A Prototype HeartQuest Ventricular Assist Device for Particle Image Velocimetry Measurements

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Abstract: The objective of this study is to fully characterize the flow within the HeartQuest ventricular assist device (VAD), a magnetically levitated centrifugal VAD, using particle image velocimetry (PIV) to identify regions of potential high shear or stagnation and validate and refine computational models of the flow. An acrylic model of the pump was designed and constructed to allow optical access into all interior regions of the pump. The geometry of the exterior housing and the use of a novel working fluid make quantitative measurements of velocity within the exit volute, blade passage, cut-water, blade tip clearance, and pump inlet possible. Highly accurate velocity measurements using particle PIV have been made in one region (the inlet elbow), and measurements in the other critical regions of the pump will be made. These measurements are used for investigation of regions with potential for hemoysis resulting from high shear stress or with potential for thrombosis caused by recirculation or stagnation. Quantitative velocity data are also needed for comparison with computational fluid dynamics (CFD) models of the VAD. In this study, experiments have again proven to be an essential complement to CFD for thorough investigations of the flow inside the pump. Key Words: Particle image velocimetry—Ventricular assist device—Index of refraction—Velocity measurement—Prototype.

INTRODUCTION

The fluid dynamics within a centrifugal ventricular assist device (VAD) are extremely important. Besides determining the overall pump performance, the local flow field affects blood damage. Stagnation can lead to potentially fatal thrombosis, and exposure to high shear stress can lead to hemoysis. Understanding the local fluid behavior inside the pump is therefore critical. The objective of this study is to fully characterize the flow within the HeartQuest VAD using particle image velocimetry (PIV) to identify regions of potential high shear or stagnation and validate and refine computational models of the flow. Steady-state velocity measurements in the front clearance gap of a previous HeartQuest centrifugal pump demonstrated the effectiveness of PIV as an accurate measurement technique (1). Furthermore, comparison with computational fluid dynamics models (CFD) showed that the numerical solutions must be validated by experiments to trust CFD as a design and analysis tool for the prediction of local flow features. In addition, PIV offers the potential of making a series of instantaneous measurements of the flow field that clearly characterizes the time-dependent flow field that results from both the blade passage and pulsatile flow through the pump.

METHODS

To accomplish PIV measurements within the HeartQuest VAD, a prototype pump that allows for optical access into nearly all interior regions of the pump was designed and built. The internal flow paths are identical to the version of the pump that has been used in animal implant tests and has been modeled extensively with CFD. The pump is run within a mock circulatory loop that includes a pulsing left ventricle and systemic resistance and compliance to completely model transient effects. The pump housing is made of acrylic and has large flat
exterior surfaces to eliminate optical distortion. In addition, a working fluid with an optical index of refraction that is nearly equal to that of acrylic is used to reduce distortion caused by refraction at the interior surface.

INDEX MATCHING

The combined effect of flat exterior surfaces and an index-matched fluid can be seen in Fig. 1 which shows the impeller as viewed through the upper housing. In Fig. 1a, the pump is filled with water, and the outer diameter of the impeller is severely distorted in the region of the inlet elbow but is round everywhere else. In contrast, Fig. 1b shows the pump filled with an index-matched fluid which effectively eliminates optical distortion.

Prior studies have used aqueous salt solutions as index-matched fluids (2), but the high concentrations of salt result in fluid densities that do not effectively model blood flow through the pump. The current study uses dibutyl phthalate (n-Butyl Phthalate) as a Newtonian blood analog. The fluid has a high viscosity at room temperature, but heating the working fluid to 50°C decreases this. At this temperature, the liquid has a viscosity of 5 cp and an index of refraction of 1.485 compared with 1.492 for acrylic for the wavelength used (532 nm).

PARTICLE IMAGE VELOCIMETRY (PIV)

Optical measurement techniques offer several advantages over physical probes. Traditional mechanical measurement probes may distort the flow that they are measuring. Second, optical techniques offer the advantage that light may be used to probe regions in which one could not easily locate a physical probe, such as the small clearance regions inside the heart pump. PIV is a technique that measures the instantaneous velocity field within an illuminated plane of the fluid field using light scattered from particles seeded into the fluid. Using a laser as a light source, one can accurately locate and shape this illuminated plane so that one can make quantitative measurements within a very thin measurement volume (3).

The accuracy and precision of measurements based on modern digital PIV techniques have been extensively studied by numerous investigators (4,5). In summary, the use of a digital camera, pulsed laser, and modern correlation-based algorithm typically results in an uncertainty of the measured velocity of approximately 1–2% of the maximum velocity being measured. The spatial resolution (distance between measured velocity vectors) of this technique is approximately \( \sqrt{V_{\text{low}}} \) of the camera field of view. In this application, these correspond to an uncertainty in velocity of 0.01–0.05 m/s and spatial resolution on the order of 0.2 mm. The temporal resolution of the measurement is determined by the time separation between laser pulses and is typically about 0.1 m/s.

Image acquisition is accomplished with a commercially available PIV system (TSI Inc., St. Paul, MN, U.S.A.). A pulsed Nd:YAG laser (Spectra Physics, Mountain View, CA, U.S.A.) at 532 nm illuminates fluorescent-filled particles (Duke Scientific, Palo Alto, CA, U.S.A.) that are added to the flow. These particles are nominally 10 \( \mu \)m in diameter and, in addition to scattering the incident light, fluoresce at 610 nm. A digital camera collects the light after it has passed through a long pass filter with cut-off of approximately 570 nm (Schott Glass Technologies, Duryea, PA, U.S.A.). The camera sees only the fluoresced light, because the filter blocks the scattered light from the nearby surfaces. Image analysis conducted to calculate velocities is done with an adaptive mesh cross-correlation algorithm created by Scarano and Riethmuller (6). The processing of velocity fields to find turbulence characteristics, shear

![FIG. 1. Comparison of view is shown through the top of the VAD using water- (a) and index-matched fluid (b).](image-url)
stress, quantify unsteady phenomena, etc. is done with programs written as part of this work.

RESULTS

A detailed presentation of the measured flow field and comparison with computational results is not the focus of this article, but examples of measured velocity fields are presented here to show the effectiveness of the prototype and measurement technique. A comparison of the measured and computed velocities at the center plane of the inlet elbow is shown in Fig. 2. Although distinct differences between the experiment and computation exist, there is a fair agreement between the two in that they both do not indicate regions of stagnation or high shear stress. The most notable discrepancy is that the CFD shows a high-velocity region toward the lower (inner radius) part of the bend, whereas the experiment shows the velocity in this region to be near the mean velocity and, rather, a high velocity region further upstream and closer to the outside diameter of the elbow.

An example of the measured velocity field for the pulsed condition (pump is operating at constant speed while left ventricle is beating) is shown in Fig. 3, which shows the velocity field at the beginning of diastole. Measurements like this have been made at 20 times during the heartbeat to resolve the transient behavior of the flow field. Whereas the flow field for the steady flow condition exhibits no regions of high shear stress, stagnation, or recirculation, areas of recirculation and stagnation are clearly identified during this and other portions of the pulse cycle.

CONCLUSIONS

The prototype pump and index-matched fluid allow optical access into all regions of the pump with negligible distortion and enable highly accurate and detailed characterization of the internal flow field. Measurements have been made at one location within the pump (inlet pipe) and will be made in several additional regions of interest. Although there is good agreement between the experiment and CFD regarding the global flow features (lack of recirculation or stagnation) for the steady flow case, there are distinct discrepancies between the two. These differences are likely due to the boundary condition applied at the inflow boundary of the inlet elbow or are the result of faulty turbulence modeling and will be corrected in future computational models. In addition, measurements of the flow field during the pulsed flow condition have been made, and these will be invaluable when validating computational models of the transient flow field that are currently being developed. The necessity of using experimental data to validate and refine computational models during the design process is clearly demonstrated by these results.

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REFERENCES


