PIV measurements in a compact return diffuser under multi-conditions

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Abstract: Due to the complex three-dimensional geometries of impellers and diffusers, their design is a delicate and difficult task. Slight change could lead to significant changes in hydraulic performance and internal flow structure. Conversely, the grasp of the pump's internal flow pattern could benefit from pump design improvement. The internal flow fields in a compact return diffuser have been investigated experimentally under multi-conditions. A special Particle Image Velocimetry (PIV) test rig is designed, and the two-dimensional PIV measurements are successfully conducted in the diffuser mid-plane to capture the complex flow patterns. The analysis of the obtained results has been focused on the flow structure in diffuser, especially under part-load conditions. The vortex and recirculation flow patterns in diffuser are captured and analysed accordingly. Strong flow separation and back flow appeared at the part-load flow rates. Under the design and over-load conditions, the flow fields in diffuser are uniform, and the flow separation and back flow appear at the part-load flow rates, strong back flow is captured at one diffuser passage under 0.2Q_{des}.

1. Introduction

Pump is one of the most energy consuming devices widely used with general machinery in industrial applications. The information about the pump efficiency, manufacturing cost and reliability is required by the end-users before installation decisions are made. Pump manufacturing industry is currently focused on improving the energy efficiency of pumps while addressing stricter and stricter manufacturing constraints [1, 2]. This is particularly of interest in deep-well multistage pump design since it has high head requirement and severe constraints on operating dimensions. In our previous work [3, 4] we proposed a new type of deep-well multistage centrifugal pump with a three-dimensional surface return diffuser, which has a compact size and high pressure conversion capability. However, additional research is needed to expand its application range and to further optimize its hydraulic performance.

Due to the complex three-dimensional geometries of the impellers and diffusers, their design is a challenging task. Small changes in the design can result in significant changes in the internal flow structures affecting the hydraulic performance [5]. Over the years, considerable effort has been devoted towards the study of flow in impellers and diffusers using both the experimental and numerical methods [5-9]; the methods include the Particle Image Velocimetry (PIV), Laser Doppler Velocimetry (LDV), Computational Fluid Dynamics (CFD) and theoretical analysis. For example,
Visser et al. [10] employed the LDV to measure the fluid flow in a low specific speed centrifugal impeller passage and showed that the core of the blade passage flow field could be described quite well by the two-dimensional potential theory at design discharge rates. Sinha and Katz [11, 12] used PIV to identify the unsteady flow structures and turbulence in a transparent centrifugal pump with a vane diffuser. Wuibaut et al. [13] measured the flow velocities in the impeller and vane-less diffuser of a radial flow pump with 2D PIV. Pedersen et al. [14] used both PIV and LDV to illustrate and measure the stall characteristics in the impeller at off-design conditions; both measurement techniques produced data in close agreement. Wu [15] used PIV to investigate the instantaneous internal flowfield in a centrifugal pump with a volute. These and other investigations have significantly contributed to the understanding of the complex three dimensional flowfields in pumps. However, majority of research have focused on the rotating impellers. It appears from the literature that enough effort has not been devoted to understand the flow mechanisms inside the diffuser; it is especially true for the compact return diffusers.

In the present work, two dimensional PIV measurements have been conducted to investigate the internal flowfield in a compact return diffuser. The phase-averaged velocity field obtained by 2D PIV measurements is compared under different flow conditions. The goal is to improve the understanding of the flow structure in a compact return diffuser and provide the guidelines for its optimal design.

2. Geometry
A single-stage pump section is chosen from a multistage deep-well centrifugal pump. The detailed geometry parameters of the impeller and the diffuser are given in our previous paper [3]. Some important pump characteristics are summarized in Table 1. The scheme of the single-stage pump cross-section is shown in Fig.2, and the model used in the test rig with the PIV system is shown in Fig. 3.

| Description                  | Parameter | Value |
|------------------------------|-----------|-------|
| Design flow rate (m³/h)      | Q<sub>des</sub> | 20    |
| Head (m)                     | H<sub>s</sub> | 11    |
| Rotational speed (r/min)     | n         | 2850  |
| Specific speed (m³/h, m, r/min) | n<sub>s</sub> | 35 |
| Impeller blade number        | z<sub>i</sub> | 7     |
| Impeller inlet blade angle (º) | β<sub>1</sub> | 32 |
| Impeller outlet blade angle (º) | β<sub>2</sub> | 15 |
| Impeller outlet blade width (mm) | b<sub>2</sub> | 12 |
| Front shroud diameter (mm)   | D<sub>2max</sub> | 119  |
| Rear shroud diameter (mm)    | D<sub>2min</sub> | 108  |
| Diffuser vanes number        | z<sub>d</sub> | 6     |
Generally, the standard deep-well centrifugal pump has a cylindrical outside wall. In order to reduce the refraction in the PIV measurements, the outside wall is extended to a square type wall. The diffuser and the entire outside wall are manufactured with transparent plexiglas as shown in Fig.1 (b). Most of the published papers employing PIV for flowfield measurements in pumps use the pump rotating speed equal to or less than 1450 rpm, since the transparent plexiglas makes it difficult to take measurements at high rotating speeds. In this work, in order to measure the flow in the diffuser at the original pump speed of 2850 rpm, the impeller was manufactured using plastic materials.

3. Experiments

Figs.2 and 3 show the scheme of the test rig and the PIV system. The PIV experiment system consists of a laser, a CCD camera, a synchronizer, a photoelectric encoder and a data processing computer. The laser used is a YAG200-NWL pulse laser, which has 200mJ pulse energy and 30 Hz pulse frequency. The CCD camera has 2K*2K light sensitive pixels, 16 frames/s frame rate and 200ns minimum frame straddling time. The TSI Insight 3G software is used for data acquisition, analysis and display. The flowfield analysis is accomplished using TECPlot software.

The three phase asynchronous motor used in the experiment has 2900 rpm rated speed and 3.3 kW rated power. A variable frequency control cabinet is used to adjust the motor rotating speed to 2850 rpm (pump rated speed). The shaft encoder is located at the end of the pump shaft, which sends out one sync pulse per revolution, and then TSI synchronizer synchronizes the impeller rotation, laser pulse, and the image acquisition. The tracing particles used are Al₂O₃ powder of approximately 1 μm
diameter, which flow synchronously with the liquid and scatter effectively the laser. Two water lubricated bearings are fastened on both sides of the shaft, and the impeller is connected with the shaft by a spline joint.

The original 3D return diffuser was designed for the deep well water pumping, which has small diameter and compact dimensions (maximum diameter is 121 mm). As a result, there is not enough space to place the camera. Therefore a plane mirror with central holes is used to refract light; it is placed at 45 deg to the axis of the test rig as shown in Fig. 3. An image of the apparatus during the PIV measurements is shown in Fig. 4.

Due to the influence of the central hole in the mirror and the outlet pipe downstream of the diffuser and the large refraction from the three dimensional surface of the diffuser vanes, we were able to capture only a partial surface in the PIV measurement as shown in Fig. 5. Two passages were selected from the captured surface, namely Region A and Region B as shown in Fig. 5. The cambered surface on the diffuser inlet side partially refracts some laser light which results in a certain degree of inaccuracy in the measurement, especially in Region B. It is important to note that only the velocity components in the plane of the laser light sheet are determined by the two-dimensional PIV measurements. The axial component of the velocity is not measured. However, from the results of CFD computations described in section 4, it was found that the out-of-plane velocity is relatively very small.

The pump inlet and outlet pressure are measured by the high accuracy pressure transmitter with 0.1% measurement error. A gate valve is used to control and change the flow rate. The flow rate is measured by an electromagnetic flow meter with 0.3% measurement error. The motor rotating speed is measured by an infrared velocimeter with 0.05% maximum uncertainty.

4. Results

In the PIV measurements, each of the measured velocity components \((u, v)\) in two orthogonal directions can be decomposed into two parts: a phase-averaged component \((\bar{u}, \bar{v})\) and a fluctuating part \((u', v')\), as shown in Eq. (1), Eq. (2) and Eq. (3) below. The phase averaged absolute velocity \(\bar{C}\) in Eq. (4) is obtained using the phase-averaged components [16].

\[
\begin{align*}
    u_i(x, y, \phi) &= \bar{u}(x, y, \phi) + u'_i(x, y, \phi), \quad i=1,\ldots,N \\
    v_i(x, y, \phi) &= \bar{v}(x, y, \phi) + v'_i(x, y, \phi), \quad i=1,\ldots,N \\
    \bar{u}(x, y, \phi) &= \frac{1}{N} \sum_{i=1}^{N} u_i(x, y, \phi), \quad \bar{v}(x, y, \phi) = \frac{1}{N} \sum_{i=1}^{N} v_i(x, y, \phi) \\
    \bar{C}(x, y, \phi) &= \bar{u}(x, y, \phi) \hat{\textbf{i}} + \bar{v}(x, y, \phi) \hat{\textbf{j}}
\end{align*}
\]

![Figure 4. Test rig](image1)

![Figure 5. Field view in CCD camera](image2)
where \( N = 300 \) is the number of instantaneous vector maps for the same impeller position and \( \phi \) is the impeller circumferential position.

The target surface for the PIV measurements is the diffuser middle section. Fig. 6 shows the phase-averaged velocity contours and streamlines obtained by PIV measurements under different flow rates with the same scale. The PIV system in this study has only one camera, which could capture only the tangential velocity and the circumferential velocity, without the axial velocity. Besides, the flow area of the diffuser passages has a gradual expansion in the middle part. At the design and over-load conditions \((Q/Q_{\text{des}} \geq 1.0)\), all the measured velocity streamlines are directed from the diffuser inlet to the outlet, and there is no evidence of back flow or recirculation.

![Velocity contours and streamlines in diffuser middle section](image)

**Figure 6.** Velocity contours and streamlines in diffuser middle section

The velocity reduces gradually from diffuser inlet to outlet, which of course is the diffuser function to transform the kinetic energy to pressure energy. As the high velocity fluid flows out of the impeller exit and passes through the diffuser, it becomes divergent and breaks into a series of sub-streams associated with the process of converting velocity into pressure. Such transition cannot only be
attributed to the wake of the diffuser vanes but also to a substantial slowdown of the flow on the convex side of the diffuser vanes, particularly when vast amount of fluid hits the vanes leading edge. Due to the diffuser blade angle being less than 90 deg, the diffuser is not able to eliminate the absolute tangential velocity completely; therefore the diffuser outlet still has relatively high velocity. At the diffuser throat, the velocity experiences a sudden drop which means large shock losses and hydraulic losses occur in this region.

An interesting phenomenon is observed when flow rate increases to 1.4Q_{des}; the velocity at the diffuser inlet upstream has a decrease compared to the value at design flow point. Generally, the velocity at the impeller exit should increase with the increasing flow rate. The velocity decrease caused by the limited diffuser flow area blocks the high velocity fluid and a large amount of energy is lost at the diffuser inlet. Such a situation leads to drop in diffuser pressure conversion capability under overload conditions, which were also shown in our previous work [3]. Also, compared to the pressure side, the diffuser suction side is more influenced by the non-uniform flow out of the impeller.

Fig. 6(c) and Fig. 6(d) compares the velocity contours and streamlines obtained by the PIV measurements under the part-loading conditions of 0.4Q_{des} and 0.2Q_{des}. At part-loading condition of 0.4Q_{des}, the velocity at the diffuser inlet edge becomes much smaller than the design value. Consequently, flow separation occurs on the diffuser suction side when the incidence angle at the diffuser vane leading edge reaches a certain threshold. As shown in Region A of Fig. 10, at relatively small flow rates, a concentrated vortex appears below the leading edge of the diffuser vane, where the flow separates intermittently due to changes in the incidence angle induced by the non-uniform outflow from the impeller at smaller flow rates. The recirculating back flow from the diffuser into the impeller occurs at 0.2Q_{des}, and the extent of the back flow is circumferentially non-uniform.

5. Conclusions
In the present work, the flowfields in a compact return diffuser have been investigated experimentally by PIV measurements. The detailed analysis on the flowfields shows that the flow rate has a very evident influence on the flow structure. Flow separation and back flow appear at the part-load flow rates, and the strong back flow is captured in the diffuser passage at part load condition of 0.2Q_{des}. At smaller flow rates, due to the changes in the incidence angle induced by the non-uniform outflow from the impeller, a concentrated vortex appears below the leading edge of the diffuser vane. This work provides a good data set to develop and validate the CFD models for flowfield inside the diffuser of centrifugal pumps.

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