Flow Visualization Measurement for Shear Velocity Distribution in the Impeller-Casing Gap of a Centrifugal Blood Pump

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A flow visualization study of a centrifugal blood pump was conducted to find the shear and velocity profiles in the back gap between the impeller and the casing. For a wide range of Reynolds numbers and specific speeds, it was found that high shear exists only in the boundary layers of the moving and stationary walls. The velocity profile was essentially laminar. It was also found that the total thickness of the high shear regions is 0.3 - 0.6 mm for conditions of artificial heart and the thickness is determined only by Reynolds number. Hence, it can be concluded that reducing the impeller velocity is the only way to reduce wall shear stress and that increasing the gap width is not effective.

** Key Words:** Flow Visualization, Boundary Layer, Shear Flow, Pump, Biofluid Mechanics

1. Introduction

It is important in the development process of a centrifugal pump for a totally implantable artificial heart to prove that there will be no blood clotting (thrombus formation) or little blood cell destruction (hemolysis). Thrombus formation seems to be caused by stagnation or standing vortices and hemolysis by high shear exposure. Flow visualization technique is useful in identifying the locations of the above undesirable flow and in establishing design concept. With information obtained from visualization, the centrifugal blood pump can be designed to eliminate such problems. This paper focuses on the shear and velocity distributions in the impeller/casing gap to apply the data for designing the gap size and the impeller velocity.

2. Materials and Methods

2.1 Experimental Procedure

The experimental setup (Fig. 1, Fig. 2) incorporates a 3-times scale-up model of the prototype blood pump made of acrylic resin having a semi-open 4-vaned centrifugal impeller (Fig. 3)\(^{(1)}\), in a continuous flow circuit including a fluid reservoir and a valve to adjust the flow rate. An important feature of the pump is the implementation of washout holes penetrating the impeller, which induce recirculatory radial flow behind the impeller to prevent blood stagnation. The working fluid is 64 wt% NaI (aq), with 0.1 wt% Na\(_2\)S\(_2\)O\(_5\) stabilizer, chosen to match the refractive indexes of the fluid and the acrylic resin\(^{(2),(3)}\). Tracer particles, explained below, were introduced to the flow and were illuminated by an Argon-ion laser light sheet (7W capacity, Model 95-7, Lexel). The images were recorded with a high speed video camera (8 bit \(\times\) 256 \(\times\) 128 pixels, 9 000 frame/s for half screen mode; Ultima-UV, Photron) and then transferred to a laser disk video recorder for subsequent computer analysis by particle tracking velocimetry ('Current', Kanomax)\(^{(4)}\).
The real size prototype pump achieves the necessary performance of 5 L/min and 14 kPa, at a rotational speed of 2700 rpm, which is too fast for flow visualization analysis. Therefore, a scale-up model was used. By using a 3-times scale-up model, the rotational speed can be reduced to 1/9 for blood, or to 1/15 for NaI (aq) whose kinematic viscosity is 3/5 of blood, based on Reynolds similarity law.

Observations are made at radii $r=0.9R$ and $r=0.7R$, where $R$ denotes impeller radius. The corresponding 'observed area' (gap) is $8.0 \times 3.2$ mm for the 3-times scale-up model. Since this is considerably smaller than the impeller radius (75 mm), the velocity of particles are considered to be tangential at the given radius.

Tracer particles are required to follow the flow and thus should have the same specific gravity as the fluid and a suitable physical shape. The tracer particles were spherical SiO$_2$ beads (MSF-1500M, Liquid Gas, Osaka, Japan), whose diameter is 0.15 mm and specific gravity 2.1 or less. This matches closely with the specific gravity of the working fluid, 1.9. In a preliminary experiment, the suspended particles did not precipitate over 10 minutes after agitation. Unfortunately, over the course of an experiment, approximately 90 minutes, the particle surfaces deteriorate and the amount of visible particles decreases. It is therefore necessary to add particles into the circuit to maintain the quality and particle density of the video image. Careful positioning and focusing of the video camera and laser light sheet, of course, is necessary to ensure clear images.

Pump characteristics are generally governed by two essential parameters, namely the Reynolds number and specific speed. The Reynolds number, in particular the radial Reynolds number, defined as $Re=\omega R^2/\nu$ ($\omega$: impeller angular velocity, $R$: impeller radius, $\nu$: kinematic viscosity), represents the ratio of inertial to viscous forces. The specific speed, defined as $n_s=\sqrt[3]{Q/(\omega R^3)}$, represents the square root of [radial velocity/tangential velocity] because $H \propto (\omega R)^2$, $n_s \propto (Q/\omega R^3)^{1/2}$. For the case where the pump and the liquid are the same in all experiments, the Reynolds number is determined by rotational speed, $\omega$, and specific speed by the ratio of flow rate to rotational speed, $Q/\omega$, which can be adjusted by the circuit resistance. Experiments were conducted at various Reynolds numbers and at various specific speeds. Both the experimental conditions of 180 rpm and 9 L/min for a scale-up model and of 2700 rpm and 5 L/min for an actual scale model correspond to Reynolds number of
5.9 × 10^4 and specific speed of 158 (rpm, m, m^3/min).

2.2 Particle tracking velocimetry

Velocity profiles were obtained by analyzing 1000 to 2000 frames in an automated process by particle tracking velocimetry software, (Kanomax, Current). Firstly, the image is binarized then the gravitational center of each particle is found as a coordinate location. The particle is then tracked over 4 frames proceeding in time.

The following parameters can be adjusted in this tracking process: the binarization threshold from gray scale (1 - 256); the frame interval or number of skipping frames; and, as is shown in Fig. 4, the maximum allowable distance between time-1 and time-2 positions (L_max), the search radius for time-3 position (M) around the projected particle using time-1 and -2, the maximum allowable angle between 1 - 2 direction and 2 - 3 direction (θ_max). These conditions extend in a similar way to time-4 position. Finally, the time-1 and -4 coordinates are determined to generate velocity vectors. Data processing parameters were set to minimize errors arising from the binarization of the image data.

The vector frame interval (number of frames between time-1 and time-4) was varied from 12 to 24 frames, and the parameter M varied from 3 to 1 pixels. At 180 rpm and 9.0 L/min, a typical reduction of 12% in the standard deviation of the curve fit could be achieved when the vector frame interval is increased from 12 to 24. When M is reduced from 3 to 1, the standard deviation is typically reduced by 2%. In reducing M, a stricter control is applied to larger velocity vectors, since M is absolute, and not represented as a fraction of L (the distance between time-1 and time-2 positions). Thus, generally, errors in larger vectors can be filtered out before those in smaller vectors.

2.3 Measurement errors

There are several sources of measurement errors as follows:

1) screen coordinates of particle gravity centers with different size and shape,
2) screen coordinates of physical boundaries,
3) coordinate calibration to actual scale,
4) tracking errors in particle identification,
5) effect of illumination thickness,
6) flow traceability of particles.

For the present experiment, the screen is composed of 256 × 128 pixels and a few particles occupying 1 to 30 pixels can be found on a image. More than 1000 frames were analyzed to obtain the present result with nearly 1000 velocity vectors. Particle images with different sizes and shapes cause approximately 1.5 pixel error, which causes 1% position error in a 130 pixel region and 10% velocity error for vectors of 15 pixels as a mean. Magnification of image by zooming or elongation of vectors by skipping frames would be useful. Image of boundary includes 3 pixel (2.3%) errors in a 130 pixel region due to unsharpness mainly caused by observed area thickness. Sheet laser thickness, 1.6 mm, causes 3% velocity errors at 70% radius (52.5 mm). Since 0.15 mm-dia particles used in the 3.2 mm gap to obtain clear images of 5 pixels as a mean, velocity data are lacking in the 0.075 mm vicinity (2.3% of gap) of the walls. The particles have a data-smoothing effect for a ±0.075 mm region. Since 0.15 mm tracer particles did not precipitate over 10 minutes as was mentioned, the traceability to flow would be satisfactory.

3. Results

3.1 Effect of specific speed (at constant Reynolds number, Re=5.9×10^4)

The notation in the figures is u: tangential velocity, U_t: impeller tip velocity, z: axial distance from casing, s: gap width. The obtained velocity and position data, normalized by U_t and s respectively, are plotted directly since particle tracking velocimetry is suitable to analyze instantaneous particle data. Then they are fitted with a curve composed of two parabolic boundary layers (δ_u, casing side and δ_v, impeller side) and a constant velocity core region. This curve fitting is adequate for Reynolds numbers within the range of Re<10^5. As the specific speed increases, namely circuit resistance is increased, there is little change in the gap tangential velocity profile though the flow rate variations result in changes in the radial velocities (Figs. 5, 6, 7(a)).

3.2 Effect of Reynolds number (at constant specific speed, n_s=158)

As Reynolds number increases, that is, rotational speed increases, the thickness of boundary layers becomes smaller and the core region expands (Figs. 5, 6, 7(b)). The impeller side boundary layer is always narrower than that at the casing side, as is clearly shown in Fig. 7(c). The data agreed with the general
tendency of boundary layer thickness, which is inversely proportional to square root of radius Reynolds number. The total thickness of the boundary layers for both walls varies from 0.3 - 0.6 mm in the actual size gap of 1 mm. The pressure requirement to the artificial heart of 50 - 200 mmHg corresponds to the impeller tip speed of 4 - 8 m/s. This speed range and the impeller radius of 25 mm, which are common for all artificial hearts, determines the thickness of the boundary layers as 0.3 - 0.6 mm, irrespective of the gap width. Thus the boundary layer thickness is given in the unit of mm.

3.3 Effect of radial position

At \( r = 0.9R \), the core velocity is almost 50% of the impeller velocity, while, at \( r = 0.7R \), the core velocity is approximately 60% of the relative impeller velocity. The core velocity seems to be approximately constant from \( r = 0.9R \) to \( r = 0.7R \), for the range of 90 to 270 rpm (Fig. 7). This is because the inward radial flow, caused by washout holes, bring the higher momentum of the circumferential region towards the central region.

3.4 Shear velocities

An assessment of wall shear velocity is important for evaluation of hemolysis. Increase of specific speed at constant \( Re \), namely increase of flow, causes a large decrease in the impeller side shear velocity at \( r = 0.9R \), but only a small decrease at \( r = 0.7R \) (Fig. 8(a)). While the casing side shear remains almost constant. Increasing Reynolds number, at constant \( \alpha_s \), causes almost proportional increase in shear stresses in all cases (Fig. 8(b)). The impeller side shear velocity is lower at \( r = 0.7R \) than at \( r = 0.9R \) since the core velocity remains almost constant from \( r = 0.9R \) to \( r = 0.7R \). On the other hand, the thickness of casing side boundary layer does not change so much at different radial positions.

3.5 Radial flow as secondary flow

The relation of boundary layer structures was examined between the tangential and the radial directions. Laser light sheet was relocated to illuminate the axis-radius plane, and the video camera was set to see the plane. The radial flow profile is composed of
three layers similar to tangential flow profile as is shown in Fig. 9. The flow near the impeller tends outward due to centrifugal effect while the flow near the casing tends inward due to high tip pressure. Usually these two effects balance each other in the flow of the middle layer for simply rotating flow, the flow tends inward due to washout hole suction in the present case.

4. Discussion

4.1 Deviation of the tangential velocity data

The data in Fig. 5 and Fig. 6 have comparatively wide deviation. Regarding the position deviations, the data within the layer thinner than the particle radius might be an error mainly caused by observed area thickness. Regarding the velocity deviations, the effect of transverse motion of particles was examined because the aforementioned secondary flow, namely inward and outward flow near the walls, might accompany axial transverse flow. When the particles having transverse component larger than 0.3% of tip velocity are excluded from the graph, the deviation becomes smaller as is shown by solid round marks in Fig. 10. This indicates that transverse motion of particles causes deviation to the tangential velocity distributions.

4.2 Gap flow classifications

A simplified model of the gap flow has been studied by many researchers using a rotating disk and a stationary disk without radial through flow\textsuperscript{33}. These revealed that flow profiles are governed by two parameters, namely the radial Reynolds number, $Re$, and the gap width Reynolds number, $Re' = ωs^2ν$ ($s$: impeller/casing gap width), or gap-radius ratio, $s/r$, as an alternative parameter. The flow pattern can be classified into four regimes by whether the flow is laminar or turbulent and by whether the two boundary layers are separate or merged (Fig. 11).

In the case of an implantable artificial heart, the necessary pump head is 50 ~ 200 mmHg, which
corresponds to an impeller tip speed of 3 - 10 m/s. The impeller radius would be 15 - 40 mm and the kinematic viscosity of blood is $2 - 4 \times 10^{-6}$ m$^2$/s. The resulting Reynolds number ranges from 0.1 - 2.0 $\times 10^5$. Therefore, the operating regime is generally laminar, regime I or II. Our model's operating conditions correspond to regime II. Typical profile difference for laminar and turbulent flows can be described with the following empirical equations$^{[6,7]}$, 

$u = K \sigma (z/\delta_w) (2 - z/\delta_w)$: for laminar regime II 

$u = K \sigma (z/\delta_w)^{1/7}$: for turbulent regime IV 

where $K$ denotes core velocity ratio against impeller velocity. Comparing the velocity gradients on the wall, the profiles obtained experimentally clearly correspond to the laminar regime II, not to the turbulent regime IV.

Fig. 7 Variation of boundary layer thickness

Fig. 8 Variation of shear velocity (Shear values are $1/15$ of actual size pump)

Fig. 9 Radial velocity profile (Standard condition)

Fig. 10 Effect of transverse motion on tangential velocity profile
5. Concluding Remarks

A flow visualization study of a centrifugal blood pump was conducted to find the shear and velocity profiles in the back gap between the impeller and the casing. For a wide range of Reynolds numbers and specific speeds, it was found that high shear exists only in the boundary layers of the moving and stationary walls and that low shear was found in the middle region of the gap. The velocity profile was essentially laminar. It was also found that the total thickness of the high shear regions is 0.3 - 0.6 mm for operating conditions of artificial heart and that the thickness is determined not by specific speed but by radial Reynolds number. Hence, it can be concluded that reducing the impeller velocity is the only way to reduce wall shear stress and that increasing the gap width more than a certain value is not effective.

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References


