Optimal design of vortex chamber pump

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Abstract. The difficult operating conditions during the pumping of abrasive solid mediums lead to the rapid wear of the mechanical parts of the pumps. The use of jet pumps can significantly increase the reliability and durability of pumping equipment. However, direct-flow jet pumps have low efficiency. The use of the centrifugal force led to the creation of new jet pumps - vortex chamber pumps. Their performance indicators are better than direct-flow jet pump ones. The geometric parameters of the flow channel of the vortex chamber pumps were optimized. The study was carried out experimentally and numerically. Numerical simulation is based on solving the RANS equations with the shear stress transport turbulence model. The geometrical dimensions of the vortex chamber pump with the best performance indicators such as pressure and flow are found. The maximum achievable operating parameters of the vortex chamber pump are analyzed. The comparison of simulation results with experimental data is made.

1. Introduction
In the technological processes of the coal, chemical, heat and power industries, agriculture, and transport, the pumping of various single and multiphase mediums is carried out by dynamic pumps, the efficiency of which significantly determines the production efficiency [1-3]. The extreme operating conditions characteristic of the given industries lead to rapid wear of the mechanical working bodies of the pumps [4-6]. Most existing pumps are not suitable for pumping abrasive medium. Positive displacement pumps are usually used for pumping clean medium [7-10]. Dynamic (turbo) pumps have a limited resource [1-3]. Jet pumps have low efficiency [11-15].

2. Literature Review
Jet pumps have such important advantages as high reliability and durability, simplicity of design, the ability to work on mixtures of various compositions and phase concentrations [11]. The reliability and durability of jet pumps are many times greater than the reliability and durability of pumps with mechanical moving working bodies. The main disadvantages of existing jet pumps are low efficiency, which does not exceed 30%. The achievable parameters during their operation on gas are limited by the features of supersonic flows [16, 17]. In papers [12, 16, 18, 19], new jet pumps, vortex chamber
superchargers (VCS), are shown. If the liquid is pumped, then the superchargers can be called vortex chamber pumps (VCP). If the gas is pumped, then the superchargers should be called vortex chamber ejectors (VCE). These pumps have higher efficiency. But the unresolved issues of the mutual influence of the geometric parameters of the vortex chamber pumps flow channel remained and the optimal operation parameters were not determined. In addition, these pumps due to the lack of movable operating elements, do not require seals and do not experience vibration during operation [17, 21]. All this allows us to argue that it is advisable to conduct a study on the determination of optimal geometric parameters. The paper [11] shows the implementation of two work processes in VCP. In this paper, attention will be paid to the working process of the pump with a drainage channel. This working process makes possible to realize the maximum efficiency of pumping solid bulk [19].

3. Research methodology
The study was carried out in three stages. At the first stage, the maximum achievable parameters of VCP operation are determined analytically. At the second stage, the geometric parameters of the pump were optimized using experimental investigations. In the third stage, numerical simulations were performed using the OpenFoam open-source CFD software, which allowed estimating the flow kinematics in VCP.

4. Results

4.1. Achievable performance parameters
The main parameters of VCP (Figure 1), like any other dynamic pump, are: flow rates $Q_{in}$, $Q_{out}$, $Q_{e}$, $Q_{s}$; outlet pressure $p_e$ and efficiency $\eta$.

The optimal pump operation parameters can be realized if the entire pumped over flow rate $Q_{in}$ enters the pump outlet and is equal to the flow rate $Q_e$, and the auxiliary or active flow rate $Q_s$ enters the drainage channel and is equal to the flow rate $Q_{out}$.

The maximum achievable outlet pressure can be determined by the relations for the vortex valves and diodes [22-24]:

$$p_e = p_R = p_s \cdot \frac{p_R}{p_s},$$

(1)

Where $p_R$ is the pressure at the periphery of the vortex chamber; $p_s$ is the pressure at the tangential supply channel; $p_R = p_s / p_s$.

The flow rate $Q_e$ can be found, given the $Q_e = Q_{in}$:
\[
Q_i = \mu_{in} A_{in} \left( \frac{2 \cdot \Delta p_{in}}{\rho} \right)^{0.5},
\]

where \(\mu_{in}\), \(f_{in}\) are the coefficient of discharge and the cross-sectional area of the suction channel respectively; \(\rho\) is the density of the pumped fluid; \(\Delta p_{in}\) is the pressure difference between the vacuum in the middle of the vortex chamber and the pressure of the suction medium

\[
\Delta p_{in} = \frac{\Delta p_{in}}{p_s} = \frac{p_{vac}},
\]

where \(p_{vac}\) is the relative pressure drop (vacuum coefficient).

The dependence of the vacuum coefficient on the vortex chamber geometric parameters must be known to determine the achievable values of flow rate and outlet pressure.

The pressure drop depends on the diameter of the vortex chamber. This was established in studies of vortex chambers [25, 26]. Experimental studies of the pressure distribution along the radius of the vortex chamber were performed. A pump model with a vortex mixing chamber with a diameter of 50, 100 and 200 mm was used. The diameter of the drainage channel of the pump was \(d_s = 10\) mm. The diameter of the drainage channel was constant. The relative diameter of the vortex chamber was \(\bar{D} = D/d_s = 5, 10, 20\). The results of the studies are shown in Figure 2. The vacuum coefficient increases with the increasing relative diameter of the vortex chamber. The designations given in the figure: \(H\) - the height of the vortex chamber; \(d_s\) is the diameter of the tangential supply channel.

![Image](image.jpg)

**Figure 2.** Vacuum coefficient as a function of the relative diameter of the vortex chamber.

### 4.2. Optimization of pump performance parameters

The geometrical parameters of the pump were optimized with two objective functions: outlet pressure and efficiency. Optimization was carried out on the basis of experimental design methods described in [27, 28]. In this case, a complete factorial experiment was carried out. Planning points accepted as a zero level: \(D = 10, d_s = 0.6\).

The regression model is obtained on the basis of experimental studies. The calculations showed that the obtained approximation model is adequate and can be used to determine the optimal values of the relative diameters of the vortex chamber and the supply channel.

Extremums of surfaces \(\bar{p}_r = f(\bar{D}, \bar{d}_s)\) and \(\eta = f(\bar{D}, \bar{d}_s)\) are found from the conditions:
Experimental studies of the pressure drop or vacuum coefficient were carried out to determine the dependence of the pressure at the pump outlet on the geometric parameters of the vortex chamber. The relative diameter of the supply channel was equal to: \( d_s = 0.42; 0.5; 0.67; 0.83 \). An approximation surface \( p_e = f(D, d_s) \) was plotted (Fig. 3). It is possible to achieve maximum values of the relative pressure on the walls of the vortex chamber, and accordingly, the outlet pressure \( p_e \), while maintaining a constant value of the relative diameter of the supply channel (Fig. 3) and changing the diameter of the vortex chamber. The monotonic nature of the change in relative pressure is observed at constant values of the relative diameter of the vortex chamber. With an increase \( d_s \), \( p_e \) increases.

**Figure 3.** The relative pressure on the walls of the vortex chamber as a function of the relative diameter of the vortex chamber and the relative diameter of the supply channel.

Ways to improve the pump parameters can be determined using the dependencies of the vacuum coefficient and relative pressure on the walls of the vortex chamber. The optimal parameters for the relative pressure on the walls of the vortex chamber are \( D_{opt} = 10, d_v(opt) = 0.8 \).

The efficiency is found as follows:

\[
\eta = \frac{N_{sup}}{N_{in}} = \frac{d_{in}}{d_s} \left( \frac{p_{vac}}{p_e} \right)^{0.5},
\]

where \( d_{in} = d_{in} / d_v \) is the relative diameter of the suction channel. The region of lower pressure in the vortex chamber is limited by radius \( r = 0.5r_v \) according to studies of vortex chambers [29, 30]. Then \( d_{in} = 0.5 \):

\[
\eta = \frac{d_{in}}{d_s} \left( \frac{p_{vac}}{p_e} \right)^{0.5}.
\]
Since \( \overline{p}_{\text{vac}} = f(\overline{D}) \) and \( \overline{p}_R = f(\overline{D}, \overline{d}_s) \), then \( \eta = f(\overline{D}, \overline{d}_s) \). The efficiency surface is plotted in Figure 4. The surface has an extremum (maximum) at \( \overline{d}_s = 0.5 \) and \( \overline{D} = 4.5 \) - \( \eta = 0.4 \) (the maximum achievable efficiency of VCP, taking into account the accepted assumptions).

The maximum values of efficiency are achieved with the increasing diameter of the vortex chamber. The monotonic nature of the change in efficiency depending on the relative diameter of the supply channel is observed at constant values of the relative diameter of the vortex chamber. With the increasing values of \( \overline{d}_s \), the values of \( \eta \) in the region \( \overline{D} > 10 \) increase, while in the region \( \overline{D} < 10 \), on the contrary.

Since the dependencies in Figure 3 and 4 are plotted according to the experimental and analytical dependencies for the vortex chambers of any devices, and not just VCP, they require additional experimental verification. The results of the efficiency experimental studies and relative pressure of VCP at \( \overline{D} = 5 \) are shown in Figure 5. The lines on the graph correspond to the calculated dependencies \( \overline{p}_R = f(\overline{D}, \overline{d}_s) \) and \( \overline{\eta} = \eta(\overline{D}, \overline{d}_s)/\eta_{\text{max}(d_s=0.7)} \).

The adequacy of the obtained model was verified by comparing the calculated surfaces and experimental data. It was found that the model is adequate with a confidence probability of 0.95 and confidence intervals: \( \Delta \overline{p}_R = 0.035 \) and \( \Delta \overline{\eta} = 0.0257 \).
The experimental dependencies of the energy characteristics of VCP at $\overline{D} = 5$ are presented in Figure 6. Efficiency is related to the value of the efficiency of construction $\overline{D} = 10$, $\overline{d_s} = 0.5$ the values of which were determined in previous studies before optimization of the design $\tilde{\eta} = \eta / \eta(\overline{D} = 10, \overline{d_s} = 0.5)$ [12, 19].

![Figure 6](image)

**Figure 6.** Experimental performance curves for VCP with $\overline{D} = 5$ and different related supply channel: (a) the related efficiency; (b) related outlet pressure.

The approximate efficiency dependencies and outlet pressure (Figure 6) adequately describe the dependencies of the energy characteristics on the geometric dimensions of the vortex chamber.

### 4.3. Numerical simulations of the flow in the pump

Experimental studies confirm the hypothesis of the effectiveness of VCP. The analysis of the flow and the study of the liquid behavior in VCP should be carried out using numerical simulation. It allows, with minimal time and resources [31], to determine the mechanism of energy transfer to the pumped over flow and to further optimize the VCP. The mathematical model includes the RANS equations [32], the SST turbulence model [33-35], and the continuity equation. The solution was implemented in the OpenFoam software package [36-39]. The adequacy of the obtained flow patterns was verified by visual comparison and quantitatively based on a comparison of the pressure distribution. The error of numerical simulation in comparison with experimental data did not exceed 15%. The maximum error was observed in the axial region. At the periphery, the error in determining the pressure does not exceed 2.4%. Several grid partitions were used and sensitivity analysis was performed [40]. The final grid partition consisted of 7 million elements. The calculation continued until the values of the residuals $10^{-4}$ were reached. Numerical studies were carried out for the construction with $\overline{D} = 4.5$, $\overline{d_s} = 0.75$.

Figure 7 shows that increased pressure at the periphery and reduced near the axis of the vortex chamber allow the pump to operate. The pumped over flow is sucked near the axis of the vortex chamber under the influence of a difference of the pressure and enters the tangential outlet channel of the pump. Flow fields (Figure 7b and 7c) explain the features of the characteristics. An increase in the relative diameter of the vortex chamber leads to a decrease in pressure at the periphery of the chamber since more fluid is needed to provide a workflow, which reduces efficiency. Figure 7c shows that further optimization of the conditions for the fluid inlet and outlet from the VCP is required since there are flow separations from walls.
Figure 7. Simulation results: (a) pressure contours of the pump flow field; (b) velocity contours of the pump flow field; (c) velocity contours along the radius; (d) streamlines.

5. Conclusion
The optimal geometric parameters of the vortex chamber pump were found using experimental studies. If the objective function is the outlet pressure, then the optimal dimensions are $D = 10$; $\delta_s = 0.8$. If the objective function is efficiency, then $D = 4.5$; $\delta_s = 0.5$. The adequacy of the obtained model was verified by comparing the calculated surfaces and experimental data. It was found that the model is adequate with a confidence probability of 0.95 and confidence intervals: $\Delta \bar{p}_e = 0.035$ and $\Delta \bar{\eta} = 0.0257$. Numerical simulations show that further optimization of the conditions for the fluid inlet and outlet from the VCP is required since there are flow separations from walls.

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