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### ПІДВИЩЕННЯ ТЕРМОДИНАМІЧНИХ ХАРАКТЕРИСТИК КОНДЕНСАТОРА ХОЛОДИЛЬНОЇ МАШИНИ ЗА ДОПОМОГОЮ НАНОЧАСТОК

В статті наведена інформація про перспективи використання наночасток для покращення термодинамічних характеристик теплообмінних апаратів холодильної машини, працюючої на ізобутані. Вплив нанодомішок розглянутий на прикладі експериментального дослідження конденсатора. Результати свідчать про підвищення коефіцієнта теплопередачі в конденсаторі на 16–24 % в залежності від режиму роботи.

**Ключові слова:** холодильна машина, наночастка, нанодомішка, коефіцієнт теплопередачі, коефіцієнт тепловіддачі, конденсатор, ізобутан.

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# ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ РІДИННО-ПАРОВОГО ЕЖЕКТОРА З КОНІЧНОЮ КАМЕРОЮ ЗМІШУВАННЯ

*У статті подана модель розрахунку геометричних та енергетичних параметрів конічної камери змішування рідинно-парового ежектора. Представлені результати експериментального дослідження плоскопаралельного рідинно-парового ежектора з камерою змішування конічної форми і проведено їх порівняльний аналіз з теоретичними даними. Виконано аналіз ексергетичної ефективності використання ежектора з конічною камерою змішування.*

**Ключові слова:** *рідинно-паровий ежектор, конічна камера змішування, експериментальне дослідження, ексергетична ефективність.*

## 1. Introduction

At the present stage of human development technological processes that can be taken only at pressures below atmospheric are more widely used in various industries. Thus, in the mechanical engineering and metallurgy — a vacuum welding and soldering metals and alloys, heat treatment in a vacuum, out-of-furnace vacuum processing and casting of liquid steel, refining metals and alloys in solid state, pumping vapor-air mixtures from condensers for steam turbines in the food industry — deodorization of plant oils, milk thickening by evaporation to a dry matter content and others.

In many cases vacuum is obtained using the energy of work jet flow of jet devices. These include multistage vacuum units, which include vapor-jet ejectors, with a total drop of pressure $10 \div 15$ and a low efficiency, which is typically less than $2 \div 10$ %. This low level of efficiency is due to the fact that the increase in pressure of one vapor-jet stage can be no more than $2 \div 3$ times. Greater degree of pressure increases at one stage lead to a sharp decline in the ejector efficiency, which is associated with choking losses during the mixing of supercritical active and subcritical passive streams.

In view of this situation, it is very relevant to use liquid-vapor ejector (LVE), which works on the principle of jet thermal compression (JTC) [1]. This principle is based on the fact that the passage of the working environment of active flow through Laval nozzle is accompanied by relaxation vaporization of the part that is expanding. The kinetics of these processes is characterized by three critical sections, which is restructuring stream. In the initial section of the LVE active flow nozzle is formed supersonic jet of finely-divided vapor-drop structure with a pressure that is less than the pressure of the environment. Then it injects hydraulic fluid of passive flow entering the receiving chamber. Hydraulic fluids of active and passive flows at the inlet in the mixing chamber pressure are aligned, and there is mixing into a single stream, after which further compression of the mixed stream is taken place in diffusor. Vapor that compressed in LVE is separated in a separator from which liquid is extracted in circulation circuit by the pump and after the heating in the heat exchanger is fed to the active LVE nozzle.

## 2. The object of research and its technological audit

*Object of research* is workflow of liquid-vapor ejector with conical mixing chamber.

LVE belongs to a class of two-phase jet devices. Today there are a large number of theoretical and experimental studies, but due to the complexity of the workflow so far no method of calculation that would more fully described processes in the LVE flow channel of the conical mixing chamber and its experimental verification. For the design of vacuum units based on LVE with conical mixing chamber it is necessary to develop a method of calculation that would authentically reflect its workflow. Thus, a detailed theoretical and experimental research and creation of method for its calculation is very important and has great practical importance.

## 3. The aim and objectives of research

*The aim of this work* is to study the influence of geometric and operational parameters of conical mixing chamber in achievable LVE performance.

To achieve this aim the following objectives have been solved:

1. Experimental study of LVE with conical mixing chamber at different initial parameters of the working fluid of active flow under the program and test method [2].
2. Experimental study of LVE with conical mixing chamber and different contraction angles.
3. Experimental study of LVE with conical mixing chamber and cylindrical section of different lengths.
4. Experimental study of LVE efficiency with conical mixing chamber.

## 4. Literature review

Changing the geometry of the mixing chamber in LVE significantly affect the performance of the ejector and vacuum unit as a whole, because most of the research connected with the study of processes that occur when mixing the two streams in mixing chambers of different geometric shapes. In [3] it is considered the mixing chamber with increased length, in which cylindrical insertion is mounted between contractor and diffuser. Also in [4] it is noted that when the pressure increase of the working fluid of active flow before nozzle, compression of vapor-air mixture is not as usual in the mixing chamber or diffuser, and behind the diffuser — in a discharge pipe. Therefore, in this paper we consider the possibility of replacing the mixing chamber and diffuser on a simple cylindrical tube and the results of experimental studies for ejectors with pipes of different diameters and lengths are given.

Empirical dependence for selecting optimal size of mixing chamber in the experimentally test range of geometric and operational ejector parameters are derived by integrating results. In [5] the results of experimental studies of gas ejectors with conical mixing chamber are shown. Transition from this type of ejectors to the cylindrical mixing chamber can significantly increase the ejector efficiency.

In [6] and subsequent works of the author, in addition to consideration of the nature of the influence of the mixing chamber geometry, the advantages of the use of supersonic nozzles for injected gas, compared with sound are shown, as in [7] the results of the experimental study are given for gas ejector with cylindrical mixing chamber and diffuser, which has a throat.

In [8, 9] the main attention is paid for optimizing the design of liquid-jet devices used for compression and supply of petroleum gas of final oil separation in the gas gathering system by changing combinations of relative length of the mixing chamber and diffuser throat. Proposed calculation technique is developed by summarizing obtained experimental data using similarity theory.

All of the above work describes the effect of geometrical parameters (diameter and length of the mixing chamber, shape of the nozzles and their number) on the achievable performance parameters of jet unit.

## 5. Materials and methods of research

To calculate the mixing chamber of variable LVE section (Fig. 1) equation of pulses and mass conservation are used. It is written in the form:

$$\left(1+\alpha_w \cdot u\right)\cdot\left(\frac{w_a^2}{\upsilon_a}\right)+f_{\text{con}}\cdot p_1=f_3\cdot\left(\varphi_3^{-1}\cdot\frac{w_3^2}{\upsilon_3}+p_3\right)+\int\limits_{f_3}^{f_{\text{con}}} p df,$$

where $\alpha_w=\dfrac{w_2}{w_a}$; $w_2$ — passive flow velocity in the inlet section of the mixing chamber; $f_{\text{con}}=\dfrac{F_{\text{con}}}{F_a}$ — basic geometrical parameter of the mixing chamber in the inlet section; $f_3=\dfrac{F_3}{F_a}$ — basic geometrical parameter of the mixing chamber in the outlet section; $\varphi_3$ — velocity coefficient of the mixing chamber:

$$\varphi_3=\frac{1}{1+\zeta_3},$$

where $\zeta_3=\left(\dfrac{\xi}{2}\right)\cdot\left(\dfrac{z_3-z_1}{D_{13}}\right)$; $\xi$ — coefficient of hydraulic friction of flows into the mixing chamber; $D_{13}$ — diameter of equivalent cylindrical mixing chamber.

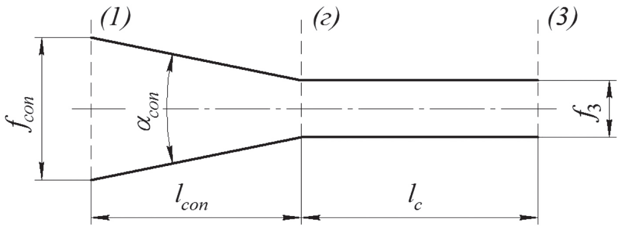


**Fig. 1.** The main parameters of the mixing chamber of variable section

To determine the impulse $I_F$ of the mixing chamber in which the inlet section has a conical contracting shape, and after it there is outlet cylindrical section, the calculation technique proposed in [10] is used:

$$I_F = \int_{f_3}^{f_{\text{con}}} pdf = \frac{1}{2}\left(f_{\text{con}} - f_3\right) \cdot \left(\frac{p_1}{p_3} + \frac{p_S}{p_3}\right) \cdot p_3,$$

where $p_S$ — static pressure at the inlet of the cylindrical section of the mixing chamber.

The equations of mass conservation of stationary flow:

$$w_3 = \frac{1+u}{f_3} \cdot \frac{\upsilon_3}{\upsilon_a} \cdot w_a.$$

In order to maximize the effectiveness of the mixing process, it is necessary to search for the optimal position of the inlet section of the active nozzle to inlet section of the mixing chamber. In LVE it is possible, since there are no choking losses and the values of the injection coefficient are at 0,01÷0,1. It should consider two limiting options for injection (Fig. 2).

The first limiting mode occurs when the outlet section of active nozzle (*a-a*) coincides with a section ($1_1$-$1_1$) (Fig. 2, *a*) and is characterized by pressure equality of active flow at the nozzle section and passive flow at the inlet of the mixing chamber. In this mixing mode, mass accession of passive flow in the developed turbulent jet layer is isobaric.

The injection equation for this case is written as for turbulent jets with variable density using a system of L. Prandtl theory equations for closure. Injection coefficient is:

$$u = 2 \cdot b_1^0 \cdot \left(\left(1 + b_1^0 \cdot (1 - I_1)\right) \cdot I_2 - b_1^0 \cdot I_3\right) + \left(1 - b_1^0 \cdot I_1\right)^2 - 1,$$

where $b_1^0$ — the relative thickness of the turbulent layer:

$$b_1^0 = c_a \cdot z_1^0,$$

where $c_a = c \cdot \frac{1+\chi}{2}$ — constant of jet with variable density; $c$ — constant for turbulent flooded jets $c \approx 0{,}27$;

$$\chi = \frac{\upsilon_a}{\upsilon_n};$$

$z_1^0$ — relative length of the jet; $I_1$, $I_2$, $I_3$ — solution integrals using universal G. Schlichting profiles.

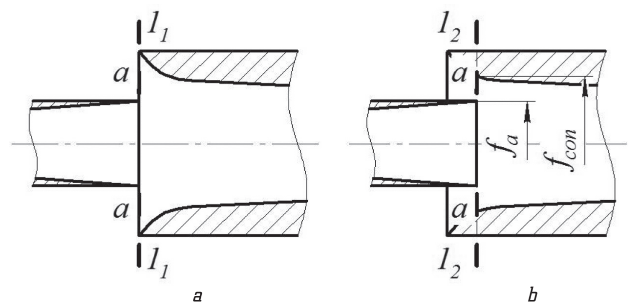


**Fig. 2.** Limiting modes of LVE injection: *a* — $p_a = p_{02}$, $\alpha_w = 0$, $\upsilon_n = \upsilon_{02}$; *b* — $p_a = p_n < p_{02}$, $\alpha_w = 1$, $\upsilon_n > \upsilon_{02}$; *a-a* — outlet nozzle section of active flow; $1_1$-$1_1$ — inlet section (first limiting mode), $1_2$-$1_2$ — inlet section (second limiting mode)

The second limiting mode occurs when shifting nozzle of active flow into the mixing chamber, then inlet section of the nozzle (*a-a*) coincides with the intersection ($1_2$-$1_2$) (Fig. 2, *b*) and characterized by velocity equality of active flow in the outlet section of the nozzle and passive flow at the inlet of the mixing chamber. In this mixing mode, mass accession of passive flow carried by leakage through the annular nozzle which area is ($f_{\text{con}} - f_a$) due to the pressure difference ($p_{02} - p_a$).

Injection equation for this case is:

$$u = \left(f_{\text{con}} - 1\right) \cdot \left(\frac{\upsilon_a}{\upsilon_n}\right).$$

Cylindrical section in the conical mixing chamber that is placed after contracting section (Fig. 1) is designed to equalize pressure fluctuations. Type of the mixing chamber and its geometry depends not only on the parameters of active and passive inlet flows, but also on the necessary parameters of the mixed outlet flow.

The relative area of the mixing chamber at inlet $f_{\text{con}}$ and outlet $f_3$ is defined by integration for sections (1) and (3) (Fig. 1):

$$f_{\text{con}} = \frac{\frac{10^{-5} \cdot w_a^2}{\upsilon_a \cdot P_2} + \frac{P_a - P_{02}}{P_2} - f_3 \cdot \left(1 + \frac{M_3^2 \cdot k_3}{\varphi_3 \cdot \beta_3}\right) \cdot \frac{P_3}{P_2} + f_3 \cdot \frac{1}{2} \cdot \left(1 + \left(\frac{P_3}{P_2}\right)^{1-n}\right)}{\frac{1}{2} \cdot \left(1 + \left(\frac{P_3}{P_2}\right)^{1-n}\right) - \frac{P_{02}}{P_2}}, \quad (1)$$

$$f_3 = \frac{\left(1+u\right) \cdot w_a \cdot w_3}{10^5 \cdot M_3^2 \cdot k_3 \cdot P_3 \cdot \upsilon_a}.$$

Components in the formula (1) can be grouped into separate systems for convenience of calculations:

$$A_{\text{con}} = \frac{10^{-5} \cdot w_a^2}{\upsilon_a \cdot P_2} + \frac{P_a - P_{02}}{P_2}, \quad (2)$$

$$B_{\text{con}} = f_3 \cdot \left(1 + \frac{M_3^2 \cdot k_3}{\varphi_3 \cdot \beta_3}\right) \cdot \frac{P_3}{P_2}, \; C_{\text{con}} = \frac{1}{2} \cdot \left(1 + \left(\frac{P_3}{P_2}\right)^{1-n}\right). \quad (3)$$

Then equation (1) taking into account simplifications (2) and (3) is:

$$f_{con} = \frac{A_{con} - {}_{con} + f_3 \cdot C_{con}}{C_{con} - \dfrac{P_{02}}{P_2}}.$$

Moreover, if the first limiting flow regime ($P_a = P_{02}$) is realized in the mixing chamber, the formula (2) can be written as:

$$A_{con} = \frac{10^{-5} \cdot w_a^2}{\upsilon_a \cdot P_2}.$$

## 6. Results of experimental research

Use of the conical mixing chamber with following cylindrical section rather than cylindrical, can not only get a high vacuum of working environment for passive flow at the inlet, but also improve the parameters of mixed flow in the outlet section of LVE. Thus, in the conical chamber flow slows down due to the contraction, and therefore increases the process of mixing the two working fluids of active and passive flows. As a result, for the same overall size of the camera, it is possible to achieve more equilibrium parameters of the mixed phases and in the LVE outlet flow is more uniform fine-structure at the LVE inlet.

The authors were experimentally investigated conical mixing chamber with different contraction angles 2÷8°. Comparing the results of experimental studies of conical and cylindrical mixing chamber, we can conclude that the first and main advantage of conical chamber is greater vacuum level that can reach with the same initial parameters of the working fluid of active flow (Fig. 3). It should be noted that in the following figures (Fig. 3–6) experimental results are marked as points and the estimated value as lines

Further experimental studies of LVE with conical mixing chamber conducted to determine the effectiveness of their use and detection of stable operating range. Thus, in Fig. 4, experimental dependence of achievable performance for conical mixing chamber with different contraction angles are shown.

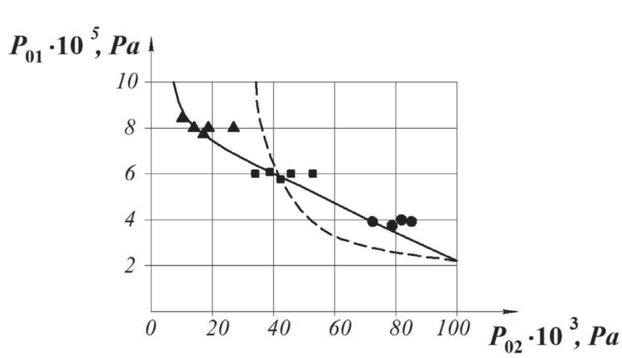


**Fig. 3.** Experimental dependence of the vacuum in the inlet section of the conical mixing chamber $P_{02}$ on the initial parameters of the working environment of active flow: ——— — conical mixing chamber; - - - - — cylindrical mixing chamber; ● — $P_{01}$ = 4 bar; ■ — $P_{01}$ = 6 bar; ▲ — $P_{01}$ = 8 bar

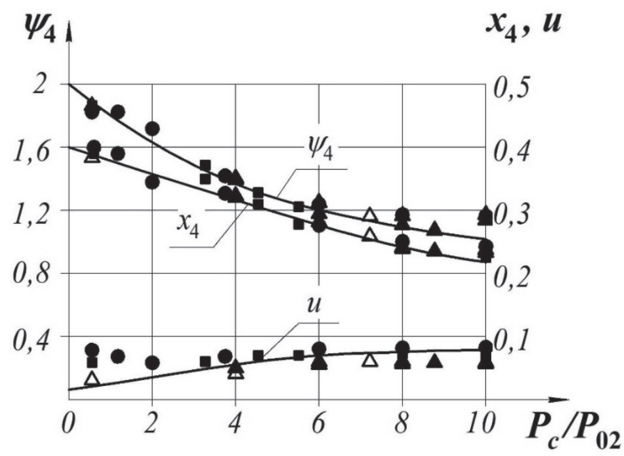


**Fig. 4.** Experimental dependence of vapor content $x_4$, vapor overproduction degree $\psi_4$ and injection coefficient $u$ *on* degree of pressure increase for passive flow in conical mixing chamber ($P_{01}$ = 4÷8 bar; $t_{01}$ = 120÷160 °C; $P_4$ = 1 bar): ● — 2°, ■ — 4°, △ — 6°, ▲ — 8°

Fig. 4 shows that the most effective use of the mixing chamber with contraction angles 4÷8°, as in a range of $P_c/P_{02}$ = 4÷9 they have satisfactory exergy indicators such as the vapor overproduction degree $\psi_4$ at 1,02÷1,03, vapor content $x_4$ almost within 0,25÷0,35 and injection coefficient $u$ = 0,06÷0,08.

The use of conical mixing chamber with contraction angles >10° is impractical, since already in experimental research of chambers with 8° contraction angle condensation jumps in section 1-1 were observed and there was a shift in modes in which there was «choking» of mixing chamber with the emergence of return currents along the LVE length (Fig. 4).

For these same reasons an increase of the initial parameters of working fluid of active flow is necessary with an increase of contraction angle as the value of the basic geometrical parameter $f_3$ decreases and less pressure ratio $P_c/P_{02}$ is created in the inlet section of the mixing chamber as shown in Fig. 4.

An important role in the design of conical mixing chamber has length of following cylindrical section. The need for its existence is the fact that for formation of a mixed two-phase flow it is not enough single contracting section in which there is only disintegration of drop structures of working fluid of active flow and mixing it with the working environment of passive flow. To obtain the necessary flow parameters at the outlet of the mixing chamber and prevent the emergence of regimes that cause «choking» it is necessary to properly determine the length of the cylindrical section.

It was experimentally investigated the conical mixing chamber with the cylindrical section having a length $(4\div6)d_3$ and without it (Fig. 5).

When using a conical mixing chamber without following cylindrical section, two-phase flow with heterogeneous structure is at the outlet. This flow hasn't permanent parameters ($p_3, T_3$). When using a conical mixing chamber with following cylindrical section having a length over $(8\div10)d_3$, it is increasingly apparent reverse flow, giving rise to the «choking» of the chamber. Investigation of conical mixing chamber with the cylindrical section having a length $(4\div6)d_3$ is shown that their use can effectively carry out the mixing process of working fluids of active and passive flows in the LVE.

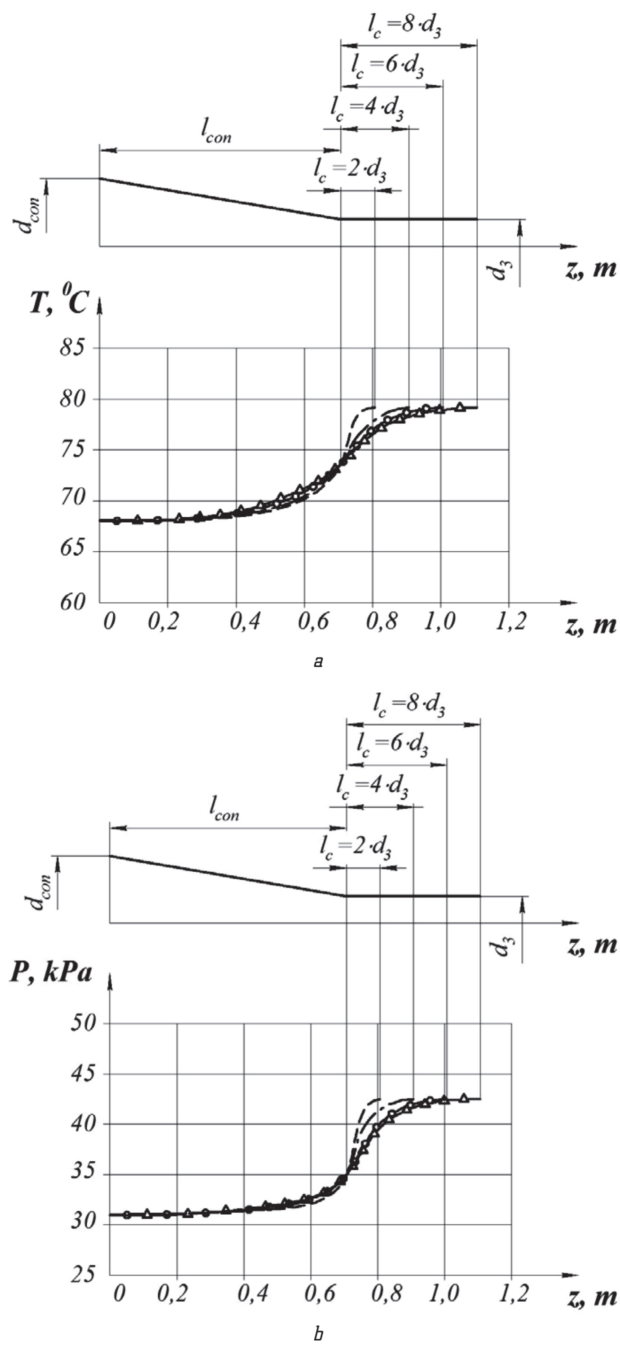


**Fig. 5.** The results of the experimental investigation of conical mixing chambers with following cylindrical sections of different lengths ($P_{01}$ = 4 ÷ 8 bar; $t_{01}$ = 120 ÷ 160 °C; $P_4$ = 1 bar): ---- $l_c = 2d_3$; -·-·- $l_c = 4d_3$; -○-○-○- $l_c = 6d_3$; -△-△-△- $l_c = 8d_3$: *a* — temperature distribution along the length of the chamber; *b* — pressure distribution along the length of the chamber

Comparing the conical mixing chamber with cylindrical, it can conclude that the conical chambers have a number of advantages that are crucial when choosing a LVE design. This, above all, greater vacuum level depth at the same initial parameters of the working fluid of active flow, the range of stable operation while maintaining performance at a sufficient level and more effective process of mixing two media of active and passive flows with the required parameters at the LVE outlet.

Exergic LVE efficiency and vacuum unit on its base is determined by such indicators as the vapor overproduction degree $\psi_4$, injection coefficient и and exergic efficiency $\eta_e$ of LVE and vacuum unit as a whole. The data is determined by the results of direct measurements and the results of data processing.

For the LVE-based vacuum unit as exergy of product flow, as well as for LVE the difference of exergy of saturated vapor at the outlet of the separator and passive exergy of passive flow at the inlet in LVE. Exergy of fuel flow is the sum of the power consumption of the circulating pump and exergy of heat carrier flow in the heat exchanger-heater [11].

As a result of exergic analysis, the values of achievable performance indicators were obtained. They are shown in Fig. 6.

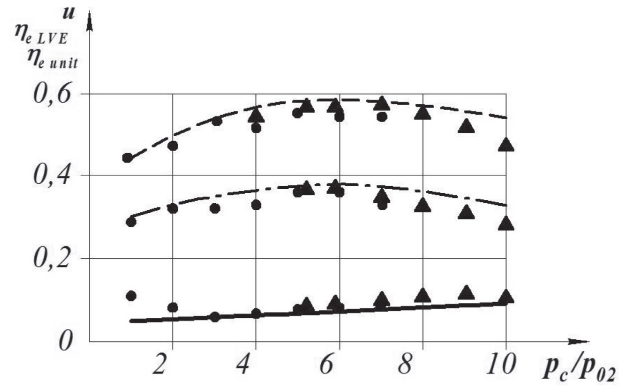


**Fig. 6.** Dependence of achievable LVE performance on degree of pressure increase for passive stream ($P_{01}$ = 8 bar; $P_a = P_{02}$ = 0,5 bar): ——— — injection coefficient; - - - - — LVE efficiency; -·-·- — vacuum unit efficiency; experimental data: ● — LVE with cylindrical mixing chamber; ▲ — LVE with conical mixing chamber

Fig. 6 shows that the LVE with conical mixing chamber can achieve a deeper vacuum level at the inlet in the receiving chamber, and they have the best performance, compared with LVE with conical mixing chamber at the same modes.

## 7. SWOT-analysis of research results

Analysis of the current state of the issue showed that the use of LVE with conical mixing chamber, workflow of which is based on the JTC principle, allows obtaining high energy efficiency at the level of 20–35 %.

The use of LVE with conical mixing chamber in existing vacuum systems requires their modernization, and sometimes complete capital restructuring.

On the basis of the LVE with conical chamber it may implement a completely new cycle of energy conversion, the advantages of which include facilitating the design of vacuum system by eliminating condensation devices after ejector and use a wide range of heat carriers.

The use of simmering underheated to saturation liquid as a working environment of the active flow in LVE is a fundamentally new method because it has no direct analogues and can only be compared with existing vapor-jet ejectors that are outdated and ineffective.

## 8. Conclusions

As a result of research:

1. It is experimentally investigated LVE with conical mixing chamber at different initial parameters of working

fluid of active flow ($P_{01}$ = 4÷10 bar; $t_{01}$ = 120÷170 °C), where it can be concluded that the maximum LVE efficiency is observed at the initial relative underheating $(1-\varepsilon_{s0})$ = 0,2÷0,4.

2. Experimental investigation of LVE with conical mixing chamber having different contraction angles showed that the mixing process working environments of active and passive flows is the maximal when the values of contraction angle are $\alpha_{con}$ = 4÷8°. When using cylindrical mixing chambers it may create the vacuum of working environment of passive flow at $P_4/P_{02}$ = 4÷6, while increasing contraction ($\alpha_к$ > 10°), the appearance of reverse currents and subsequent «choking» of mixing chamber are observed.

3. It is experimentally investigated LVE with conical mixing chambers with following cylindrical section of different lengths, which showed the effectiveness of use the mixing chambers with the length of the cylindrical section $(4\div6)d_3$.

4. As a result of experimental investigation of LVE vacuum unit workflow dependence of achievable performance indicators (vapor content $x_4$, vapor overproduction $\psi_4$ and injection coefficient $u$) on vacuum level $P_4/P_{02}$ is received. It is shown that the highest LVE performance is observed for pressure in the range $P_4/P_{02}$ = = 4÷9 for conical mixing chamber.


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## ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ЖИДКОСТНО-ПАРОВОГО ЭЖЕКТОРА С КОНИЧЕСКОЙ КАМЕРОЙ СМЕШЕНИЯ


В статье приведена модель расчета геометрических и энергетических параметров конической камеры смешения жидкостно-парового эжектора. Представлены результаты экспериментального исследования плоскопараллельного жидкостно-парового эжектора с камерой смешения конической формы и проведен их сравнительный анализ с теоретическими данными. Выполнен анализ эксергетической эффективности применения эжектора с конической камерой смешения.



**Ключевые слова:** жидкостно-паровой эжектор, коническая камера смешения, экспериментальное исследование, эксергетичекая эффективность.



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