Proceedings of the 9th International Conference on Heat Transfer and Fluid Flow (HTFF'22)
Prague, Czech Republic – July 31, 2022 - August 02, 2022
Paper No. HTFF 155
DOI: 10.11159/htff22.155

Flow Visualization in the Impeller and Diffuser of a Centrifugal Pump using Time-Resolved Particle Image Velocimetry

Rodolfo M. Perissinotto[1], William D.P. Fonseca[1], Rafael F.L. Cerqueira[2], William Monte Verde[2], Jorge L. Biazussi[2], Erick M. Franklin[1], Antonio C. Bannwart[1], Marcelo S. Castro[1]
[1]School of Mechanical Engineering - University of Campinas, UNICAMP
Rua Mendeleyev, 200, Cidade Universitária, Campinas-SP, Brazil.
rodolfomp@fem.unicamp.br
[2]Center for Petroleum Studies - University of Campinas, UNICAMP
Rua Cora Coralina, 350, Cidade Universitária, Campinas-SP, Brazil.

Abstract **-** The present paper describes an experimental study on the flow dynamics within a centrifugal pump impeller. A transparent pump prototype made of acrylic parts was firstly developed for flow visualization purposes. Then, single-phase flow experiments were conducted in different impeller rotational speeds and water flow rates. A time-resolved particle image velocimetry (TR-PIV) system was used as the flow visualization method. As a result, velocity fields were obtained in the whole impeller. They reveal that the flow behaviour is dependent on the pump operational condition. When the pump works at the best efficiency point (BEP), the flow is uniform and the streamlines follow the blade curvature. However, when the machine works at off-design conditions, the flow becomes complex, with the presence of turbulent structures which cause a reduction in the pump performance. This type of result may be useful to validate numerical simulations and support the proposition of new mathematical models, new impeller geometries, among other applications.

Keywords**:** Centrifugal Pump, Fluid Mechanics, Single-Phase Flow, Particle Image Velocimetry.

1. Introduction

Single-phase flows in centrifugal pumps are highly complex, with the presence of distorted velocity profiles, pressure gradients, high shear stresses, and, in addition, structures such as vortices and recirculation zones. The general characteristics of these flows directly influence the pump performance, leading to a reduced head, flow rate, and efficiency, depending on the operational conditions. Hence, the investigation of the flows in impellers and diffusers is important to engineers and scientists working to improve the design of centrifugal pumps.

Many experimental works available in the literature use the particle image velocimetry (PIV) method to visualize the single-phase flows and measure instantaneous velocities and derived quantities. We may cite, as a few examples, Pedersen et al. [1], Krause et al. [2], Feng et al. [3], Keller et al. [4], Mittag and Gabi [5], Li et al. [6], and Shi et al. [7]. However, most of them performed their measurements in limited areas, such as a single impeller channel or the volute tongue regions.

Thus, this paper presents an experimental study of the flow inside the whole stage of a transparent centrifugal pump, including all the impeller channels, by using a modern visualization technique: the time-resolved PIV (TR-PIV).

2. Experiments and Image Processing

The experimental loop consists of a water flow line with a tank, a booster pump, and instruments to measure flow rate, pressure, and temperature. Furthermore, the facility has a transparent centrifugal pump that was especially developed to enable flow visualization in the impeller and volute. The geometric characteristics of this pump prototype were based on a real electrical submersible pump (ESP) impeller, model P23, series 538, from *Baker Hughes* ®, frequently used as an artificial lift method in the oil and gas industry. A photograph of the test facility is displayed in Fig. 1.

The time-resolved PIV system is a *DualPower 30-1000* model from *Dantec Dynamics*. The system is able to provide an energy of 30 mJ per pulse when operating at a repetition rate of 1000 Hz. Fluorescent particles of PMMA doped with rhodamine were added to the water to serve as tracers. For the rotation (N) of 300 rpm, the tests were carried out at four flow rates (Q) which are multiples or fractions of the best efficiency point (Q_{BEP}), according to Table 1. Then, at a constant flow rate Q = 1800 kg/h, other tests were conducted at two different rotations: N = 600 rpm and N = 900 rpm.

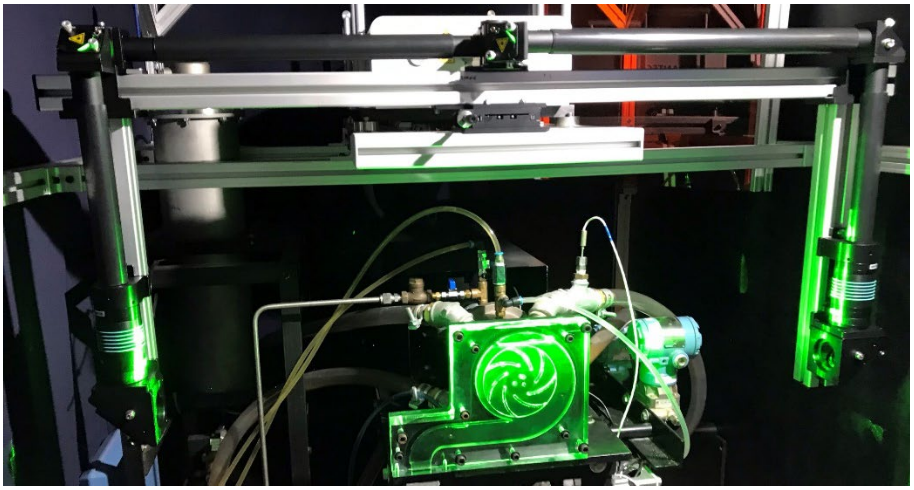

Figure 1. Experimental facility with focus on the PIV system and centrifugal pump.

Each condition requires an additional experiment, which consists of capturing 500 pairs of flow images in the *Dynamic Studio®* software. This whole set of images must be acquired with the impeller at a fixed position. This procedure ensures that the channels and blades are always at a known position, so the average velocity fields can be correctly calculated. The impeller position is defined by an angular encoder, which is used as a trigger to activate the laser and the camera.

Table 1. Test matrix with four of the six conditions analyzed.

Condition	$Q = 0.0\ Q_{BEP}$	$Q = 0.2\ Q_{BEP}$	$Q = 1.0\ Q_{BEP}$	$Q = 1.5\ Q_{BEP}$
$N = 300$ **rpm**	0 kg/h	150 kg/h	750 kg/h	1100 kg/h

In this work, the images were processed in the computer using a *MathWorks MatLab®* algorithm, which was developed to mask the images (defining the region of interest) and then remove the angular displacement of the impeller between each pair of images (making the impeller stationary). This procedure was inspired in the recent studies by Tielicke and Sonntag [8] and Liu et al. [9]. In this case, a relative velocity vector is obtained without considering the angular component due to the impeller motion, i.e., the result is similar to tracking the flow particles in a non-inertial coordinate system that rotates jointly with the impeller.

3. Preliminary Results and Discussions

Figure 2a presents an example of a raw image acquired by the camera and Fig. 2b an example of a processed image that considers the impeller's motion. For the latter, the velocity vectors have a component that represents the angular velocity. This term must be removed by the procedure described in Section 2, in order to facilitate the analysis of the flow in each impeller channel.

Then, Fig. 3 indicates the effect of Q on the velocity fields, for a constant N. As expected, the velocity magnitudes and orientations depend on Q. At low flow rates (Fig. 3a and Fig. 3b, $Q < Q_{BEP}$), the flow is characterized by the presence of distorted profiles, vortices and recirculation regions. At the best efficiency point (Fig. 3c, $Q = Q_{BEP}$), the flow is uniform and the vectors are aligned with the blades. However, at high flow rates (Fig. 3d, $Q > Q_{BEP}$), the vectors deviate from the blades. In this last case, the velocity is higher near the suction blade and lower near the pressure blade.

Finally, Fig. 4 reveals the influence of N on the flow velocity, for a constant Q. As can be observed, the orientation and magnitude of the velocity vectors change as a function of N. Besides, it is clear that the fluid is faster in the channels on the right side of the impeller, and slower in the ones on the left side. This fact is a consequence of the volute geometry, i.e., the volute spiral possibly reduces the flow velocity in the channels which are closer to the solid walls.

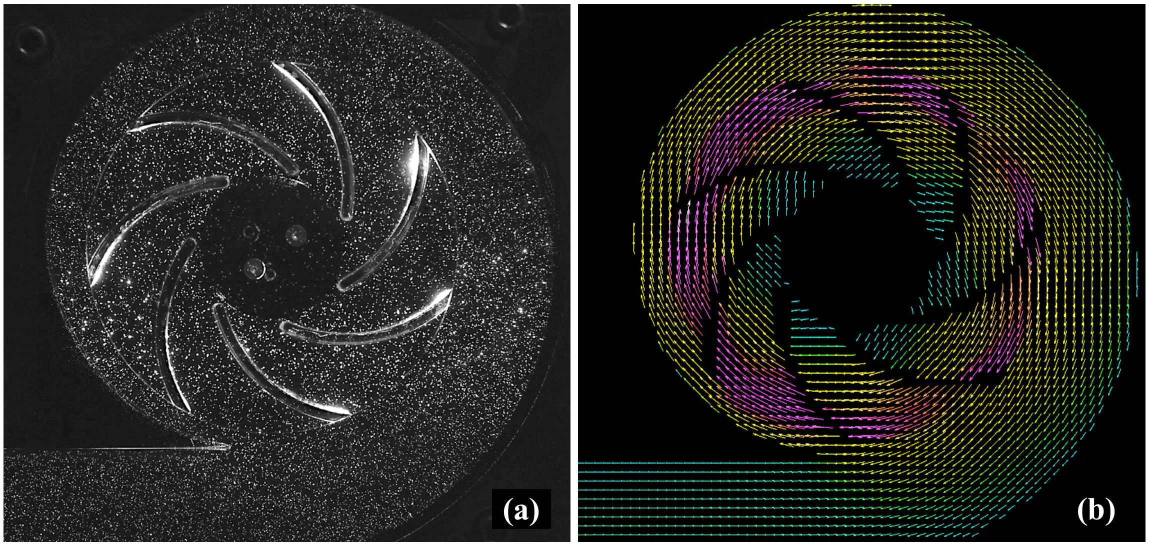

Figure 2. Example of (a) raw image with particles and (b) velocity field considering the impeller rotation.

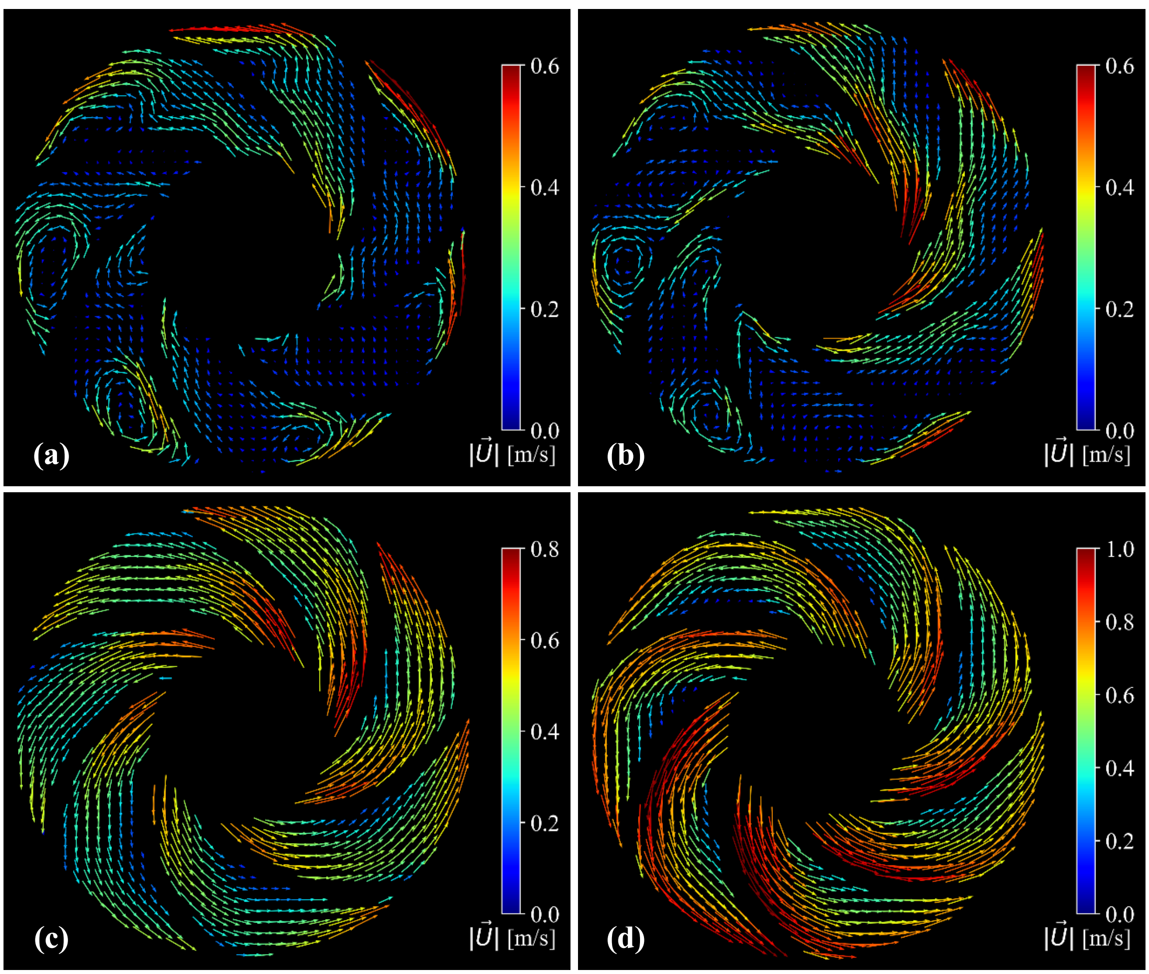

Figure 3. Velocity fields at (a) $Q = 0$, (b) $Q = 150$ kg/h, (c) $Q = 750$ kg/h $= Q_{BEP}$, (d) $Q = 1100$ kg/h, for $N = 300$ rpm.

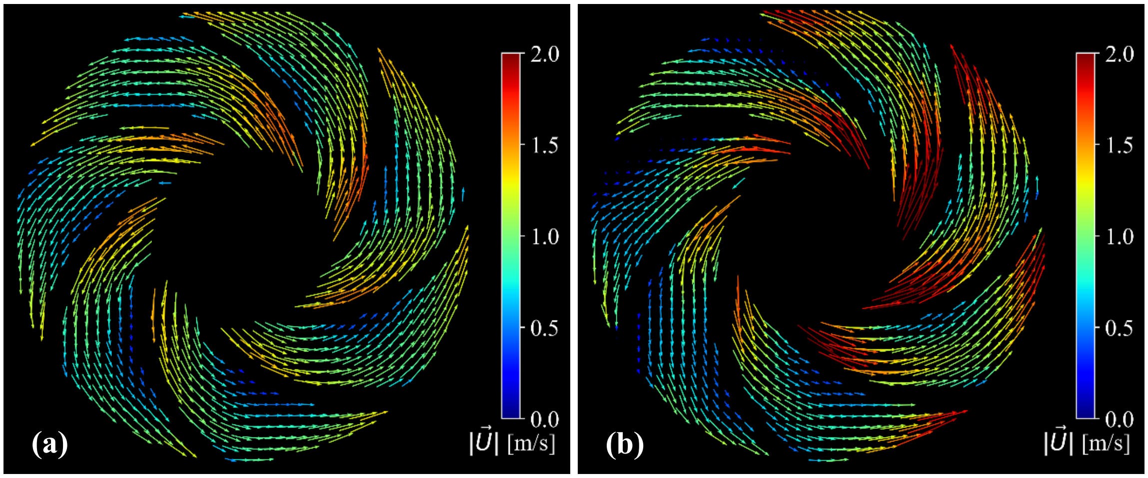

Figure 4. Velocity fields at (a) N = 600 rpm and (b) N = 900 rpm for a constant Q = 1800 kg/h.

4. Conclusion

We performed time-resolved PIV experiments in the stage of a centrifugal pump and processed the acquired images, obtaining the velocity fields in all impeller channels simultaneously. It was observed that the pump operational condition influences the magnitude and direction of the vectors. At flow rates distant from the BEP, the velocity profiles become distorted and the flow often presents structures such as vortices. Furthermore, the flow in the impeller is not axisymmetric, i.e., there are relevant variations depending on the channel being analyzed, due to the spiral geometry of the volute.

Acknowledgements

We gratefully acknowledge the support of EPIC - Energy Production Innovation Center, hosted by the University of Campinas (UNICAMP) and sponsored by Equinor Brazil and FAPESP – The Sao Paulo Research Foundation (Process Number 2017/15736-3). We also thank FAPESP for providing the PIV system used in this research through the Multi-User Equipment program (Process Number 2019/20870-6). We acknowledge the support of ANP (Brazil's National Oil, Natural Gas and Biofuels Agency) through the R&D levy regulation. The acknowledgments are also extended to Center for Petroleum Studies (CEPETRO), School of Mechanical Engineering (FEM), and ALFA Research Group.

References

[1] Pedersen, N.; Larsen, P.S.; Jacobsen, C.B. *Flow in a centrifugal pump impeller at design and off-design conditions - Part I: particle image velocimetry (PIV) and laser doppler velocimetry (LDV) measurements*. J. Fluids Eng. 2003, 125, pp. 61–72.

[2] Krause, N.; Pap, E.; Thévenin, D. *Investigation of off-design conditions in a radial pump by using time-resolved-PIV*. Proceedings of the 13th Int Symp on Applications of Laser Techniques to Fluid Mechanics, Lisbon, Portugal, 2006.

[3] Feng, J.; Benra, F.K.; Dohmen, H.J. *Comparison of periodic flow fields in a radial pump among CFD, PIV, and LDV results*. Int. J. Rotating Mach. 2009, 2009, 410838.

[4] Keller, J.; Blanco, E.; Barrio, R.; Parrondo, J. *PIV measurements of the unsteady flow structures in a volute centrifugal pump at a high flow rate*. Exp. Fluids 2014, 55, 1820.

[5] Mittag, S.; Gabi, M. *Experimental investigation on pump-intake-elbow systems using refraction index matching and TR-SPIV*. Proceedings of the Int Symp on Transport Phenomena and Dynamics of Rotating Machinery, Honolulu, Hawaii, 2016.

[6] Li, X.; Chen, B.; Luo, X.; Zhu, Z. *Effects of flow pattern on hydraulic performance and energy conversion characterization in a centrifugal pump*. Renew. Energy 2020, 151, pp. 475–487.

[7] Shi, B.; Zhou, K.; Pan, J.; Zhang, X.; Ying, R.; Wu, L.; Zhang, Y. *PIV test of the flow field of a centrifugal pump with four types of impeller blades*. J. Mech. 2021, 37, pp. 192–204.
[8] Thielicke, W.; Sonntag, R. *Particle Image Velocimetry for MATLAB: Accuracy and enhanced algorithms in PIVlab*. Journal of Open Research Software 2021, 9, p. 12.
[9] Liu, X-D.; Liu, Z-Q.; Zhong, Q.; Li, Y-J.; Yang, W. *Experimental investigation of relative velocity field based on image rotation method in pump impeller*. Flow Meas. Instrum. 2021, 82, 102061.