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# WATER-AIR EJECTOR WITH CONICAL-CYLINDRICAL MIXING CHAMBER

Andrii Sliusenko[a,*], Vitalii Ponomarenko[a], Inna Forostiuk[b]

[a] *National University of Food Technologies, Educational and Scientific Institute of Technical Engineering by name of academician I.S. Hulyi, Department of Technological Equipment and Computer Technology Design, Volodymyrska 68, 01601 Kyiv, Ukraine*

[b] *National University of Food Technologies, Department of Foreign Languages for Professional Purposes, Volodymyrska 68, 01601 Kyiv, Ukraine*

[*] corresponding author: andriy_slyusenko@ukr.net

Abstract. In the paper, the hydrodynamics of the liquid-gas mixture in the mixing chamber of the ejectors at different spatial positions was analyzed and the comparative study of such ejectors was carried out. It was found that a more ordered mode of movement of the mixture in the mixing chamber is created as a result of the coincidence of the velocity vector of liquid drops and the direction of gravity in the vertical position of the ejectors. This leads to increasing the volume entrainment ratio almost twice. The analysis of the liquid-gas mixture flow in the mixing chamber, evaluation calculations and research allowed to develop and to patent a jet apparatus with a conical-cylindrical (combined) mixing chamber. It was also found that for such ejectors, the volume entrainment ratio is 15–55 % higher than for a jet apparatus with a cylindrical mixing chamber due to the reduction of the resistance of the passive flow into the mixing chamber and prevention of the formation of reverse-circulating flows. A study has been conducted on liquid-gas ejectors in the range of the main geometric parameter $m$ (ratio of the mixing chamber area to the nozzle area) 9.4–126.5, which allowed to establish its rational values at which the maximum volume entrainment ratio is achieved ($m$ = 25–40).

Keywords: Ejector, mixing chamber, spatial position, reverse-circulation flows.

## 1. Introduction

A jet apparatus (ejectors) is rather simple and reliable equipment that has not been fundamentally changed since its invention and at the same time, it is complex in terms of processes occurring in the flow part [1–4]. A significant disadvantage of such an apparatus is the low efficiency, which does not usually exceed 30 %, that is a stimulus to find more advanced designs.

Since the main components of the jet apparatus are the receiving chamber, the mixing chamber, the working nozzle (sprayer) and the diffuser, their design, position relative to other elements and geometric dimensions have a significant impact on the effective operation of the ejector [5–8].

The main indicators of a jet apparatus are the efficiency (ratio of useful energy to expended energy) and entrainment ratio ($ER$) – the ratio of the flow rate of the passive medium to the flow rate of the active medium. If the phase flow rate is expressed in units of mass, then the entrainment ratio is mass. However, for water-gas ejectors, this ratio is usually expressed in terms of the volumetric flow rates of the phases. In this study, $ER$ is volumetric entrainment ratio.

The main advantage of the ejector as a jet pump is the absence of moving parts with friction surfaces, which is important when working in hot or aggressive environments. Jet apparatuses have low metal consumption, they are compact and simple in design, which ensures their reliability. By these, their priority in almost all industries as individual equipment or auxiliary units is determined. It is generally accepted that the use of jet apparatuses is due to the high efficiency of processes in jet flows.

Ejectors are used as water jet pumps, vacuum systems for suction of liquids and gases and mixers of liquids, gases, etc. [9–12]. In the food industry, ejectors are used to saturate beverages with carbon dioxide, pasteurization and sterilization of food, for mixing media, aeration during fermentation, etc. [13–16]. In particular, in the sugar industry, jet apparatuses allow to improve the process of sulfitation of water and sugar solutions, to carry out the process of removal of ammonia from condensates in intensive and energy efficient mode, to create two-section saturators and to receive sugar solutions with high quality indicators. The undeniable advantages of jet apparatuses allow them to be used in the disposal of emissions from sugar factories, which will help to reduce the material and energy costs of production and improve environmental safety.

The purpose of the ejector is the main criterion in its design. So, when using ejectors as jet pumps, the criterion in its design is the dynamic pressure.

When using ejectors for heat-and-mass transfer processes, there must be created a significant phase contact surface and its rapid renewal, there must be a sufficient contact time, and the required number of phases. Such requirements are set after the analysis of the basic equation of mass transfer.

It should be noted that in a jet apparatus, mainly two types of working nozzles are used. They provide the formation of compact and dispersed jets of liquids. In the first case, these are jet nozzles with a continuous spray pattern, which interacts with the gas phase on the outer surface only. Ejectors with such working nozzles are used as jet pumps, where the pressure of the mixture at the outlet is important.

The working nozzles in the ejectors that form a dispersed jet of liquid are nozzles of the centrifugal-jet type. Such nozzles allow to receive drops of liquid at insignificant distance from a nozzle and to provide the maximum surface of contact of phases for mass transfer.

When jet apparatuses are used for technological processes related to heat-and-mass transfer, the *ER* index becomes decisive. If the flow rate of the active (liquid) phase is simple enough to regulate, then providing the required amount of passive (gas) phase, which is required for the implementation of these processes according to the technological regulations, is a problem not solved so far.

For example, to carry out the sulfitation process, it is necessary to have a jet apparatus with a high volume entrainment ratio. As for the pressure of the mixture at the outlet of the ejector, its kinetic energy is sufficient for a centrifugal separation of liquid and gas.

The value of the efficiency and entrainment ratio largely depends on the hydraulic losses, most of which fall on the receiving and mixing chambers. They are caused by reverse-circulation flows in the mixing chamber, cavitation effects, energy and mass transfer between phases, hydraulic friction caused by a significant pressure gradient, and other complex processes [1–4].

The phenomenon of reverse-circulation flows in the mixing chamber is known and covered in different works [17–24]. However, no effective methods have been proposed to eliminate them. There are only a few technical solutions that can reduce the reverse-circulation flow and thus increase the efficiency of the ejector, but their use is limited. These include the replacement of one central jet of fluid by multiple jets of the same equivalent cross section [18], and profiling the mixing chamber by installing inserts that correspond to the size of the reverse-circulating zones [24]. The latter leads to an increase in the efficiency of the jet apparatus by 11 % when compared to the ejector having a cylindrical mixing chamber.

However, the introduction of inserts in the mixing chamber has a two-fold effect – on the one hand, energy losses are eliminated because of the separation of the flow. On the other hand, friction losses increase. With increasing the liquid flow rate from the working nozzle of the ejector, the size of the separation zones decreases and, accordingly, the size of the replacement bodies becomes excessive – so the positive effect of their installation decreases. The larger the relative size of the inserts, the narrower the range of operation modes of the ejector in which the total effect of their introduction is positive.

As it was noted, a leakage of liquid from the nozzle into the mixing chamber leads to a formation of a cavitation zone [1, 2]. Usually, in the ejector, there is a vortex cavitation, which contributes to the additional destruction of liquid droplets, and to a formation of vortex zones with local pulsations of speed and pressure. Such cavitation effects occur at the beginning of the cylindrical mixing chamber and are extremely unfavorable and lead to a decrease in the efficiency of the jet apparatus.

The impossibility of quantitative accounting of the influence of these processes on the ejection capacity of the apparatus, does not yet allow to create a reliable and accurate mathematical model of their work and to calculate the basic dimensions of the ejectors on its basis.

Taking this into account, one of the main directions of creating a jet apparatus with a high entrainment ratio are experimental studies of their work in order to establish patterns and features of energy and hydrodynamic phenomena.

Thus, the purpose of this work is to develop a jet apparatus with a dispersed jet of liquid and a high entrainment ratio. Intensification of technological processes connected with mass transfer will be possible with this apparatus. In particular, on the basis of such an apparatus, the operation of a sulphitation station in the sugar industry was intensified.

The study consists of two stages. At the first stage, the hydrodynamics of the liquid-gas mixture in the mixing chamber of a jet apparatus was analysed and their operation at different spatial positions was investigated. At the second stage, taking into account the results of the first one, the operation of a jet apparatus with a high entrainment ratio was designed and studied.

## 2. Materials and methods

During the study, the ejector with a dispersed liquid jet has been investigated. To establish the patterns of hydrodynamics of the two-phase flow in the mixing chamber of the jet apparatus, an experimental setup was constructed (Figure 1).

The setup consists of a pump, a piping system, a water tank, shut-off and control valves and it is equipped with control and measuring instrumentation. The fluid flow was measured with a rotary flow meter type KV-1.5, accuracy class 1.5 (relative error ± 1.5 %). The fluid pressure in the working nozzle was controlled by an OBM-1-160 manometer, accuracy class 1.5, in addition, the relative error of the measurement results of the apparatus is ± 1.5 % (the nozzle and the manometer were placed on the same axis). Gas consumption was measured with a PREMA

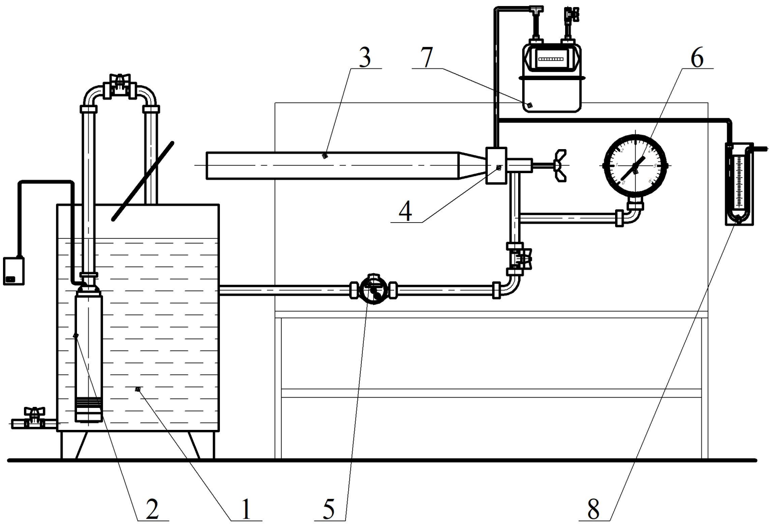


Figure 1. Experimental setup (1 – liquid container; 2 – pump; 3 – mixing chamber of the jet apparatus; 4 – nozzle with receiving chamber; 5 – liquid flow meter; 6 – manometer; 7 – gas flow meter; 8 – differential manometer).

G 1.6 volumetric gas flow meter (relative error of the measurement± 1.5 %). The vacuum in the receiving chamber was mm$H_2O$ measured with a differential manometer, with an error of ± 1 mm. Photographing the flow of the liquid-gas mixture in the mixing chamber was carried out with a digital camera Canon PowerShot SX40 HS.

The jet apparatus could be placed both horizontally and vertically.

The working nozzle of the ejector was a nozzle of centrifugal-jet type with two inclined supply channels (pipes) (Figure 2) [25] and replaceable nozzles with a diameter ($d_{noz}$) of 4 mm and 6.2 mm. The manufacturing accuracy of the nozzle and ejector components corresponded to tolerance grades 7–9 [26].

This nozzle has a peculiarity: when the liquid is fed into the vortex chamber 3 through inclined supply channels 5, which are arranged so that both edges of the supply channel are adjacent to it tangentially, but on different sides of the axis, it takes moments of momentum in different directions. This inlet of the liquid into the vortex chamber promotes the formation of a highly turbulent flow that moves in the direction to the nozzle 4 and flows out of it in the form of a dispersed jet. The formed liquid droplets constantly change shape and size, which is the most favorable for achieving a high entrainment ratio [27] and conducting mass transfer processes in a jet apparatus.

The mixing chambers of the jet device had a diameter ($D_{mech}$) of 19 mm, 27 mm and 45 mm, and a length $L_{mech} = 8D_{mech}$. The distance from the nozzle to the initial section of the mixing chamber was equal to the diameter of the nozzle: $L = d_{noz}$.

The study was carried out in a water-air system at a phase temperature of 20 °C and a relative air humidity of 85 %, in order to exclude heat exchange processes from consideration. The thermophysical properties of the working liquid and the gas phase have a significant impact on the results of the study.

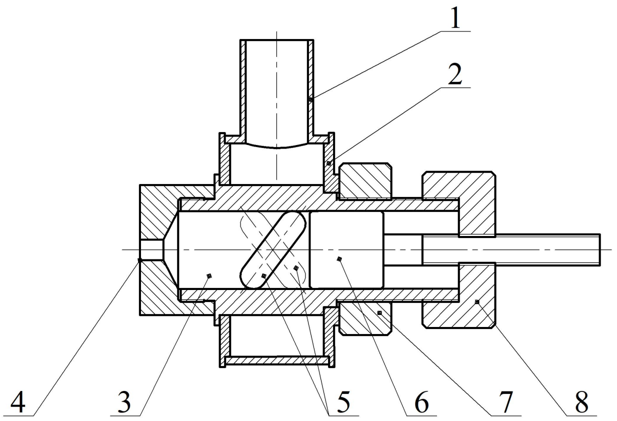


Figure 2. Nozzle design (1 – liquid inlet pipe; 2 – housing; 3 – vortex chamber; 4 – nozzle; 5 – supply channels; 6 – plunger; 7,8 – nut).

The greater the difference between the temperatures of the phases, or the partial pressure of water vapour in the gas phase at a given temperature and equilibrium, the greater the effect they have on the ejection ability of the apparatuses. In the ejector phase, equilibrium is achieved in terms of temperatures, partial pressures of water vapour, and also degassing of the liquid occurs due to rarefaction in the receiving chamber of the ejector. Moreover, the further the phases are from an equilibrium, (large temperature difference between phases or low air humidity) the greater the influence of accompanying processes. At equal and low phase temperatures and high humidity, heat and mass transfer processes are insignificant and have a minimal impact on the measurement results.

In experimental studies, water was used as the working fluid, which filled the liquid container. After the working cycle, the water from the jet apparatus returned to the same container, so the working fluid circulated in a closed loop and its physical properties were the same for all experiments. This made it possible to exclude the influence of these factors on the experimental results. Physical properties of the liquid based on temperature were determined on the basis of tables of the thermo-physical state of water and water vapour [28].

The modes of operation of the jet apparatus were changed by adjusting the pressure of the liquid in the nozzle, which was controlled by the manometer. At least three experiments were carried out, each lasting two minutes. Indicators of liquid and gas flow meters at the beginning and at the end of experiments, liquid pressure in the nozzle, and the vacuum in the receiving chamber were recorded.

Experimental data processing was carried out by well-known methods (elimination of gross errors according to Student's t-test at a significance level of 0.05, the result was brought to the arithmetic mean value) and was performed with the help of Microsoft Office Excel spreadsheet processor; graphs were plotted in OriginPro 8, Microsoft Office Excel programs.

## 3. Results and discussion

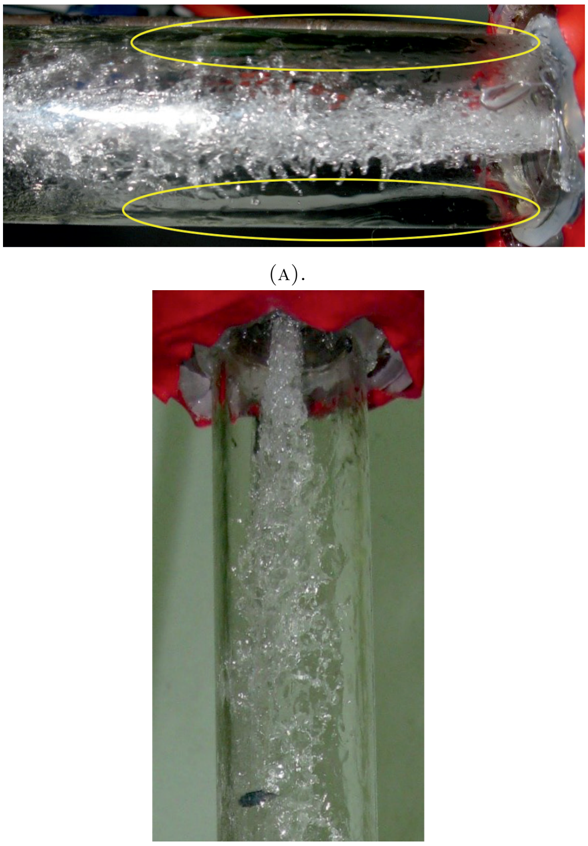
### 3.1. Study of the hydrodynamics of the liquid-gas mixture in the mixing chamber and the operation of the ejector at various spatial locations

Both the vertical and the horizontal placement are well known in the practice of using ejectors. However, it needs to be investigated whether the spatial position affects the operational characteristics of ejectors operating in a subsonic mode.

Figure 3 shows the process of decomposition of the liquid jet from the nozzle and the formation of a two-phase flow in the initial section (part) of the cylindrical mixing chamber at horizontal (Figure 3a) and vertical (Figure 3b) positions of the ejector with the basic geometric parameter (ratio of the mixing chamber area to the area of the nozzle) $m = 45.5$ (with $d_{noz} = 4\,\text{mm}$, $D_{mech} = 27\,\text{mm}$). The pressure of the liquid $P$ in the nozzle is 0.3 MPa.

An analysis of the flow regime of the liquid-gas mixture shows that at the horizontal position of the ejector (Figure 3a) at the beginning of the cylindrical mixing chamber, there are significant reverse-circulation flows, and in its lower part there, there is a reverse movement of water, and in the upper part – a reverse movement of water-air mixture. With a decrease in the main geometrical parameter of the ejector, the reverse flows also decrease.

Drops moving to the upper wall of the mixing chamber (above the horizontal axis of the jet apparatus) reach it. Then, they are reflected downwards and carried away by the central mass of the flow and are moved further along with it. Therefore, in the upper part of the mixing chamber, there are reverse-circulation flows of only the water-air mixture.


(a).

(b).

Figure 3. Decomposition of the liquid jet in the cylindrical mixing chamber with $d_{noz} = 4\,\text{mm}$, $D_{mech} = 27\,\text{mm}$: (A) horizontal position of the ejector; (B) vertical position of the ejector.

In the case that liquid droplets move to the lower wall of the mixing chamber (below the horizontal axis of the ejector), they remain on it and form a layer of liquid, which is broken due to the friction against the wall, and under the action of the vacuum created in the ejector, part of the liquid changes its direction of motion. So there are significant reverse-circulation fluid flows in the lower part of the mixing chamber.

When the ejector is in a vertical position (Figure 3b), the flow pattern in the mixing chamber differs significantly from the flow in its horizontal position. The operation of the ejector is characterized by a more uniform spray pattern without any clearly expressed reverse-circulation flows, which is due to the formation of an ordered liquid-gas flow as a result of the coincidence of the droplet velocity and gravity vectors.

Thus, the analysis of the hydrodynamics of the liquid-gas mixture in the mixing chamber of the ejector, depending on its spatial position, shows the difference in the formation of a two-phase flow in the initial section. Obviously, for the formation and maintenance of the reverse-circulation movement, the energy of the flow is expended, which leads to a decrease in its velocity and, consequently, in the volumetric entrainment ratio.

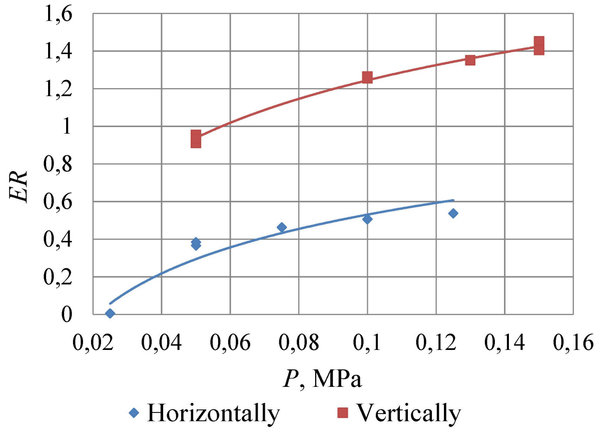


FIGURE 4. Dependence of $ER$ on $P$ at different spatial positions of the ejector with $d_{noz} = 6.2\,\mathrm{mm}$, $D_{mech} = 45\,\mathrm{mm}$ ($m = 52.7$).

This is confirmed by the presented data of comparative studies (Figure 4) of a jet apparatus with a cylindrical mixing chamber ($D_{mech} = 45\,\mathrm{mm}$) and a nozzle with inclined supply channels ($d_{noz} = 6.2\,\mathrm{mm}$) in a horizontal and vertical position depending on the pressure of the active flow in injector $P$.

The vertical placement of the ejector for these modes of operation makes it possible to almost double the entrainment ratio ($ER$). Similar results were obtained for a water-air jet apparatus with other values of $m$. In all cases, the entrainment ratio of a vertically mounted ejector is higher than the one of the same ejector placed horizontally. An increase in the volumetric entrainment ratio is explained by a decrease in hydraulic losses in the mixing chamber, which is associated with the friction of the flow against its wall and the elimination of zones of reverse-circulation flows, which is achieved due to the coincidence of the trajectory of the liquid-gas mixture movement with the direction of the action of the force of gravity.

Thus, placing the ejectors in a vertical position is one of the simple ways to increase the volumetric entrainment ratio.

Another way to increase this indicator is to design the mixing chamber of the ejector of such a shape that minimizes the resistance to the entry of the passive flow into the mixing chamber and the formation of reverse-circulation flows is prevented.

### 3.2. DESIGN AND RESEARCH OF THE JET APPARATUS WITH A HIGH ENTRAINMENT RATIO

The analysis of the fluid movement in the ejector shows that the leakage of the active medium from the working nozzle into the mixing chamber is similar to the movement of fluid through a pipeline with a sudden expansion and is characterized by significant head (energy) losses $h_{s.e}$ and reverse-circulation flows, which depend on the ratio of the diameters.

To reduce the head loss $h_{s.e}$, it is recommended to make the transition between parts of the pipeline using cone divergent tubes (diffusers). The diffuser opening angle $\beta$ is taken in the range of 3–8°, which is explained by low hydraulic losses and the continuous nature of the flow [29]. The head losses with this design of the pipeline are determined by the formula:

$$h_{dif} = \varphi h_{s.e} \tag{1}$$

where $\varphi$ – empirical coefficient, which depends on the angle $\beta$ ($\varphi = 0.4$–$1.2$).

A similar technical solution was proposed to use in the initial section of the mixing chamber. The angle of expansion of the conical part is, by 3–8°, smaller than the angle of the spray pattern of the liquid from the nozzle, and the walls of the mixing chamber are touched by the liquid jet at the connection point of the conical and cylindrical parts. With this design of the mixing chamber, there is an annular space between the outer surface of the spray pattern of the liquid and the inner surface of the conical part, which makes the ejection of the passive flow over a sufficient length possible.

The proposed design of the jet apparatus with a conical-cylindrical (combined) mixing chamber was designed, researched, and patented [30]. To compare the value of the entrainment ratio of the ejector with a combined mixing chamber (the angle of expansion of the conical part is 25°), another ejector of a similar design, but with a cylindrical mixing chamber, was constructed. Their designs are shown in Figure 5.

The receiving chambers of two ejectors are cylindrical, with a gas distributor 5 installed inside. The gas distributor is a disk with holes equally spaced around the perimeter. With this design of the receiving chamber, it is possible to distribute the passive gas phase with a minimal resistance along the entire perimeter of the active liquid jet.

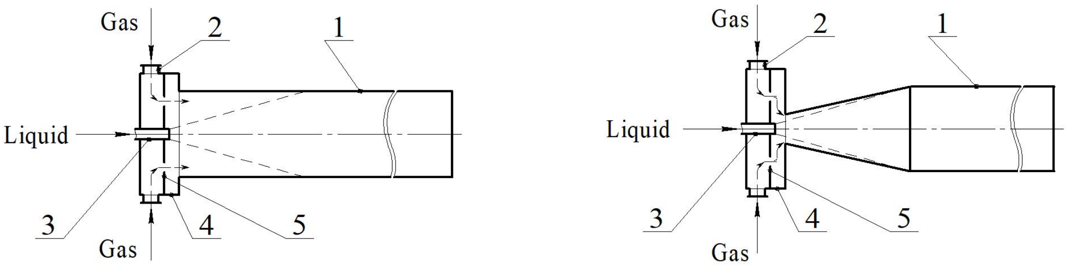
On the basis of the experimental data, graphs (Figure 6) of the dependence of the hydrostatic pressure drop $\Delta P_{mix}/\Delta P_{act}$ on the volumetric entrainment ratio $ER$ for jet apparatuses with cylindrical and conical-cylindrical mixing chambers and different values of the main geometric parameter $m$ were plotted.

The relative values of hydrostatic pressure were calculated from the formula:

$$\frac{\Delta P_{mix}}{\Delta P_{act}} = \frac{p_{mix} - p_{pas}}{p_{act} - p_{mix}} \tag{2}$$

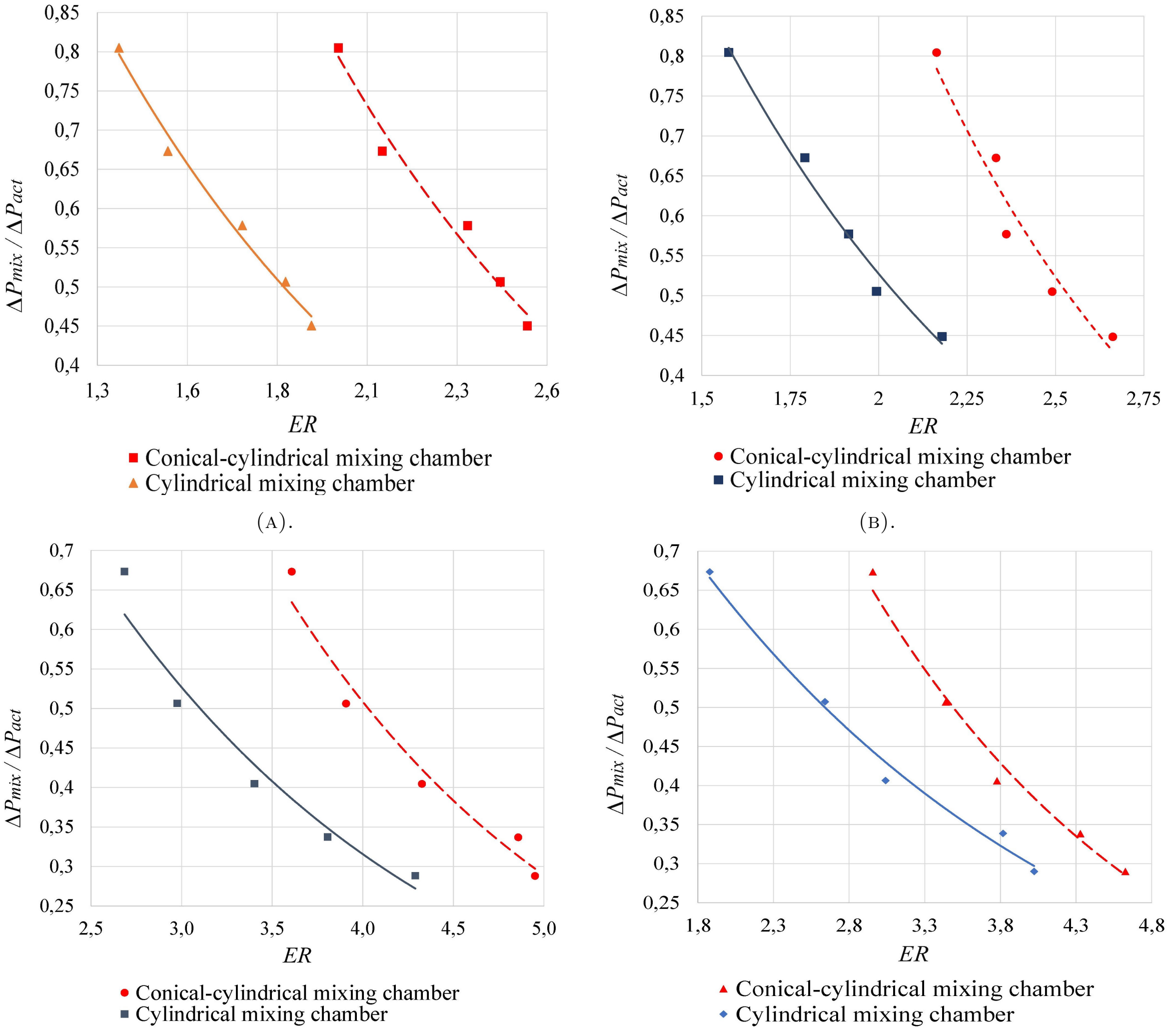
where $p_{mix}$ – the pressure of the mixture at the outlet of the ejector [Pa]; $p_{pas}$ – pressure of the passive medium (gas) in the receiving chamber [Pa]; $p_{act}$ – the pressure of the active medium (fluid) in the nozzle [Pa].

It has been shown by the analysis of the experimental data results (Figure 6) that in the range of the investigated values of $m$, the modification of the



(a). (b).

Figure 5. Designs of jet apparatus: (A) with a cylindrical mixing chamber; (B) with a combined mixing chamber. 1 – mixing chamber; 2 – passive medium supply pipe; 3 – motive nozzle; 4 – receiving chamber; 5 – gas distributor.



(a). (b). (c). (d).

Figure 6. Dependence of $\Delta P_{mix}/\Delta P_{act}$ on $ER$ for jet apparatuses with different mixing chambers and different values of the basic geometric parameter $m$: (A) $m = 9.4$ ($d_{noz} = 6.2$ mm, $D_{mech} = 19$ mm); (B) $m = 19$ ($d_{noz} = 6.2$ mm, $D_{mech} = 27$ mm); (C) $m = 22.5$ ($d_{noz} = 4$ mm, $D_{mech} = 19$ mm); (D) $m = 45.5$ ($d_{noz} = 4$ mm, $D_{mech} = 27$ mm).

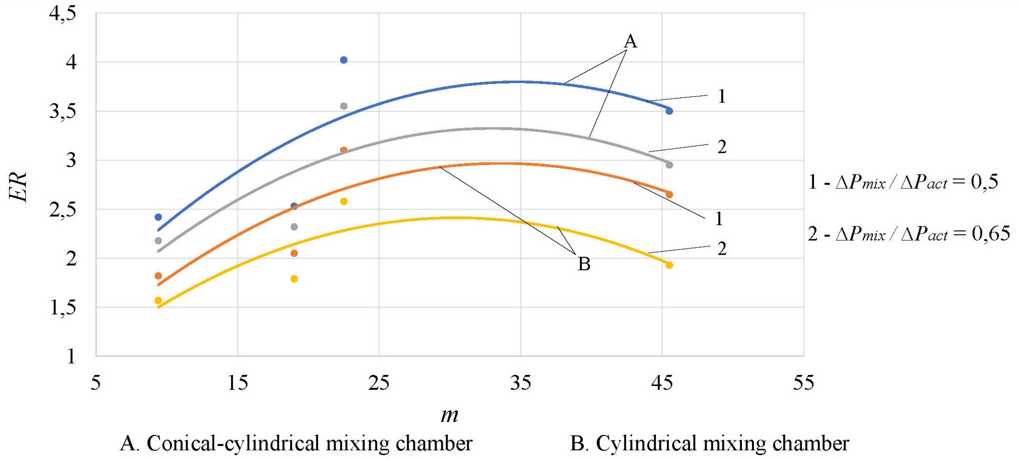


Figure 7. Dependence of $ER$ on $m$ for the ejectors with different values of $\Delta P_{mix}/\Delta P_{act}$ and different mixing chambers.

mixing chamber with an initial conical section leads to the increase in the volumetric entrainment ratio. This is due to the decrease in hydraulic losses linked with the formation and support of the movement of reverse circulation flows.

So, at $\Delta P_{mix}/\Delta P_{act} = 0.5$ for the ejector with a conical-cylindrical mixing chamber and $m = 9.4$, the entrainment ratio increases from 2.42 to 2.53 with $m = 19$, continues to grow to 4.02 with $m = 22.5$, and further decreases to 3.5 with $m = 45.5$.

In addition, it can be seen from the graphs above that the increase in $ER$ for all cases causes a decrease in the parameter $\Delta P_{mix}/\Delta P_{act}$, which is explained by the losses of pressure in the mixing chamber.

On the basis of the presented data, the graphs of the dependence of the volumetric entrainment ratio $ER$ on the main geometric parameter $m$ at different values of $\Delta P_{mix}/\Delta P_{act}$ for jet apparatuses with cylindrical and conical-cylindrical mixing chambers were constructed (Figure 7).

With the same value of the relative hydrostatic pressure drop ($\Delta P_{mix}/\Delta P_{act} = 0.5$), $ER$ of the jet apparatus with the conical-cylindrical mixing chamber is 23–32 % higher (depending on the value of $m$) as compared to the $ER$ of the ejector, which has the cylindrical mixing chamber.

At higher values of $\Delta P_{mix}/\Delta P_{act}$, the volumetric entrainment ratio for both ejectors decreases due to the increasing pressure of the mixture at the outlet of the jet apparatus.

The operational characteristics of a jet apparatus depend significantly on the main geometric parameter $m$. The maximum entrainment ratio for these operating modes is achieved at $m = 25$–$40$.

Depending on the task set before the ejector, from the given graphs, it is possible to define optimum mode parameters of a jet apparatus with the given geometric dimensions.

## 4. Conclusions

The efficiency of a jet apparatus is reduced by the reverse-circulation flows, which are explained by the vacuum in the receiving chamber.

At the horizontal position of the jet apparatus at the initial part of the mixing chamber, there are significant reverse-circulating flows (in its lower part, the reverse-circulating water flows are formed, and in the upper part – water-air mixture), and at the vertical position of the ejector, the more ordered hydrodynamic flow regime is observed. As a result, with the vertical placement of the ejector, the entrainment ratio is almost twice as high as compared to the horizontal one.

Based on the analysis of the flow regime of the liquid-gas mixture in the mixing chamber, evaluative calculations and studies, which were carried out, a new design of the jet apparatus was patented. The mixing chamber of this apparatus is made as conical-cylindrical with the opening angle of the conical part smaller by 3–8° than the angle of the liquid spray pattern from the working nozzle.

Based on the research, it was found that in the jet apparatus with a combined mixing chamber, the zone of reverse-circulation flows is eliminated and a 15–55 % higher entrainment ratio is achieved as compared to the ejector having a cylindrical mixing chamber.

The range of values of the basic geometrical parameter $m$ at which the highest entrainment ratio of the jet apparatus is reached ($m = 25$–$40$) was established.

Further studies of the operation of the ejectors with the conical-cylindrical mixing chamber (as well as other innovative designs of apparatuses, including pulsating ones) are necessary and will be carried out in order to establish the optimal size to achieve the maximum volumetric entrainment ratio. Finding the dependence of the value of the entrainment ratio on the mixture pressure at the outlet from the ejector (back pressure) is the next most important task and a separate study is required. Such an apparatus can be used to improve technological processes associated with mass transfer. In particular, in the sugar industry, this can help stabilize the work of sulfitators.

## References

[1] J. Wang, H. Cheng, S. Xu, et al. Performance of cavitation flow and its induced noise of different jet pump cavitation reactors. *Ultrasonics Sonochemistry* **55**:322–331, 2019. `https://doi.org/10.1016/j.ultsonch.2019.01.011`.

[2] Y. P. Kabanov, G. V. Shevchenko. K voprosu opredeleniya kavitatsionnyih harakteristik struynyih nasosov. *Chelyabinskiy fiziko-matematicheskiy zhurnal* **1**(2):94–99, 2016.

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

[4] G. Besagni, R. Mereu, F. Inzoli, et al. 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**:628–651, 2017. `https://doi.org/10.1016/j.applthermaleng.2017.04.111`.

[5] Z. Aidoun, K. Ameur, M. Falsafioon, et al. Current advances in ejector modeling, experimentation and applications for refrigeration and heat pumps. Part 2: Two-phase ejectors. *Inventions* **4**(1):16, 2019. `https://doi.org/10.3390/inventions4010016`.

[6] A. Shah, I. R. Chughtai, M. H. Inayat. Experimental and numerical investigation of the effect of mixing section length on direct-contact condensation in steam jet pump. *International Journal of Heat and Mass Transfer* **72**:430–439, 2014. `https://doi.org/10.1016/j.ijheatmasstransfer.2014.01.032`.

[7] X. Yang, X. Long, X. Yao. Numerical investigation on the mixing process in a steam ejector with different nozzle structures. *International Journal of Thermal Sciences* **56**:95–106, 2012. `https://doi.org/10.1016/j.ijthermalsci.2012.01.021`.

[8] B. Kitrattana, S. Aphornratana, T. Thongtip, et al. Comparison of traditional and CRMC ejector performance used in a steam ejector refrigeration. *Energy Procedia* **138**:476–481, 2017. `https://doi.org/10.1016/j.egypro.2017.10.229`.

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

[10] Y. V. Martynenko, V. I. Bolobov, V. A. Voronov. Use of liquid-gas ejector in liquefied natural gas (LNG) sampling system. *E3S Web of Conferences* **266**:01006, 2021. `https://doi.org/10.1051/e3sconf/202126601006`.

[11] S. Shen, X. Qu, B. Zhang, et al. Study of a gas–liquid ejector and its application to a solar-powered bi-ejector refrigeration system. *Applied Thermal Engineering* **25**(17-18):2891–2902, 2005. `https://doi.org/10.1016/j.applthermaleng.2005.02.012`.

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

[13] K. Samoichuk, J. Poludnenko, N. Palyanichka, et al. Experimental investigations of sugar concentration for counterflow jet mixing of drinks. *Technology audit and production reserves* **2**(3(34)):41–46, 2017. `https://doi.org/10.15587/2312-8372.2017.100173`.

[14] A. I. Sokolenko. *Intensifikatsiya teplo-masoobminnih protsesiv v harchovih tehnologiyah.* Feniks, Kyiv, 2011.

[15] V. Ponomarenko, N. Pushanko. *Ejection devices in mass transfer processes of sugar industry.* LAP LAMBERT Academic Publishing, Saarbrucken, 2014.

[16] S. Akteriana. Improving the energy efficiency of traditional multi-stage steam-jet-ejector vacuum systems for deodorizing edible oils. *Procedia Food Science* **1**:1785–1791, 2011. `https://doi.org/10.1016/j.profoo.2011.09.262`.

[17] M. T. Kandakure, V. G. Gaikar, A. W. Patwardhan. Hydrodynamic aspects of ejectors. *Chemical Engineering Science* **60**(22):6391–6402, 2005. `https://doi.org/10.1016/j.ces.2005.04.055`.

[18] E. Y. Sokolov, N. M. Zinger. *Struynyie apparatyi.* Energoatomizdat, Moscow, 1989.

[19] A. F. Yatsenko, T. A. Ustimenko. Teoreticheskie i eksperimentalnyie issledovaniya vodovozdushnogo ezhektora. *Naukovi pratsi Donetskogo natsionalnogo tehnichnogo universitetu* **23**(196):247–253, 2012. `http://ea.donntu.org/handle/123456789/11573`.

[20] Y. Tang, Z. Liu, Y. Li, et al. Visualization experimental study of the condensing flow regime in the transonic mixing process of desalination-oriented steam ejector. *Energy Conversion and Management* **197**:111849, 2019. `https://doi.org/10.1016/j.enconman.2019.111849`.

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

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

[23] S. Gül, Z. S. Özdogan. Ejector type solid circulation system analysis for circulating fluidized beds. *International Journal of Multiphase Flow* **84**:116–128, 2016. `https://doi.org/10.1016/j.ijmultiphaseflow.2016.04.020`.

[24] S. Y. Smyk, A. G. Butenko. Modelling of work central ejectors with the purpose of increase of their efficiency. *Modern Science: Researches, Ideas, Results, Technologies* **1**(3):150–152, 2010. `http://modern.science.triacon.org/en/issues/2010/files/2010_1(3)_23.htm`.

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

[26] DSTU ISO 286-1-2002. ISO tolerances and fits. Standart, State committee of Ukraine for technical regulation and consumer policy. Kyiv, 2003.

[27] V. Ponomarenko, T. Dimitrov, A. Sliusenko, et al. Liquid jet gas ejectors: designs of motive nozzles, performance efficiency. *Proceedings of university of Ruse* **58**(10.1):91–95, 2019.

[28] A. A. Aleksandrov, B. A. Grigoryev. *Tablitsy teplofizicheskikh svoystv vody i vodyanogo para.* Moskovskiy energeticheskiy institute, Moscow, 1999.

[29] I. E. Idelchik. *Spravochnik po gidravlicheskim soprotivleniyam.* Mashinostroenie, Moscow, 1992.

[30] V. V. Ponomarenko, A. M. Sliusenko. Liquid-gas ejector, 2020. Ukraine patent UA 122296 C2.