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Experimental Flow Visualisation of an Artificial Heart Pump

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Abstract : Flow visualization techniques were employed to qualitatively visualize the flow patterns through a 400% scaled up centrifugal blood pump. The apparatus comprised of a scaled up centrifugal pump, high speed video camera, Argon Ion Laser Light Sheet and custom coded particle tracking software. Reynolds similarity laws are applied in order to reduce the rotational speed of the pump. The outlet (cutwater) region was identified as a site of high turbulence and thus a likely source of haemolysis. The region underneath the impeller was identified as a region of lower flow.

Key words : Artificial Heart, Centrifugal Pump, Flow Visualisation, LVAD.

1. Introduction

Flow visualisation is an important technique used in a wide variety of applications. It can be used to identify the flow characteristics of a design, highlighting areas where modifications may improve the pattern of fluid flow. A common application of flow visualisation is in the area of aerodynamics. By determining the flow patterns over an aircraft wing or car body, it is possible to minimise the drag forces by optimising the aerodynamic shape. Another specialised application of flow visualisation is in the area of blood pump design[1, 2] When designing a blood pump, consideration must be given to its traumatic effect on blood. One such trauma is classified as *Hemolysis*, and results from the shearing and rupturing of the Red Blood Cells (RBC) and release of haemoglobin into the bloodstream[3]. Another factor plaguing blood pump design is *Thrombosis*, which is the formation of blood clots in regions of low flow[1]. By employing flow visualisation techniques, it is possible to determine areas of high shear, turbulence and low flow or stagnation.

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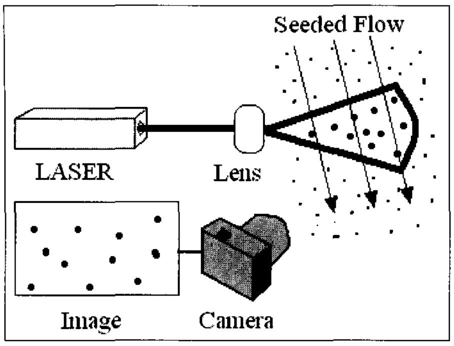

Fig. 1 PIV Technique

Results from flow visualisation studies can be categorized under two levels, Qualitative and Quantitative. A Qualitative study involves studying captured images, and can instantly identify regions of low flow or stagnation as well as turbulent regions. As mentioned previously, this information is useful for identifying the regions of the pump susceptible to thrombosis formation and blood cell destruction respectively. Investigators may then target these regions for further quantitative analysis. Such quantitative analyses commonly use Particle Image Velocimetry (PIV) techniques to identify particle velocities. This data can be used to replicate boundary layers encountered within the pump, providing an opportunity to calculate shear stress levels. This information can be related directly to thresholds of shear stress estimated to cause hemolysis[1, 4]. Flow visualisation studies are often conducted in conjunction with computational fluid dynamics (CFD) to relate and refine theoretical CFD models.

There are a number of techniques available to conduct flow visualisation studies. The most common method (PIV) [*Fig. 1*], introduces seeding particles into the pumping medium. These particles may be illuminated by a light source (commonly LASER) and their motion captured by a high speed camera. Qualitative results can be instantly inferred from the images. Particle tracking procedures may then be applied to quantify the particle velocities from the captured data and help to calculate boundary layers and shear stresses. Alternative procedures involving oil streaking are used, but are generally purely qualitative. It is however possible to quantify the results by measuring the streak lines and relating those to the oil viscosity, but are plagued with large error margins. A group from Tsukuba University (JAPAN) have successfully conducted flow visualisation tests on a scaled up version of their centrifugal blood pump design[2, 3]. Heartquest (USA) used oil streaking and PIV techniques to quantify flow in the gap region between the impeller shroud and casing in an attempt to minimise shear and maximise washout[5, 6].

The investigation presented was undertaken in three stages, using the particle seeding method: Preparation of a rig for testing to be conducted, Utilisation of adequate equipment and implementation of an experimental technique to produce results, and Qualitative analysis of captured data to identify target regions for further detailed quantitative analysis.

Images should be captured from these target regions at design capacity [*Fig. 2*] and below capacity pump flow rates [*Fig. 3*]. It is envisaged that the final implanted artificial heart will not always run at design conditions of 5L/min as the level of assistance required is dependant on the individual patients level of heart failure. Therefore, the effect of lower flow conditions on turbulence and stagnation should not be overlooked.

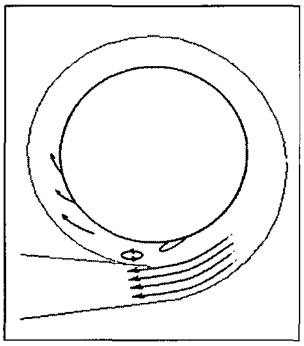

Fig. 2 Effect on outlet flow at design capacity

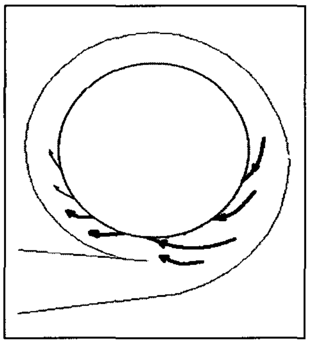

Fig. 3 Effect on outlet flow below design capacity

2. Materials and methods

The first stage of this research was to construct an experimental rig to enable flow visualisation of the centrifugal pump. Since a camera was to be used in the investigation, a limitation by way of the camera frame rate hinders the ability to accurately study an actual size pump, as the impeller rotational speed at operating point is extremely fast. In an attempt to reduce this rotational speed, improve camera resolution and thus result accuracy, a 4:1 scale model designed using Reynolds similarity laws was manufactured [*Fig. 4*]. Such a process reduced the rotational speed to 5% of the original value, thus mimicking the operating conditions of the smaller prototype whilst increasing the accuracy of the high speed camera images. The pump material was Perspex to allow a light source to penetrate the casing and illuminate the seeding particles.

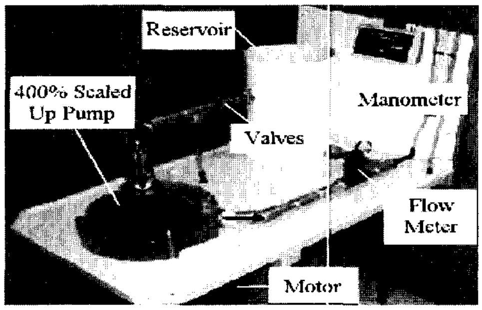

Fig. 4 Scaled up model experimental rig

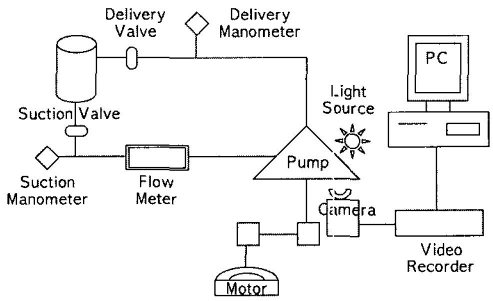

Fig. 5 Schematic of experimental rig

A schematic of the experimental setup is illustrated in [*Fig. 5*] with the actual set-up shown in [*Fig. 6*]. Neutrally buoyant seeding particles were introduced into the pumping medium and illuminated by a 0.5 Watt LASER light source. The LASER was directed to produce a thin sheet of light (2mm) by passing it through an arrangement of lenses. Owing to the relatively low LASER power, only small sections of the pump could be illuminated at any one time. Sections targeted corresponded to regions of expected low flow or turbulence [*Fig.7*], and the motion of particles in these areas was captured with a high speed camera at frame rates ranging from 25 fps to 3000 fps.

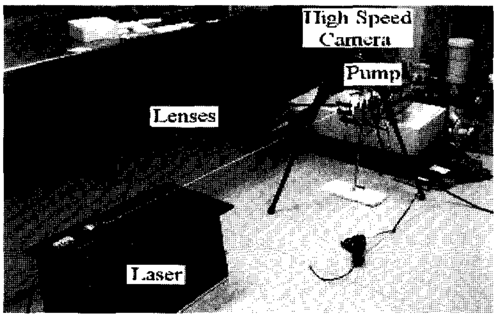

Fig. 6 LASER and Camera arrangement

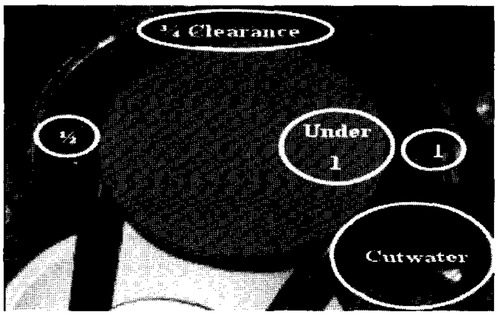

Fig. 7 Targeted regions under pump

Captured high speed camera data was processed using custom coded particle tracking software developed in MATLAB. By knowing the frame rate and thus time between frame, and measuring the distance travelled by each individual particle between consecutive frames, particle velocity can be calculated.

3. Results

The initial analysis from the images recorded at 25 fps provided qualitative results of the areas of interest. While operating the pump at design capacity, turbulence at the cutwater region is minimal[*Fig 8*]. However, operation below design capacity increased turbulence dramatically and the level of recirculation increased [*Fig. 10*] as expected [*Fig. 3*].

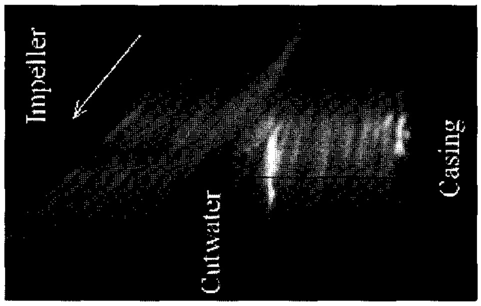

Fig. 8 Streak lines in cutwater (design capacity)

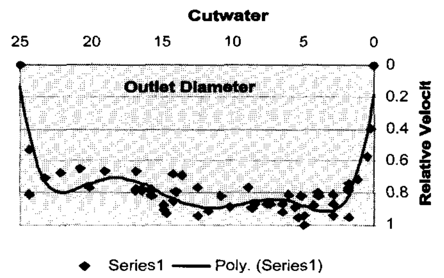

Fig. 9 Velocity profile (design capacity)

Fig. 10 Streak lines in cutwater (low capacity)

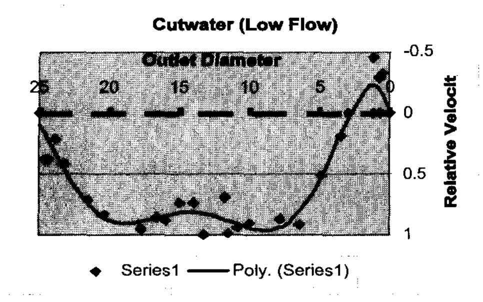

Fig. 11 Velocity profile (low capacity)

Analysis beneath the impeller revealed high particle velocities. However, the majority of this velocity vector is in the tangential direction, with a relatively low component in the radial direction [*Fig. 12*].

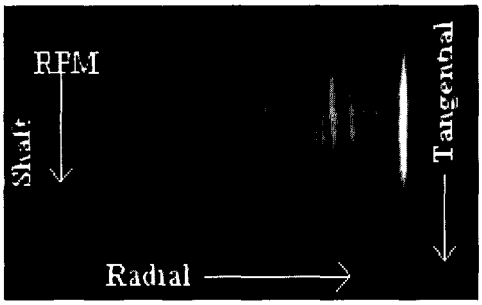

Fig. 12 Streak lines beneath impeller

To further enhance the level of investigation in the selected sections, captured images at 1000 3000 fps were quantitatively analysed by tracking individual particles. Velocity profiles and thus boundary layers were developed by plotting the normalised velocities against the position of the particle in the flow. Normalised velocities (Measured Velocity / Maximum Measured Velocity) allow for comparison of boundary layers in different flow conditions irrespective of capacity.

[*Fig. 9*] depicts the velocity profile produced across the 25mm diameter outlet pipe at the cutwater under design capacity conditions. [*Fig. 11*] shows the same boundary layer produced at below design capacity conditions. A qualitative analysis of the gap 1 region is in [*Fig 13*] with the velocity profile in [*Fig 14*].

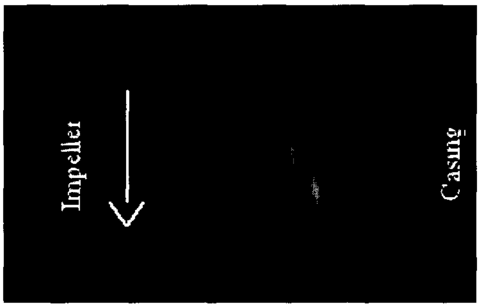

Fig. 13 Streak lines in clearance 1

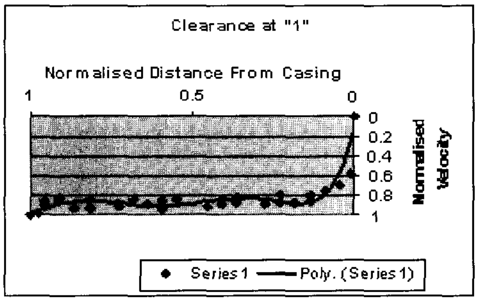

Fig. 14 Velocity profile in clearance 1

4. Discussion

The experimental technique produced useful qualitative results and provided a basis for a quantitative analysis on particular pump sections.

Increased turbulence was found at the cutwater section under low capacity conditions, with eddys forming at the outer section of the outlet pipe. This can also be seen in the velocity profile as there is a degree of reverse flow [*Fig 11*].

Not only would this turbulence give rise to hemolysis, but the continual recirculation allows for blood to stagnate in this region, leading to a potential site of thrombus formation. Operating the pump at design capacity reduced the level of turbulence, but gave rise to a smaller boundary layer thickness, that is the distance from the casing to the maximum velocity [*Fig 9*]. This gives rise to a higher shear rate, as shear is determined by the rate of velocity change multiplied by the fluid viscosity. Further calculations are required to determine the value of shear stress and relate this to the hemolysis threshold.

A region of low flow was identified beneath the impeller, due to the back shroud shielding this region from the mainstream flow. This is evident by the relatively small radial velocity component. For adequate washout, this value must be maximised. Due to the width of the LASER sheet (2mm) and the clearance gap (2mm), the particle velocities captured refer to both the outward radial flow caused by viscous forces imparted on the fluid by the rotating impeller, and the inward component near to the casing wall. In any case, the relative value of these components is low, creating a region with poor washout and thus a large potential for thrombus formation.

With a clearance gap/impeller radius spacing ratio of 0.2 and a Reynolds number in the order of 10^5, a laminar REGIME II type velocity distribution is expected[7] and confirmed in the clearance "1" region [Fig 14]. Again, the gradient of this distribution can be related to shear stress and compared to the hemolysis threshold.

5. Conclusion

The flow visualization technique described provided valuable insight into the internal flow patterns within the centrifugal blood pump design, identifying the region beneath the impeller as a stagnation zone together with the outflow and clearance regions as potential sites for hemolysis.

Turbulence was found at the cutwater section. This was further emphasized when the pump was operated at capacities below the design value, as encountered in the practical application of the implanted artificial heart where the patient may not require the designed flow rate of 5 L/min.

This tool is vital in evaluating future artificial heart pump designs with respect to its potential for blood damage.

6. References

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