PROCESS OF SUGAR SOLUTIONS SULFITATION IN TERMS OF HYGIENIC REQUIREMENTS FOR EQUIPMENT OPERATION

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Abstract:

Operation of the sulfitation station at a sugar factory involves violations of sanitary requirements for production facilities due to instability of the equipment. It is possible to correct the situation with an integrated solution: by stabilizing flows and improving the design of the jet apparatus. The aim of the research is to study the hydrodynamics of jet apparatus.
Material for the study is the jet apparatus with a dispersed liquid jet and hydrodynamic processes occurring in the mixing chamber. Theoretical (the theory of added mass), experimental (generally accepted methods of studying the hydrodynamics of flows), analytical (statistical processing of results) research methods are used.

Designs of jet apparatus with a dispersed liquid jet and improved performance characteristics are developed. On their basis, the equipment for carrying out heat and mass transfer processes in sugar industry (sulfitators) is proposed. The possibility of using the theory of added mass in the calculation of such apparatus is shown, the main reasons why the calculation by this method leads to inaccuracies are noted, and the energy transfer coefficient is found.

It is concluded that complex relationships between the elements of the ejector and physical phenomena in the mixing chamber, and the impossibility of their quantitative accounting do not allow creating an accurate mathematical model of its operation so far. The possibility of applying the theory of added mass to the calculation of jet apparatus with dispersed liquid jets is presented, and new designs of jet apparatus for using in food industry are proposed.

Keywords: jet apparatus, dispersed jet, added mass, energy transfer coefficient.

Introduction

The process of water sulphitation in the sugar industry is used for disinfection, lowering the pH of feed water to 5.8 - 6 for the possibility of sucrose diffusion from beet chips. The sulphitation of juice and syrup is carried out in order to reduce the color when the dyes are bound with sulfur ions. It should be noted that the best result is obtained when treating water or solutions with sulphitation gas, which is obtained by burning lump sulfur in rotary drum kilns. The vacuum in such kilns is created by jet apparatus, which are the main equipment of the sulphitation plant.

The first sulphitators for the sugar industry were designed at the beginning of the last century as jet apparatus, but after an unsuccessful implementation they were forgotten for many years and only in the seventies of the last century they were used for this process again. Due to design miscalculations and insufficient knowledge of the process, sulphitators have significant drawbacks and they need to be improved.

Due to the fact that the work of the sugar factory is extremely unstable, the operating mode of the sulphitation station is constantly changing. Quite often, there is a situation when the fluid flow decreases to a critical value, and the jet apparatus develops low thrust or stops working at all. At the same time, a new problem arises: in addition to the fact that the liquid is not processed with sulphitation gas and the technological process is disrupted, it enters the production room, causing suffocation and respiratory distress of personnel.

Let us consider the situation when the fluid flows, on the contrary, increase. In this case, the pressure of the liquid in the working nozzle of the jet apparatus increases, the speed of the jet in the mixing chamber, the vacuum, and the entrainment ratio also increase, which leads to a decrease in the phases contact time. As a result, the quality of solutions treatment decreases, and at the exit from the sulphitation apparatus decreasing the SO_2 utilization factor is observed. This leads to damage of the equipment (through the holes, which are formed due to chemical corrosion) and to air pollution.

Both the first and the second situations are highly undesirable. It is necessary to solve such a problem in a complex manner: to stabilize the operation of the jet apparatus, which is possible with a stable liquid flow and improving the jet apparatus design.

Stabilization of the liquid flow is achieved quite simply - a liquid circulation loop is performed. If there is a lack of liquid to maintain constant pressure in the working nozzle of the ejector, part of it is taken from the damping tank at the outlet of the sulphitation plant. This ensures stable operation of the ejector and, accordingly, constant operational characteristics.

However, the quality of water or sugar solutions treatment depends on the design of the jet apparatus. Since the process of liquid sulphitation is a mass transfer process, one of the main requirements must be met: a significant contact surface of the phases with its intensive renewal.

The fulfillment of these requirements leads to the use of a centrifugal-jet nozzle as a working nozzle of jet apparatus. They are characterized by a spray pattern, which is uniformly filled with liquid drops. A significant contact surface of the phases is created, and the processes of drops formation, their impingement, and re-formation contribute to significant intensification of mass transfer processes.

The hydrodynamic instability of the drops surface stimulates an increase in the rate of transfer of the gas phase at the molecular and convective levels on opposite sides of the interphase of contact surface and transfers it to a transient state. Taking into account the simplicity of design, the absence of moving elements, ejection of a passive flow in rather significant volumes without additional energy consumption, jet apparatus are one of the most promising types of equipment that combine all the advantages of the hydrodynamic method of processes intensification.

Thus, the improvement of the jet apparatus design is going to ensure the stable operation of the sulphitation station and the fulfillment of sanitary requirements for production area.

It should also be noted that similar problems are faced where jet apparatus are used as equipment for the implementation of technological processes connected with mass transfer transitions. In food industry, the examples of such processes are pasteurization and sterilization of food products, saturation of drinks with carbon dioxide, mixing, aeration during fermentation, purification of dusty air, etc.

Examples of technological processes in the sugar industry that can be carried out in jet apparatus are sulphitation (treatment of water and sugar syrup with a gas containing SO_2), saturation (treatment of a sugar solution with a saturation gas with a CO_2 content of 35 ... 40%), deammonization (removal of ammonia from condensates). The indisputable advantages of jet apparatus allow them to be used in the disposal of emissions from sugar factories, which helps reduce material and energy production costs and improves the environmental situation.

The area of jet technology application is expanding every year [17, 18].

Fundamentally, the design of the jet apparatus has practically not been changed since the time of the first patenting in 1858. Despite the numerous studies, both theoretical and experimental, the main drawback of jet apparatus (low entrainment ratio, efficiency does not exceed 30%) has not been eliminated either. In this context, the search for the optimal design of the ejector, the mathematical study of its operation is being continued. The study on computer modeling of working processes in the ejector has been actively carried out during last period.

According to the state of the active flow, there are (Lyamaev) jet apparatus with a compact liquid jet and a dispersed one. The most studied jet apparatus are those of the classical type with a compact liquid jet.

The theoretical description of the processes in such apparatus is not considered separately. However, it should be noted that the mechanism for the formation of a vacuum in the receiving chamber in ejectors with a compact and dispersed jet of liquid is different.

In the ejectors with a compact active flow, the interaction with the gas phase is carried out mainly by the outer side of the spray pattern. As a result of friction part of the gas moves with the liquid, and this causes rarefaction (ejection).

When the ejector operates with a dispersed jet of liquid, it disintegrates into drops at a close distance from the cutoff of the active nozzle, and each formed drop interacts with the gas phase in the cocurrent gas-liquid flow.

Such a difference in the mechanism of interaction of an active liquid flow with a gas phase, however, is not taken into account in the theoretical consideration of the operation of jet apparatus. Therefore, when ejectors with a dispersed jet of liquid are calculated, additional errors arise in determining their characteristics.

The first works on the study of ejectors and the creation of calculation methods were carried out in the twenties of the last century. Theoretical studies in which the work of jet apparatus is considered are based on a number of physical laws: the law of conservation of mass, the law of conservation of energy, and the law of conservation of momentum. Due to the complexity of the processes occurring in the flow path of the jet apparatus (mixing chamber), the impossibility of their quantitative accounting, an accurate theoretical description of these processes has not been proposed yet.

In recent years, there has been a significant increase in interest in jet apparatus, and this is the reason why new experimental data on the hydrodynamics of ejectors [3-5] and mass transfer processes in them have appeared in the literature [6-7]. The instrumental methods of studying the flow regimes in the mixing chamber of ejectors are being improved in order to obtain a reliable picture of the movement of the emulsion [8-9]. Mathematical [10-13] and computer modeling of their work [14-16] are carried out.

The current line of research, which relies on computer modeling, also raises a lot of questions. The imperfection of the mathematical support for describing the processes occurring in the flow path of jet apparatus does not allow to obtain satisfactory results in a wide range of variable parameters and to take into account the design features of various ejectors.

The **aim** of this study is to develop the more advanced method for calculating and designing jet apparatus with a dispersed jet of liquid. Investigate the jet apparatus experimentally and provide evidence of the possibility of such an approach to the calculation.

In particular, the use of high-efficiency jet apparatus in the sugar industry will allow improving the processes of sulfitation of water and sugar solutions, carrying out the process of de-ammonization of condensates in an intensive and energy-efficient mode, creating two-section saturators and obtaining sugar solutions with high quality indicators, and utilizing the aggressive emissions from technological equipment. In addition, the improvement of the design of the jet apparatus and their operation will allow avoiding emergency situations when the emission of an aggressive gas phase into production facilities or the environment is possible.

Materials and Methods

Jet apparatus with a dispersed liquid jet and hydrodynamic processes occurring in the mixing chamber were studied. Theoretical (the theory of added mass), experimental (generally accepted methods of studying the hydrodynamics of flows), analytical (statistical processing of experimental results with the exception of gross errors after the Student's criterion at a significance level of 0.05) research methods were used.

The main difficulty of theoretically finding the characteristics of the ejector is in the ambiguity of the description of the process of jets turbulent mixing, their interaction in the space bounded by the rigid walls of the "mixing chamber" with open inlet and outlet. The presence of solid walls in the ejector makes it possible to create a pressure inside it, which differs from the pressure of both the low-pressure gas and the high-pressure medium. Energy is supplied to the ejector by a working fluid with a pressure p_p, a low-pressure passive medium (gas) is under a pressure p_n. The mixture after passing through the mixing chamber will have a pressure p_s, which is intermediate between p_p and p_n.

Usually, the processes occurring in jet apparatus are described by three laws:

- the law of conservation of mass:

$$G_s = G_p + G_n \tag{1}$$

where G_s, G_p, G_n is the mass flow rate of the mixture, working and low-pressure media, respectively, kg/s.

- the law of conservation of energy:

$$E_p + E_n = (1+k)E_s \tag{2}$$

where E_p, E_n, E_s is the energy of liquid, gas and mixture, respectively, J; k is the entrainment ratio.

- the law of conservation of momentum:

$$\mathrm{I}_{1p} + \mathrm{I}_{1n} = \int_{f_3}^{f_1} p_s df + \mathrm{I}_{3s} \tag{3}$$

where I_{1p}, I_{1n} is the impulse of working and low-pressure (gas) flows in the inlet section at the level of the end of the nozzle, kg · m/s;

I_{3s} is the impulse of the mixed flow in the outlet cross-section of the mixing chamber, kg · m/s;

$\int_{f_3}^{f_1} p_s df$ is the integral of the momentum over the side surface of the mixing chamber between the cross-sections of the active flow inlet and the cross-section of the mixed flow outlet, kg· m/s;

f is the side surface area of the mixing chamber of the ejector, m^2.

Flow impulse in an arbitrary cross-section of the mixing chamber:

$$I = G \cdot v + p_s \cdot F_{mc} \tag{4}$$

where G is the mass flow, kg/s; v is the flow velocity, m/s; F_{mc} is the area of the mixing chamber, m^2.

These equations are used for the theoretical description of the processes occurring in the mixing chamber of classical ejection apparatus with a compact jet of liquid and make it possible to find their basic dimensions.

Simultaneous solution of these equations is accompanied by the adoption of a number of simplifying assumptions and the substitution of empirical coefficients obtained during field studies, which reduces the value of the above equations.

To calculate liquid-gas ejectors with a dispersed jet of liquid, the possibility of using a mathematical description of the ejection process based on the Butakov-Hemeon model is considered.

Results and Discussion

The need to intensify technological processes in the sugar industry led to the creation of sulfitators, saturators [18], to increase the entrainment ratio, a two-stage liquid-gas ejector was developed [20], an ejector with a conical-cylindrical (combined) mixing chamber [21]. Other designs of jet apparatus and equipment based on them were also proposed. The solutions were aimed at intensifying the mass transfer (absorption) processes occurring in the mixing chamber of ejectors with a dispersed jet of liquid, which allows to stabilize their operation, achieve high entrainment ratio and use aggressive gases for their intended purpose, eliminating emergency emissions into the atmosphere.

Since the phase contact surface plays an important role in these processes, the active nozzle of such ejectors are centrifugal-jet nozzles with a spray angle of up to 30°. The practice of operating sulphitators confirms the advisability of using such jet apparatus in equipment.

When calculating ejectors, the methods and recommendations related to the calculation of ejectors with a compact liquid jet were first used. Due to the different mechanism for the formation of rarefaction and the water-gas mixture in the ejector, there was made an attempt to take into account this difference.

The Butakov-Hemeon theory (theory of added mass) is known to describe the process of air ejection by a flow of solid bulk material when it is reloaded. The main consequence of this is the formation of air flows in the flow of falling solid bulk materials due to dynamic interaction, which is the cause of significant dust release.

Let us consider the possibility of applying this theory to the description of the ejection process of a water-gas jet apparatus, taking into account the peculiarities of the formation of liquid droplets during the outflow from the nozzle, the physical properties of the media and the phenomena arising from the interaction of flows.

To show the versatility of this model and the possibility of its application in cases other than air ejection by solid material, we will retain the designations and the order of calculations, which was proposed in the study [22].

The main provisions of the model are that part of the kinetic energy of particles is lost to overcome the resistance of the medium. The amount of losses is determined through the force of the aerodynamic drag of these particles.

In the first approximation, the following assumptions are introduced: the liquid drops formed when it is sprayed from the nozzle are equal in size and are quasi-stationary; drag to the movement of drops is directly proportional to their speed.

Model mathematical expression:

$$dE_0 = nR_0 dx = nR_0 v_i d\tau , \qquad (5)$$

where E_0 is the consumed energy, J; n is the number of falling particles per second, pcs / s; R_0 is the drag force, N; dx is the coordinate of the flying particle path; v_i is the speed of the i-th particle, m/s; τ is the particle flight time, s.

The lost kinetic energy of the drops movement is converted into the kinetic energy of the flow of the gas phase E_n, which moves with the drops (the effect of added mass):

$$dE_{г} = Q_{г} dp , \qquad (6)$$

where Q_n is the volumetric flow rate (added mass), m^3/s; dp is the driving force of air movement (pressure difference along the length of movement of liquid drops), Pa.

Under the assumptions introduced, the lost kinetic energy of liquid drops transforms into the kinetic energy of the gas phase (added mass):

$$nR_0 dx = Q_г dp \quad (7)$$

Integration gives the expression:

$$Q_г \Delta p = \int_0^l nR_0 dx, \quad (8)$$

where $\Delta p_n = p_1 - p_2$ is the differential pressure, Pa;

p_1, p_2 is the pressure in the inlet section of the mixing chamber at the level of the nozzle and in the outlet, respectively, Pa;

l is the mixing chamber length, m.

Since the energy from liquid drops to the gas phase is not completely transferred due to losses to the phases mixing, and the formation of heat during friction, then in the equation (8) such energy transformations will be taken into account by the energy transfer coefficient ξ_e. Then the equation will be written in the form:

$$Q_n \Delta p_n = \xi_e \int_0^l nR_0 dx \quad (9)$$

The pressure difference of the gas phase flow through the mixing chamber can be expressed through the sum of the drag coefficients:

$$\Delta p_n = \varsigma \frac{v_n^2}{2} \rho_n \quad (10)$$

where ς is the total drag coefficient; v_n is the gas phase velocity, m/s; ρ_n is the gas phase density, kg/m^3.

The total drag coefficient consists of the sum of the coefficients of local drag ξ and the drag along the length of the mixing chamber λ:

$$\varsigma = \sum \zeta + \lambda \quad (11)$$

Then (9) will be rewritten in the form:

$$Q_n \varsigma \frac{v_n^2}{2} \rho_n = \xi_e \int_0^l nR_0 dx \quad (12)$$

Let us multiply the last equation and divide by $\frac{F_{mc}}{F_{mc}}$, denote as:

$$R_n = \frac{1}{2} \varsigma \rho_n \frac{1}{F_{mc}} \quad (13)$$

where R_n is the gas phase drag per unit area of the mixing chamber (hydraulic characteristic of the mixing chamber). Then:

$$Q_n R_n v_n^2 F_{mc} = \xi_e \int_0^l n R_0 dx \tag{14}$$

Aerodynamic drag force of a liquid dropt R_0 is determined by the expression:

$$R_0 = f_0 \frac{\pi d^2}{4} \frac{v_{ot}{}^2}{2} \rho_n \tag{15}$$

where f_0 is the drop drag coefficient; d is the drop diameter,m ДОДАНО АНДРІЄМ,; v_{ot} is the relative velocity of the drop, which is found as: $v_{ot} = v_p - v_n$, m/s; v_p is the velocity of fluid leakage from the injector nozzle, m/s; v_n is the velocity of gas entrained by liquid drops m/s.

The force of aerodynamic drag to liquid drops R_0 is proportional to the drop cross-sectional area and the square of the relative velocity. It should also be noted the peculiarities of the motion of liquid drops relative to solid spherical particles. On the moving phase interface, the tangential component of the velocity differs from zero, as a result of which a circulation of the medium arises inside the drop, which contributes to a better flow around. The separation of the flow begins at higher values of the *Re* number than for a solid spherical particle. As a result, the velocity of the drops is greater than the velocity of a solid particle of the same diameter and density. In addition, at certain values of the Reynolds and Weber criteria, the drops begin to deform and vibrate due to the mobility of the interface and the uneven distribution of static pressure over its surface. There is a sharp increase in the drag coefficient in comparison with a hard sphere at the same Reynolds numbers.

Due to the forces of surface tension, capillary pressure arises at the interface boundary, which tends to provide the drop with a shape that, for a given volume, would have a minimum surface, that is, the shape of a sphere. On the other hand, when an external jet flows around the drop, forces arising from pressure irregularities act on its surface and tend to break the spherical shape of the drop [23]. That is, the aerodynamic drag force to liquid drops largely depends on their shape and the regime of gas flow around the surface. Finding the relative velocity of the drops in a gaseous medium is a difficult task, which at the present time does not have an exact analytical expression either.

It is obvious that the total instantaneous drag force of all liquid drops R_0 is variable along the length and cross-section of the mixing chamber. Therefore, the drag force can be found as the average integral value of the drag of all drops n:

$$n \cdot R_0 = f_o \cdot \frac{\pi \cdot d^2}{4} \cdot \frac{\rho_n}{2 \cdot n} \int_n v_{ot}^2 \cdot d \cdot n \tag{16}$$

where $v_{rel} = v_p$ - $v_г$ - is the relative speed in the given section, m/s.

When calculating the resistance to motion of liquid drops, along with the difficulty of determining the relative velocity of the drops, there is also a difficulty in determining the drag coefficient $f_{0.}$ When using the assumption of drops phericity, the drag coefficient $f_0 = f\,(Re)$ depends on the Reynolds number:

$$Re = \frac{d \cdot v_p \cdot \rho_p}{\mu} \tag{17}$$

where μ is the fluid dynamic viscosity, Pa·s.

Usually this relation is written in the form: $f_0 = B(Re)^n$ and is represented by a large number of formulas. Moreover, the experimental data for the aerodynamic drag coefficient differ from the data obtained according to these formulas and it is explained by the difference in the shape of the drops from the sphere, which leads to a change in the drag coefficient. The criterion for the stability of the drops shape is the Weber criterion (the ratio of aerodynamic forces and surface tension forces):

$$We = \frac{\rho_p \cdot d \cdot v_{ot}^2}{\sigma} \tag{18}$$

!!! у формулі поміняти *ot* на *rel*

where ρ_p is the fluid density, kg/m^3; σ is the surface tension, N/m.

The larger the Weber criterion is, the more the drop is deformed, the greater the difference between the drag coefficient and f_0 of a spherical drop is. Moreover, under the conditions of a drop flying in the mixing chamber of the ejector, the Weber number is variable along its length. That is, the drag coefficient of a drop depends on *Re* and *We*: $f_0 = f\,(Re, We)$.

So, instead of the indicated criteria, the Ohnesorge criterion (*On*) is used, which is a combination of the indicated criteria, is constant in length and does not depend on the relative flow velocity around the drop:

$$On = \frac{Re^2}{We} = \frac{\rho_p \cdot d \cdot \sigma}{\mu^2} \tag{19}$$

The calculated drag coefficient for drops fits the experimental data better at Ohnesorge numbers 1800 ...7000 and can be calculated by the relation [24]:

$$f_0 = 33193 Re^{-0,6} On^{0,23} \tag{20}$$

Then the general expression for determining the aerodynamic drag force of liquid drops in the ejector will be as follows:

$$n \cdot R_0 = 33193 \cdot Re^{-0.5} \cdot On^{0.23} \cdot \frac{\pi \cdot d^2}{4} \cdot \frac{\rho_n}{2 \cdot n} \int_n v_{ot}^2 \cdot dn \tag{21}$$

Integration of the expression within *n* will allow us to find the average aerodynamic drag force:

$$n \cdot R_0 = 33193 \cdot Re^{-0.5} \cdot On^{0.23} \cdot \frac{\pi \cdot d^2}{4} \cdot \frac{\rho_n}{2 \cdot n} \cdot v_{ot}^2 \cdot n \tag{22}$$

The velocity of liquid flow from the nozzle is determined by the formula for the volumetric fluid flow rate:

$$Q_p = \mu_f \cdot f_c \cdot \sqrt{\frac{2 \cdot \Delta p_p}{\rho_p}} \tag{23}$$

where μ_f is the coefficient nozzle flow rate; f_c is the nozzle cross-sectional area, m^2; Δp_p is the differential pressure at which liquid flows out of the nozzle, Pa.

Since:

$$v_p = \frac{Q_p}{f_c} \tag{24}$$

Then:

$$v_p = \mu_f \cdot \sqrt{\frac{2 \cdot \Delta p_p}{\rho_p}} \tag{25}$$

For the simplest case, when the energy transfer coefficient ξ_e = 1, formula (14), taking into account (22), will be written in the form:

$$Q_n \cdot R_n \cdot v_n^2 \cdot F_{mc} = 33193 \cdot Re^{-0.5} \cdot On^{0.23} \cdot \frac{\pi \cdot d^2}{4} \cdot \frac{\rho_n}{2 \cdot n} \cdot v_{ot}^2 \cdot n \int_0^l dx \tag{26}$$

Integration of the last expression within the mixing chamber length l and after a series of transformations allows us to obtain the expression:

$$Q_n^3 - Q_n^2 (nf_0 \rho_n l \frac{\pi d^2}{8} \frac{1}{F_{mc}}) \frac{1}{R_n} + Q_n (2nf_0 \rho_n l \frac{\pi d^2}{8} v_p) \frac{1}{R_n} - (nf_0 \rho_n l \frac{\pi d^2}{8} v_p^2) \frac{F_{mc}}{R_n} = 0 \tag{27}$$

Denote:

$$a = -nf_0 \rho_n l \frac{\pi d^2}{8} \frac{1}{F_{mc}} \frac{1}{R_n} \tag{28}$$

$$b = 2nf_0 \rho_n l \frac{\pi d^2}{8} v_p \frac{1}{R_n} \tag{29}$$

$$c = -nf_0 \rho_n l \frac{\pi d^2}{8} v_p^2 \frac{F_{mc}}{R_n} \tag{30}$$

In the last expressions, by W it can be denoted:

$$W = n \cdot f_0 \cdot \rho_n \cdot l \cdot \frac{\pi \cdot d^2}{8} \cdot \frac{1}{R_n} \tag{31}$$

With such notation, equation (27) takes the form of a cubic equation:

$$Q_n^3 + Q_n^2 a + Q_n \cdot b + c = 0 \tag{32}$$

The solution of the last equation makes it possible to determine the amount of the gas phase that has joined to n drops of liquid in the mixing chamber of the ejector.

The obtained relations under the accepted assumptions are similar to the equations of the Butakov-Hemeon theory for solid particles. This allows us to conclude about the versatility of the technique and the possibility of its application, not only in those cases for which it was developed. The proposed approach to the description of the ejection process based on the principle of added mass is more consistent with the physical essence of the processes occurring in the mixing chamber, requires fewer empirical coefficients.

The conducted field studies of jet apparatus, however, revealed a significant difference between the obtained experimental values of the entrainment ratio and those calculated according to the above equations. The actual entrainment ratio is 8...12 times different from that obtained according to this technique.

The main disadvantage of the above equations is that the energy transfer coefficient is taken equal to one ($\xi_e = 1$). The main factors leading to this result are the following ones.

- Force factors.

The force of gravity distorts the trajectory of the liquid flow, which is formed at the nozzle, and when the drops hit the chamber wall or when they collide, the kinetic energy of the flow is significantly reduced.

The contact of the liquid flow to the wall of the mixing chamber causes the appearance of tangential stresses or frictional forces on the wall, which also leads to a decrease in the energy of the flow.

The flight of liquid drops in a gaseous medium is accompanied by resistance and redistribution of the kinetic energy of the liquid and gas, and the transformation of its part into thermal energy.

- Energy factors.

Due to the imbalance of phases and the appearance of specific rarefaction zones in the inlet chamber of the ejector, exchange processes of liquid degassing occur, affecting the formation of drops. At the same time, the process of saturation of the gas phase with water vapor occurs, which leads to a decrease in the energy of the flow of the liquid-gas mixture and reduces the actual entrainment ratio.

- Random factors.

These include the formation of reverse flows of liquid in the lower part of the mixing chamber of a horizontally placed ejector, which occur under certain modes, circulation flows of the water-gas mixture in its upper part.

Algorithm for finding the entrainment ratio according to the added mass theory of Butakov-Hemmeon.

The main equation for finding the volumetric flow rate of the gas phase is equation (32), which is solved by D. Cardano's formula with the introduction of a new variable Z, is related to Q_n by the equality:

$$Z = Q_n + \frac{a}{3} \tag{33}$$

The entrainment ratio is found from the well-known expression:

$$k = \frac{Q_n}{Q_p} \tag{34}$$

When calculating the values of the entrainment ratio, it is noted its significant relation on the size of the drops, which are formed when they outflow the nozzle. In the literature, there is little unambiguous and reliable information on the size of drops in the spray pattern of a nozzle. According to research, the average diameter of liquid drops *d* depends on the following operating and design parameters of the nozzle:

$$\frac{d}{d_c} = f\left(A, \frac{D}{d_c}, \frac{h}{d_c}, Re, \frac{\mu^2}{\rho_p \sigma d_c}, \frac{\rho_p}{\rho_n}\right) \tag{35}$$

where A is the geometrical characteristic of the nozzle; D is the mixing chamber diameter of the nozzle, m; d_c is the nozzle diameter, m; h is the nozzle channel length, m.

The average drop diameter changes proportionally – $Re^{-0,7}$. An increase in the diameter of the outlet nozzle leads to an increase in the dispersion – $d \sim d_c^{0,4...0,64}$. As the viscosity of the liquid increases, the spraying deteriorates ($d \sim \mu^{0,2...0,5}$). Surface tension has little effect on the degree of dispersion ($d \sim \sigma^{0,1...0,2}$). The presented relation for the average drop diameter establishes the influence of the above criteria on the dispersity of the spraying, but does not take into account all the design features of individual nozzles, and does not allow finding a reliable drop diameter.

When investigating the operation of a centrifugal-jet nozzle [25] with a nozzle diameter of 4 mm at water supply pressures within 0.2 ... 0.4 MPa by the pulse counting method, which is based on taking into account the pulses arising in the electrical circuit when it is closed by drops of liquid with a certain size of the gap between the ends of the sensors located in the spray pattern, drops sizes were found experimentally. At a feed pressure of 0.2 MPa, the geometric diameter of the drops was d_1 = 272 μm, which corresponds to the Sauter drop diameter d_{32} = 724 μm. In addition, when the fluid supply pressure changes, the dropt diameter also changes, and it is inversely proportional to the square root of the pressure in the nozzle. We are using these data to calculate the ejection coefficient according to the Butakov-Khemeon theory as applied to ejectors.

To find the entrainment ratio experimentally, a hydraulic stand was created, on which jet apparatus with a cylindrical mixing chamber and a centrifugal-jet nozzle with an insert were investigated (Fig. 1). The order of work on the hydraulic stand corresponded to the generally accepted one and was carried out according to a two-factor experimental plan, which was worked out to study ejectors with different diameters of nozzles and mixing chambers.

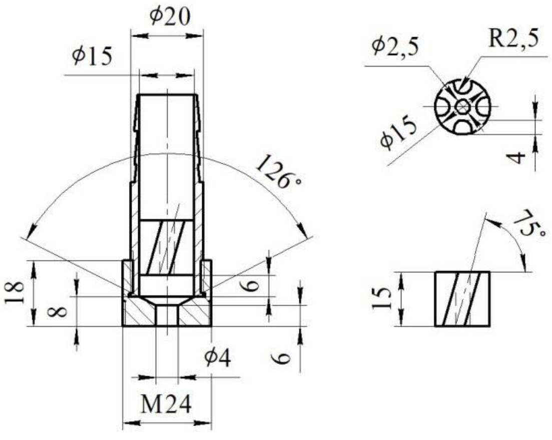

Fig. 1 Centrifugal-jet nozzle

The diameters of the mixing chambers (D_{mc}) varied in the range of 8 mm, 15 mm, 19 mm, 27 mm, 45 mm, and the diameters of the nozzles – 4 mm, 6 mm, 8 mm.

Fluid flow was measured with a rotary flow meter type KV-1.5, accuracy class 1.5. The fluid pressure in the nozzle was controlled by an OBM1-160 manometer, accuracy class 1.5. Gas consumption was measured with a PREMA G 1.6 volumetric gas flow meter. The vacuum in the mixing chamber was measured with a differential manometer in mm H_2O. Statistical processing of the experimental results was carried out with the exception of gross errors according to the Student's criterion at a significance level of 0.05, averaging the results to the arithmetic mean; graphs were built in Origin Pro 8, CurveExpertPro-2.2.0, Microsoft Excel programs.

For example, the calculation results and research data of a jet apparatus with a mixing chamber with a diameter of 19 mm and a centrifugal-jet nozzle with a diameter of 4 mm are shown in Table 1. With this combination of ejector sizes, the highest numerical values of the entrainment ratio are obtained.

Table 1. Comparative data of the designed entrainment ratio with the real one, according to the added mass theory

	Liquid pressure, *P*, MPa	Drops diameter, d_{32}, μm	Designed entrainment ratio	Real entrainment ratio	Transmission ratio
1	0,05	1448	19,26	2,17	0,1127
2	0,075	1182	22,28	2,46	0,1104
3	0,1	1023	25,32	2,59	0,1023
4	0,175	774	34,34	3,51	0,1022
5	0,2	724	37,34	3,69	0,0988
6	0,25	648	43,29	3,72	0,0859
mean value	-	-	-	-	0,102

The transmission coefficient takes into consideration the design features of this jet apparatus and the influence of factors that cannot be taken into account theoretically.

The graph of the relation of the real entrainment ratio and the designed one according to the theory of the added mass with an average transmission ratio of 0.102 and an error of 4.75% is shown in Fig. 2.

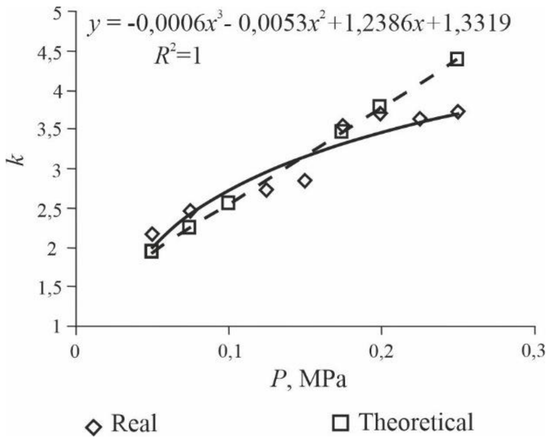

Fig. 2 Relation of the real and theoretical entrainment ratio k on the liquid pressure P in the centrifugal-jet nozzle for the ejector with d_c = 4 mm, D_{mc} = 19 mm

Thus, the proposed calculation of jet apparatus with a dispersed jet of liquid based on the theory of the added mass of Butakov-Hemeon, taking into account refinements when calculating the resistance of a liquid-gas jet and the drag force of drops, and accepting the experimentally established energy transfer coefficient, makes it possible to determine the flow rate of the gas phase, accordingly, the actual entrainment ratio.

It should be noted that a higher gas phase ejection rate also indicates a higher vacuum created in the ejector receiving chamber. For the operation of sulfitators, this indicator is also very important for the reason that in this way the draft in sulfur combustion furnaces increases and the risk of gas release into the production room is reduced.

4. Conclusions

The use of jet apparatus with a dispersed jet of liquid in the food industry is constrained by their insufficient previous study, both theoretically and experimentally. One of these constraining factors is the dependence of the ejection capacity of the apparatus on fluctuations in the flow rate of the active phase. A decrease in its consumption is especially dangerous, since in this case there is a decrease in the vacuum in the receiving chamber.

The imperfection of the theoretical description of the operation of ejectors and scientifically based methods for calculating the hydrodynamic, consumption, mass transfer characteristics of apparatus and the impossibility of taking into account all the factors affecting its operation, complex relationships between the elements of the ejector, and results of experimental research, which are sometimes controversial, do not allow creating jet apparatus with high energy performance. It also holds back the promotion of this type of apparatus in industry.

There was studied the possibility of calculating the jet apparatus and the entrainment ratio of a water-gas ejector with a dispersed jet of liquid on the basis of the Butakov-Hemmeon theory (the principle of added mass). According to the theory the change in the kinetic energy of the system occurs due to the addition of another phase.

Investigations of jet apparatus with a cylindrical mixing chamber and a dispersed liquid jet have been carried out, and the empirical energy transfer coefficient (equal to 0.102) has been determined, which makes it possible to calculate and predict their characteristics.

The calculation of ejectors according to the above ratios makes it possible to design an apparatus, the use of which in the sugar industry as a sulfitator will allow avoiding emergency situations when the emission of an aggressive gas phase into production facilities or the environment is possible.

A number of designs of jet apparatus for the food industry have been developed and patented.

Further research will be aimed at clarifying the methodology for calculating jet apparatus, checking its adequacy to experimental data, developing new designs, which will be presented in subsequent studies.

Conflicts of Interest

"The authors declare no conflict of interest."

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