CFD Simulation of a Vortex Ejector for Use in Vacuum Applications

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Abstract. Two different types of ejectors used for pumping gas, liquid and two-phase flows, as well as for evacuation of enclosed spaces have been analyzed. The results of CFD simulation of Dubinsky’s Vortex ejector operation process are presented. The results of numerical simulation and experiment for different modes of ejector operation for passive flow and total back pressure are compared.

1. Introduction

Ejector is a device in which the total pressure of the fluid flow increases under the action of another flow having higher pressure. The transfer of energy from one flow to another occurs by turbulent mixing.

There are two different types of ejectors: Jet ejector (Fig. 1) and Vortex ejector (Fig. 2). The operation process of Jet and Vortex ejectors differs significantly. In Jet ejector, the kinetic energy of the ejecting flow (active) allows to increase the pressure of the passive gas, ensuring its movement (ejection). The use of the Jet ejector in the engineering devices allows obtaining more simple and reliable technical solutions as compared with the use of mechanical superchargers. Jet ejectors are widely used in vapor compression systems [1], refrigeration and adsorption systems [2, 3], and sometimes in vacuum processes and technologies [3].

![Figure 1. Schematic diagram of the Jet ejector: (1) – high-pressure gas nozzle; (2) – low-pressure gas nozzle; (3) – mixing chamber; (4) diffuser.](image)

![Figure 2. Schematic diagram of the Vortex ejector: (1) – swirling nozzle of high-pressure gas; (2) – low-pressure gas nozzle; (3) – mixing chamber; (4) diffuser.](image)
In the Vortex ejector, supply of active gas inside the ejector is carried out through a swirling nozzle, which leads to formation of the intensive swirling vortex flow. Centrifugal forces acting on the gas elements in the ejector lead to the formation of a radial gradient of static pressure; the minimum of the radial gradient is in the central region of the swirling flow, providing supply of the passive flow.

Regardless of the type and purpose of the ejector, it always contains the main structural elements: high-pressure gas nozzle (1) being active and ejecting, low-pressure (passive or ejected) gas nozzle (2), mixing chamber (3), and, typically, the diffuser (4). However, comparing these two types of ejectors makes it possible to define several important disadvantages of Jet ejectors. These concern large weight-size parameters and noise, and the complexity of flow separation, in particular two-phase flows.

Vortex ejectors provide the possibility of pumping out and creating a high suction, as well as partial or full implementation of separate gas-liquid flows [4-6].

Research of Vortex ejectors dated back to the late 40s of the 20th century, when the scientific team of M.G. Dubinsky proposed the first design of the Vortex ejector, which is shown in Fig. 3 [7, 8]. Studies of Dubinsky ejector have shown that when vacuuming enclosed volumes, it is possible to obtain the residual pressure of 1000 Pa [9]. Experimental studies of Dubinsky, Kolyshev, Piralishvili, Biryuk, Volov and other scientists allowed performing the optimization of the Vortex ejector geometry, and to determine the optimal performance parameters corresponding to the most efficient operation modes [4,5]. In particular, it is shown that if a pressure of the active air flow is 0.2 MPa, then the suction flow rate reaches its maximum. This mass flow rate is usually expressed in form of dimensionless parameter of the ejector called the ejection coefficient $n$. It represents the relation $n = m_p/m_a$, where $m_p$ is the mass flow rate of the passive ejected gas, and $m_a$ is the mass flow rate of the active ejecting gas. Studies show that with certain geometric parameters of the ejector, the ejection coefficient can reach a value of $n = 4$ or more [5]. Furthermore, detailed experimental studies of flow parameters of the Vortex ejector at different pressures in the passive gas nozzle and in the output section are given in paper [10].

![Figure 3. Dubinsky Vortex ejector [8,9]:](image)

(1) – swirling nozzle of ejecting (active) flow; (2) – nozzle of ejected (passive) flow; (3) – mixing chamber; (4) – scroll diffuser; (5) – slot diffuser; (6) – vortex chamber; (7) – control valve; $d_1$ – diameter of the swirling nozzle; $d_2$ – diameter of the passive nozzle; $d_4$ – outlet diameter of the diffuser; $d_{vc}$ – diameter of the vortex chamber; $d_{mc}$ – diameter of the mixing chamber; $l_2$ – length of the passive nozzle; $l_{vc}$ – length of the vortex chamber; $l_{mc}$ – length of the mixing chamber; $R_{dif}$ – radius of diffuser bending.

There are a number of publications in the literature concerning the use of Vortex ejectors in mixing [11,12] and combustion devices [13,14], dust collectors [15], cleaning of fuel injectors [16], as well as in studies of ejector’s geometry influence on its parameters [17,18,19], and numerical simulation of the
ejectors’ operation process [20,21]. Nevertheless, despite all the results obtained, the design proposed by Dubinsky remains the most effective for vacuum applications. This can be explained by the optimal flow structure formed inside the ejector. However, the problem of interrelation of flow structure in vortex ejector with integral characteristics of its operation process is far from over. One of the possible solutions is the CFD simulation of the ejector with the subsequent comparison and analysis of the results with the data of available experiments. This is exactly the purpose of the present paper.

2. Formulation of CFD simulation

The CFD simulation was carried out for Vortex ejector of following dimensions: diameter of the swirling nozzle \( d_1 = 12 \) mm, diameter of the passive nozzle \( d_2 = 4 \) mm, outlet diameter of the diffuser \( d_4 = 50 \) mm, diameter of the vortex chamber \( d_{vc} = 50 \) mm, diameter of the mixing chamber \( d_{mc} = 25 \) mm, length of the passive nozzle \( l_2 = 50 \) mm, length of the vortex chamber \( l_{vc} = 50 \) mm, length of the mixing chamber \( l_{mc} = 35 \) mm.

The calculation grid (Fig. 4) of the flow region was multiblock structured; the total number of elements was about 3 million. To calculate the gas flow, Reynolds-averaged Navier-Stokes equations were used. The turbulence was described by the SST-model.

Total temperature and total pressure at the swirling nozzle of active flow were constant for all the calculations and equal to \( T_1^* = 300 \) K and \( p_1^* = 0.42 \) MPa. Total temperature at the nozzle of passive flow was also constant and equal \( T_2^* = 300 \) K, but total pressure at this boundary \( p_2^* \) was varied from 14 to 42 kPa. Total pressure at the diffuser outlet \( p_4^* \) was varied from 21 to 168 kPa. The walls of the computational domain were considered to be adiabatic.

![Figure 4. Calculation grid.](image)

The results of calculations were summarized using the following dimensionless parameters:
- \( \sigma = p_1^*/p_2^* \) – the ratio of the total pressures of active and passive flow;
- \( n = m_p/m_a \) – ejection coefficient;
- \( \pi = p_4^*/p_2^* \) – relative total back pressure.

3. Results and discussion

Simulations were carried out for different values of \( \sigma \) and \( \pi \). Figures 5–10 show the results for \( \sigma = 10 \) and \( \pi = 0.1 \). The analysis of the results obtained shows that there are some different flow regions inside the calculation domain of ejector. In the vortex chamber, an intensely swirling flow is formed with a predominance of the circumferential velocity component. At the rear end of the mixing chamber, the part with the reduced pressure (Fig. 5) and that of axial velocity component (Fig. 9) is clearly visible. This part is shaped like a cone with a base on the rear end wall of the ejector.
Figure 5 shows that minimum total pressure ($\approx 4000$ Pa) is achieved on the axis of the ejector near nozzle of passive flow. This value defines passive mass flow which is equal to $m_A = 4.3$ kg/h for this operation mode. The flow structure and contours of axial and circumferential velocity components, shown in Fig. 9 and 10, lead to the conclusion that maximum circumferential velocity is almost constant when moving from swirling nozzle cross-section to mixing chamber.

On the other hand, axial velocity component increases as the flow moves from vortex chamber to mixing chamber and diffuser. Analysis of Mach number contours shows that there are supersonic compartments in the slot diffuser forced by super critical relative total back pressure and sudden enlargement. Axial velocity in this region has a maximum value of 415 m/s that suggests that Vortex ejector operates partially as Jet ejector.
Figures 11-13 show a comparison of the calculated data with the experimental results obtained by Epifanova et al. [10]. Experimental values for different $\sigma$ and $\pi$ are shown by dotted lines; and the dashed lines show the results of CFD simulations. It is necessary to note that there is a good correlation of the results obtained for $\pi \leq 0.15$. For $\pi > 0.15$, a qualitative correspondence is observed, characterized by a decrease in both the ejection coefficient and passive mass flow to zero. Analyzing the dependence of the active mass flow on relative total back pressure, it can be concluded that the proposed calculation approach was adequate. It is confirmed by the quantitative coincidence of numerical and experimental results.

The discrepancy between the numerical and experimental values of the ejection coefficient and passive mass flow for $\pi > 0.15$ is caused by the approach of total back pressure to the value $\geq 1$ atm. This significantly changes the structure of the flow in the Vortex ejector and leads to the restructuring of the velocity and pressure distributions. The analysis of this phenomenon requires additional studies and correction of turbulence modeling and boundary conditions.

**Figure 11.** Active mass flow depending on relative total back pressure: dotted lines - experiments [10]; dashed lines – calculations.

**Figure 12.** Passive mass flow depending on relative total back pressure: dotted lines - experiments [10]; dashed lines – calculations.

**Figure 13.** Ejection coefficient depending on relative total back pressure: dotted lines – experiments [10]; dashed lines – calculations.

4. **Conclusion**

The CFD simulation has revealed the flow structure in a Vortex ejector under the conditions of vacuum pressure at the outlet. It is shown that circumferential velocity component of swirling flow is almost constant along the length of the ejector, while axial velocity component increases as the flow moves from vortex chamber to mixing chamber and diffuser. Decrease in the absolute total pressure at the outlet during the operation of the Vortex ejector is similar to that of Jet ejector. Good correlation of the results is obtained for relative total back pressure $\pi \leq 0.15$. When $\pi > 0.15$, velocity and pressure distributions are restructured that causes the discrepancy between the experimental and calculated results that requires additional research.
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