Experimental and numerical research on influence of winglets arrangement on vortex pump performance

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Abstract. Vortex pumps are widely used in wide range of hydro-transportation applications. Main disadvantage of this type of pump design is low efficiency. Despite ongoing effort to improve vortex impeller performance precise algorithm for their optimal design doesn't exist. One of the ideas is to use winglets (super-vortex) on the tip of the impeller blades. Conducted literature studies have shown that there is not yet clarified principle of winglet design. Authors have performed numerical simulations and measurements for three different arrangements of winglets with varying impeller coverages. From the obtained results recommendation for optimal winglet placement is deducted.

1. Introduction

Transporting solid-fluid mixtures is a very important part of many industries. The use of free flow pumps is justified when pumping liquids mixed with solids or fibrous materials. The main applications of this type of pumps are:

- Sewage pumps - clogged mainly by textiles, plastic and foils
- Hydraulic transport pumps - e.g. used in mining for shipment of goods
- Pumps used in the food industry (e.g. fish)
- Paper pulp pumps

Typical sewage pumps are single stage with radial, diagonal or axial flow. Radial and semi-axial pumps usually have volutes as collective element and in the case of pumps with axial flow, the diffusers are used. Apart from the basic parameters and dimensions characterizing the pump in the free flow units, the parameter called the free flow passage is additionally used. It determines the maximum size of solid part that can flow freely through the pump. As a rule, the simplified shape of the contamination is assumed as a sphere and its diameter is the value of the maximum dimension of free flow passage.

One type of radial flow pumps are the vortex impeller pumps. The semi-open vortex pump impeller with radially curved blades causes a strong swirling of the inflowing liquid stream in the space between the impeller and the pump casing. Swirling and centrifugal forces produce a pressure gradient that allows fluid to be transported along with the solids inside it to the volute casing from which the flow is directed to the outlet diffuser. Flow in free flow pumps is characterized by many vortex structures, which cause a significant reduction in efficiency (up to 30% compared to typical centrifugal pumps).

To stabilize the flow, it is possible to use partially covered impeller blades, which reduce leakage losses over impeller blade. The available literature defines the simplified design algorithm of the
vortex impeller. Most design data (assumptions, basic dimensions, etc.) are based on the collection of catalogue data from several manufacturers. The concept of structural approach to vortex impellers with winglets remains unresolved. It is justified to carry out a study on the influence of the design parameters of this type of rotors on the operation of the pump (efficiency and performance of the unit).

A very good summary of the international literature available on Vortex pumps can be found in the article by Gerlach et al [1]. The authors provide recommendations for the effective design of Vortex centrifugal pumps; however, the influence of impeller winglets has been based only on simple geometries. The influence of winglets on the operating parameters of Vortex pumps was found in [2] and [3]. The authors of the those articles came up similar conclusions - the impeller winglets clearly improve its energy parameters. Interestingly, Cervinka M. [4], presents different point of view. Numerical simulations carried out by the authors gave different results and the coverage of the impeller reduced its performance. It is very likely that this inconsistency was caused by a different pump design (impeller hidden in the back of the volute wall). In addition, the simulation results have not been validated and are different to those obtained by authors in [2] and [3]. Ultimately, the lack of a clear and unambiguous definition of the impact of winglets on work parameters is one of the main motivations for this work.

2. Object of research
Free-flow pumps have impellers with a significant gap between front wall of the volute. The main purpose of this design feature is to obtain a free passage through the route from the inlet of the pump to the outlet diffuser. It allows to transport hydro-mixtures with large sizes of solid fractions. Impellers in typical free-flow pumps are equipped with radial or backward curved blades that generate a recirculation (vortex) that arises in front of the impeller. The incoming fluid is forced into a highly swirling flow. The vortex created this way transports the liquid along with any solid, fibrous or gas bodies. One of the types of radial flow pumps are pumps with "vortex" impellers. The semi-open impeller of the "vortex" pump with radially curved blades causes strong turbulence of the inflowing liquid stream in the space between the impeller and the body.

On the test rig submersible free flow pump was used. Volute chamber of chosen pump unit is closed by the lid with the inlet opening. Use of a removable cover of the body makes it much easier to access the rotor (Fig. 1). Nominal parameters of test pump units are \( Q_n = 50 \text{ m}^3/\text{hr} \) and \( H_n = 16.5 \text{ m} \). Base dimensions of pump impeller are shown in table 1.

| \( d_1 \) (mm) | \( d_2 \) (mm) | \( b_2 \) (mm) | \( b_4 \) (mm) | \( x_1 \) (mm) | \( \beta_1 \) | \( \beta_2 \) |
|---------------|---------------|---------------|---------------|---------------|------------|------------|
| 65            | 162           | 29            | 65            | 34            | 29         | 32         |

Figure 1. Test pump unit section.
This pump was chosen because impeller is positioned inside volute. The impeller hub is in line with the rear wall of the pump chamber. Thanks to this application impeller winglets will not block flow passage, which in the case of the inset impeller could occur.

Additional criterion used when choosing the pump for testing was the ease of access to the pump impeller and its small size. The angles $\beta_1$ and $\beta_2$ determine the angle of the blade for its inlet and outlet, respectively. The blade has a single curvature and its profile was created by a two-arc method.

The impeller and winglet geometries used for the measurements were printed on a 3d printer (FDM) using PETG material (Fig. 2). As a result, dimensional difference between the CAD model used for simulation and the real impeller and winglets were minimized. PETG as material was chosen mainly because of its printing qualities and durability [6]. During measurements none of the parts were damaged.

![Figure 2. Impeller printed with PETG.](image)

All research was conducted in specially designed test rig. A 3d model is shown in Figure 3. It is equipped with a flow meter, pressure transducers and network meter. The measurement process was carried out for the entire throttle valve opening range.

![Figure 3. Test bench visualization.](image)
Winglet geometries are created by single arc method with the same inlet and outlet $\beta$ angles as those of mean line of impeller blade. Inlet diameter of winglet blade equals $d_1 = 88\text{mm}$. Outlet diameter is the same as impeller. Sample winglet geometry is shown at Figure 4.

For the comparison of different winglet arrangements two additional parameters were used: coverage coefficient and minimal free passage diameter (Fig. 5). Coverage coefficient is described as:

$$\theta = \frac{A_w}{A_{bb}}$$

where:

$A_w$ – winglet area
$A_{bb}$ – between blades area

Free flow passage is used to describe maximum diameter of solid substance that may freely pass through the impeller without clogging pump unit. For the purpose of accuracy Simulated Annealing Algorithm was used to solve optimization problem of minimizing sphere diameter fitted between impeller blades and front cover of pump. Sphere surface was constrained by both geometries.

In this work, eleven different geometries were investigated. Designs were made for three different winglet arrangements and three different cover coefficients (Fig. 6). In order to properly compare measured geometries two additional impellers were added: open and closed.
Figure 6. Studied winglet geometries.

Cover coefficients, maximum free flow sphere diameters and winglets arrangements for each geometry are described in table Table 2.

| Id. | Coverage coefficient | Max sphere diameter, mm | Winglets arrangement |
|-----|----------------------|-------------------------|----------------------|
| 1   | 0.25                 | 44.0                    | TRUE                 |
| 2   | 0.25                 | 43.1                    | TRUE                 |
| 3   | 0.25                 | 43.6                    | FALSE                |
| 4   | 0.33                 | 43.2                    | TRUE                 |
| 5   | 0.33                 | 42.4                    | TRUE                 |
| 6   | 0.33                 | 42.7                    | FALSE                |
| 7   | 0.4                  | 42.5                    | TRUE                 |
| 8   | 0.4                  | 41.8                    | TRUE                 |
| 9   | 0.4                  | 41.9                    | FALSE                |
| 10  | 1                    | 35.6                    | TRUE                 |
| 11  | 0                    | 45.4                    | FALSE                |

Most manufacturers of free flow pumps use inlet or outlet diameter as a dimension for free passage. This approach is not very accurate. In vortex pumps that has an impeller positioned inside volute
chamber \((x_1+b_2<=b_3)\) free flow passage is usually smaller than inlet or outlet diameter of the pump. The inlet diameter of tested pump is equal to 65mm. However, for an impeller without winglets (id. 11 in table Table 2) free flow passage is equal to 45.4 mm. This gives ~20mm difference. This is significant and that is why this additional parameter was also included.

Range of coverage coefficients used for geometry creation were based on previous experiences [7].

3. Analysis of the influence of winglets arrangement – measurements

Figures 7 to 9 show the performance curves for all measured geometries. Head and flow are shown as values relative to optimal parameters for open impeller geometry (id 11). Measurement results for both sides winglet and suction side winglet placement indicate concise increase in head and efficiency along with increase of the coverage coefficient. Pressure side winglet gave smallest gain in pump head. Furthermore, along with coverage coefficient increase head curve for pressure side winglet began to decrease. For cover coefficient of 40% pressure side winglet head curve almost coincide with open impeller (Fig. 9).

**Figure 7.** Performance measurements for winglets geometries with \(\theta = 25\%\).

**Figure 8.** Performance measurements for winglets geometries with \(\theta = 33\%\).
Figure 9. Performance measurements for winglets geometries with $\theta = 40\%$.

Highest improvement in head was obtained for winglets positioned over suction side of the impeller blade (Fig. 3). The increase in efficiency is noticeable but the results for different winglet positions are not straightforward. For example, highest efficiency gain was obtained for pressure side winglet with $\theta = 25\%$ but with further increase of coverage efficiency for that winglet position decreased. Furthermore, winglets for both sides and winglet for suction side had similar efficiencies for $\theta = 25\%$ and $\theta = 40\%$ but it diverged for $\theta = 33\%$. This might lead to conclusion that beside coverage coefficient and winglet position there are others geometrical parameters that influence impeller efficiency.

Additional information obtained from the conducted measurements is that using winglets over suction side of the impeller caused extension of the flow range with high efficiency. This occurred in suction side winglets with cover coefficients 33% and 40% as is seen in figure 8 and Fig. 9.

The most important conclusion from the measurements carried out is that the use of any geometry of winglets increase pump head and efficiency. This is a clear confirmation of the theory that volumetric losses caused by flow over the blades can be significantly reduced by using winglets.

Figure 10. Relative head and efficiency as a function of coverage coefficient, values for optimal flow.
4. Numerical model

Free-flow pumps cannot be treated as typical centrifugal pumps. It is necessary to make a few arrangements in the composition of computational domains. Based on the analysis of free flow pumps described by Ihor Krishtop et al [5], it was assumed that the highest accuracy and compliance with measurement data would be obtained for a shortest distance of the front wall of the rotor domain (cylinder) to the front volute wall. In this case numerical simulations were conducted in order to obtain rough flow structures inside different impeller – winglets configuration. That is why turbulence model k-epsilon Realizable was chosen as sufficient. Unstructured tetrahedral mesh was used. For the CFD analysis Ansys FLUENT software was used. Model used for simulations was divided into two domains: impeller and volute with inlet and outlet. The boundary conditions were defined as: mass flow at the inlet with turbulence intensity \( I = 5\% \) and pressure at outlet. More detailed information about, gr, calculation parameters and model validation one can find in [7].

Results of performed simulations are shown in figures 11 to 15. In order to visualize differences between different winglets arrangements open (Fig. 10) and closed (Fig. 11) impellers were included. For each front view of impeller two unwrapped half-cylindrical sections where added at \( d=100\text{mm} \) and \( d=140\text{mm} \).

![Figure 11. Relative velocity LIC for closed impeller.](image1)

![Figure 12. Relative velocity LIC for open impeller.](image2)
Figure 13. Relative velocity LIC for impeller with both side winglets and $\theta = 40\%$.

Figure 14. Relative velocity LIC for impeller with both side winglets and $\theta = 40\%$.

Figure 15. Relative velocity LIC for impeller with both side winglets and $\theta = 40\%$. 
From presented figures it can be observed that varying degree leakage loss reduction occurred for all winglet arrangements. Additionally, it is easy to notice that winglet placement over section side of impeller most visibly reduces water transfer above impeller blades.

5. Conclusion
Reducing the water transfer over the top of the blades by using their partial cover increases the pump operating parameters (H(Q)). Further work on optimizing the shape of the rotor winglets should focus on achieving the highest possible increase in pump parameters and efficiency while maintaining maximum free passage. In addition, it is necessary to test various types of rotor winglets, e.g. with fixed width or different β-angles for blades and winglets.

For all values of coverage coefficient and all arrangements of winglets increase in pump head and efficiency was seen. Among all of the examined cases the highest-pressure increase was obtained when placing winglets over suction side of impeller.

Numerical calculations of free flow pumps allow for a rough determination of the operating parameters of such pumps. In order to obtain more accurate results of numerical calculations, based on the development described in [5] calculations should be conducted as transient. In addition, subsequent validation measurements should be made when significant changes in rotor and winglets are applied.

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