Influence of the Passive Flow Initial Parameters on the Efficiency of Liquid-Vapor Ejectors

Serhii Sharapov(✉), Vyacheslav Arsenyev, Maxim Prokopov, and Viktor Kozin

Sumy State University, 2 Rymskogo-Korsakova Street, Sumy 40007, Ukraine
s.sharapov@kttf.sumdu.edu.ua

Abstract. The article deals with the issue of creating a vacuum in various industries and equipment using two-phase jet devices, namely liquid-vapor ejectors working on principle of stream thermal compression. The principle of stream thermal compression implies boiling of the working fluid in the expanding part of the active flow nozzle. The influence of the initial parameters of the passive flow on the efficiency of the mixing process is based on extensive literature analysis of the works of modern domestic and foreign authors. The character of the influence of temperature, relative humidity and the content of the passive flow at the entrance to the receiving chamber on the geometric and regime parameters of the mixing chamber is established. The results of numerical and experimental investigations of the influence of the passive flow initial parameters on the efficiency of liquid-vapor ejectors are presented. Exergetic analysis of the efficiency of these devices with various passive flow environments is performed.

Keywords: Liquid-vapor ejector (LVE) · Two-phase jet device
Active flow · Passive flow · Receiving chamber · Mixing chamber
Exergetic efficiency

1 Introduction

Now more and more technological processes, using vacuum, are becoming increasingly widespread. The efficiency of using liquid-vapor ejectors for such purposes, which working process is based on the principle of jet thermal compression, has been numerically modeled and experimentally confirmed in the scientific works [1–3].

The efficiency of mixing the active and passive flows in the mixing camera directly depends on the initial parameters of the passive flow. Thus, when water vapor is used as a passive flow that on an entrance to the reception chamber can be in a saturated or superheated state as a result of process of mixing we will receive a two-phase stream of uniform homogeneous structure. In the case where the passive flow is air or an air-vapor mixture, during the mixing process, the injected pure air or a part of it from the air-vapor mixture takes away a part of the moisture from the active flow, that is necessary to pass into the state of moist air. This increases the time required for the

V. Ivanov et al. (Eds.): DSMIE 2018, LNME, pp. 346–355, 2019.
https://doi.org/10.1007/978-3-319-93587-4_36

process of mixing and, accordingly, entails a change in the geometric and regime parameters of the mixing chamber and LVE in general.

2 Literature Review

The scientific work [4] describes the influence of the geometric dimensions of the mixing chamber on the degree of completeness of exchange processes between the active and passive flows. In an experimental study of a water-air jet device on a transparent model, it is noted that in the vast majority of operating modes, not all trapped air is constricted in the flowing part of this device and is discharged into the injection pipe. Some of the working fluid of the passive flow returns to the receiving camera, forming reverse currents at the walls of the mixing camera of the device. This phenomenon is especially visualized in $p_c/p_н > 15$.

According to the results of experimental studies of two-phase jet devices, a large number of works have been published that describe the influence of the regime parameters (loss coefficients, compression indexes and temperature of the working fluid of the active flow) [5–8].

The calculation methods discussed above don’t prove the diversity of operating modes for vacuum two-phase jet devices, don’t allow us to determine the boundaries of the transition from one process of operation to another, don’t describe the dependence of the characteristics of devices from the shape, the length of the mixing camera, and a number of other parameters. These techniques are applicable, as a rule, only for the selected operating process of the device in a narrow range of its parameters.

Marchenko and Prokopov approached the study of the working process of a two-phase jet device operating in a compressor process the most fundamentally [1].

The authors of the article have improved the method of calculating by Marchenko and Prokopov that can be applied to vacuum aggregates, revealed a number of peculiarities of the vacuum regime of the operation of the liquid-vapor ejector, associated with the influence of the initial parameters of the working fluid of the active flow on the efficiency of the operation of the LVE.

3 Research Methodology

3.1 Numerical Research

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. While 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. Scheme of vacuum unit based on LVE and the representation of its workflow presented in [1].

The calculation of the mixing camera of a variable cross-sectioninduced the use of a mathematical model that is based on the equations of impulse signals and mass conservation [2, 3]. The initial parameters determining the efficiency of the mixing process are temperature, moisture content and vapor content of the passive flow at the entrance to the mixing camera.

In the general case, the expressions for the specific enthalpy h02 and entropy s02 of the passive flow at the entrance to the receiving chamber of the LVE are written as:

$$h_{02} = h'_{02} + x_n \cdot r_{02}, \tag{1}$$

$$s_{02} = s'_{02} + \frac{x_n \cdot r_{02}}{T_{02}}, \tag{2}$$

where h'_{02} – a specific enthalpy in a liquid state, J/kg, s'_{02} – a specific entropy in a liquid state, J/(kg K), x_n – a steam quality, kg/kg, r_{02} – a specific heat of a vaporization, J/kg, T_{02} – temperature, index "02" indicates the value of the parameters at the entrance to the receiving chamber.

We will consider the limited cases, when the passive flow is in the saturated vapor state (x_n = 1) and in the superheated vapor state.

In the first case, its temperature is a function of the thermodynamic parameters $t_{02} = f\left(P_{02}, h'_{02}, s'_{02}, r_{02}\right)$ and remains constant at a certain pressure.

In the second case, at the same pressure, its temperature can take any values, above the saturation temperature. Such parameters as enthalpy, entropy and specific volume are determined from tables of thermophysical properties.

The speed of the passive flow at the input to the reception department is:

$$w_\kappa = \varphi_1 \cdot \sqrt{2000 \cdot \left(h_{01} - h'_{02} - \left(s_{01} - s'_{02}\right) \cdot T_{02}\right)}, \tag{3}$$

where φ_1 – a coefficient of speed of the reception chamber, h_{01} – a specific enthalpy of the active flow at the input to the mixing chamber, J/kg, h_{01} – a specific entropy of the active flow at the input to the mixing chamber, J/(kg K).

You can see from the formula (3), the speed of the passive flow will increase as its temperature T_{02} grows. Since a subcritical mixing of the active and passive flows will proceed in the mixing chamber, the following condition will be observed:

$$M_2 = \frac{w_\kappa}{a_{2*}} < 1, \tag{4}$$

$$a_{2*} = \sqrt{10^5 \cdot k_2 \cdot P_2 \cdot \upsilon_2 \cdot \beta_2^{-1}}, \tag{5}$$

where a_{2*} – a local speed of the passive flow, m/s, k – a specific heats ratio, P – pressure, Pa, υ – a specific heat volume, m^3/kg, β – a volumetric steam quality, index "02" indicates the value of the parameters at the entrance to the mixing chamber.

Obviously, the temperature T_{02} will influence the geometric parameters of the reception chamber and the conical tapering portion of the mixing chamber. If in the reception chamber the working medium of the passive flow is in a state of superheated steam, then at the same pressure it takes a larger specific heat volume $\upsilon_{02}{}'$, accordingly, with the same mass flow of the passive flow, the relative area of the input section of the reception chamber $\bar{f}_1$ should be larger.

$$\bar{f}_1 = \frac{\upsilon'_{02} \cdot w_a}{\upsilon_a \cdot w_\kappa} \tag{6}$$

Proportionally $\bar{f}_1$, the relative area of the entrance section of the mixing chamber also increases $\bar{f}_\kappa$. At the output from the mixing chamber the flow is a homogeneous jet, so the relative area of the mixing chamber at the output $\bar{f}_3$ remains constant for all mixing cases (passive flow states at the input to the receiving chamber). Thus, the area ratio $\bar{f}_\kappa / \bar{f}_3$ will also increase as the temperature ratio T_{02}/T_2 grows.

It should also be noted that the length of the conical convergent portion of the mixing chamber increases with increasing of the relative area $\bar{f}_\kappa$ at the entrance to the mixing chamber, with constant values of the relative area $\bar{f}_3$ and the confusion angle of the conical section of the mixing chamber. This is because the passive flow rate, which is in the superheated steam state w_κ, is higher, than in the saturated vapor state, and it takes a longer time to get the total pressure $p_г$, which is set at the input of the flow into the cylindrical part of the mixing chamber.

When injecting humid air or a steam-air mixture, formulas (1) and (2) are needed to find the parameters of the working environment of the passive flow at the entrance to the reception chamber are recorded in this form:

$$h_{\mathcal{CM}} = h_{cB} + h_n, \tag{7}$$

$$\dot{m}_{\mathcal{CM}} \cdot h_{\mathcal{CM}} = \dot{m}_{c.B.} \cdot h_{c.B.} + \dot{m}_n \cdot h_n, \tag{8}$$

where $h_{см}$ – the enthalpy of the steam-air mixture at the input to the reception chamber, $h_{c.в.}$ – the enthalpy of dry air at the input to the reception chamber, h_n – the enthalpy of water vapor at the input to the reception chamber, $\dot{m}_{см}$ – the mass flow rate of steam-air mixture at the input to the reception chamber, $\dot{m}_{c.в.}$ – the mass flow rate of dry air at the input to the reception chamber, $\dot{m}_n$ – the mass flow rate of vapor at the input to the reception chamber.

A humidity φ_n of steam-air mixture is determined by the formula:

$$\varphi_n = \frac{P_s(T_d)}{P_s(T)} \cdot 100\% \tag{9}$$

where P_s – a saturated air pressure at the appropriate temperature, T_d – the temperature of dew point T – the air temperature, that is contained in the steam-air mixture at the entrance to the reception chamber.

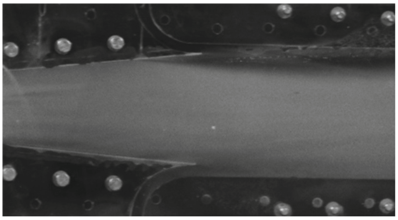
The vapor content of the working medium of the passive flow influences on the nature of the mixing process. The steam content of the steam-air mixture is determined from the ratio:

$$x_n = \frac{\dot{m}_n}{\dot{m}_{\mathcal{CM}}} \tag{10}$$

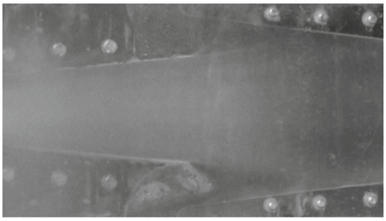
The value of the gas constant of the vapor-air mixture, that determines its thermodynamic parameters, makes it possible to say sufficiently with what properties it will possess.

3.2 Experimental Research

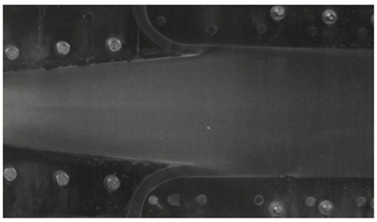
An experimental study of liquid-vapor ejector was carried out on a transparent model according to the program and test procedure, described in the work [2]. The results of the evaluation of the influence of the initial parameters of the working fluid of the passive flow on the efficiency of the mixing process obtained experimentally, confirmed the results of numerical simulation using the calculation method proposed by the authors of the article (Fig. 1).



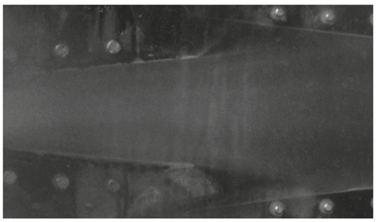
$P_{01} = 4$ *bar*, $T_{01} = 130^0C$, $P_a = 0{,}8$ *bar* (cylindrical mixing chamber (MC))



$P_{01} = 4$ *bar*, $T_{01} = 130^0C$, $P_a = 0{,}8$ *bar* (conical MC)



$P_{01} = 10$ *bar*, $T_{01} = 175^0C$, $P_a = 0{,}52$ *bar* (cylindrical MC)



$P_{01} = 10$ *bar*, $T_{01} = 175^0C$, $P_a = 0{,}45$ *bar* (conical MC)

Fig. 1. The influence of the convergence degree of the conical mixing chamber to the mode of its operation.

Figure 1 presents the results of an experiment in which cylindrical and conical mixing chambers were studied in the range of the initial parameters P_{01} = 4–10 bar, T_{01} = 130–175 °C at a pressure in the output section of the nozzle P_a = 0,45–0,8 bar. In values P_{01} < 4 bar the active flow doesn't have sufficient energy to eject the passive flow, and at pressures P_{01} > 10 bar the active flow has a very high speed, as a result of which the mixing process is completed not in the cylindrical part of the mixing chamber, but in the diffuser.

Figure 1 shows that it is possible to achieve lower pressure of the passive flow with larger initial operating fluid parameters of the active flow. For the same reasons, as the convergence angle was increased, it was required to increase the initial parameters of the working fluid of the active flow, because the basic geometric parameter was decreased f_3 and in the input section of the mixing chamber was a smaller ratio of pressures P_c/P_{02}.

4 Results

The results of numerical investigations are shown in Figs. 2, 3, 4, 5 and 6. The temperature influence of the passive flow on the nature of the mixing process is shown in Figs. 2 and 3.

In general, it can be said that the geometric dimensions of the liquid-vapor ejector, operating on the superheated vapor, are larger, than LVE, that injects saturated vapor, as evidenced by the change in the basic geometric parameter of the mixing chamber at the input $\bar{f}_к$ and at the output $\bar{f}_3$ while the temperature increasing of the working medium of the passive flow at the input to the reception chamber T_{02} (Fig. 2).

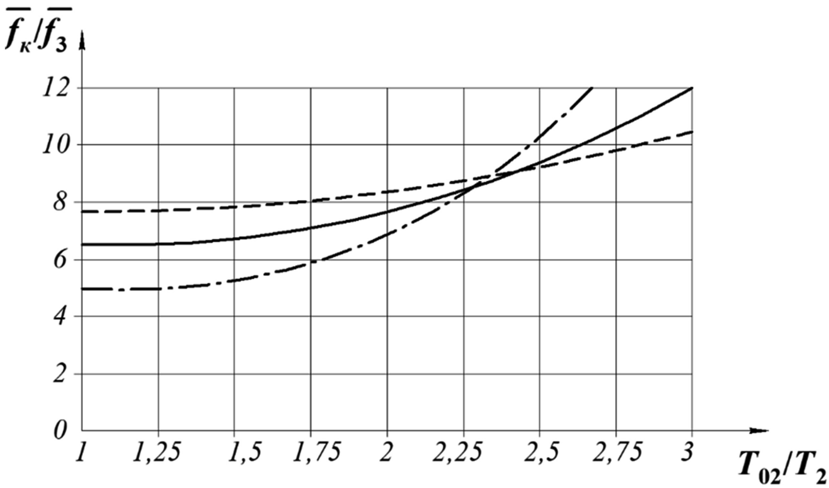


Fig. 2. Dependence of the area ratio $\bar{f}_к/\bar{f}_3$ from the temperature ratio T_{02}/T_2 when: $P_a = P_{02}$ = 0,05 bar, T_{02} = 30–100 °C; - · - · - – P_{01} = 2 bar, —— – P_{01} = 4 bar, - - - - – P_{01} = 6 bar.

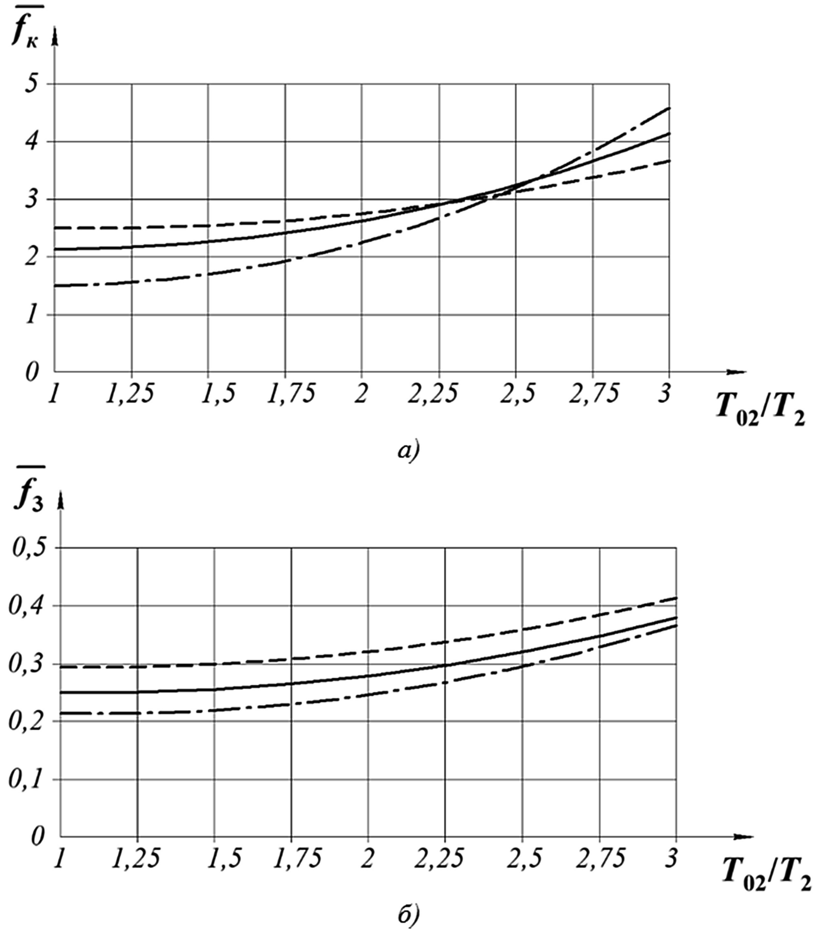


Fig. 3. The influence of the temperature ratio T_{02}/T_2 on the main geometric parameter at the input $\bar{f}_к$ (*a*) and at the output $\bar{f}_3$ (*б*) when: $P_a = P_{02} = 0{,}05$ bar, T_{02} = 30–100 °C; - · - · - – P_{01} = 2 bar, —— – P_{01} = 4 bar, - - - - – P_{01} = 6 *bar*.

Figure 4 shows that the higher degree of air dryiness, the more moisture will be taken away from the active stream, and the less overproduction of vapor will be at the exit from the ejector and the injection ratio.

Figure 5 shows how the vapor content of the passive flow affects the main geometric parameters of the mixing chamber at the input and output. When the air content in the vapor mixture increases, the basic geometric parameters of the mixing chamber of the liquid-vapor ejector rapidly increase, that leads to more rapid flow regimes and a lesser degree of completeness of metabolic processes between them, as in the case of a passive superheated flow as a working medium.

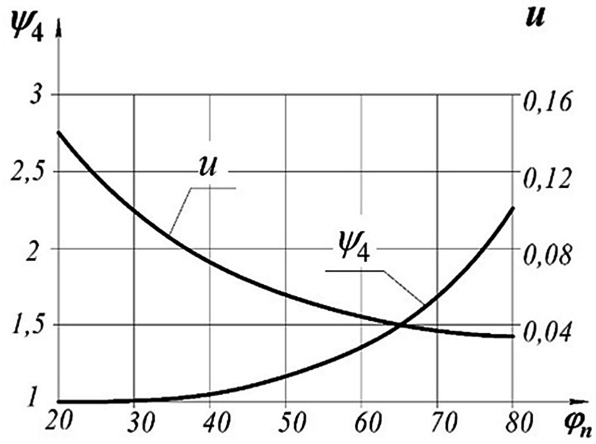


Fig. 4. Dependence of the overproduction of vapor degree ψ_4 and the injection coefficient u from the relative humidity φ_n of the passive flow ($P_a = P_{02}$ = 0,2 bar).

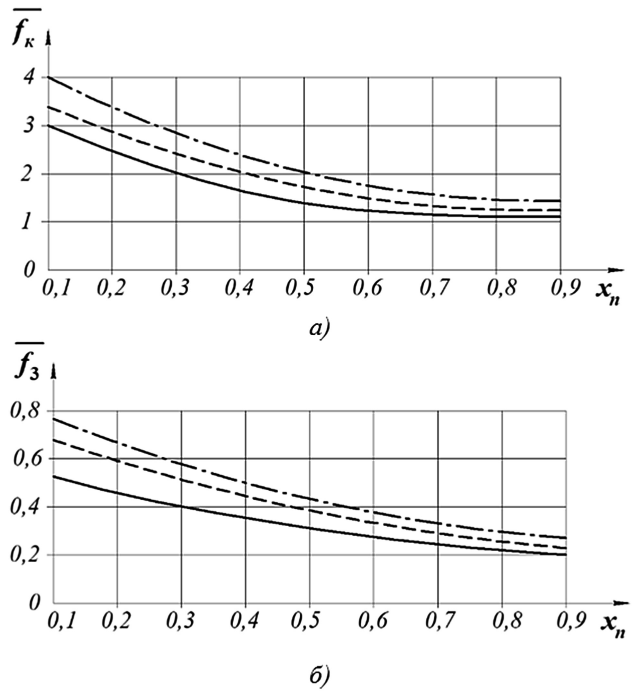


Fig. 5. The vapor content influence of the passive flow x_n on the basic geometric parameter of the mixing chamber at the input $\bar{f}_к$ (*a*) and at the output $\bar{f}_3$ (*б*) when: $P_a = P_{02}$ = 0,2 bar; - · - · - – P_{01} = 1,5 bar, —— – P_{01} = 2 bar, - - - - – P_{01} = 4 bar.

Analyzing the effect of vapor content on the geometric parameters of the mixing chamber, it can be argued that it, like the moisture content, affects the achievable parameters of the liquid-vapor ejector and the vacuum unit as a whole (Fig. 6).

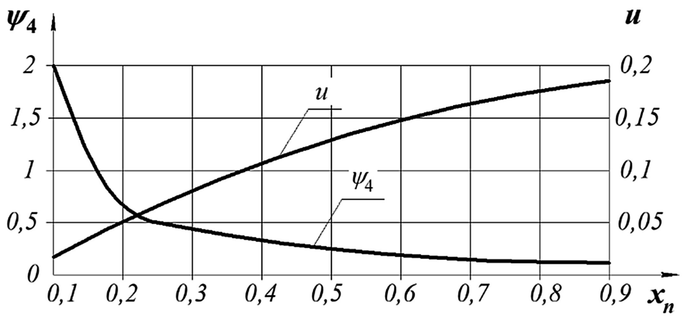


Fig. 6. The vapor content influence of the passive flow xп on the accessible effective figures of the liquid-vapor ejector.

5 Conclusions

As a result of the study, that touches on the influence of the initial parameters of the passive flow on the efficiency for the mixing process and the entire working process of the liquid-vapor ejector as a whole, the following conclusions can be drawn:

1. The temperature of the passive flow at the input to the reception chamber affects the geometric parameters of the mixing chamber. The more it is greater at the same pressure, that is, the greater the degree of superheat of vapor, the more time is required for the liquid phase of the passive flow to “vaporize” and complete the mixing process, and, therefore, the greater the geometric dimensions are near the mixing chamber.
2. The use of a passive vapor air mixture or air as working media also affects the geometry of the mixing chamber. Increasing the moisture content and vapor content of the passive flow also increases the time of the mixing process, which in turn leads to an increase in the geometric dimensions of the mixing chamber.

References

1. Marchenko, V., Osipov, V., Prokopov, M., Sharapov, S.: Principle of stream thermocompression: conception of energetic efficiency and prospect of realization is in small heat energetic. MOTROL. Motoryzacja i energetylca rolnictwa **11A**, 70–76 (2009)
2. Sharapov, S., Arsenyev, V.: Experimental study of a liquid-vapor ejector with a cylindrical mixing chamber. Refrig. Equip. Technol. **52**(2), 87–92 (2016). (in Russian)
3. Sharapov, S., Arsenyev, V., Kozin, V.: Experimental investigation of liquid-vapor ejector with conical mixing chamber. Technol. Audit Prod. Reserves **4**(1(30)), 50–55 (2016)

4. Tsegelskiy, V.: Two-phase jet apparatus. N.E. Bauman MSTU, Moscow (2003). (in Russian)
5. Shurchkova, Yu.: Adiabatic Boiling. Practical Use. Naukova dumka, Kyiv (1999). (in Russian)
6. Kudirka, A.A., Glants, D.M.: The jet pump designing for circulation systems of boiling water-moderated reactors. In: Energy Machines and Plants. Proceedings American Society of Mechanical Engineers, vol. 1, pp. 1312–1321 (1974)
7. Smolka, J., Bulinski, Z., Fic, A., Nowak, A.J., Banasiak, K., Hafner, A.: A computational model of a transcritical R744 ejector based on a homogeneous real fluid approach. Appl. Math. Model. **37**(3), 1208–1224 (2013)
8. Hemidi, A., Henry, F., Leclaire, S., Seynhaeve, J.M., Bartosiewicz, Y.: CFD analysis of a supersonic air ejector. Part I: Experimental validation of single-phase and two-phase op-eration. Appl. Therm. Eng. **29**(8), 1523–1531 (2009)