14th Australasian Fluid Mechanics Conference
Adelaide University, Adelaide, Australia
10-14 December 2001

Leakage Flow and Shear Stress in the Clearance Gap of a Heart Pump Model

L.P.Chua, K.S.Ong, T.M.Zhou and S.C.M.Yu

School of Mechanical and Production Engineering

Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

Abstract

This study presents an estimation of the leakage flow through the clearance gap between the impeller and the stationary casing of a centrifugal heart pump model and the shear stress distribution inside the gap. From the velocity field measurements that have been done in the clearance gap [1,2], the volumetric flowrate inside the gap could be roughly estimated. With the velocity profiles obtained, the leakage flow through the clearance gap was found to be about 0.000944 m^3/s and 0.000766 m^3/s by numerical integration, which has caused about 20% to 30% losses of the inlet flow depending on the flow conditions. This first time experimentally measured leakage flow for this blood pump is consistent with the finding of Yamada et al. (1997)[3]. From the velocity profiles, the shear stress distributions can also be obtained. It is found that the highest shear stress is 206 Pa, which is far below the hemolysis threshold value of 400 Pa suggested, by Sallem and Hwang (1984) [4].

Introduction

Leakage loss is the loss of capacity through the running clearances between the rotating element and the stationary casings. Leakage can take place in one or several of the following places, according to the type of the pump. These are: 1) in the gap between the casing and the impeller; 2) between two adjacent stages in multistage pumps; 3) through the stuffing box; 4) through axial thrust balancing devices; 5) through bleed-off bushings when used to reduce the pressure on the stuffing box; 6) past vanes in open impeller pumps and 7) at any bleed-off used for bearing and stuffing box cooling [5]. In this study, the leakage loss that takes place in the gap between the casing and the impeller of the centrifugal heart pump was estimated.

The velocity inside the small gap was measured at three different positions in the 1mm clearance gap, which are 0.25mm, 0.5mm and 0.75mm from the surface of the stationary casing of the pump. Three different inlet flow conditions with the flow coefficient $\Phi = Q/(2\pi r^2 b\omega)$ (where Q is the inlet flowrate, b is the width of the impeller vane and r is the radius of the impeller and ω is the pump rotating speed) = 0 (fully closed condition), 0.04 (50% flow condition) and 0.078 (fully opened condition) were used during the measurement. From the velocities obtained in the clearance gap, it was found that the velocities obtained are not constant at each location. The velocity distributions are different at different locations [2]. Therefore, the amount of the leakage flow through the clearance gap between the casing and the impeller could not be obtained by applying a simple calculation. If the velocity was constant, the total leakage flowrate could be simply estimated by multiplying the velocity with the circumference area of the gap.

Since the velocity is varying at different measuring point in the gap. More complicated numerical determination needs to be applied. With the radial velocities obtained from the three different depths at different locations, and the zero velocities assumed at the stationary casing surface and the impeller with the non-slip condition, the volumetric leakage flow through the clearance gap between the impeller and the pump casing could be obtained. Figure 1 shows a typical radial velocity profile at a particular location.

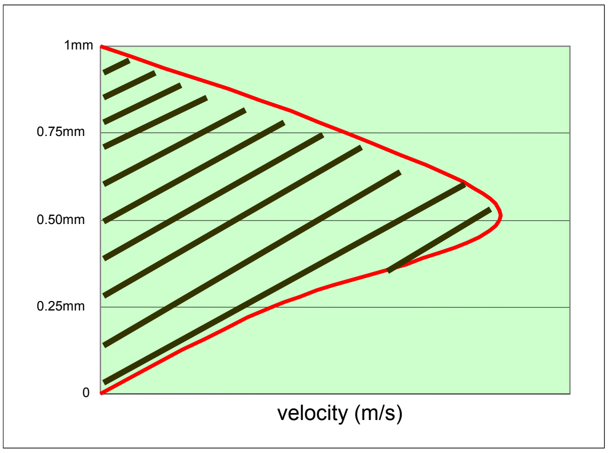

Figure 1 A typical radial velocity profile in the 1mm gap

Shear stress is another engineering quantification that can be used to describe the flow pattern in the clearance gap. Shear stress has significant implications on the performance of a blood pump. Excessive shear stress level could cause hemolysis while too low a value may cause early aggregation of platelet and subsequent thrombi formation. The threshold values depend on shear exposure time and contact surface [4]. High shear level can lead to platelet activation which initiates the coagulation process. However, shear stress levels that are not sufficient to result in cell lysis may still cause sub-lethal damage, for instance, morphological changes in red blood cells and platelets.

Method

Only the radial velocities were used in the determination of the leakage flow in the 1mm clearance gap, this is because they are the only contributors, leading the fluid to flow radially towards the eye of the impeller. With the non-slip condition the velocity on the stationary casing wall was assumed to be zero. On the other hand, for the impeller side, it is assumed that there will be no radial velocity due to the fluid flow is following the motion of the impeller, which is in tangential direction.

The velocity measurements were done at the interval of 5 degree and at 7 different radial locations over the surface of the impeller [1]. Therefore, there will be 504 measuring points over the clearance gap. With the three velocities obtained from three different depths at each point, and the zero velocities assumed at the stationary casing surface and the impeller shroud surface, the radial velocity profile at a particular location in the clearance gap can be obtained (see Figure 2).

Numerical method could be applied to calculate the mean velocity of the profile. Simpson's rule was used in this study to obtain the mean velocity of the profile. The shaded area as shown in Figure 1 was firstly numerically integrated with expression

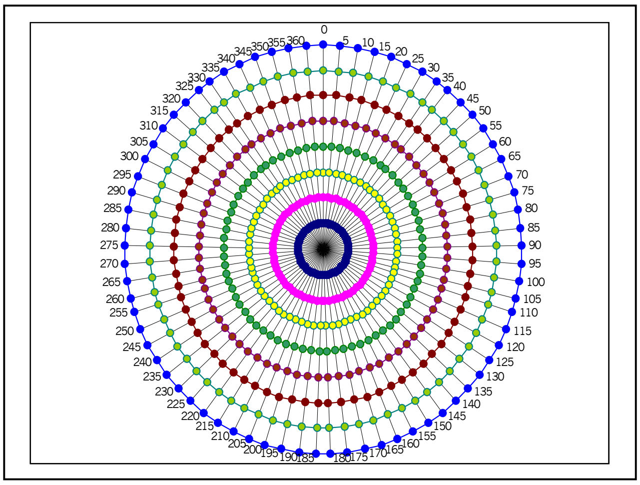

Figure 2. Mesh in the gap according to the seven different radial locations and angular interval

$$S_5 = \frac{1}{3}(0.25)[f(x_0)+4f(x_1)+2f(x_2)+4f(x_3)+f(x_4)] \quad (1)$$

where S_n is the numerically integrated area
h is the width of the subintervals (=0.25)
n is the quantity of the interval (=5)

The mean velocity of the velocity profile can then be obtained by dividing the integrated area by the distance from the stationary casing surface to the impeller surface, which is 1mm in this case.

The velocity obtained from a particular location by Simpson's rule was assigned to represent the fluid flow velocity of a particular meshed block.

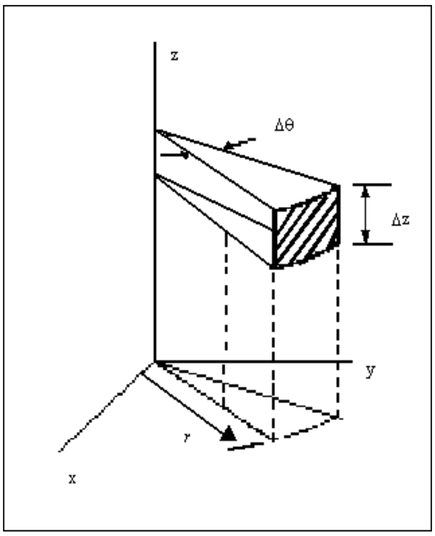

Figure 3. A small area of the circular strip at a particular radial location r

A typical meshed portion is shown in Figure 3. By multiplying the representative velocity with the circumference area of the small meshed block, the volumetric flowrate of each small meshed portion can then be obtained. The determination of the circumference area is expressed as

$$dA = \int_0^{1.0} \int_0^{\frac{2\pi}{72}} r\,d\theta\,dz \quad (2)$$

where dA is the outer circumference surface area of the 5^o strip, shaded area in Figure 3
r is the outer diameter of the meshed portion

The total volumetric leakage flowrate through the clearance gap can be obtained from the accumulative value of the volumetric flowrate of each portion.

An estimation of shear stress at different locations can be obtained by using the velocities obtained from the measurements [2]. In this investigation, two velocities were measured, the tangential velocity that is on the y-axis and the radial velocity that is on the x-axis in the Cartesian coordinate system. Owing to the accessibility, the velocity in the z direction could not be obtained. However, the grid map of the gap as described in the previous section is in polar coordinate system. Therefore, the shear stress estimation is based on polar coordinate. The velocities in x direction (radial velocity) and y direction (tangential velocity) were measured at 0.25mm intervals in the 1mm clearance gap.

Therefore, we can have an estimation of shear stress on x-y plane at different ξ of 0.25, 0.5 and 0.75. Since the velocities were measured in three different ξ, seven radial positions, and in every five degree angular position, the shear stress on any particular measuring point is contributed by its surrounding points. The shear stress distribution was calculated by the expression:

$$\tau_{r\theta} = \frac{1}{r}\frac{\partial u}{\partial \theta} + \frac{\partial v}{\partial r} - \frac{v}{r} \quad (3)$$

Results and discussion

The roughly estimated volumetric leakage flowrate from the velocity obtained experimentally for different inlet flow conditions, which are fully opened, fully closed and 50% flow are shown in Table 1. Note that the volumetric flowrate has been doubled with the assumption that the leakage flow at both side of the impeller are to be the same.

From Table 1, it can be observed that, the fully opened condition has given the highest volumetric leakage flow compared with the other two conditions. For the fully opened condition, the inlet flowrate was recorded as about 0.00557 m^3/s. Therefore, the leakage loss through the 1mm clearance gap between the pump casing and the impeller is about 16.9% of the inlet flow. At the 50% inlet flow condition, the leakage flowrate is about 0.00267 m^3/s. The leakage flowrate is less than that at fully opened condition, but due to the inlet flow at this condition is about half of that at fully opened condition, the leakage loss is about 28.7 % of the inlet flow. Furthermore, the leakage flowrate through the clearance gap at the fully closed condition has been estimated as about 0.000526 m^3/s, this is the lowest among the three conditions. This could be due to there is no inlet flow at the inlet of the pump, and the fluid keep recirculating in the pump. It can also be observed from Table 1, the estimated leakage loss at different radial positions were quite consistent, with only a small variation with an estimated uncertainty of about 8% and thus a good continuity of fluid flow in the clearance gap was demonstrated.

	Fully opened condition	Fully closed condition	50% flow condition
Radial position	Volumetric flowrate (m^3/s)	Volumetric flowrate (m^3/s)	Volumetric flowrate (m^3/s)
69.5mm	0.000928	0.000540	0.000760
78mm	0.000944	0.000528	0.000767
86.5mm	0.000930	0.000520	0.000756
95mm	0.000940	0.000517	0.000770
103.5mm	0.000928	0.000528	0.000768
112mm	0.000967	0.000517	0.000767
120.5mm	0.000972	0.000534	0.000772
Mean volumetric flowrate (m^3/s)	0.000944	0.000526	0.000766

Table 1. Volumetric leakage flowrate of fully opened condition, fully closed condition and 50% flow condition.

By comparing with the leakage flow estimation of the prototype, the volumetric leakage flowrate in the 5 times larger model are comparable to those in the prototype, which are reported at about 20-40% (1~2 l/m) of the total inlet flow [3]. However, the estimated leakage loss in the gap of the prototype pump by Yamada et al. (1997) was not obtained by any measurement of the gap velocity, but was estimated indirectly from the input and the output of the pump. The present estimation of leakage flow, provide concrete evidence in supporting the indirect estimation of the leakage flow of the prototype.

Figure 4 shows a typical shear stress contour plot at ξ = 0.5 at operating condition (50% flow). It is found that the shear stress is distributed uniformly except at some regions near to the location of the splitter plate and cutwater. It can be observed that the high shear stresses are more likely on the region where the splitter plate and cutwater is situated. Furthermore, most of the high shear stresses are at the edge or the middle of the impeller. These regions are critical as high level of shear stress is more prone to hemolysis.

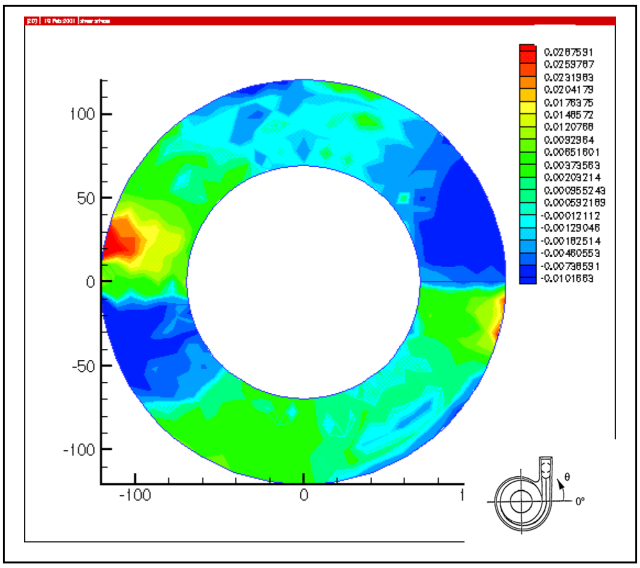

Figure 4. Shear stress distribution at ξ = 0.50, operating condition

The variation of the shear stress in the model pump for different ξ planes are found to be between $3x10^{-3}$ and 0.25 Pa for fully opened condition; between $5x10^{-3}$ and 0.31 Pa for fully closed condition and between $2x10^{-3}$ and 0.28 Pa for 50% flow condition. The lowest and the highest shear stress from the three cases are $2x10^{-3}$ and 0.31 Pa. Since the pump rig used for the measurement is a 5 times scaled up model from the prototype by applying similarity law, therefore the dimensionless shear stress of the prototype can be determined from the expression $(\tau/\rho U^2)_m = (\tau/\rho U^2)_p$ [6]. The subscript m and p denote the model and prototype pumps respectively. Therefore, the lowest and the highest shear stress from the three cases are equivalent to 1.5 to 228 Pa for the prototype pump using blood as medium. The lowest shear stress of 1.5 Pa is above the range of yield stress (0.1-0.6 Pa) at which the aggregates in human blood are disrupted and the blood begins to flow [7]. Thrombosis is more likely to take place in these low shear stress regions. On the other hand, the highest shear stress obtained is about 228 Pa which is far below the value of 400 Pa quantified by Sallem and Hwang (1984) [4] as the threshold at which hemolysis occurs. Therefore, it could be predicted that hemolysis would not occur in the clearance gap. However, the threshold values of shear stress level depend on shear exposure time and contact surface. Thus, the washout mechanism that could lead the fluid flows towards the eye becomes important to reduce the chances of occurring of hemolysis. From the velocity distributions that have been discussed in [2], it can be observed that the double-spiral volute design has yielded washout mechanism region in the clearance gap. Therefore, it could be inferred that modifications on the design of the pump are required. For example, increase the number of the volute, which can provide more washout mechanism regions to flush the fluid towards the eye of the impeller. Thus, preventing the blood from exposing to high level of shear stress in long time and cause hemolysis.

Conclusion

The amount of leakage flow in the gap was numerically integrated from the flow profiles. The volumetric leakage flowrate in the 5 times larger model are comparable to those reported in the prototype by an indirect estimation from the inlet and outlet of the pump, which are about 20-40% of the total inlet flow [3]. The present estimation of leakage flow provides concrete evidence in supporting the indirect estimation of the leakage flow of the prototype.

The highest shear stress obtained is about 228 Pa which is far below the value of 400 Pa quantified by Sallem and Hwang (1984) [4] as the threshold at which hemolysis occurs. Therefore, it could be predicted that hemolysis would not occur in the clearance gap. The distribution of shear stress has projected the region that hemolysis and thrombus formation are likelihood to occur. Most of the high shear stresses are found at the edge and the middle of the impeller. In addition, the locations of the cutwater and the splitter plate have influenced the shear stress distribution greatly. The shear stress levels at the region after the origin of the splitter plate and the cutwater are found to be high. These regions are critical as shear stress has significant implications for the performance of the blood pump as excessive shear stress level could cause hemolysis. All these measurements will not only improve the understanding the flow mechanism of the flow but also to improve the pump design in the future.

Nevertheless, the fluid medium used in this investigation, air, is much less dense, less viscous and simpler in comparison with blood. Therefore, the results obtained may underestimate the true value. However, the results are useful in qualifying as well as quantifying to a certain extent efficiency of the pump and the shear stress distribution. Thus, the potential locations of high hemolysis and thrombus formation at the clearance gap of the pump could be identified.

References

[1] Ong, K.S., 2001, Gap velocity measurements of a blood pump model, first year Ph. D. confirmation report, School of Mechanical and Production Engineering, Nanyang Technological University.

[2] Chua, L.P., Ong, K.S., Yu, C.S.M., Chan, W.K. and Wong Y. W., Measurements of gap velocity in a heart pump model, 14^{th} Australasian Fluid Mechanics Conference, 2001 (Abstract submitted)

[3] Yamada, T., Nishimura, K., Park, C.H., Kono, S., Yuasa, S., Tsukiya, T., Akamatsu, T., Matsusa, K., Ban, T., Chronic animal experiment with magnetically suspended centrifugal pump, Artif. Organs, **21(7)**, 1997, 635-640.

[4] Sallem, A.M., Huang, N.H.C., Human red blood cell hemolysis in a turbulent shear flow, contribution of Reynolds shear stress., Biorheology., **25**,1984, 783-797.

[5] Stepanoff, A.J., Centrifugal and axial flow pumps., John Wiley and Sons, 1984

[6] Liou, T.M., Chang, W.C., Liao, C.C., LDV measurements in lateral model aneurysms of various sizes., Exp. Fluids., **23,** 1997, 317-324

[7] Mazumdar, J.N., Biofluid mechanics., Word Scientific, 1992