

IMPROVING CENTRIFUGAL PUMP BY ADDING VORTEX ROTOR

Tihomir Mihalić, Srđan Medić, Živko Kondić

Original scientific paper

The improvements of the characteristics of centrifugal pump were investigated in this work experimentally and with computational fluid dynamics (CFD) analysis of the influence of adding vortex rotor to centrifugal one. The idea behind that improvement is in creating the so-called coherent structures of eddies and turbulence in the peripheral area of the vortex rotor mounted at the back side of centrifugal rotor. Research on the energy transformations in the centrifugal vortex pump in this work was carried out using control volume method for simulations of the flow in the centrifugal and the centrifugal vortex pump, and also by taking measurements of relevant parameters that describe the performance of pumps at their physical models. The measurement results were used as experimental validation and verification of numerical simulations; in contrast, flow visualization derived from the numerical simulation was used to interpret measurements. In deriving that experimental procedure, special care was taken with the flow measurements. The reason for this is in the fact that the flow measurements had the biggest influence on the overall measurement uncertainty. However, flow measurements were the most demanding with regard to experiment design and in taking the measurement readings. This experimental - CFD research made it possible to undertake an assessment of vortex rotor contribution on the head of centrifugal vortex pump. The influence of the vortex rotor on the efficiency of the centrifugal vortex pump was studied in contrast to the efficiency of a centrifugal pump with the same geometry. An analysis of the structure of flow was conducted in order to better understand the energy transformations that are the result of interaction between vortex rotor and the flow from the channels of centrifugal part of centrifugal vortex rotor.

Keywords: centrifugal vortex pump, computational fluid dynamics, energy transformation, flow measurement, pump performances, unsteady flow

Poboljšanje centrifugalne pumpe dodavanjem vrtložnog rotora

Izvorni znanstveni članak

Poboljšanja karakteristika centrifugalne pumpe istraživana su u ovom radu primjenom eksperimenta i računalne dinamike fluida (CFD). Istraživan je utjecaj dodavanja vrtložnog na centrifugalni rotor. Pokretačka zamisao ovog načina poboljšanja je u stvaranju tzv. tokova koherentnih struktura i turbulencije na vanjskom promjeru vrtložnog rotora koji je pričvršćen na stražnjoj strani centrifugalnog rotora. Proučavanje energetskih transformacija u ovom radu provedeno je primjenom numeričke metode kontrolnih volumena za simuliranje strujanja u centrifugalnom i centrifugalno vrtložnom stupnju te mjerenjem relevantnih parametara na njihovim fizikalnim modelima. Rezultati mjerenja korišteni su za validaciju i verifikaciju numeričkih simulacija dok su vizualizacije strujanja proizišle iz računalne dinamike fluida poslužile za interpretaciju eksperimentalnih rezultata. Pri dizajniranju eksperimenta posebna pažnja pridala se mjerenju protoka, zato što je mjerenje protoka imalo najveći utjecajni faktor na ukupnu nesigurnost provedenih eksperimenata. Pri tome je organiziranje mjerenja protoka bilo najzahtjevnije. Ovo eksperimentalno-numeričko istraživanje omogućilo je procjenjivanje utjecaja vrtložnog rotora na visinu dobave centrifugalno vrtložne pumpe te na njenu iskoristivost u usporedbi sa sličnom centrifugalnom pumpom. Analiza struktura strujanja dala je bolje razumijevanje mehanizama energetskih pretvorbi koje su rezultat interakcija vrtložnog rotora i strujanja fluida koje dolazi s centrifugalnih lopatica.

Ključne riječi: centrifugalno vrtložna pumpa, energetska pretvorba, karakteristike pumpe, mjerenje protoka, nestacionarno strujanje, računalna dinamika fluida

1 Introduction

Any improvements of the pump performances can provide financial and energy savings and by that have a positive impact on the environment.

One way of improving the characteristics of centrifugal pumps is by adding a vortex rotor to the centrifugal rotor by which energy of induced vortices at the vortex rim is added to the fluid energy gained in centrifugal rotor Fig. 1, as demonstrated in [1, 2, 3] and [4].

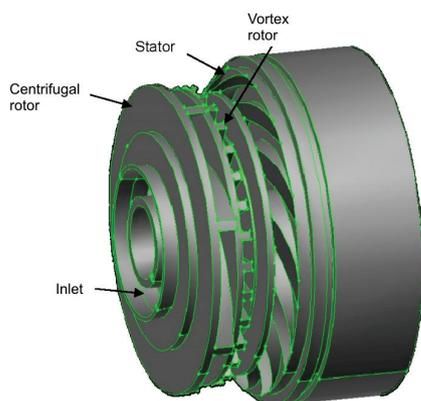


Figure 1 Centrifugal vortex pump stage

Fig. 1 shows one stage of the centrifugal vortex pump with major components. On the periphery of the disc of the centrifugal rotor on the stator side, the vortex rim (rotor) is installed. There is a gap between the stator cover and vortex radial vanes that, together with the gap between centrifugal vanes and the stator, entrance forms a peripheral-lateral annular vortex chamber.

The resulting additional kinetic energy of coherent structures induced at the vortex rim transforms to the head H_4 , which is added to the bulk head (pressure) obtained in the centrifugal rotor of the centrifugal vortex pump H_{cen} as shown in Eq. (1):

$$H = H_{cen} + H_4. \quad (1)$$

Mere physical simulations (experiments) do not provide all the necessary information about the structure of the energy conversions. Therefore, the use of the joined method, computer simulations (CFD) together with experiment, can provide insight into the structure of flows and the quantification of parameters, which helps in understanding the processes of energy conversions [5, 6, 7].

The numerical simulations of unsteady flow in centrifugal pumps and centrifugal vortex pumps were conducted using the control volume method.

The objectives of this research were to clarify the mechanisms of energy conversion in a centrifugal vortex pump and to confirm the positive impact of a vortex rim on the pump characteristics. To do that it was necessary to research the flow structures occurring in the vortex chamber and the interaction of this flow with vortex rotor.

2 Experimental models

The rotor and stator, formed from transparent plexiglass, are also embedded in a transparent casing of plexiglass to enable flow visualization, both in the passages of the rotor and the stator and in the zone of special interest for research, i.e. the chamber between the rotor and the stator, where the vortex rim is located (Fig. 2).



Figure 2 Centrifugal and centrifugal vortex pump stage made of Plexiglas for experimental research

The experimental assembly [8] was made in accordance with the following standards: ISO 5167-1, 4:2003 and ISO / TR 15377:2007.



Figure 3 Pump stage housing

The housing of the researched pump stages (centrifugal or centrifugal vortex) is designed to allow very fast exchange between pump stages (Fig. 3). Furthermore, the housing provides all the necessary seal between the rotor zone and the suction zone, between the front plate of the rotor and the housing, between the stator and the housing.

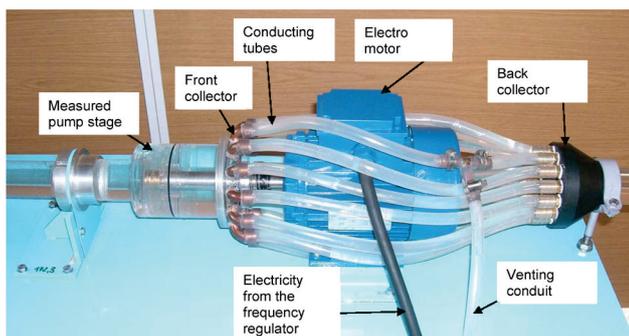


Figure 4 Measurement section

2.1 Preparing the flow for taking measurements

Fig. 4, shows the measurement section of the centrifugal vortex and centrifugal test pump stages, [9]. Fluid from the pump stage is conducted by front collector through 14 connectors, and evenly distributed on the outer diameter of the front collector. The collector is designed in such a manner as to introduce as few instabilities to the flow as possible in order to not affect the measurement results. The fluid is conducted from the front collector with 14 tubes that allowed fluid to go around the electric motor without changing its hydrostatic energy and to simultaneously smooth the flow. These 14 tubes then merge at the back collector.

3 Numerical models

Between physical and numerical models, geometric, kinematic and dynamic conditions for similar work were satisfied. A simplification of geometries was conducted only in areas that do not affect the flow in the stator and rotor.

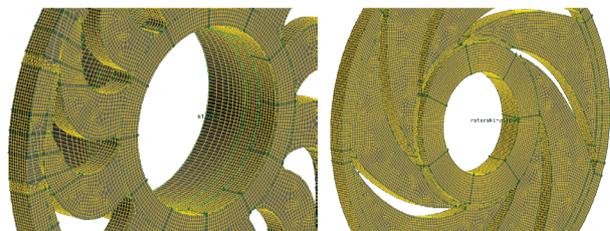


Figure 5 Structured mesh of the stator (left) and the rotor (right)

In the used CFD model, the rotor rotates unrestrained, and is connected to the rest of the domain with a sliding mesh boundary condition. The output tube is connected with the output from the stator with the interface boundary condition because there the flow is less demanding for mesh quality.

The entire continuum is meshed with 3 340 658 control volumes with the largest volume edge of 0,3 mm. Of the total number of control volumes, 85 % of them were hexahedral control volumes, Fig. 5.

The research was conducted at the rotor angular speed $n = 2910$ 1/min, time step was 8×10^{-5} s. The selected time step showed rapid convergence solutions. For the working fluid, water of standard properties at 25 °C was used.

Turbulence was modelled using a hybrid detached eddy simulations (DES SST) model, [10] and [11].

At the entrance to the domain, a pressure-inlet boundary condition was used, while at the exit from the domain, an outlet-vent boundary condition was used, because it allows adjustment of the loss coefficient at the exit, [12].

The boundary condition outlet vent is defined by pressure loss (attenuation) that is proportional to dynamic pressure:

$$\Delta p = k_L \cdot \frac{1}{2} \cdot \rho \cdot v^2 \tag{2}$$

Loss coefficient k_L in the boundary condition outlet vent (2) is a number, and the whole simulation was

conducted varying it; $k_L = 0$ (fully open valve), 2, 5, 10, 20, 60, 300 (fully closed valve), [13].

4 Research results

Fig. 6 shows the $Q-H$ characteristics of a centrifugal and a hybrid centrifugal vortex pump stage. It is evident that the characteristics of the centrifugal vortex pump smoothly follow the characteristics of centrifugal pump from the maximum flow to the flow $105 \text{ m}^3/\text{day}$ ($1,22 \text{ l/s}$). After the flow $105 \text{ m}^3/\text{day}$ ($1,22 \text{ l/s}$), the characteristics of the centrifugal vortex pump continue to rise steeply as a characteristic of vortex pumps in [14], in contrast to the characteristics of centrifugal pump, which grows slower than the characteristics of the centrifugal vortex pump to its maximum at flow rate of $65 \text{ m}^3/\text{day}$ ($0,75 \text{ l/s}$), and then begins to decline steeply. This form of performance curve (falling steeply after its maximum) represents the instability of the pump, because the pump can generate two different flow rates at a given head, left and right from the maximum $Q-H$ characteristic curve, [15].

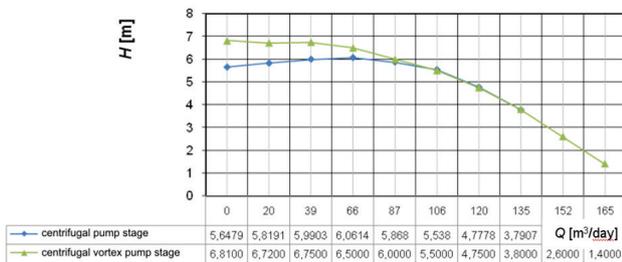


Figure 6 $Q-H$ characteristics of centrifugal vortex and centrifugal pump stage

Adding a vortex rotor to the centrifugal pump stage provided a rising pump $Q-H$ characteristic, which ensures the stability of its operation. This confirmed one of the positive roles of the vortex rim in the centrifugal vortex pump stage.

4.1 Quantification of the amount of the head generated by vortex rotor

The contribution of eddy processes on the amount of the head and the corresponding increase in pressure depends on the flow rate, and the given flow rate depends on the magnitude of the axial component of absolute velocity of the fluid from the discharge of centrifugal rotor to the entrance in the diffuser channels. The lower the flow rate and the smaller the axial velocity component are, the greater the number of the vortex rim passages participating in the momentum change between the fluid contained in these passages, at that instant of time, and the main stream of the fluid from the centrifugal rotor to the diffuser, [16].

Fig. 7 clearly shows that the vortex rim in the centrifugal vortex pump stage begins to increase the amount of the head from the flow rate $105 \text{ m}^3/\text{day}$ ($1,22 \text{ l/s}$) to the zero flow. This property is very convenient, because if there is a higher demand on the pump, so as to overcome the greater resistance, the vortex rim is increasingly helping the pump.

The swirl effect achieved by vortex rim increased the magnitude of the head of the plain centrifugal pump stage for a maximum of 23,13 % (average increase of 11,64 %).

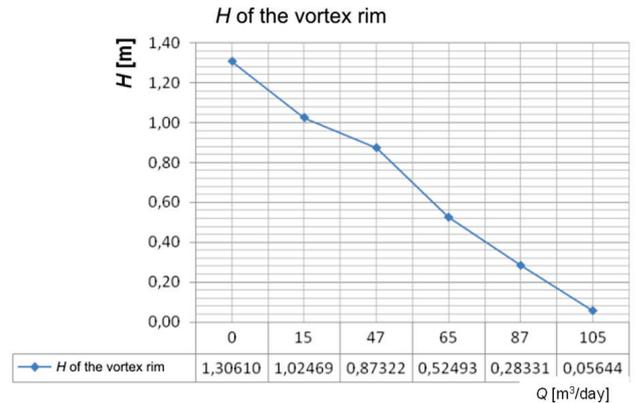


Figure 7 Contribution of the energy fluxes from the vortex rim to the increase of head H

4.2 Characteristic of vortex part of the centrifugal vortex pump

Fig. 8 shows the head of vortex part of centrifugal vortex pump calculated with CFD simulation of the researched centrifugal vortex pump by taking out centrifugal rotor. As evident from the figure, the vortex rotor produced a maximum of 0,63 m of head working alone, while operating in synergy with the centrifugal rotor; it generated a maximum of 1,306 m of head as can be seen from Fig. 9. Therefore, the vortex rotor in synergy with the centrifugal rotor generates a double head, as opposed to working alone. The reason for this is in the fact that when it works in synergy with the centrifugal rotor, it affects the secondary stream which already gained a certain amount of energy in the centrifugal rotor (Fig. 9).

$Q-H$ of the vortex part of the centrifugal vortex pump stage

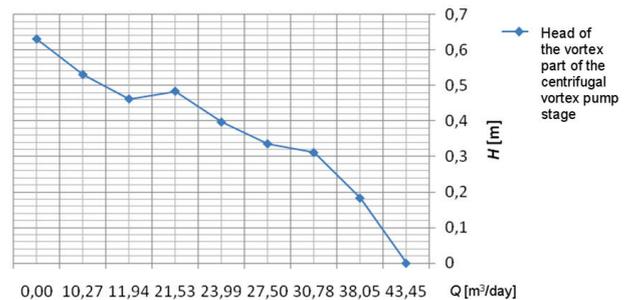


Figure 8 Head of vortex part of the centrifugal vortex pump

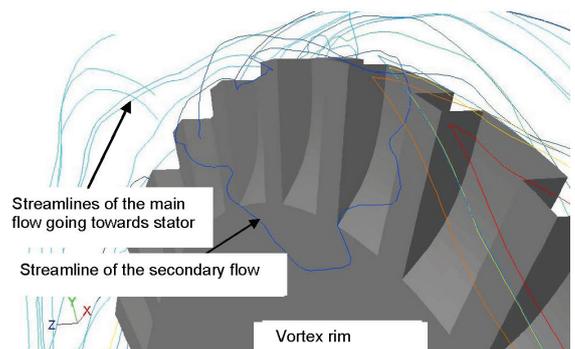


Figure 9 Main and secondary fluid flow

From Fig. 8 it can be seen that when a vortex rotor is working alone, it creates a steep drop-down characteristic with a small flow. When working alone vortex rotor consumes 33,66 W of power, while the maximum power brought to centrifugal vortex pump stage is 108,25 W.

4.3 Comparison of the centrifugal vortex and centrifugal pump efficiency

Fig. 10 shows a comparison of efficiency curves of the centrifugal vortex and centrifugal pump stage researched in this work. It can be assumed that both curves show a greater efficiency than would be present with the utilization of actual pumps. The reason for this is that the numerical models do not take into account friction losses due to wall roughness, and losses due to fluid flow through clearances [17]. However we assumed that the numerical models of real pump geometry will calculate efficiency curves with the realistic trends and mutual correlations.

Efficiency of the centrifugal vortex and centrifugal pump stage

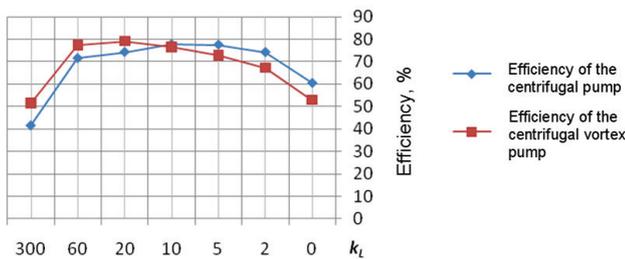


Figure 10 Efficiency curves of centrifugal vortex and centrifugal pump

A comparison of the efficiency curves (Fig. 10) shows that at high flow rates (low loss coefficient $k_L = 0$ to 10) centrifugal pump obtained greater efficiency than centrifugal vortex pump. That was expected as we conducted flow analysis. The vortex rotor at high flow rates does not get enough fluid from the main flow (coming from the centrifugal rotor, Fig. 9) so it does not increase the head (Fig. 6), while at the same time it contributes significantly to the increase of entropy. In that working range, the vortex rotor only creates turbulence, and its kinetic energy is converted into losses. Thus, in this working range the vortex rotor is "parasitic part" in the centrifugal vortex pump, [14].

In contrast, at low flow rates (high loss coefficient $k_L = 10$ to 300) the efficiency of the centrifugal vortex pump is greater than that of the centrifugal pump. In this working range, the vortex rotor grips sufficient amount of fluid from the main stream and contributes to increasing the level of head (Fig. 6). Its kinetic energy is not transferred entirely to the creation of fluid turbulence, but a part of its kinetic energy is used to create a coherent flow structure and to accelerate the flow of secondary stream, [18].

It is also evident from Figure 10 that the best efficiency point of the centrifugal vortex pump is shifted to the left (to the smaller flow rates, and higher head) in comparison to the centrifugal pump.

5 Conclusion

This work has proven and quantified the benefits of the centrifugal vortex pump stage in relation to the centrifugal one. The method used was based on the unsteady CFD experiments and experiments on physical models. This method has been validated and verified and thus is a valuable tool for flow simulation and performance determination in various turbo machines. Detailed measurements on the physical models of the power consumed to drive the centrifugal and the centrifugal vortex pump stage resulted in a more accurate quantification of energy balance. This led to prove that the kinetic energy of coherent vortex structures created by the vortex rim is added to the fluid flowing from the passages of the centrifugal rotor and thus increases the total energy of the fluid before entering the stator. Furthermore, this extra energy is added to the main fluid stream by the longitudinal vortices generated by the edges of the vortex rim due to a change of kinetic energy of eddies and by the radial vortices detached from vortex rim vanes.

Centrifugal vortex pumps generate an increased head for a maximum of 23,13 % (average increase of 11,64 %) compared to the centrifugal pumps with the same geometry operating at the same angular velocity. Furthermore, the vortex rim of the centrifugal vortex pump increases the amount of the head for working range from 0 to 57 % of maximum flow. At higher flow rates, it does not affect the level of head. Also this research has shown that adding vortex rotor to the centrifugal one improves the character of $Q-H$ characteristics which become steeply sloping as opposed to the characteristics of centrifugal pump. That increases pump stability disabling it of running in "pumping" mode.

It has been found that vortex rotor head is 210 % higher when operating in synergy with centrifugal impeller than when acting alone.

The efficiency of the centrifugal vortex pump is increased for the working regime 0 to $0,57 \cdot Q_{max}$, while at the higher flow rates, efficiency is actually lower than that of the centrifugal pump. It can be concluded that at higher flow rates centrifugal vortex pump wastes driving energy on spinning vortex rim. At lower flow rates the contribution of vortex rotor to the head is significant while it does not consume additional driving energy. This suggested that there must be some mechanism that recovers a part of the energy that otherwise is lost in centrifugal pumps. This mechanism is explained by the coherent structures which act as an energy bridge between the main fluid flow and the kinetic energy of the vortex rotor.

Preliminary research also demonstrated a great superiority of the centrifugal vortex pump for cavitation resistance. However this must be a topic of another detail study.

6 References

- [1] Mihajlović, P. O.; Jurević, M. I.; Borisovič, K. P.; Isaakovič, R. A.; Pavlovič, T. I. New rotary-vortex pumps for crude oil production in the complicated conditions, 1st

- International conference of technical sciences, Russia, Voronež, 2001.
- [2] Isaaković, R. A.; Vasiljević, G. N. High-head, economical modification of multistage centrifugal pump for oil production, 2nd International conference of technical sciences, Russia, Voronež, 2003.
- [3] Karakulov, S. T.; Meljnikov, D. J.; Pereljman, M. O.; Dengaev, A. V. Ways of increasing efficiency of oil exploitation from oil wells, 3rd International conference of technical sciences, Russia, Voronež, 2005.
- [4] Melzi, E. Vortex impeller for centrifugal fluid-dynamic pumps, European Patent Application EP1 961 965 A2, Italy, 2008.
- [5] Navratil, P.; Balate, J. Simulation of Control of Multi-Variable Control Loop: Steam Turbine. // International Journal of Simulation Modelling, 10, 2(2011) pp. 53-65.
- [6] Tic, V.; Lovrec, D. Design of Modern Hydraulic Tank Using Fluid Flow Simulation. // International Journal of Simulation Modelling, 11, 2(2012), pp. 77-88.
- [7] Santhakumar, M.; Asokan, T. Investigations on the Dynamic Station Keeping of an Underactuated Autonomous Underwater Robot. // International Journal of Simulation Modelling, 10, 3(2011), pp. 145-157.
- [8] Franjić, K. Measurements in mechanics of fluid. Engineering handbook IP1, Školska knjiga, Zagreb, 1996, pp. 1015–1034.
- [9] Goldstein, R. J. Fluid mechanics measurements, 2nd edition, Taylor & Francis, USA, 1996.
- [10] Spalart, P. R. Detached-eddy simulation. // Annual Review of Fluid Mechanics, 41, 1(2009), pp. 181–202.
- [11] Travin, A.; Shur, M.; Strelets, M.; Spalart P. R. Physical and Numerical Upgrades in the Detached-Eddy Simulation of Complex Turbulent Flows, Advances in LES of Complex Flows, Kluwer Academic Publishers, (2002), pp. 239–254.
- [12] Launder, B. E.; Spalding, D. B. Lectures in Mathematical Models of Turbulence, Academic Press, London, 1972.
- [13] Fluent Inc: Fluent 12 user guide, Fluent Inc.
- [14] Mihalić, T.; Guzović, Z.; Sviderek, S. Improving centrifugal pump by adding vortex rotor. // Journal of Energy Technology - JET, 4, 2(2011), pp. 11-20.
- [15] Feng, J.; Benra, F. K.; Dohmen, H. J. Comparison of Periodic Flow Fields in a Radial Pump among CFD, PIV and LDV Results. // International Journal of Rotating Machinery, 2009, Article ID 410838, 10 pages, ISBN 1023621X.
- [16] Dochterman, R. W. Centrifugal-vortex pump, General Electric Company, United States Patent 3,936,240, USA, 1974.
- [17] Lobanoff, V. S.; Ross, R. R. Centrifugal pumps – Design & Application, 2nd edition, Butterworth-Heinemann, USA, 1992.
- [18] Matijašević, B.; Sviderek, S.; Mihalić, T. Numerical Investigation of the Flow instabilities in Centrifugal Fan. // WSEAS Conference on Fluid Mechanics and Aerodynamics, Agios Nicolaos, Greece, 2006.

Authors' addresses

Dr. sc. Tihomir Mihalić, dipl. ing.

University of Zagreb
Faculty of Mechanical engineering and Naval Architecture
Ivana Lučića 5, 10000 Zagreb, Croatia
E-mail: tihomir.mihalic1@zg.htnet.hr

Dr. sc. Srdan Medić, dipl. ing.

Karlovac University of Applied Sciences
Trg J. J. Strossmayera 9, 47000 Karlovac, Croatia
E-mail: smedic@vuka.hr

Doc. dr.sc. Živko Kondić, dipl. ing.

Varaždin University of Applied Sciences
J. Križanića 33/6, 42000 Varaždin, Croatia
E-mail: zkondic@velv.hr