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Application of jet thermal compression for increasing the efficiency of vacuum systems

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Abstract. The article describes the principle of jet thermal compression with reference to vacuum systems. We consider liquid-vapor ejectors, the working process of which is based on this principle, as an alternative to existing steam jet ejectors. The results of a theoretical and experimental investigations of the liquid-vapor ejector of a vacuum unit are presented. With the help of thermodynamic analysis of exergetic efficiency, the range of operation of the liquid-vapor ejector and the vacuum unit on its base is determined, at which its performance is at the maximum level. The efficiency of vacuum creation by such units is estimated by the example of various pumped media, such as saturated, superheated steam and steam-air mixture.

1. Introduction

Due to the high rates of development of modern industry, technological the vacuum processes are becoming increasingly widespread, which makes it possible to improve the quality of final products significantly, obtained by reducing the content of harmful impurities as a result of protecting technological systems from interaction with the atmosphere and increasing the degree of completeness of processes and opens up broad prospects for the development of new, more technological processes, unrealizable in the conditions of an atmospheric pressure.

One of such methods is the using of jet devices in which the creation of vacuum occurs due to the active energy propulsion jet stream. Such apparatuses include aggregates that comprise steam jet ejectors which, as a rule, are multistage at the relation of pressure 10-20 and their total efficiency is 2-10% [1].

This low efficiency of existing vacuum systems based on steam-jet ejectors leads to the need to develop new, more sophisticated devices. These liquid vapor ejectors are operating on the principle of the jet thermal compression, in which the injection of the passive flow is carried out by a working steam jet, which is formed by the boiling of liquid supplied into the active nozzle [2]. When implementing such active flow expansion cycle of the working stream occurs on the left of the lower boundary curve. In this case, the emergence of limiting critical flow regimes at the entrance to the mixing chamber, which significantly reduces the efficiency of steam jet ejectors, is virtually eliminated.

2. Principle of jet thermal compression and working process of liquid-vapor ejector

Vacuum units based on steam jet ejectors (Figure 1), used in a modern industry, have a number of disadvantages, the main one of which are the "impact" losses that occur when supercritical active and subcritical passive flows are mixed. The low efficiency of such devices is also a consequence of the fact that it is possible to increase the pressure in one steam-jet stage by no more than 2-3 times under the condition of a high level of energy conversion.

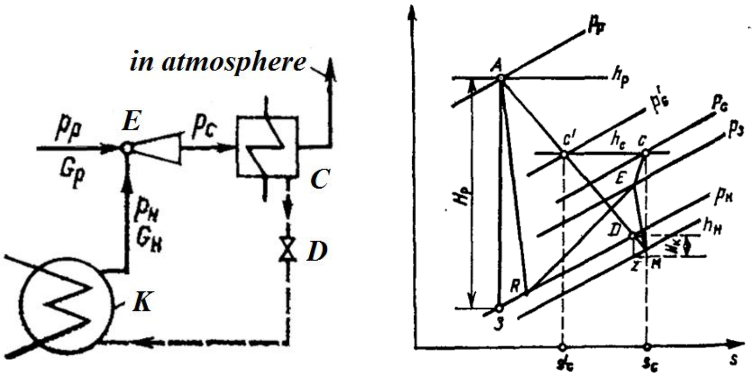

Figure 1. Scheme (left) and cycle (right) in h,s-coordinates of the classical unit based on the steam jet ejector: E – steam jet ejector, C – cooler, K – condenser, D – drainage condensate from the refrigerator.

In consequence of this situation, the using of a liquid-vapor ejector operates on the principle of jet thermal compression, which is that at the inlet to the nozzle of the active flow, the working flow is in a state of metastable superheated liquid becomes very topical. Passage of the processing medium of the active flow through the Laval nozzle is accompanied by a process of relaxation vaporization in the expanding part of it. The flow of the working medium of the active stream through the Laval nozzle corresponds to process 1_a-2_a (Figure 2).

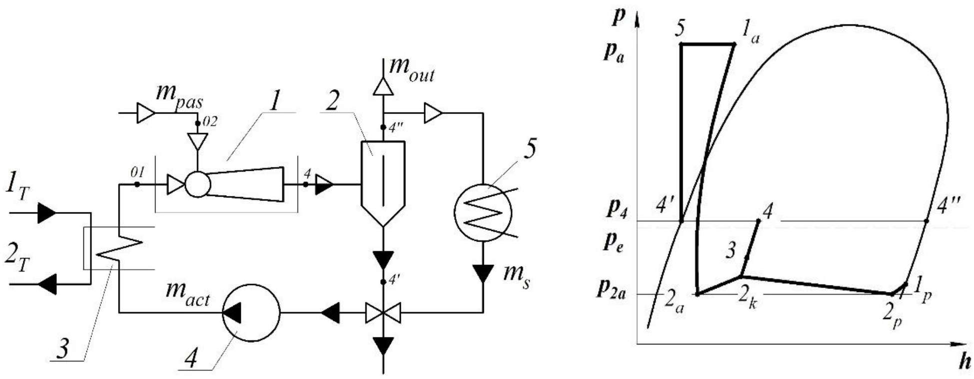

Figure 2. Scheme of vacuum unit based on liquid-steam ejector (left) and the representation of its workflow in p, h-coordinates (right): 1 – liquid-vapor ejector, 2 – separator, 3 – heat exchanger, 4 – circulating pump, 5 – condenser.

A supersonic jet of a finely dispersed vapor-drop structure with a high volumetric vapor content, that pressure is less than the pressure of the surrounding medium ($p_a < p_o$), is formed in the exit section of the nozzle of the active stream of the liquid-vapor ejector. Further, it injects the working medium of the passive stream, that enters the receiving chamber with the pressure p_{02}. At the entrance to the mixing chamber, the pressure of the active and passive stream media is equalized (processes 2_a-2_k and 2_n-2_k, respectively). In the mixing chamber, the working media of the active and passive streams are mixed into one with the reaching of the pressure p_3 (process 2_k-3). In the diffuser there is a subsequent compression of the mixed flow and a pressure p4 equal to the pressure at the exit from the ejector (process 3-4).

Produced in the liquid-steam ejector 1, a vapor is separated in the separator 2 from that the saturated liquid is taken by the pump 4 into the circulation circuit and after heating in the heat exchanger 3 is fed into the active nozzle of the ejector (Figure 2).

The mathematical model of the working process of the liquid-vapor ejector, operated in the evacuation mode, is numerically described as a system of equations for one-dimensional adiabatic motion in the quasi-equilibrium thermodynamic approximation for the distinguished boundaries of the current section of the flow:

- equation of state of a thermally metastable vapor-drop environment

$$\upsilon = \upsilon_{liq}\left(t_{liq}\right) + x \cdot \left[\upsilon_{vap}\left(p\right) - \upsilon_{liq}\left(t_{liq}\right)\right]$$

$$d\left[\frac{w(z)\cdot F(z)}{\upsilon}\right] = 0$$

- equation of conservation of mass (with allowance for the phase transition)

$$dx = \chi(z)\cdot\left[\frac{\upsilon}{w(z)}\right]dz$$

- equation of total enthalpy (I law of thermodynamics)

$$d\left[h_{liq}\left(t_{liq}\right) + x\left(h_{vap}\left(p\right) - h_{liq}\left(t_{liq}\right)\right) + \frac{w^2(z)}{2}\right] = 0$$

- momentum equation (pulse)

$$d\left[\frac{w^2(z)\cdot F(z)}{\upsilon}\right] = -F(z)dp - \tau_w \cdot \Pi(z)dz$$

- equation of the entropy production (II law of thermodynamics)

$$d\left\{s_{liq}\left(t_{liq}\right) + x\left[s_{vap}\left(p\right) - s_{liq}\left(t_{liq}\right)\right]\right\} = \delta s_{diss} > 0$$

and is also supplemented by the kinetic functions of vaporization, the characteristics of crushing and polydisperse distribution of the liquid phase, and critical regimes [3].

3. The theoretical analysis of experimental investigations

The purpose of the experimental studies was to determine the range of the initial parameters of the working fluid of the active stream, under that the maximum efflux efficiency of the boiling, underheated liquid saturation of the active flow from the expanding channels is observed. Such a range is observed at the values of the relative initial underheating ($1 - \varepsilon_{s0}$) at the level of 0,2-0,4 (Figure 3).

The relative initial underheating is the determining factor in the efficiency of the efflux of the working jet from the expanding channels and is determined by the formula:

$$\left(1 - \varepsilon_{s0}\right) = \frac{P_0 - P_{s0}}{P_0} = 1 - \frac{P_{s0}}{P_0}$$

where P_{s0} is the saturation pressure at temperature t_0.

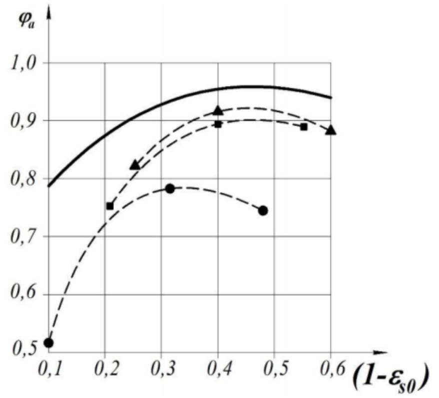

Figure 3. The experimental dependence of the speed coefficient of the active flow nozzle from the value of the relative initial underheating of the working fluid (P_{01} = 3÷10 *bar*, t_{01} = 130÷175^0*C*, P_a = 0,5÷1,0 *bar*).

The character of the process of mixing active and passive streams was studied in mixing chambers of different geometric shapes [4-5]. They were cylindrical and conical with a subsequent cylindrical section. The angle of convergence of conical mixing chambers was within 5-12^0.

On the basis of an experimental study of a liquid-vapor ejector with mixing chambers of various geometric shapes, the dependence of achievable efficiency indicators (vapor content x_4, overproduction of vapor ψ_4 and injection coefficient u) on the depth of the vacuum P_c/P_{02} created by it (Figure 4).

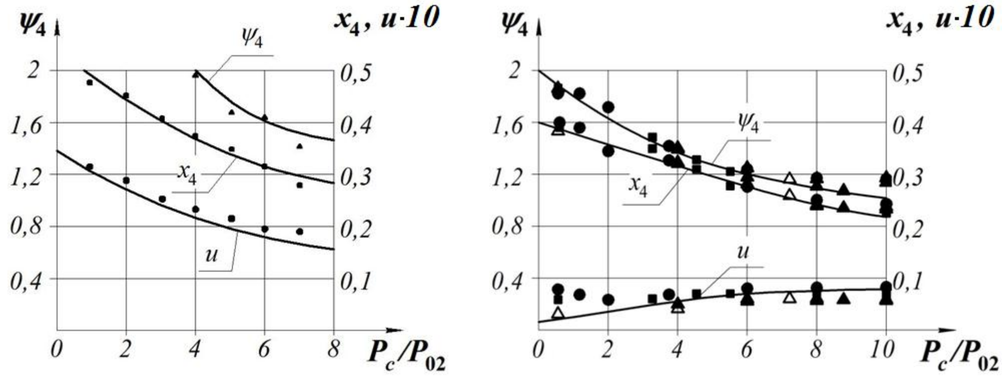

Figure 4. Experimental dependence of vapor content x_4, overproduction of vapor ψ_4 and injection coefficient u from the degree of increase in the pressure of the passive flow in cylindrical chamber (left): ● – P_{01} = 4 *bar*, ■ – P_{01} = 6 *bar*,▲ – P_{01} = 8 *bar*, in conical chamber (right) with different convergent angles: - - - - 2^0, - · - · - 4^0, -□-□-□- 6^0, -△-△-△- 8^0.

The range of effective operation of the liquid-vapor ejector with a cylindrical mixing chamber, and the initial parameters of the working fluid of the active stream specified above, is in the interval P_c/P_{02} = 4-6.

The transition from the cylindrical mixing chambers into conical chambers with the subsequent cylindrical section allows to achieve more significant depth of the vacuum. Using it in a liquid-vapor ejector, that working process is based on the principle of jet thermal compression, based on the mixing of two subcritical flows, it is possible to avoid limiting operation modes of the ejector and "locking" the mixing chamber. Having investigated the conical mixing chambers with different confusion angles, it can be concluded that the mixing process is most effective in chambers with confusion angles of 4-8^0 in the range of working fluid pressures P_{02} = 4-9 bar.

4. Vacuum systems of exergetic efficiency

For an assessment of power efficiency of the vacuum unit on the basis of liquid-vapor ejector, it is most correct to involve the exergy method of thermodynamic analysis, the main provisions of that are presented in [6-8]. The use of this method makes it possible to express and rank different energy flows unequivocally in thermomechanical systems.

Exergetic efficiency is defined as the ratio of the exergy of the product flow E_P to the exergy of the fuel stream E_F of the system:

$$\varepsilon_{ex} = \frac{E_P}{E_F}$$

For the liquid-vapor ejector, as a product exergy, the difference between the exergy of the saturated vapor at the outlet from the separator and the exergy of the passive stream at the inlet to the liquid-vapor ejector is considered. As an exergy of the fuel flow, the difference between the exergy of the active stream at the inlet to the liquid-vapor ejector and the exergy of the liquid at the outlet from the separator is considered.

For the vacuum unit (Figure 2), as the exergy of the product flow, as well as for the liquid-vapor ejector, the difference between the exergy of the saturated vapor at the outlet from the separator and the exergy of the passive flow at the inlet to the liquid-vapor ejector is considered. The fuel flow exergy is the sum of the power consumption of the circulation pump and the exergy of the coolant flow in the heat exchanger-preheater.

As a result of exergetic analysis, theoretical and experimental values of achievable performance indicators was received (Figure 5).

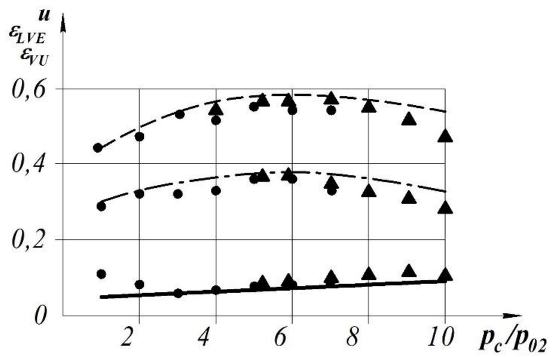

Figure 5. Dependence of achievable performance indicators of liquid-vapor ejector from the degree of increase in the pressure of the passive flow (P_{01} = 8 bar, P_a = P_{02} = 0,5 bar): results of theoretical investigations: —— – injection coefficient, - - - - – exergetic efficiency of liquid-vapor ejector, - · - · - – exergetic efficiency of vacuum unit, experimental data: ● – liquid-vapor ejector with cylindrical mixing chamber, ▲ – liquid-vapor ejector with conical mixing chamber.

To estimate the efficiency of using a liquid-steam ejector in vacuum systems, the predicted efficiency of vacuum installations based on it is numerically calculated [9-10]. The considered schemes differ in pumped out media - saturated and superheated water vapor and steam-air mixture. Analyzing the obtained results of comparison of the basic schemes and the proposed scheme on the basis of a liquid-vapor ejector operating on the principle of jet thermal compression, it can be concluded that the introduction is expedient, since it allows reducing the consumption of boiler steam used in the basic version for active Flow steam jet ejector, reduce the initial parameters of the working medium of the active flow and increase the efficiency by 1,5-3 times.

5. Conclusions

Comparing the working processes of the classical steam jet ejector and liquid-vapor ejector operating on the principle of jet thermal compression, it can be asserted that the liquid-steam ejector has a more efficient workflow, which makes it possible to convert the working jet energy of the active flow with less cost and more efficiency.

Analyzing the results of numerical studies of FPE and evaluating its effectiveness, it can be concluded that it is expedient to use FET to create a vacuum in a wide range of passive flow pressures and injecting various media with a sufficiently high degree of perfection of the working process for jet devices.

In the experimental investigation of the active stream nozzle in the range of the initial parameters of the working fluid of the active flow P_{01} = 3÷10 bar, t_{01} = 130÷175^{0}C, $(1 - \varepsilon_{s0})$ = 0,2-0,4, the character of the change in the working fluid parameters of the active flow was confirmed. Its expiration from the expanding channels into the pressure region below the atmospheric pressure (P_{02} = 0,45-0,85 bar), with the possibility of achieving maximum efficiency (φ_a = 0,768-0,917). The character of the effect of structural and regime parameters on the level of vacuum achieved in mixing chambers of various geometric shapes has been experimentally investigated and the possibility of achieving maximum efficiency indicators by optimizing the flow part ($\alpha_к$ = 4-8^0, P_4/P_{02} = 2-3,5 – for cylindrical mixing chamber, P_4/P_{02} = 3-5 – for conical mixing chamber). By correlating the mathematical model as a result of experimental research and introducing the appropriate coefficients, a range of parameters for the active and passive flow media (P_4/P_{02} = 4-9) is established, ensuring maximum efficiency of the liquid-vapor ejector (u = 0,03-0,1, ε_{LVE} = 0,45-0,55, ε_{VU} = 0,3-0,38).

Based on the results of the exergy analysis of vacuum installations based on liquid-steam ejectors that eject saturated, superheated water vapor and steam-air mixture and their comparisons with existing installations based on steam jet ejectors with the determination of efficiency indicators for the introduction of new technology, an increase in their efficiency of 1.5-3 times.

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