Determination of ejection coefficient of liquid-gas ejector with combined mixing chamber

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Abstract

Introduction. The aim of the research was to develop a method for determining the actual ejection coefficient of a liquid-gas ejector with a combined mixing chamber.

Materials and methods. Theoretical calculation methods were used (balance equations of mass and energy in the form of the Bernoulli equation and the laws of hydrodynamics), experimental methods (ejection coefficients of an ejector with a combined mixing chamber were experimentally determined on a hydraulic bench in order to determine the experimental constant). The Sokolov-Zinger graph-analytical method was used to compare the ejection coefficients.

Results and discussions. A characteristic feature of the ejector with a combined mixing chamber is the presence of the initial conical and subsequent cylindrical parts of the mixing chamber. The angle of opening of the conical part is 3–8° less than the angle of the flame of spraying liquid from the nozzle. Such a design reduces the hydraulic resistance to the entry of liquid and prevents the formation of back-circulation flows. The ejection coefficient of a jet device with a combined mixing chamber is by 15–55% higher than that of an ejector with a cylindrical mixing chamber.

The joint solution of the balance equations for the conical and cylindrical parts of the mixing chamber, taking into account the energy losses in each, makes it possible to determine theoretical flow rates of the phases in the ejector for different operating modes.

The coefficient k takes into account the influence of energy redistribution between phases during ejection and the design of the mixing chamber. When the pressure increases from 0.05 to 0.25 MPa coefficient k increases from 3.6 to 4.8 in a rational exponent function.

The effective ejection coefficient is defined as the product of the theoretical ejection coefficient and the experimental constant, while the error does not exceed 5%.

Conclusions. The proposed calculation method allows you to determine the effective ejection coefficient of a liquid-gas ejector with a combined mixing chamber.

Introduction

Liquid-gas ejectors (jet devices) are characterized by high intensity of processes in jet streams (Balamurugan et al., 2007; Liu, 2014). Considerable interest in these devices is caused by their indisputable advantages: simplicity of design, absence of tribological problems, compactness, the possibility of installation in any place of the production premises, minimal needs for maintenance and repair (Ivanov et al., 2021; Kong et al., 2015; Sliusenko et al., 2021).

Such devices are widely used in various industries for heat and mass exchange processes (Tashtoush et al., 2019), in particular during sulfitation of liquids in the sugar industry (Ponomarenko et al., 2015). The sulfitation process (treatment of water or sugar solutions with sulfite gas with an SO_2 content of 10–15%) is one of the main technological processes in the sugar production. Traditionally, it was carried out in bubbling apparatus by blowing gas through the juice layer. Due to the significant disadvantages of such devices, jet ejection devices with high intensity of mass transfer processes were introduced into the technological process of water sulfitation. However, due to insufficient study of the process and miscalculations in the design, they had a number of disadvantages: insufficient processing efficiency due to the use of ejectors with a compact liquid jet, low SO_2 utilization rate, significant air pollution with harmful emissions.

To carry out such processes, a design of a liquid-gas ejector with a conical-cylindrical (combined) mixing chamber was developed and patented (Ponomarenko V.V., Sliusenko A. M. (2020), *Liquid-gas ejector, UA Patent 122296*; Riffat et al., 2005). Such a jet device at moderate pressures of liquid supply to the working nozzle (0.1–0.3 MPa) allows increasing the ejection coefficient k (ratio consumption of the passive flow to the flow of the active flow) in comparison with an ejector with a cylindrical mixing chamber (Sliusenko et al., 2021).

It should be noted that the ejection coefficient is the main operating characteristic of jet devices (Riffat et al., 2005), needed in analyzing the functioning of ejectors, their revision and design. To determine the ejection coefficient of jet devices, various methods are used, which are divided into several main groups (Elbel and Lawrence, 2016; Zegenhagen et al., 2015):

- Methods based on balance equations (Sun et al., 1995)
- Empirical dependencies (Zhu et al., 2008)
- Theoretical dependencies obtained because of solving the equations of non-separability, amount of motion, energy and state using experimental constants (Ismagilov et al., 2016).

Combined methods of calculations with the use of balance equations of mass and energy and the introduction of empirical coefficients (test constants), in particular, coefficients of energy loss, resistance, and friction (Aidoun et al., 2019; Chen et al., 2020; Zhu et al., 2008).

Since the liquid-gas ejector with a combined mixing chamber is innovative (Ponomarenko V.V., Sliusenko A. M. (2020), *Liquid-gas ejector, UA Patent 122296*), there is no method that allows to determine the k, taking into account its design features (the initial conical part of the mixing chamber).

The purpose of the research was to develop a method for determining the actual ejection coefficient of a liquid-gas ejector with a combined mixing chamber based on mathematical modeling of the ejection process using mass and energy balance equations and an empirical coefficient (research constant).

Materials and methods

The subject of research was an ejector with a conical-cylindrical mixing chamber, the object of research was the ejection processes that take place in it.

Theoretical and experimental research methods were used to achieve the defined goal.

Theoretical methods

Mathematical modeling of the ejection process in a liquid-gas ejector with a combined mixing chamber was carried out on the basis of the equations of conservation of mass and energy (the law of conservation of energy is written in the form of the Bernoulli equation) and using the laws of hydrodynamics.

For mathematical modeling, a calculation scheme of the ejector (Figure 1) was developed and characteristic of cross-sections were determined (cross-section *I-I* – at the nozzle section; cross-section *II-II* – the point of connection of the conical and cylindrical parts of the mixing chamber; cross-section *III-III* – exit from the chamber mixing of the mixture, in which the parameters of the two-phase flow acquire a constant value).

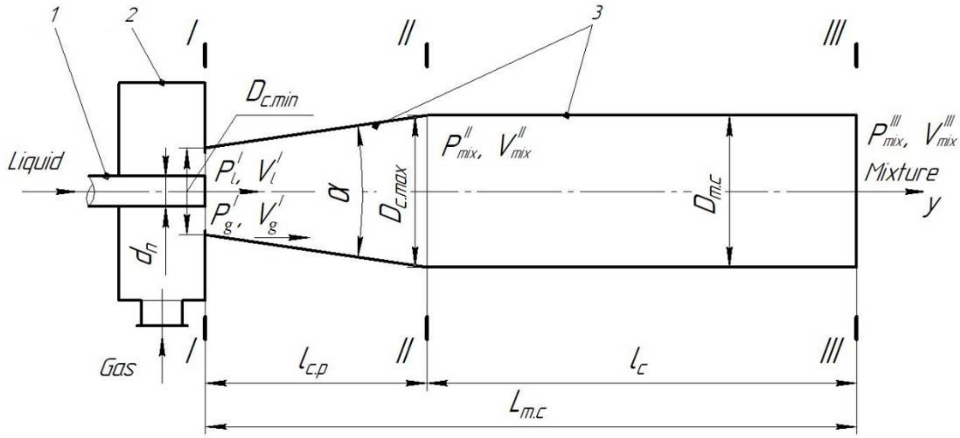

Figure 1. Calculation scheme of the ejector
1 – working nozzle; 2 – reception chamber; 3 – mixing chamber

Flows in the mixing chamber of the ejector are characterized by the following parameters (the upper index shows which section the indicator refers to):

P_l^I – fluid pressure at the outlet of the working nozzle;

P_g^I – pressure (reduction) in the receiving chamber;

P_{mix}^{II} – the pressure of the liquid-gas mixture at the boundary of the conical and cylindrical parts of the mixing chamber;

P_{mix}^{III} – the pressure of the liquid-gas mixture at the exit from the mixing chamber;

V_l^I – liquid speed at the exit from the working nozzle;

V_g^I – gas velocity at the entrance to the mixing chamber;

V_{mix}^{II} – the velocity of the liquid-gas mixture at the boundary of the conical and cylindrical parts of the mixing chamber;

V_{mix}^{III} – is the velocity of the liquid-gas mixture at the exit from the mixing chamber.

Subscripts: *l* – liquid, *g* – gas, *mix* – mixture.

Superscripts: *I* – section *I-I*, *II* – section *II-II*, *III* – section *III-III*.

Experimental methods

The ejector with a conical-cylindrical mixing chamber (Figure 2) is a receiving chamber 2 with a cover 4 and gas phase inlet nozzles 3, to which a conical adapter 5 with an expansion angle of 25° is attached. The cylindrical part of the glass-mixing chamber 6 was installed coaxially to it. The joint between them was sealed.

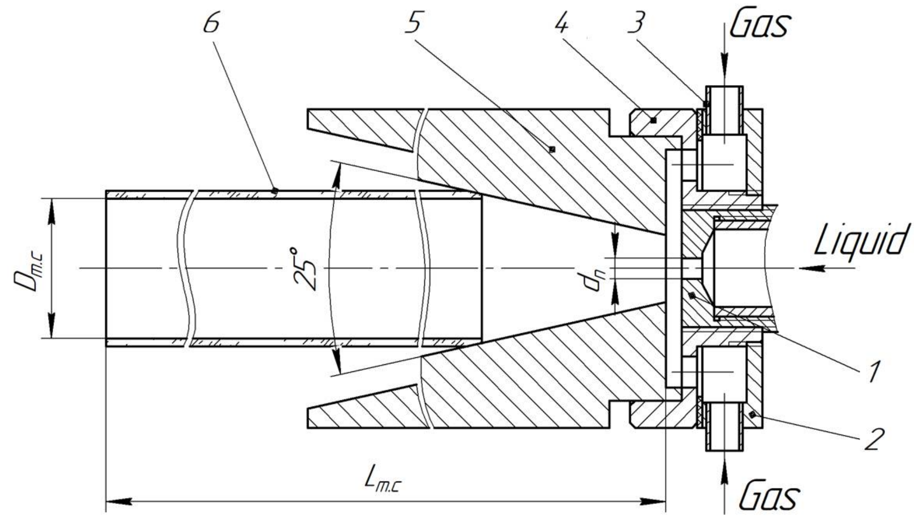

Figure 2. Ejector with a combined mixing chamber (schematic image):
1 – injector nozzle; 2, 4 – cover and housing of the reception chamber; 3 – inlet pipe;
5 – conical part of the mixing chamber; 6 – cylindrical part of the mixing chamber

The working nozzle of the ejector is a centrifugal jet nozzle with inclined inlet channels (Figure 3). Such a nozzle has a liquid spray torch angle of 29°. Since the angle of expansion of the conical part of the mixing chamber is 25°, the condition is ensured when it is by 3-8° smaller than the angle of the liquid spray torch (Ponomarenko et al. 2015; Sliusenko et al., 2021).

The main dimensions of the nozzle: nozzle diameter – d_n = 4 mm, length of the nozzle channel l_n = 5 mm, diameter of the nozzle twisting chamber – 10 mm. The nozzle is made according to the seventh quality of accuracy. The roughness of the surfaces of the twisting chamber and supply channels is Ra = 1.25, and the nozzle channel is Ra = 0.16 (grinding).

With the adopted dimensions, the main geometric parameter of the ejector m (the ratio of the area of the mixing chamber with a diameter of $D_{m.c}$ = 19 mm to the area of the nozzle nozzle) is m = 22.56.

A detailed description of the experimental set up and research methodology can be found in (Sliusenko et al., 2021). The experimental installation consisted of a liquid tank, a pump, a system of pipelines, shut-off and regulating valves and was equipped with control and measuring devices: liquid flow meter KV-1.5, gas flow meter PREMA G 1.6, manometer OBM1-160, differential manometer.

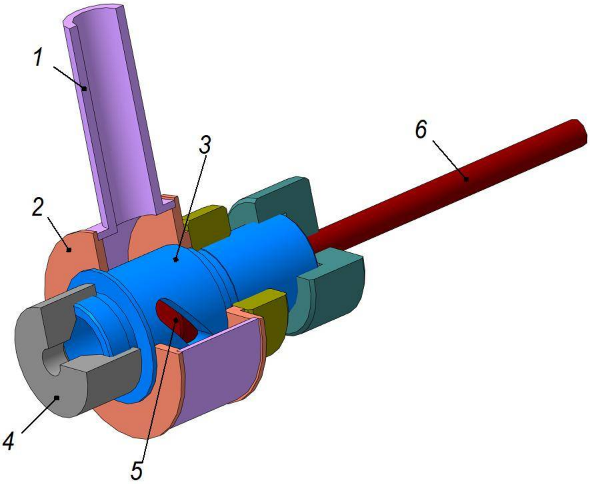

Figure 3. 3-D model of a centrifugal jet nozzle with two inclined inlet channels: 1 – liquid inlet pipe; 2 – housing; 3 – vortex chamber; 4 – nozzle; 5 – supply channel; 6 – plunger

Changing the working characteristics of the ejectors was carried out by adjusting the liquid pressure in the working nozzle (in the range of 0.05–0.25 MPa), which was controlled by a manometer.

Processing of experimental data was carried out by well-known methods (exclusion of gross errors according to the Student's criterion at a significance level of 0.05, the result was reduced to the arithmetic mean value).

To compare the obtained results of determining the ejection coefficient for the ejector with a combined mixing chamber with the grapho-analytical method of Sokolov-Zinger (Shestopalov et al., 2016; Wang et al., 2023), the value $\Delta p_c / \Delta p_p$ was found for the pressures in the control sections and the main geometric characteristic of the ejector $m = D^2_{m.c} / d^2_n$ was determined. According to the graphs, at the corresponding values of $\Delta p_c / \Delta p_p$ and m, the ejection coefficients were determined.

Results and discussion

Justification of the design of the ejector with a combined mixing chamber

Analysis of the liquid flow in the initial part of the ejector (Han et al., 2018; Kandakure et al., 2005) showed that the conical expansion of the mixing chamber (its initial part) leads to a decrease in hydraulic resistance and, accordingly, an increase in the useful energy of the liquid jet for gas ejection. At the same time, the opening angle of the diffuser is taken in the range of 3–8°, at which minimum hydraulic losses and uninterrupted movement of liquid (Bi et al., 2017; Lu et al., 2010; Smyk et al., 2010). It should be noted that the proposed opening angle of the diffuser depends on the type of nozzle through which the liquid flows out (the specified angle is relevant for the flow of liquid through the hole in the form of a compact jet of liquid).

Based on our own preliminary calculations and experimental studies, the mixing chamber is made of a combined one – with an initial conical and subsequent cylindrical sections. The opening angle of the conical part is 3–8° smaller than the angle of the liquid spray torch (Ponomarenko V.V., Sliusenko A. M. (2020), Liquid-gas ejector, *UA Patent 122296*). With this design, the annular gap between the torch of the atomized liquid and the conical wall at the beginning of the receiving chamber ensures guaranteed ejection of the gas phase and contributes to the creation of a zone of high rarefaction (Singh et al., 2019).

The transition to the cylindrical part of the mixing chamber of the ejector takes place at the point of impact of liquid drops against its walls, which ensures the operation of the ejector without the formation of reverse circulation flows (Tang et al., 2019). The diameter of the cylindrical mixing chamber is selected from the condition of achieving the maximum ejection coefficient (optimal value of the main geometric parameter of the ejector) (Al-Manea and Al-Jadir, 2021; Yan et al., 2022). Thus, this leads to an increase in the efficiency and *k* cone of the ejector.

When the opening angle of the conical part of the mixing chamber is less than 3° for the angle of the liquid spray torch, liquid drops will fall on the conical wall and move along it, which leads to an increase in hydraulic resistance (Wang et al., 2019). If the angle of expansion of the conical part of the mixing chamber is greater than 8° of the angle of the liquid spray torch, the liquid drops will not touch the conical walls, the gap between the inner surface of the conical part of the mixing chamber and the outer surface of the spray torch will increase, reverse circulation flows will occur, and the ejection coefficient will decrease (Lu et al., 2010).

Mathematical modeling of the ejection process in an ejector with a conical-cylindrical mixing chamber

For mathematical modeling of the ejection process in the ejector with a combined mixing chamber, two characteristic zones were chosen (Figure 1).

Zone 1 – passive flow ejection zone (conical section of the mixing chamber between sections *I – I* and *II – II*).

$$0 < y < l_{c.p},$$

where $l_{c.p}$ – length of the conical part of the mixing chamber.

Boundary conditions for the section I – I.

The conical part of the mixing chamber also serves as the receiving chamber of the ejector. In this zone, due to the friction between the phases, part of the energy is converted into heat (Lu et al., 2010). However, in the first approximation, we will not consider these transient processes.

The speed of the liquid from the nozzle of the nozzle is found from the expression:

$$V_l^I = \mu \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho \cdot_l}}, \qquad (1)$$

and fluid consumption ($Q_l = V_l^I \cdot f_n$):

$$Q_l = \mu \cdot f_n \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho \cdot_l}}, \qquad (2)$$

where μ – injector flow rate; f_n – area of the nozzle; ΔP – the pressure difference under which the liquid is sprayed from the nozzle of the nozzle; ρ_l – density of the liquid.

The gas phase is ejected from the receiving chamber of the ejector, which moves along with the active flow. Let's write down the mass balance equation for the input *I-I* and output *II-II* sections:

$$m_l^I + m_g^I = m_{mix}^{II} = m_{mix}^{III}. \quad (3)$$

Note that the mass of the mixture at the end of the first zone m_{mix}^{II} is equal to the mass of the mixture at the exit from the ejector m_{mix}^{III}.

The mass flow of each of the flows can be found if its speed in the given section is known:

$$m_i = \rho_i \cdot V_i \cdot F_i, \quad (4)$$

where ρ_i – density of the *i*-th phase;
V_i – velocity of the corresponding phase in the *i*-th section;
F_i – area of the *i*-th section.

Express the mass flow of liquid in the inlet section *I – I*:

$$m_l^I = \rho_l \cdot V_l^I \cdot f_n = \rho_l \cdot \mu \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho_l}} \cdot \frac{\pi \cdot d_n^2}{4}. \quad (5)$$

Mass flow of the gas phase in the inlet section *I – I*:

$$m_g^I = \rho_g \cdot V_g^I \cdot f_{c.p} = \rho_g \cdot V_g^I \cdot \frac{\pi}{4} \cdot \left(D_{c.min}^2 - d_n^2\right), \quad (6)$$

where ρ_g – density of the gas;
$f_{c.p}$ – the area of the annular channel (gap) between the nozzle and the beginning of the conical part of the mixing chamber.

Zone 2 is a zone of simultaneous movement of phases (cylindrical part of the mixing chamber between sections *II - II* and *III - III*).

In this zone, there is a compatible movement of phases to the exit from the mixing chamber with the alignment of all kinematic and energy characteristics (Yan et al., 2022). If the liquid and gas at the beginning of the zone in section *II - II* have different velocities, then at the exit in section *III - III*, the flow rate of the phases does not change, but only their redistribution along the cross section and equalization of velocities occurs.

The mass flow rate of the mixture in the initial section *III – III*:

$$m_{mix}^{III} = \rho_{mix} \cdot V_{mix}^{III} \cdot F_{m.c} = \rho_{mix} \cdot V_{mix}^{III} \cdot \frac{\pi \cdot D_{m.c}^2}{4}. \quad (7)$$

where $D_{m.c}$ – diameter cylindrical part of the mixing chamber.

The energy balance equation in the form of Bernoulli's equation (Sliusenko et al., 2021) (the energy balance is not related to weight, but to a unit volume of liquid $V = \frac{m}{\rho}$) for sections *I-I* and *III-III*:

$$\frac{\left(V_l^I\right)^2}{2 \cdot g} + \frac{\left(V_g^I\right)^2}{2 \cdot g} = \frac{\left(V_{mix}^{III}\right)^2}{2 \cdot g} + \Delta p, \quad (8)$$

where g – acceleration of gravity;
Δp – specific losses of flow energy between sections *I - I* and *III - III*

$$\Delta p = \Delta p^{I-II} + \Delta p^{II-III}, \tag{9}$$

where Δp^{I-II} – specific input energy losses of the phases between sections *I–I* and *II–II*;

Δp^{II-III} – specific energy losses of the mixture between sections *II–II* and *III–III* (along the length of the cylindrical part of the mixing chamber).

Energy losses in the conical ejection zone are determined by Bord's formula:

$$\Delta p^{I-II} = \varsigma \cdot \frac{\left(V_l^I\right)^2}{2 \cdot g}, \tag{10}$$

where ς – total resistance coefficient of the conical section:

$$\varsigma = \varsigma_e + \varsigma_{c.p}, \tag{11}$$

where ς_e – coefficient of resistance to expansion; $\varsigma_{c.p}$ – the resistance coefficient along the length of the conical part can be determined by the formula:

$$\varsigma_{c.p} = \lambda \cdot \frac{l_{c.p}}{D_{c.p}}, \tag{12}$$

where λ – resistance coefficient along the length of the pipe (depends on the viscosity and roughness of the pipe);

$D_{c.p}$ – the average diameter of the conical part of the ejector:

$$D_{c.p} = \frac{3D_{c.\min} + D_{c.\max}}{4}$$

Energy losses in the cylindrical part of the mixing chamber $\Delta \mathrm{p}^{\mathrm{II-III}}$:

$$\Delta p^{II-III} = \varsigma_c \cdot \frac{\left(V_{mix}^{III}\right)^2}{2 \cdot g}, \tag{13}$$

where ς_c – resistance coefficient along the length of the cylindrical part of the mixing chamber:

$$\varsigma_c = \lambda \cdot \frac{l_c}{D_{m.c}}, \tag{14}$$

wherel_c – length of the cylindrical part of the mixing chamber.

The length of the mixing chamber is chosen so that the velocity of the liquid and gas phases at its exit are the same:

$$V_g^{III} = V_l^{III} = V_{mix}^{III}.$$

We also note that the mass flow rate of both gas and liquid phases in the cross section *III–III* is equal to the mass flow rate of these phases in the cross section *II–II*. The cylindrical part of the mixing chamber is intended only for transporting phases and equalizing flow characteristics (velocities, cross-sectional concentrations) due to exchange processes between them (Yan et al., 2022).

After writing down all the balance equations, we will find one of the main characteristics of the ejector (Ponomarenko et al., 2015) – the consumption of the gas phase, and therefore the ejection coefficient.

The mass flow rate of the gas phase is determined from the mass balance equation (3):

$$m_g^I = m_{mix}^{III} - m_l^I. \tag{15}$$

In order to determine the mass of the mixture at the exit from the mixing chamber (section *III–III*), it is necessary to determine the speed V_{mix}^{III}. The latter can be found from equation (8):

$$\frac{\left(V_{mix}^{III}\right)^2}{2{\cdot}g}=\frac{\left(V_l^I\right)^2}{2{\cdot}g}+\frac{\left(V_g^I\right)^2}{2{\cdot}g}-\Delta p .$$

After the transformation, we have:

$$V_{mix}^{III}=\sqrt{\left(V_l^I\right)^2+\left(V_g^I\right)^2-2{\cdot}g\cdot\Delta p} . \tag{16}$$

From the mass balance equation (3), substituting the corresponding expressions:

$$V_g^I\cdot\rho_g\cdot\frac{\pi}{4}{\cdot}\left(D_{c.min}^2-d_n^2\right)=V_{mix}^{III}\cdot\rho_{mix}\cdot\frac{\pi{\cdot}D_{m.c}^2}{4}-\mu{\cdot}\rho_l\cdot\frac{\pi{\cdot}d_n^2}{4}\cdot\sqrt{\frac{2{\cdot}\Delta P}{\rho_l}} . \tag{17}$$

we will find the velocity of the gas phase.

The density of the mixture depends on:

$$\rho_{mix}=\beta{\cdot}\rho_l+\left(1-\beta\right){\cdot}\rho_g \tag{18}$$

where β – liquid content per unit volume of the mixture.

Let's perform a number of simple transformations and enter the notation of expressions:

$$a=\rho_g^2{\cdot}f_{c.p}^2-\rho_{mix}^2{\cdot}F_{m.c}^2 , \tag{19}$$

$$b=2{\cdot}\rho_g\cdot f_{c.p}{\cdot}\left(V_l^I\right){\cdot}\rho_l{\cdot}f_n , \tag{20}$$

$$c=\left(V_l^I\right)^2{\cdot}\rho_l^2{\cdot}f_n^2-\left(V_l^I\right)^2{\cdot}\rho_{mix}^2{\cdot}F_{m.c}^2+2{\cdot}\Delta p{\cdot}g\cdot\rho_{mix}^2{\cdot}F_{m.c}^2 , \tag{21}$$

Equation (17) will take the form:

$$a{\cdot}\left(V_g^I\right)^2+b{\cdot}\left(V_g^I\right)+c=0 . \tag{22}$$

Its roots:

$$\left(V_g^I\right)_{1,2}=\frac{-b\pm\sqrt{b^2-4{\cdot}a{\cdot}c}}{2{\cdot}a} . \tag{23}$$

One of the roots, as the calculations show, has a negative value and it is not accepted in the further calculation.

After finding the speed of the gas phase at the entrance to the mixing chamber, its flow rate is determined:

$$Q_g=\left(V_g^I\right){\cdot}f_{c.p} . \tag{24}$$

With a known flow rate of the gas phase, the ejection coefficient is unambiguously found.

Thus, the proposed calculation method allows you to determine the flow rate of the gas phase, and therefore the ejection coefficient of the liquid-gas ejector with a conical-cylindrical mixing chamber.

Model validation

The adequacy of the mathematical model is checked by comparing the calculated ejection coefficient with its experimental value.

The algorithm for finding the ejection coefficient according to the proposed by us mathematical model is as follows.

1.Given the known nozzle flow coefficient μ and the pressure under which spraying ΔP occurs, determine the fluid velocity at the exit from the injector nozzle according to equation (1)

$$V_l^I = \mu \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho_l}}.$$

2.With a given diameter of the injector nozzle, determine the volume flow of liquid according to equation (2)

$$Q_l = \mu \cdot f_n \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho_l}}.$$

3.Determine the energy losses in the conical part of the mixing chamber according to formula (10)

$$\Delta p^{I-II} = \varsigma \cdot \frac{\left(V_l^I\right)^2}{2 \cdot g}.$$

4.Find the total resistance coefficient ς of the conical part, if all the structural dimensions of the ejector are known.

5. Determine the energy losses in the cylindrical part of the mixing chamber according to formula (13)

$$\Delta p^{II-III} = \varsigma_c \cdot \frac{\left(V_{mix}^{III}\right)^2}{2 \cdot g}.$$

6.Calculate the total energy losses in the ejector mixing chamber according to formula (9):

$$\Delta p = \Delta p^{I-II} + \Delta p^{II-III}.$$

7.Determine the unknowns *a, b, c* using formulas (19-21):

$$a = \rho_g^2 \cdot f_{c.p}^2 - \rho_{mix}^2 \cdot F_{m.c}^2,$$

$$b = 2 \cdot \rho_g \cdot f_{c.p} \cdot \left(V_l^I\right) \cdot \rho_l \cdot f_n,$$

$$c = \left(V_l^I\right)^2 \cdot \rho_l^2 \cdot f_n^2 - \left(V_l^I\right)^2 \cdot \rho_{mix}^2 \cdot F_{m.c}^2 + 2 \cdot \Delta p \cdot g \cdot \rho_{mix}^2 \cdot F_{m.c}^2.$$

8.If *a, b, c* are known, determine the gas velocity at the entrance to the mixing chamber according to formula (23)

$$\left(V_g^I\right)_{1,2} = \frac{-b \pm \sqrt{b^2 - 4 \cdot a \cdot c}}{2 \cdot a}.$$

9.Calculate the volume flow of gas at the entrance to the conical part of the mixing chamber according to formula (24)

$$Q_g = \left(V_g^I\right) \cdot f_{c.p}.$$

10.With known volume flow rates of liquid and gas, determine the volume coefficient of ejection of the liquid-gas ejector according to the formula:

$$k = Q_g / Q_l.$$

Comparative data of the results of calculating ejection coefficients based on the developed mathematical model and experimental data (own research) for an ejector with a conical-cylindrical (combined) mixing chamber are presented in Table 1. As for the accuracy of the obtained results, the calculations were performed with accuracy to the fourth significant digit. Experimental studies were carried out at least three times, the exclusion of gross errors was carried out according to the Student's criterion at a significance level of 0.05, and the average arithmetic value of the ejection coefficient was taken.

The work of the ejector is characterized by accompanying processes (cavitation, shock waves, liquid evaporation) (Besagni et al., 2017; Jafarian et al., 2016), which are accompanied by redistribution of energy and its losses, which are extremely difficult to take into account analytically. Therefore, to correlate the calculated ejection coefficient, an experimental constant was found and its average value was determined.

Table 1

Comparative data of calculated ejection coefficients with experimental ones

No of experiment	Liquid supply pressure P, MPa	Ejection coefficient		Correction factor
		calculated	experimental	
1	0.05	1.152	3.652	3.17
2	0.1	1.208	3.908	3.235
3	0.15	1.254	4.295	3.425
4	0.2	1.305	4.728	3.622
5	0.25	1.361	4.825	3.545
Average value	-	-	-	3.4

The graph of the dependence of the ejection coefficient (experimental and calculated) on the liquid pressure with the average value of the experimental constant equal to 3.4 is presented in Figure 4.

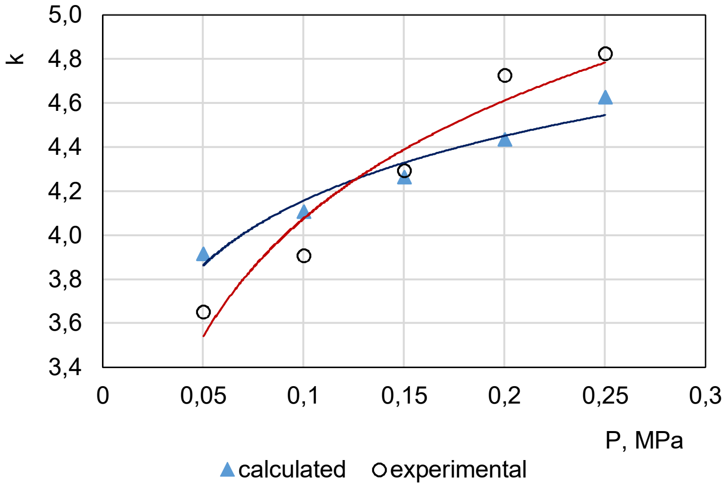

Figure 4. Dependence of the experimental and theoretical ejection coefficient *k* on the liquid pressure *P* in the nozzle for an ejector with d_n = 4 mm, $D_{m.c}$ = 19 mm (*m* = 22.56)

At the nominal operating mode of the ejector of 0.1–0.2 MPa, the error in determining the ejection coefficient does not exceed 5%.

A comparison of own results of determination of ejection coefficients with results of other researchers was carried out. When determining the ejection coefficient according to the data of Sokolov-Zinger (Shestopalov et al., 2016; Wang et al., 2023) when using the theoretical pressure characteristic (graph of the dependence of the ejection coefficient on the pressure) for an ejector with the main geometric characteristic according to our researches $m = D^2_{m.c} / d^2_n = 19^2 / 4^2 = 22.56$ the maximum value of the ejection coefficient reaches a value of 4.8 when:

$$\Delta p_c / \Delta p_p = (p_c - p_l) / (p_p - p_l) = 0.038,$$

where p_c – pressure of the mixture at the exit from the ejector, MPa ($p_c = 0.1$ MPa);

p_p – pressure of the active medium, MPa ($p_p = 0.25$ MPa);

p_l – pressure of a low-pressure medium, MPa ($p_l = 0.006$ MPa).

This value of the ejection coefficient was recorded by us during experimental studies of ejection processes in an ejector with a combined mixing chamber at the pressure of the active medium $p_p = 0.25$ MPa.

When the pressure of the active medium increases, the ejection coefficient of the innovative ejector reaches higher values than the *k* ejector with a cylindrical mixing chamber (Ponomarenko et al., 2020), which is explained by the presence of the initial conical part of the mixing chamber, as a result of which the formation of reverse-circulation flows of phases is prevented.

Conclusions

1. The selection of the main dimensions of the innovative ejector with a conical-cylindrical mixing chamber is justified. In particular, the angle of the conical part of the ejector is taken to be 3-8° smaller than the angle of the liquid spray plume, which ensures the operation of the ejector works without the formation of reverse circulation flows.
2. A mathematical model of the ejection process based on the mass and energy balance equations is proposed (the energy balance is written in the form of the Bernoulli equation) and an algorithm for finding the main operating characteristic of the ejector – the theoretical ejection coefficient – is given.
3. The average value of the experimental constant is set, which is equal to 3.4, which allows determining the valid ejection coefficient.
4. The ejector with a combined mixing chamber is recommended for use in mass transfer processes of food production, in particular during sulfitation of sugar production liquids, which is explained by its higher ejection coefficient by 15-55% compared to the ejector with a cylindrical mixing chamber.

References

Aidoun Z., Ameur K., Falsafioon M., Badache M. (2019), Current advances in ejector modeling, experimentation and applications for refrigeration and heat pumps. Part 1: Single-Phase Ejectors, *Inventions*, 4(1), p. 15, https://doi.org/10.3390/inventions4010015

Al-Manea A., Al-Jadir T. (2021), Effect of ejector design parameters on flow structure inside the mixing chamber, *IOP Conference Series: Earth and Environmental Science*, 779, pp. 10–88, https://doi.org/10.1088/1755-1315/779/1/012033

Balamurugan S., Lad M., Gaikar V., Patwardhan A. (2007), Hydrodynamics and mass transfer characteristics of gas-liquid ejectors, *Chemical Engineering Journal*, 131, pp. 83–103.

Besagni G., Mereu R., Inzoli F., et al. (2017), Application of an Integrated Lumped Parameter-CFD approach to evaluate the ejector-driven anode recirculation in a PEM fuel cell system, *Applied Thermal Engineering*, 121, pp. 628–651, https://doi.org/10.1016/j.applthermaleng.2017.04.111

Bi R., Hu M., Wang S., et al. (2017), Effect of throat length on steam ejector critical back pressure, *Chemical Engineering Transactions,* 61, pp. 1945–1950, https://doi.org/10.3303/CET1761322

Elbel S., Lawrence N. (2016). Review of recent developments in advanced ejector technology, *International Journal of Refrigeration*, 62, pp. 1–18, https://doi.org/10.1016/j.ijrefrig.2015.10.031

Ivanov V., Shevchenko O., Marynin A., Stabnikov V., Gubenia O., Stabnikova O., Shevchenko A., Gavva O., Saliuk A. (2021), Trends and expected benefits of the breaking edge food technologies in 2021–2030, *Ukrainian Food Journal*, 10(1), pp. 7-36, https://doi.org/10.24263/2304-974X-2021-10-1-3

Lu H., Ni G., Li R., Xu Z. (2010), An experimental investigation on the performance of conical nozzles for argon cluster formation in supersonic jets, *Journal of Chemical Physics*, 132 (12), pp. 124–303, https://doi.org/10.1063/1.3356024

Han Y., Wang X., Sun H., et al. (2018), CFD simulation on the boundary layer separation in the steam ejector and its influence on the pumping performance, *Energy*, 167, pp. 469–483, https://doi.org/10.1016/j.energy.2018.10.195

Hrama M., Sidletskyi V., Elperin I. (2022), Intelligent automatic control of sugar factory evaporator operation using behavior prediction subsystem, *Ukrainian Food Journal*, 11(1), pp. 148–163, https://doi.org/10.24263/2304-974X-2022-11-1-14

Chen H., Zhu J., Ge J., Lu W., Zheng L. (2020), A cylindrical mixing chamber ejector analysis model to predict the optimal nozzle exit position, *Energy*, 208, pp. 118–302, https://doi.org/10.1016/j.energy.2020.118302

Kandakure M.T., Gaikar V.G., Patwardhan A.W. (2005), Hydrodynamic aspects of ejectors, *Chemical Engineering Science*, 60, pp. 6391–6402, https://doi.org/10.1016/j.ces.2005.04.055

Kong F., Kim H. D. (2015), Analytical and computational studies on the performance of a two-stage ejector–diffuser system, *International Journal of Heat and Mass Transfer*, 85, pp. 71–87, https://doi.org/10.1016/j.ijheatmasstransfer.2015.01.117

Lu H., Ni G., Li R., Xu Z. (2010), An experimental investigation on the performance of conical nozzles for argon cluster formation in supersonic jets, *Journal of Chemical Physics*, 132(12), pp. 124–303, https://doi.org/10.1063/1.3356024

Ponomarenko V., Pushanko N. (2015), Sprays fluid: an effective way to intensify the processes in the food industry, *LAP LAMBERT Academic Publishing*, *Saarbrucken.*

Riffat S., Jiang L., Gan G. (2005), Recent development in ejector technology – a review, *International Journal of Ambient Energy*, 26(1), pp. 13–26, https://doi.org/10.1080/01430750.2005.9674967

Shestopalov K.O., Petrenko V.O., Volovyk O. (2015), Investigation of an experimental ejector refrigeration machine operating with refrigerant R245fa at design and off-design working conditions. Part 1. Theoretical analysis, *International Journal of Refrigeration*, 29, https://doi.org/10.1016/j.ijrefrig.2015.02.004

Singh J., Zerpa L.E., Partington B., Gamboa J. (2019), Effect of nozzle geometry on critical-subcritical flow transitions, *Heliyon*, 5(2), e01273. https://doi.org/10.1016/j.heliyon.2019.e01273

Sliusenko A., Ponomarenko V., Forostiuk I. (2021), Water-air ejector with conical-cylindrical mixing chamber, *Acta Polytechnica*, 61(6), pp. 768–776.

Smyk S. Yu., Butenko A. G. (2010), Modelling of work central ejectors with the purpose of increase of their efficiency, *Modern Science: Researches, Ideas, Results, Technologies*, 1(3), pp. 150–152.

Tang Y., Liu Z., Li Y., Li Ya, Wu H., Zhang X, Yang N. (2019), Visualization experimental study of the condensing flow regime in the transonic mixing process of desalination-oriented steam ejector, *Energy Conversion and Management*, 197, pp. 111–849, https://doi.org/10.1016/j.enconman.2019.111849

Tashtoush M., Al-Nimr M. A., Khasawneh M. A. (2019), A comprehensive review of ejector design, performance, and applications, *Applied Energy*, 240, pp. 138–172, https://doi.org/10.1016/j.apenergy.2019.01.185

Wang C., Liang J, Huo H., (2019), Numerical study of effects of geometric parameters on the flow and cavitation characteristics inside conical nozzle of autonomous underwater vehicles, *Advances in Mechanical Engineering*, 11, pp. 58–84.

Wang K., Wang L., Gao R. (2022), An extended mechanism model of gaseous ejectors, *Energy*, 264, 126094, https://doi.org/10.1016/j.energy.2022.126094

Yan J., Li R., Wang C. (2022), Optimization of three key geometries of a steam ejector under varied primary nozzle geometries, *Entropy (Basel)*, 25(1), 15, https://doi.org/10.3390/e25010015

Zegenhagen M. T., Ziegler F. (2015), A one-dimensional model of a jet-ejector in critical double choking operation with R134a as a refrigerant including real gas effects, *International Journal of Refrigeration*, 55, pp. 72–84

Zhu Y., Cai W., Wen C., Li Y. (2008), Simplified ejector model for control and optimization, *Energy Conversion and Management*, 49, pp. 1424–1432.