Influence of different volute casings theoretical methods design on pump working processes

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Abstract. The work is devoted to determining the influence of methods and recommendations for the design of a volute casing on the flow structure and the efficiency of the double-entry centrifugal pump. Volute casing designed by the constant-velocity method of the fluid according to the recommendations of A. Stepanoff, volute casing designed by the method of conservation of angular momentum of the flow, and the recommendations of C. Pfleiderer and A. Lomakin were designed and researched. The proposed designs were compared with the base volute casing. The analysis was performed based on the results of numerical simulation of the working process of the pump in the software ANSYS CFX at different flow rates. One impeller geometry and a constant volute casing outlet diameter were used to minimize the influence of other pump design factors on the working process of the volute casing. The distribution of pressure and velocity in the volute casing is analysed. Analysis of velocities and angular momentum along the volute casing showed the same deviation of the values. In general, the characteristics of the flow inside the volute casing conform indicated method. The article provides recommendations for choosing a method of designing a pump volute casing.

1. Introduction
To drain the fluid from the impeller of the pump to the outlet and the conversion of kinetic energy into static pressure using outlet casings of various designs. Volute casings are used for double-entry pumps. There are two methods of designing a volute casing. The first method is the conservation of angular momentum of the flow. The second is a constant-velocity method. In addition to designing methods, there are also recommendations from various scientists for volute casing’s parameters of width and inlet diameter, the position of the tongue, and the shape of the cross section. At the moment there are no clear recommendations in which cases which method should be used. Usually, the choice of method is based on the tradition of designing volute casings for each organization.

Many scientists analysed and compared volute casing, which are building by these methods. For example, A. Knapp et al. [1] compared the change in the structure of fluid flow at different flow rates in volute casings, constructed by the recommendation of C. Pfleiderer and A. Stepanoff. In the research numerical simulation and a physical experiment were performed. Obtained results have coincided. The volute casing designed by the A. Stepanoff recommendation has higher efficiency at the flow rates higher than the nominal ones, while the volute casing designed by the C. Pfleiderer method has the best indicators at the flow rates below the nominal ones. Similar results were obtained by H. Alemi et al. [2] when they compared volute casing designed by the same methods. O. Litfin et
al. [3] investigated three variants of volute casings, designed according to Stepanoff’s method for the same pump but for different flow rates. The authors confirmed that at a constant velocity of the fluid along the volute casing, the highest value of efficiency is observed. Increasing the rated flow leads to a decrease in the slope of the head characteristic and expands the range of efficient operation of the pump. An increase in flow rate leads to reducing the steepness of the H-curve characteristic and expanding the range of efficient operation of the pump.

A. Niven et al. [4] used the constant velocity method in designing the volute casing of the single-blade impeller pumps. According to the results of the calculations, there are slight fluctuations in the velocity of the flow within 4% for the nominal flow rate. L. Tan et al. [5] research volute of the sewage single-stage volute pump. The authors determined the optimal inlet diameter of the volute casing \( D_3 \), which corresponds to the highest values of the head. The pressure fluctuations and radial force reduce as \( D_3 \) grows. Also, the influence of the value of \( D_3 \) and the shape of the cross-sectional of the volute casing or the annular casing on the losses in the pump is considered in the article [6] A. Parygin et al. Opposite opinion had I. Krishtop et al. [7], which propose recommendations for the calculation and design volute casing of the rotodynamic pump using constant angular momentum methods.

The literature review indicates the relevance of the research on the working process of volute casing. The analysis revealed insufficient coverage of the influence of the method and the initial parameters of the design of the volute casing on its characteristics. The work is dedicated to the analysis of the flow structure in volute casings, which are designed by the method of conservation of angular momentum of the flow and by the constant-velocity method in order to find a more efficient design of volute casing for pump.

2. Volute casing design methods and recommendations

The main parameters of the volute casings are the width of the volute casing \( b_3 \), the inlet diameter of the volute casing \( D_3 \), and the volute throat area volute casing. Scientists give various recommendations for their values. The article considers the recommendations of A. Stepanoff, C. Pfleiderer, A. Lomakin and J. Gulich for design the volute casing.

2.1. Stepanoff design method

According to the recommendations of A. Stepanoff [8] the width of \( b_3 \) for pumps with low specific speed \( n_s \) is chosen by the formula:

\[
b_3 = 2 \cdot b_2,
\]

where \( b_2 \) is the outlet width of the impeller.

The value of the \( D_3 \) affects the efficiency and noise level. The author proposes to choose \( D_3 \) according to the schedule specified in [8] by the following ratio:

\[
\rho = \frac{D_3 - D_2}{D_2},
\]

where \( D_2 \) – impeller diameter.

A. Stepanoff argues that the best characteristics of the pump can be obtained by design a volute casing by the constant-velocity method in all sections of the volute casing. It means the cross sectional area should increase in proportion to the angle at which the section is located relative to the volute tongue.

The average velocity in the volute casing is proposed to be found by the formula:
\[ c_3 = K_3 \sqrt{2gH}, \]
where \( K_3 \) – the coefficient, which obtained experimentally, is chosen according to the graph [8] and depends on \( n_s \).

2.2. Pfleiderer design method
According to the recommendations of C. Pfleiderer [9] for pumps with a low value of \( n_s \) is determined by the formula:

\[ b_3 = b_2 + 1 \ldots 2 \text{ mm}. \]

The diameter \( D_3 \) is determined by the formula:

\[ D_3 = 1,033 \cdot D_2. \]

C. Pfleiderer is a supporter of the method of the conservation angular momentum of the flow. He believes that the velocity in the volute casing should decrease due to the action of centrifugal force on the flow. As a result, the average velocity in the volute casing are decreasing with increasing cross sectional area. From this reasoning, it follows that the velocities at each point of the volute casing vary according to the law of areas, ie:

\[ c_u \cdot r = K \]  \hspace{2cm} (1)

where \( c_u \) – circular component of the absolute speed at a distance \( r \) from the axis of rotation, \( K \) – angular momentum of flow velocity.

2.3. Lomakin design method
A. Lomakin [10] recommends using the following dependence for \( b_3 \):

\[ b_3 = b_2 + 0,05 \cdot D_2, \text{ мм}. \]

The choice of diameter \( D_3 \) is determined by the formula:

\[ D_3 = (1,033 \ldots 1,05) \cdot D_2. \]

The method of determining the shape of the volute casing by A. Lomakin is based on the method of conservation of angular momentum of the flow (formula 1).

2.4. J. Gulich recommendation
J. Gulich [11] is not a supporter of unambiguous requirements for the methods of designing volute casing described above. The efficiency of volute casing designed by the constant velocity method can be on the same level with those designed by the method of conservation of angular momentum of the flow. According to J. Gulich, the best solution may be to design a volute casing:

a) for \( n_s < 90 \ldots 130 \) by the constant-velocity method;

b) for \( n_s > 90 \ldots 130 \) by the method of conservation of angular momentum.

3. Characteristics of the pump and volute casings
According to the methods described above, three volute casings were constructed (Fig. 1) for the centrifugal double-entry pump which were compared with base volute casings. The main characteristics of the pump and volute casings are shown in Table 1.
Table 1. Main pump characteristics.

| Design parameters:         | Symbol | Units | Stepanoff | Pfleiderer | Lomakin | Base |
|----------------------------|--------|-------|-----------|------------|----------|------|
| Design Head                | $H$    | m     | 100       | 100        | 100      | 100  |
| Nominal flow rate          | $Q_{nom}$ | m$^3$/h | 2000      | 2000       | 2000     | 2000 |
| Rotational speed           | $n$    | rpm   | 980       | 980        | 980      | 980  |
| Specific speed             | $n_s$  | -     | 60        | 60         | 60       | 60   |
| **Impeller:**              |        |       |           |            |          |      |
| Impeller outlet diameter   | $D_2$  | mm    | 850       | 850        | 850      | 850  |
| Impeller outlet width      | $b_2$  | mm    | 69        | 69         | 69       | 69   |
| Number of blades           | $z$    | -     | 6         | 6          | 6        | 6    |
| **Volute casing:**         |        |       |           |            |          |      |
| Inlet diameter             | $D_3$  | mm    | 930       | 878        | 884      | 868  |
| Volute casing width        | $b_3$  | mm    | 138       | 71         | 111      | 140  |
| Design method              | -      | -     | $c_3=\text{const}$ | $c_r=\text{const}$ | $c_r=\text{const}$ | $c_r=\text{const}$ |

Figure 1. Comparison of the geometrical forms: (a) Stepanoff and base volute casing; (b) Pfleiderer and base volute casing; (c) Lomakin and base volute casing.

4. Numerical simulation

An unstructured computational grid filled with tetrahedra and with prismatic layers near the solid walls of the solid model of flowing part of the pump was built in ANSYS ICEM. The total number of elements of the calculated model was about 2.7 million elements. Elements size is selected via mesh independence test. The simulation of the pump working process was conducted using the software ANSYS CFX. The numerical model of the pump consists of inlet pipe, semi-volute, impeller, volute casing, outlet pipe (Fig. 2). To increase the productivity and speed of calculation, the created calculation area consisted of one half of the flow part of the double entry pump.

Water at 25 °C was selected as the working fluid. For boundary conditions, a mass flow rate and normal flow direction were applied at the inlet while an opening pressure and direction were specified at the outlet. It was used the Reynolds-Averaged Navier-Stokes method with the standard $k-\varepsilon$ turbulence model. The parameter of the interface between the rotor and the stator elements is “Stage”. The pressure value was determined according to ISO 9906:1999 [12] at a distance of two diameters straight pipe from the respective flange ($D_{in}, D_{out}$).
5. Results

The analysis of volute casing constructed according to the recommendations of A. Stepanoff, C. Pfleiderer, A. Lomakin, and base volute casing showed a significant influence of the geometric parameters of the volute casing on the pump characteristics caused by changes in the fluid flow conditions in the volute casing.

The figure 3 shows the characteristics of the pump with different volute casings in the range of flow rate from 1000 m$^3$/h to 2400 m$^3$/h.

![Figure 3. Pump performance](image)

(a) $Q$-$H$ curve; (b) $Q$-$\eta$ curve; (c) $Q$-$P_{shaft}$ curve; (d) losses in volute casings.
According to Figure 3a, the head at $Q_{nom}$ is the same for all volute casings except the Lomakin design, which has lower head values. The profile and cross sectional area of the volute casing affects the steepness of the H-curve characteristic. At flow rate below $Q_{nom}$, the pump with the Pfleiderer volute casing has the highest head and the lowest head at flow rate above $Q_{nom}$. The pump with Stepanoff and Pfleiderer volute casings at (0.7…1.0)$Q_{nom}$ has higher head values compared to the base volute casings. At flow rate higher $Q_{nom}$, the head characteristics of the Stepanoff volute casing coincide with the base volute casing.

Figure 3b shows the dependence of efficiency from the flow rate. Stepanoff`s volute casing has the highest efficiency in the entire flow rate range. The efficiency of the base volute casing is higher than the efficiency of the Pfleiderer and Lomakin volute casings. A significant reduction in the cross sectional area leads to a shift of the maximum efficiency to a lower flow rate and leads to a decrease in the value of efficiency.

The largest shaft power has a Pfleiderer volute casing. Other volute casings have similar steepness $P_{shaft}$-curve characteristics. The difference in shaft power values between the volute casings varies within 4%.

There is no direct influence of the volute casing cross sectional area on the characteristics of the pump. They can be explained by the influence of the flow structure in the volute casing and additional vortex losses. The obtained results can be confirmed by the volute casings losses dependence on the flow rate (Fig. 3d).

*Figure 4. Pressure contours at $Q_{nom}$: (a) base model; (b) Stepanoff model; (c) Pfleiderer model; (d) Lomakin model.*
For a detailed analysis of the working process of the pump, the distributions of velocity and static pressure in the longitudinal sections of the impeller and volute casings are presented (Fig. 4, Fig. 5).

The distribution of pressure in the impellers for all analysed variants of the volute casing are similar. For volute casings, there is a slight difference in the pressure increase in the radial direction. Increasing the radial size of the volute casing leads to an increase in pressure at the periphery (near the wall), this is due to the action of centrifugal forces. There is also an uneven value of the pressure distribution along the inlet to the volute casing (except for the volute casing according to the method of Stepanoff), which can be explained by the uneven velocity distribution (Fig. 5).

The distribution of the absolute velocity in the impeller of the pump for variants of the volute casing designs according to the recommendations of A. Stepanoff, C. Pfleiderer, and A. Lomakin are similar and uniform. For the case with basic volute casing, there is unevenness between the leading edges of the impeller, which can be explained by the influence of the volute tongue on the flow in the impeller. It should be noted that the basic variant of the volute casing has a separation zone in the diffuser part of the volute casing, which reduces its efficiency. Other volute casings have much smaller separation zones. Increasing the volute casing in the radial direction and the cross sectional area leads to a decrease in absolute velocity. In the volute casing constructed by the Stepanoff method, a coaxial velocity distribution is observed, which has a positive effect on the pressure distribution at the inlet to the volute casing.

![Velocity contours](image_url)

**Figure 5.** Velocity contours at $Q_{nom}$: (a) base model; (b) Stepanoff model; (c) Pfleiderer model; (d) Lomakin model.
The change of absolute velocity, circumferential component of the absolute velocity and angular momentum in 8 cross sections in volute casing were analysed (Fig. 6 and Fig. 7).

**Figure 6.** Volute casing radially cross section used for analysis.

**Figure 7.** Characteristics of volute casings at $Q_{nom}$: (a) velocity curve; (b) $V_u R$ curve; (c) $V_u$ curve; (d) cross section area.
According to the obtained results (Fig. 7a), the absolute velocity of the flow in the A. Stepanoff volute casing is not absolutely constant and varies within 8%. This is explained by the fact that Stepanoff's theory of constant velocity takes into account the friction and volumetric losses by the coefficient K₁ which obtained experimentally. The results obtained from the use of this coefficient can not be absolutely reliable due to the variety of pump designs. Therefore, the obtained results can be considered satisfactory. The change in velocity in the Pfleiderer, Lomakin, and base volute casings has a larger range and varies between 13%, 37%, and 17%.

Figure 7b shows the change in the angular moment of the flow in the volute casings. The volute casing designed by the method of conservation the angular momentum and Pfleiderer’s recommendations has a range of change of the angular moment within 8%. However, if the cross section Pl. 45 (Fig. 6) is not taken into account, the deviations are only 4% and the results can be considered as corresponding to the method of conservation the angular momentum. The base volute casing has the smallest fluctuation in the angular moment and is within 6%, which suggests that it was designed by this method. For the Stepanoff and Lomakin volute casing, this fluctuation in the angular moment is between 8% and 21%. In this case, for the Stepanoff volute casing there is a slight uniform increase in the angular moment, and for Lomakin – decrease. The change in angular momentum corresponds to the change in a cross sectional area along the volute casing (Fig. 7d). The significant non-uniformity of the angular moment distribution in the Lomakin volute casing is explained by the large cross sectional area, which is determined by the choice of the values D₃ and bₗ₃.

Comparison of the angular moments at the outlet of the impeller and in the cross section Pl.360 (figure 6), which is using for calculation indicates that at the Q_max of the pump deviation is 16%, 2.5%, 18% and 30%, respectively, for Stepanoff, Pfleiderer, basic and Lomakin volute casings. The obtained results additionally confirm the conservation of the angular momentum of fluid in the Pfleiderer volute casing.

Analysis of the change in the circumferential component of the absolute velocity (V₉) (Fig. 7c) indicates the absence of constant values in all variant of volute casings. The Stepanoff volute casing, calculated at a constant velocity method, has a deviation of V₉ within 8%. The changes in the value of V₉, for the Pfleiderer, Lomakin and base volute casings are 11%, 38% and 18%, respectively. The Pfleiderer volute casings has the highest value of V₉, which is explained by the smallest cross sectional area of the volute casing.

6. Conclusion

In the article analysis of the volute casings designed by the constant velocity method and the method of conservation angular momentum of the flow, and according to the recommendations of A. Stepanoff, C. Pfleiderer and A. Lomakin for the double-entry centrifugal pump was presented.

According to the considered graphs of the distribution of the absolute velocity and angular momentum of the flow, it can be concluded that the base volute casing was designed according to the method of conservation of angular momentum, which does not meet the recommendations of J. Gulich.

The change in velocity in the volute casings, designed on the constant velocity method and Stepanoff's recommendations, is in the range of 8%, which is not due to friction losses and volumetric losses. Given this, it can be argued that the volute casings corresponds to the theoretical method.

The volute casing, designed according to the method of conservation of angular momentum of the flow and the recommendations of C. Pfleiderer, has a range of change of angular momentum of 4% (excluding the Pl. 45). That is, it corresponds to the theory. It has the highest velocity values due to the smallest cross sectional areas and as reason the biggest hydraulic losses.

In a volute casing designed by the method of conservation the angular momentum and recommendations of A. Lomakin, the angular momentum of the flow is not constant. The non-conservation of the angular momentum in the Lomakin volute casing can be explained by the large cross sectional area, the determination of which is influenced by the choice of the values of D₃ and bₗ₃ from a sufficiently large range, which introduces an error. To design a new volute casing for the
considered pump, it is not advisable to use Lomakin's recommendations regarding the choice of values $D_3$ and $b_3$.

Design a volute casing by method of constant velocity is recommended to use for to obtain a higher value of efficiency, a flat head characteristic, as well as to obtain lower hydraulic losses.

Design a volute casing by method of conservation angular momentum of the flow is recommended to use for to obtain a steep head characteristic. The disadvantage of this method is the lower efficiency (4%) and higher hydraulic losses than in the Stepanoff’s volute casing.

The obtained results are useful for choosing methods and recommendations for designing volute casings for new pumps with $n_s$ in the range 50...70. In the future it is planned to conduct a similar research for pumps with $n_s$ in the range 90... 130.

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