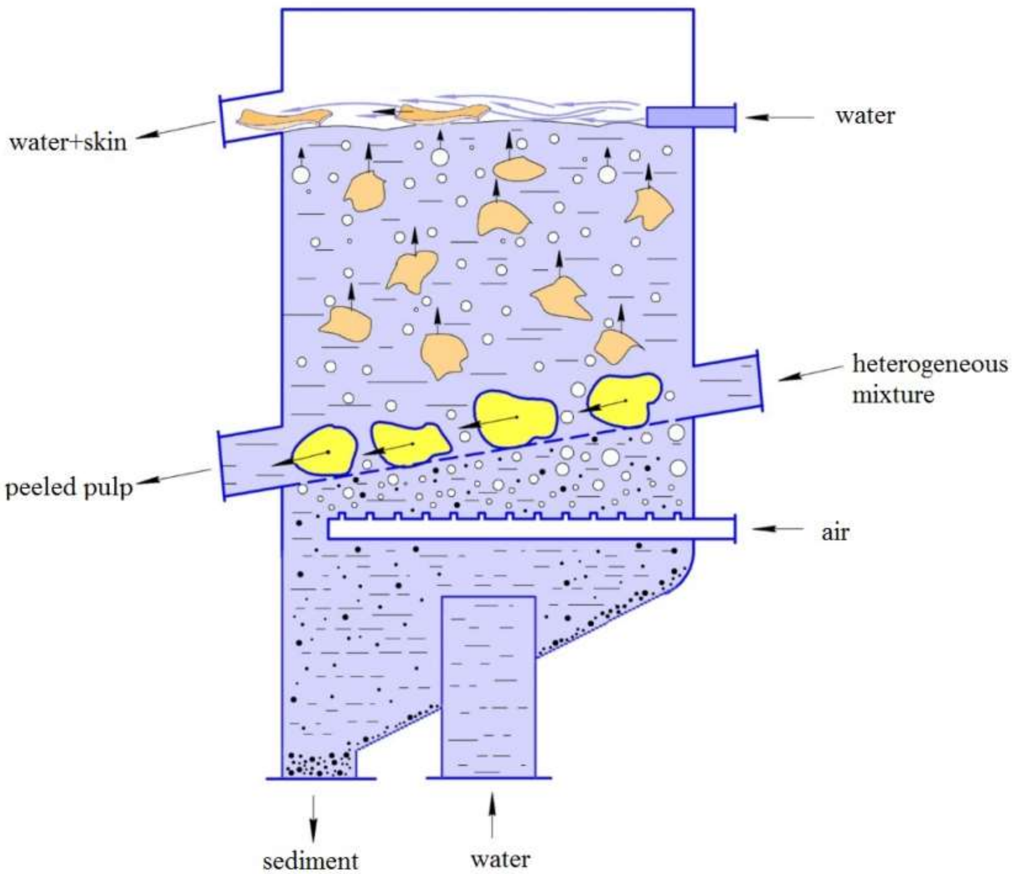

Fig. 4. Schema of the method for separating a solid inhomogeneous mixture in a three-phase fluidized bed.

The loaded raw material, falling on the distribution grid, due to the presence of the gradient of velocity and pressure, is exposed to the oscillating gas-liquid flow. The variable, pulsating speed of the gas-liquid flow out flowing from various holes begins to wash the pulp of the peeled root crops rolling down the inclined grate. When moving along an inclined grate, the pulp with adhering skin will in any case be parallel to the oncoming jet of the gas-liquid flow. Oscillating jets from several (3-5) sections simultaneously run onto one adhering skin.

The oscillating flow rate of the gas-liquid layer is ensured by the developed design of the gas distribution grid.
The pressure on the incoming flow side P_1 will be more than that on the back side P_2. Naturally, when $P_1 > P_2$, the pressure gradient in the pulp is directed from the inside out. In addition, adjacent jets contribute to the peeling process and rapidly increase the peel area and then instantly peel off a piece of thin skin film from the pulp. The separated pieces of skin are carried away together with the gas-liquid flow up to the water surface. Then from the surface of water, under the action of water jets, a light component is blown out through the nozzle.

4. Calculation of substance energy in flow

For our object of research, the principle of operation of which is described in Section 1, it is necessary to calculate the exergy of the substance in the flow, since a stationary process occurs, associated with the mixing of substances – air, water and solids, without heat exchange (see Section 3, conditions 1 ÷ 3).
Consider a steady flow of foam – a solution of water and air with parameters u, v, s, T and p. The parameters characterizing the state of equilibrium with the environment are denoted by $u_{am}, v_{am}, s_{am}, T_{am}$ и p_{am}. To determine the exergy e of the flow, it is required to find the maximum work in the transition from the state of entry into the TPFB apparatus to the state of exit from it.
The work of movement of a flow of matter (foam) pv minus the part that is spent on overcoming the pressure of the environment, for the final change in state is determined by the expression [4]

$$pv - p_{am}v = v(p - p_{am}). \tag{1}$$

Subject to the formula (3.5) [4] we receive

$$e = i - i_{am} - T_{am}(s - s_{am}) = i - T_{am} + c \tag{2}$$

or, in the differential form
$de = di - T_{am}ds.$
Function e is exergic, since it is uniquely determined by the parameters of substance and environment. As can be seen from the formula (2), its value is directly related only to the ambient temperature T_{am}, and pressure p_{am} is included only in the additive constant $c = -(i_{am} - T_{am}s_{am}) = -(u_{am} + p_{am}v_{am} - T_{am}s_{am})$. This means that the ambient pressure p_{am} matters only when calculating the absolute value of the function e [4]. In our calculations, the use of the exergy difference Δe is required, and the pressure p_{am} does not affect the characteristics of process in question, since the constant c is reduced.
Below are given (Table 1) the results of calculations of the exergy of water and air in the flow at several temperatures and a pressure of 0.2 MPa (at the inlet).

Table 1

T, K	water			air		
	i, kJ/kg	**s, kJ/(kg·К)**	**e, kJ/kg**	**i, kJ/kg**	**s, kJ/(kg·К)**	**e, kJ/kg**
291	75.5	0.2677	-2.4007	291.01	6.6404	-1641.35

298	104.77	0.367	-2.027	298.08	6.6642	-1641.2
303	125.66	0.4365	-1.3615	303.1	6.6812	-1641.13

5. Compiling the exergy balance equation

To compile the equation of the exergy balance of the TPFB apparatus, it is necessary to mentally surround the system under consideration with a control surface and determine the flows of incoming and outgoing exergy.

In the most general case, when flows of matter, heat, work enter and leave the system, the exergy balance is written in the form [4] $\Sigma E_i' + \Sigma E_q' + \Sigma L' = E_i^{"} + \Sigma E_q^{"} + \Delta E + \Sigma L^{"} \Sigma D$ (3)

$$\Sigma E' = \Sigma E^{"} + \Sigma D \tag{4}$$

In real installations, irreversible processes occur (friction, heat transfer at a finite temperature difference, throttling, chemical transformations, etc.), accompanied by energy dissipation, therefore, for them, the inequality

$$\Sigma E' > \Sigma E^{"} \tag{5}$$

The exergy low in the system (unit) is therefore determined as

$$\Sigma D = \Sigma E' - \Sigma E^{"} \tag{6}$$

The exergies of the incoming and outgoing flows of matter and energy are calculated from the parameters of these flows, directly measured on the operating devices, or calculated for the designed ones.

Let us compose the equation of the exergy balance of the TPFB apparatus on the basis of formulas 3 ÷ 6, and taking the following simplifications.

1) In the TPPS apparatus, the mixing process takes place simultaneously with the outflow process. When air and water are mixed, no heat is generated or absorbed.

2) At the exit from the cleaning apparatus, the pulp and skin of root and tuber crops are heated to several temperatures. Then the pulp and skin are carried away by the water into the TPFB apparatus. Therefore, the heat of peeling the skin will not be taken into account in the calculations.

3) Air and water have different temperatures, but the difference is small. When mixing, heat exchange occurs between air and water. But, this heat does not affect the dissolution process.

4) The air concentration in a three-phase solution is low and does not affect the temperature, i.e. the temperatures of water and foam at inlet and outlet of the TPFB apparatus are equal.

5) The presence of a solid phase in a three-phase flow is taken into account by it created by the hydraulic resistance p_m.

6) The calculation of the exergy of the three-phase flow at the outlet of the apparatus is carried out for the angle of the best location of the sectioned lattice – 20°, and the flow rate ~ 15 mm/s, i.e. at hydraulic resistance of the sectioned grating $p_g = 100$ Pa [2, 3].

The exergy balance of the TPFB unit, based on 1 kg of outgoing three-phase solution

$$G_w\left(e_w - e_w^{\mathrm{p}}\right) = G_{air}\left(e_{air}^{\mathrm{p}} - e_{air}\right) + \Sigma D \tag{7}$$

The indices “w” and “air” at e show that exergy is related to water or air relatively.

Due to the mixing of water and air, the entropy at the outlet of the TPFB apparatus for both agents increases by the entropy of mixing, while the exergy decreases. Therefore, for each component it is necessary to calculate the output exergy. The correction for the entropy of mixing is defined as $\Delta s_p = 8.314/\mu_i \, lnz_i$, where μ_i is molecular weight of i th component of mixture (foam); z_i is molar portion of that component.

When mixing 39 kg/s of water with 3.9 kg/s of air, the mass fraction of air in the three-phase solution is $g_{air} = 3.9/(39+3.9) = 0.091$, water – $g_w = 0.909$. When we pass from mass fractions to molar fractions, we receive:

$$z_w = (g_w/\mu_w)/(g_w/\mu_w + g_{air}/\mu_{air}) = (0.91/18)/(0.91/18 + 0.091/28.84) = 0.9404$$

Respectively $z_{air} = 0.0596$. Then, for water $\Delta s_w^{\mathrm{p}} = (8.314/18)ln0.9404 = -0.0284$ kJ/(kg·K) and for air $\Delta s_{air}^{\mathrm{p}} = (8.314/28.84)ln0.0596 = -0.813$ kJ/(kg·K).

Water exergy at outlet

$e_w^{\mathrm{p}} = i_w^{\mathrm{p}} - T_{am}(s_w^{\mathrm{p}} - \Delta s_w^{\mathrm{p}}) = 75.5 - 291(0.2677 + 0.0284) = -10.6651$ kJ/(kg·K.

Whereat, enthalpy i_w^{p} and entropy s_w^{p} are adopted at the parameters p_{out} and T_{out}.

Air entropy at outlet

$$s_{air}^{\mathrm{p}} = s^{\mathrm{p}} - \Delta s_{air}^{\mathrm{p}} = c_{\mathrm{p}} ln(T_{\mathrm{p}}/T_{am}) - (R/\mu_{air}) ln(p_{am}/p^{\mathrm{p}}) - \Delta s_{air}^{\mathrm{p}}$$

At $c_p = 1.01$ kJ/(kg·K), $\mu_{air} = 28.84$ kg/mole

$s_{air}^{\mathrm{p}} = 1.01ln(98/291) - (8.314/0.19)ln(0.1/0.19) - (0.813) = 1.022$ kJ/kg.

and $e_{air}^{\mathrm{p}} = i_{air}^{\mathrm{p}} - 291 s_{air}^{\mathrm{p}} = 300.2 - 291 \cdot 1.022 = 2.798$ kJ/kg.

here $i_{air}^{\mathrm{p}} = 300.2$ kJ/kg and $p_{out} \approx 0.15$ MPa.

The pressure of the solution at the outlet of the TPFB apparatus is less than at the inlet due to the hydraulic resistance of the column of three-phase liquid mixture $p_{c.mix}$, cleaned from the skin of material p_m and sectionalized grill p_g:

$\Delta p_{tot} = p_{c.mix} + p_m + p_g = 1700 + 800 + 100 = 2600$ Pa.

Full exergy loss

$\Sigma D = 39(-2.4007 + 10.6651) - 3.9(2.798 - 1699.2) = 6938$ kJ/s

completely internal, since there is no heat loss to the environment. All loss is internal and consists of technical and personal losses. The latter is the result of irreversible mixing of water and air and is defined as a decrease in exergy due to mixing

$D_{per} = T_{am}(G_w \Delta s_w^{\mathrm{p}} + G_{air} \Delta s_{air}^{\mathrm{p}}) = 291[39(0.0284) + 3.9(0.813)] = 1245$ kJ/s.

Therefore, the technical loss is $D_t = 5693$ kJ/s. It occurs due to the installation of a sectional grate, loading peeled vegetables, etc.

Table 2 shows the results of exergy calculations for various water and air flow rates.

Table 2

G_w, kg/s	G_{air}, kg/s	ΣD, kJ/s	D_{per}, kJ/s	E', kJ/s	E", kJ/s	η
9	0.9	1604	287	1498.686	96.26854	0.064

12	1.2	2138	382	1998.248	128.3581	0.064
25	2.5	4455	797	4163.018	267.4126	0.064
39	3.9	6951	1244	6494.307	417.1637	0.064
43	4.3	7663	1372	7160.39	459.9497	0.064
59	5.9	10515	1883	9824.721	631.0938	0.064
63	6.3	11228	2010	10490.8	673.8798	0.064
77	7.7	13723	2457	12822.09	823.6308	0.064

6. Efficiency of TPFB apparatus

Operation of the TPFB apparatus is characterized by the exergy efficiency

$$\eta_{\mathrm{e}} = E''/E' = 1 - \Sigma D/E' \quad (8)$$

The calculated efficiency values are shown in Table 2. As can be seen from Table 2, the efficiency of the apparatus is about 7%. Such a low efficiency is characterized by the fact that there is no heat exchange in the apparatus, and the losses of exergy in the apparatus are associated with the hydrodynamic regime of the flow. A vegetable to be peeled and its skin constitutes a definite resistance. The greater this resistance, especially the resistance of the skin, the lower the efficiency of the apparatus. But, this contradicts the purpose of the TPFB apparatus: good functioning of the apparatus, i.e. good peeling of skin is accompanied by an increase in hydraulic resistance and a decrease in efficiency. But this does not mean that the device does not fulfill its function, does not peel vegetables. In this case, the exergy efficiency characterizes only the hydrodynamic resistance of the apparatus, but not the technological function of the apparatus.

To assess the energy-technological efficiency of the apparatus, a mixed exergy indicator of efficiency should be used as an objective function, as done in [5].

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