Study Of Flow Field In An Advanced Bladeless Rotary Blood Pump Using Particle Image Velocimetry

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Abstract
Understanding the flow characteristics of a rotary blood pump is the first step towards increasing its acceptance as cardiac assist device. One has to consider the damage to the blood cells due to hemolysis and thrombosis that occur in the pumps. Hemolysis or red blood cell damage occurs in regions of high shear stresses. The shear stresses cannot be eliminated, but can be substantially reduced through proper design of the pump. Therefore characterizing the different flow regimes in various areas of the pump is very important. A better understanding of the flow fields can be very useful in the judicious design of the pump. Furthermore, experimental data are needed to validate the numerical codes used for design purposes. Hence focus of this investigation is to obtain flow characteristics for various flow regimes using non-intrusive Particle Image Velocimetry (PIV). A three disc optically clear magnetic drive bladeless pump, which is an evolved version of the Tesla pump, is investigated. The casing and the impeller discs are made of acrylic. The refractive indices of the impeller and pump casing material and the blood simulant liquid are matched (1.485). This minimizes the light scattering at the liquid solid interfaces and facilitates the application of PIV. The blood simulant fluid is composed of saturated aqueous sodium iodide (NaI) solution, glycerin and distilled water. The fluid approximates the steady flow kinematic viscosity of blood. Neutrally buoyant silver coated hollow glass spheres are used as seed. The PIV images are analyzed using the cross correlation technique to obtain the velocity vector maps. The velocities obtained are an average of 700 - 1000 image pairs. An uncertainty analysis was carried out to ensure that the error levels encountered were in the acceptable range. An ensemble size of 750 data sets results in an uncertainty level of ±1.3%.

Introduction

Nearly five million Americans are said to be living be problematic hearts and more than fifty thousand tend to be diagnosed every year (National Heart, Lung, and Blood Institute website). Though a small number of donor heart are available for heart transplants, the demand is substantially higher. Cardiac assist devices are also required to alleviate the stress on heart during open heart surgeries and in recovery. Therefore the development of artificial heart and cardiac assist devices is very important.

The usage time of these cardiac assist devices are currently limited due to a variety of reasons. These include the damage to the blood cells due to hemolysis and thrombosis that occur in the pumps. Hemolysis or red blood cell damage occurs in regions of high shear stresses. Though shear stresses are inherent characteristic of viscous flow and cannot be eliminated, they can be reduced through judicious design of the pump. Thrombosis is the formation of blood clots due to complex reactions of blood. It has been found that stagnation regions are more prone to thrombus formation. The emphasis has also been placed on developing new or improving the existing rotary blood pumps to reduce effects of hemolysis and thrombosis. One candidate for use as a cardiac assist
device is the rotary bladeless disc pump.

The bladeless disk pump is modeled after a pump invented by Nikola Tesla in the early part of the 20th century. A distinguishing characteristic of Tesla Turbomachinery is that the rotor is composed of flat parallel co-rotating discs, spaced along a shaft. It is also referred to as bladeless because of its use of the boundary layer effect and not fluid impinging upon the blades as in a conventional turbine or pump. The disk pump utilizes the viscous properties of the fluid in its functioning. In the conventional configuration, a motor is attached to the shaft and the fluid enters axially and exits radially.

The ideal measurement technique for obtaining flow field in the rotary pumps should be able to characterize the two/three-dimensional flow field in the pump over a wide field of view. Intrusive velocity measurement methods compromise the flow field by disturbing the flow in the pump; therefore, non-intrusive techniques are the preferred method to study the flow behavior. This suggests the use of a non-intrusive optical technique, which would provide measurements of velocity at multiple spatial points in planer (2D/3D) fields. The Particle Image velocimetry (PIV) is one such a method.

The use of various flow visualization techniques for artificial organs have been reported in the literature and a detailed literature review is provided by Sastry (2006). These include particle streak imaging using fluorescence in a prototype SUN Medical Technology pump. Laser Doppler anemometry (LDA) has also been used to obtain velocity in blood pumps however, the technique is limited to instantaneous point measurement. Subramanian, et al. (2000) applied PIV to the study of heart valves and Wernet, et al. (2000) compared the advantages of PIV with respect to LDA as applied to heart valves. Most recently Day, et al. (2001) have reported recent progress in applying PIV to an acrylic model of the HeartQuest pump and have presented velocity field data for the pump inlet; however, no mention is made regarding number of data pairs or the measurement uncertainty.

Sankovic et al. (2004) have used PIV technique in making measurements in a centrifugal blood pump to obtain stress levels. A thorough uncertainty analysis was carried out. The impeller consisted of seven blades with an outside diameter of 35mm. Velocity measurements were made in the volute exit and diffuser region for pump speeds of 3000-3850 rpm at a physiological pressure of 12 kPa. Four hundred data pairs were used for each resultant mean vector velocity resulting in uncertainty levels of about ±2.9%.

The goal of this study is to develop a better understanding of the flow in a bladeless disk pump and its suitability as a blood pump. The objective of this work includes characterizing the flow in key regions in the pump. Particle Image Velocimetry (PIV) will be used in this investigation.

Methodology

A three disc optically clear magnetic drive bladeless pump is investigated. The casing and the impeller discs are made of clear acrylic. The impeller is made of two hollow acrylic cylinders between which three disks are placed and held together by four symmetrically located pins. The flow enters the impeller axially. The pump schematic and the flow path are shown in Figure 1. The refractive indices of the impeller, the hollow cylinder and pump casing material (all made out of acrylic) and the blood simulant liquid are matched (1.485). This minimizes the light scattering at the liquid solid interfaces and facilitates the application of PIV. The impeller floats in this liquid. On the fore part of the rear cylinder, magnetic strips are placed. The casing is held circumferentially
and coupling magnets are placed in line with the magnetic strips on the impeller. The coupling magnets and the pump rotor are driven by a DC motor.

The flow loop consists of the rotary bladeless disc pump, reservoir, a flowmeter, a differential pressure gauge, an appropriate amount of tubing and a valve. The reservoir is placed at a height of 23 cm above the pump. The flow is led from the reservoir through a 1.0 cm tubing to the pump. A variable area type flowmeter (King Instrument Company, accuracy ±1% of full scale reading of 7.6 lpm) is placed downstream of the pump. A differential pressure gauge (Orange Research Inc.) is used to obtain the pressure drop across the pump. The differential pressure gauge has a full scale reading of 10 psi with an accuracy of ±2%. The working fluid used for this study was a mixture of water, sodium iodide and glycerin with a specific gravity of 1.69. The sodium iodide/water solution was selected such that the refractive index of acrylic was matched, and was measured to be 1.485 ± 0.001. Silver-coated glass spheres, 15 micron in diameter were used as the particles and were neutrally buoyant. The fluid approximates the steady flow kinematic viscosity of blood (3.2 cS at 20°C) and was used earlier by Subramanian et al. (2000). The kinematic viscosity is matched to that of blood for shear rates greater than 500 s⁻¹ (Subramanian, et al. (2000)).

The flow diagnostic for the test setup is the PIV system which includes laser, optics system, CCD camera, Digital Delay Generator (DDG), Optical Encoder and processing hardware and software to obtain the velocity flow field.

PIV System
Particle Image Velocimetry is a technique for measuring the in-plane two-component velocity field of a flow seeded with tracer particles small enough to accurately follow the flow. A pulsed laser light sheet is used to illuminate the particles entrained in the flow. The light scattered by the particles is collected normal to the plane of the light sheet and is imaged onto a CCD camera, where the positions of the particles are recorded at each instant the light sheet is pulsed. The data processing consists of determining the average displacement of the particles over a small interrogation region in the image between pulses of the light sheet, known as cross-correlation. The
time interval between light sheet pulses is used to compute the flow velocity.

The PIV set-up used is described in detail by Sastry (2006). The PIV hardware consists of a 120 mL/pulse Nd:YAG laser (532 nm wavelength), laser light sheet optics, a CCD camera (Kodak ES1.0, Redlake MASD Inc; resolution: 768 x 484 pixels) equipped with a 200 mm Micro Nikkor lens (Nikon). The camera is controlled by a host computer through a PIXCI-D2X frame grabber board (EPIX, Inc., Buffalo Grove, IL). The laser beam (3.5 mm diameter) is formed into a light sheet (0.37 mm thick; 256 mm wide) using a combination of cylindrical and spherical lenses. The image pair acquisition was synchronized to the impeller rotation using a once per rev signal, which then triggered the digital delay generator (DDG). The DDG in turn sends a signal to the PC through PIV 2000 processor, which then fires the laser and acquires the images from the PIV camera. Figure 2 shows a schematic diagram of the PIV setup. For each of the operating conditions 700 to 1400 pairs of single exposure image frames were obtained. The image pair acquisition and processing is done using the PIVACQ and PIVPROC software.

![PIV System Diagram](image)

**Figure 2: PIV System**

**Test Locations:**

Data was taken in the locations given in Figure 3. In Figure 3, a box with a location number in it indicates the FOV of that particular location while a location number adjacent to a line gives the plane of incidence of the laser light sheet.

Location 1 is at the bottom right corner when looking into the inlet of the pump as shown in Figure 3. It is a small back flow region about as wide as the separation between the impeller and the housing. The flow here is similar to Couette flow between cylinders. Field of view is 13mm x
13mm. Location 2 is similar to location 1 in the sense that it is also flow between cylinders. This location is situated in the space between the top of the impeller and housing. The height of the gap is the difference in radii of the outer and inner cylinders. Field of view for this location is 12mm x 12mm. Location 3 is at the very front. It is taken just below the inlet, on the bottom right to the viewer. It is a back flow region which means that the fluid in this region does not contribute directly to the pump output, but helps in keeping the pump afloat. Field of view in this case is 13mm x 13mm. Location 4 is the space between two discs as shown. Field of view at this location is 75 mm x 75 mm.

These locations were selected after substantial consideration. Locations 1 and 2 which are between the impeller and the housing and the flow profile data at these locations are critical in improving pump design. Similarly location 3 is a back flow region, where it was interesting to observe the flow pattern. Location 4, which lies in between discs gives the velocity profile of the fluid that is being acted on by the viscous forces.

Figure 3: Schematic of the test locations

**Uncertainty analysis**

The PIV images are analyzed using the cross correlation technique. The velocities obtained are an average of 700-1000 image pairs. Each experiment has to take into consideration the two uncertainties; the random uncertainty and the systematic uncertainty. The random uncertainties pertain to actual measurement of the physical quantities. These elements can be sampled with available procedures and apparatus. They are based on statistical estimates from samples.

The systematic uncertainty cannot be sampled with the available procedures and/or apparatus and are generally estimated. The systematic error for a measured variable is that fixed error which remains after all the calibrations have been made. The systematic uncertainty consists of the spatial & the temporal uncertainties involved in the measurement of the particle on the CCD array.
The timing error associated with an Nd:YAG laser is negligible (approximately $2 \times 10^{-5}$). The accuracy in the measurement of distance on the CCD array for system used is approximately 0.1 to 0.2 pixels (Wernet and Pline, 1993). The total displacement of the particle is 16 for a sub region size of 64. Thus neglecting timing uncertainty, the total full scale displacement uncertainty is the total bias uncertainty for the system. The systematic error for the PIV system is 0.6%.

An uncertainty analysis was carried out to ensure that the error levels encountered were in the acceptable range. Figure 4 is a plot of number of data sets on x-axis vs. random error on the y-axis. The plot shows that the error is proportional to the inverse square root of the number of measurements. Theoretically we would have to take infinite number of data sets for the random uncertainty to be zero. But it has to be noted that for a flow with a certain degree of turbulence, random error will never go to zero. In the example, random error for Location 3 (Speed 3000 rpm, Volume Flow rate – 3 lpm) is plotted. The uncertainty for 750 data sets is ±1.3%.

**Results and Discussion**

Flow field data in the space between the impeller and the housing (locations 1 and 2) are shown in Figures 4a and 4b respectively. The dashed line shows the actual position or the resting state position of the impeller surface. But due to wobble of the impeller, the gap between the two cylinders varies during the experiment and thus velocity vectors are obtained for a region greater than the resting state distance between the inner and the outer cylinders. From the velocity vector maps it is observed that the velocities adjacent to the surface of the rotating impeller surface are less than the velocities slightly further away. This is because the representative maps are an ensemble averaged and at several instants, there is no flow in the area due to the wobble of the impeller.
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Figure 4: a) Velocity profile at location 1: Speed – 2000rpm, Flowrate - 2lpm, Δp – 22.4kPa.

Figure 4: b) Velocity profile at location 2: Speed - 2000rpm, Flowrate – 3lpm, Δp – 20.7kPa
This experimental data was compared to the phenomenon of Couette flow between cylinders. Figure 5 is plot of the velocities obtained via experiment comparing it to the theoretical value.

![Figure 5: Velocity Distribution Curve - Location - 3, All Speeds](image)

From Figure 5, it is observed that the non dimensional velocity at the surface of the inner cylinder differs from the theoretical value. Reasons for this might be the assumptions made in the derivation of the theoretical equations that do not reflect the physical situation. Unfortunately the current design of the pump housing prevents experimental data to be taken in the axial plane. Another reason for this departure could be due to dissipation losses which have been neglected in the theoretical criteria. A third reason can be attributed to the wobble of the rotating inner cylinder which could actually contribute to velocity components in other directions. A fourth reason is that due to the wobble of the impeller, the ensemble mean of the velocities near the inner rotating cylinder is less than the actual instantaneous value. The flow is not similar to Couette flow between cylinders. The deviation occurs due to existence of flow velocities in the axial and the radial direction. However, near the outer stationary surface the experimental velocity profile is similar to the Couette flow. Unstable flow was encountered at Locations 1 and 2 due to the wobble of the impeller.
Figure 6: Velocity profile at location 3: Speed–3000rpm, Flowrate–3lpm, Δp–43.1kPa.

Figure 6 depicts the velocity profile at location 3. The plane in which the data is taken is about 3 mm in front of the rotating cylinder. From the velocity plots it can be observed that the rotating impeller influences the flow in this area. Since the velocity of the rotating cylinder is function of the angular velocity and the radius, the velocity of the fluid in this region, for the most part, is also seen to increase with increase in angular velocity and radius. At large radii (bottom right corner in the velocity vector plots) the velocities decrease. This is because of proximity of the pump housing and the wall effects take precedence over influence of the rotating impeller.

Figure 7 shows the velocity profile at location 4. It is observed that the maximum velocity is around 4.5m/s at distance slightly less than that of the radius and the flow velocity decrease from this maximum value as we go towards the outer extreme. This is primarily because of the proximity of the stator housing wall begins to affect the flow velocity. The theoretical velocity at the tip of the disc is about 5.6 m/s. Another reason for this discrepancy is that the flow is occurring in between two discs which are set very close to each other and the viscous effects tend to dominate and reduce the velocity of the fluid.
Summary

The objective of this study was to develop a technique capable of imaging the flow field inside a bladeless disc blood pump and obtaining the flow velocities in various areas of the disc blood pump. The experimental results obtained will be useful for validation of computer codes. This study is among the first to characterize flow inside a disc pump used as a type of cardiac assist device. The work presented in this study is an important step towards understanding the physics of flow in such pumps.

Flow in the spacing between the impeller and the housing (Locations 1 and 2) is not similar to Couette flow between cylinders. Deviations occur due to existence of flow velocities in the axial and the radial direction, which were not considered. Though, near the outer stationary surface the experimental velocity profile approximated the theoretical ones.

At location 3, it can be inferred that the rotating impeller influences the flow in this area and the velocity of the fluid in this region seen to increase with increase in angular velocity and radius. At large radii the velocities decreases due to the proximity of the pump hosing and here the wall effects take precedence over influence of the rotating impeller. And at location 4, the flow is similar to the flow over a disc.

References


