Effect of tip clearance on wall shear stress of an axial LVAD

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Abstract. Wall shear stress is a crucial parameter used for blood damage analysis, and typically a value of 400 Pa is set as a limit. Tip clearance is a major factor contributing to hemolysis and pump efficiency. In this study, different tip gap configurations are used to analyse the wall shear stress developed on the blade surface of a constant thickness blade design, and a varying thickness blade design using CFD analysis. It was found that, for a particular geometry, as the clearance gap reduces, flow rate over the high wall shear stress area decreases even though the high wall shear stress span is found to extend. For each design, the optimum clearance gap is iteratively attained, keeping the maximum WSS as a limiting factor. Thus a better pump designs is obtained, whose leakage flow patterns are lower than that of the initial design, hence also leading to higher pump efficiency.

1. Introduction
American Heart Association’s Heart Disease and Stroke statistics 2003 update show that 552,000 new congestive heart failure cases are diagnosed each year in USA alone and death due to CHF is estimated to cross 52,827 each year [1]. The limited number of donor hearts for a heart transplantation points to the importance of mechanical devices for life support. A left ventricular assist device is a mechanical pump which pumps blood from the left ventricle of the heart and to aorta, which is the major artery arising from the heart, just as a healthy heart would do. The first VAD was implemented by DeBakey in 1969 [1]. An axial flow LVAD consists mainly of 3 parts: Flow straightener, Diffuser, and Impeller blades. Flow straightener straightens blood flow to reduce shock losses. The varying pitch of the impeller blades leads to an increase in tangential speed along the length of the impeller. The flow exits the impeller into the stationary diffuser blades. These are curved in the opposite direction to the impeller blades. Their role is to dissipate the angular motion of the fluid so that it is directed linearly out of the pump, hence flow generates a large pressure head at the exit of the pump.

1.1. Design Considerations for an LVAD
Blood damage in LVADs occur mainly due to factors like, high or very low shear, recirculation, flow separation, rough pump geometry, and stagnation regions. Axial flow pumps work at a higher speed compared to centrifugal pumps causing RBCs to be exposed to higher degrees of shear stress, but they have the advantage of using lower power and having better implantability. Below are the two main criteria to be followed while designing an LVAD.
1.1.1. Hemolysis
Due to the high speed of rotational of the impeller, flow through the LVAD is turbulent in nature. The Reynolds number for the pump under study is nearly 4500. Blood cells are naturally evolved to flow in laminar regime. Hence, under turbulent flow conditions, they undergo structural changes. The high shear rates cause deformation of blood cells, red blood cells become spherical rather than disk-shaped and eventually lose their haemoglobin. This is called hemolysis.

According to Giersiepen - Heuser power law blood damage model [2], hemolysis and platelet activation are the function of both shear stress level ($\tau$) and residence time or exposure time ($t$). Their expression for hemolysis index using power law model is shown in equation (1) below.

$$HI = 3.62 \times 10^{-7} \times \tau^{2.416} \times t^{0.785}$$  \hspace{1cm} (1)

1.1.2. Thrombosis
Low shear rate triggers the formation of clots or thrombus. Clots can grow in size, blocking the blood flow in the pump, or can even break off and be carried into the circulatory system. Recirculation regions, very low shear stress areas, flow separation, sharp edges etc. can lead to hemolysis, thrombosis as well as platelet activation.

Briefly, hemolysis occurs at very high shear stresses (above 150 Pa) and is a known complication of LVADs. Usually, a limit of 400 Pa is kept for the Wall Shear Stress (WSS). A region of very low shear stress below 1 Pa and subsequent flow stasis is critical for thrombus formation. The activation of platelets (volumes above shear stresses of 50 Pa) might lead to pump thrombosis or thromboembolic events, which are serious adverse events in LVAD patients. Von Willebrand factor is also referred to in the literature whose degradation occurs at low shear stress (3-10 Pa) [threshold of 9 Pa is used] and causes acquired Von Willebrand syndrome which affects bleeding complications. To guarantee successful operation of an LVAD, it has to be proven that these parameters caused by the LVAD are within acceptable limits. In this study, hemolysis is modelled as a function of WSS.

Several design modifications have been tried on LVAD design to optimize the design based on hemolysis and thrombosis constrains. Jingchun Wu et al. [5], used stator blade to reduce circumferential component of the flow, while LaRose et al. [6] used a multiple rotor design, with each rotor rotating opposite to each other. Huachun Wu et al. [7] compared a uniform thickness blade impeller with a variable thickness blade impeller, and found lower WSS and better pressure distribution for the later. Schule et al. [4], compared the numerical and experimental results of flow inside the most widely used LVAD, the HM-II, and found that WSS was 585Pa, near the leading edge tip of impeller blade and these exceeded critical limits [400Pa]. Tip clearance causes blood flow losses that lead to reduction in the efficiency of the pump. Sinnott et al. [3], showed that including an impeller-housing clearance can affect the pressure rise across the pump, the shear losses and the flow rate. For high efficiency, low power consumption a smaller pump is required, but there is a problem of cavitation associated with it, hence the blade tip speed has to be limited to 10 m/s. It is evident from the literature that tip clearance contributes to high WSS which leads to hemolysis. The main objective of this work is to compare the WSS and leakage flow characteristics of the constant thickness blade design and varying thickness blade design and optimizing the designs respectively.

2. Methodology
Bladegen, a blade-design software program specifically for turbomachinery, was used to generate the pump geometry including the impeller blades. Turbogrid, the meshing tool used, was used to generate a computational mesh with acceptable element aspect ratios. CFX by ANSYS Incorporated was used to simulate the flow through the computational model of the LVAD. CFX solved the Reynolds-averaged Navier-Stokes equations in this three-dimensional computational domain. CFD-post was used to analyse the results obtained, using contours and isosurfaces.
2.1. Geometry
In this study we have analysed two impeller geometries, one with a constant/isochorous thickness of 0.5mm, denoted as “ISO scheme”, and another with varying thickness along its length, denoted as “VAR scheme” [7]. The design consisted of 4 blades, with a chord length of 72mm for each. The inlet and exit vane angles were 12° and 75° respectively. The hub diameter and outer diameter were 14.8 and 18.5mm respectively. The blade tip clearance of the initial design for both schemes was 0.3mm. The impeller was designed based on the above specifications using Bladegen. The required parameters were entered into the BladeGen’s initial meridional configuration dialog box. First geometry was generated with a constant thickness of 0.5mm as shown in Fig. 1 (a) (ISO scheme).

![Figure 1. (a) Constant blade thickness geometry (ISO Scheme), (b)Varying blade thickness geometry (VAR Scheme )](image)

The second geometry (VAR scheme) to be obtained had a varying thickness blade geometry. The blade thickness increased from 0.147mm at the leading edge to 0.998mm at 40% of the length, and then decreased to 0.092mm at trailing edge parabolically as in Fig.1 (b). This variation was incorporated using bladegen and the second geometry was also obtained. Separate geometries were generated for each of the above two schemes with different tip gap configurations for comparing WSS and leakage flow. Different normal tip clearance gap configurations, which have a constant tip clearance gap throughout the length, i.e 0.3 mm, 0.2 mm, 0.1 mm, 0.09 mm, 0.08 mm, 0.07 mm were generated. Varying tip clearance gap configurations, having linear tip gap variation from the leading edge to the trailing edge, i.e 0.1 mm at the LE to 0.09 mm at TE [0.1-0.09], 0.1mm at LE to 0.08mm at TE [0.1-0.08] etc. were also generated.

2.2. Meshing
The computational mesh was generated using Turbogrid. It uses unstructured hexahedral grids to obtain faster speed and higher meshing quality. Automated topology meshing method was used for easier meshing. A more refined o-grids were used in regions expected to have large gradients, that is, the tip clearance gap. Appropriate edge split was also done of high mesh error regions to minimize the error by changing the value of edge split factor. A major reduction in the tip clearance mesh error was rectified by increasing the number of elements on the tip gap. The grid independent results were obtained at 358460 and 391650 elements corresponding to ISO and VAR schemes for 0.3mm tip clearance configuration. The quality of mesh was maintained above 0.8.

2.3. Boundary Conditions and Parameters
Mass flow rate of 0.1055 kg/s was set as the inlet boundary condition, while the outlet boundary condition was set to constant pressure of 14600 Pa. The shroud wall was set as a no-slip counter rotating wall with 7000 rpm. The working fluid, blood, is considered as a Newtonian fluid with dynamic viscosity of 0.0035Pas and density of 1055kg/m3. The turbulence model used was k-ω.
3. Result and Discussion

The validation was done by finding the maximum WSS over the blade surface. Maximum WSS was found to be 373 Pa for ISO scheme and 343 Pa for VAR scheme which were according to the reference journal [7]. The maximum WSS occurred at the upstream third of the impeller blades as shown in Figure 2 as per the results by Schule et al. [4].

![Figure 2. WSS along the impeller blade.](image)

The WSS distribution over the impeller blade for each geometry was analysed. A polyline was created at blade tip for each of the geometries and WSS was plotted along the polyline as shown in Figure 3 and 4. Leakage flow was also analysed by creating isosurfaces of axial velocity, its length was also obtained for comparison of each case.

![Figure 3. WSS along polyline in ISO scheme geometries](image)

An optimum tip gap configuration, having minimum leakage flow, is found out for both schemes, corresponding to the tip gap configuration maintaining WSS below the critical limit for hemolysis, which is 400Pa. For ISO scheme the optimum tip gap configuration is found to be 0.1mm while for VAR scheme the tip gap configuration could be further reduced to 0.08mm. The length of the polyline for which the WSS values were greater than 150Pa, high WSS, was measured and tabulated. The optimum conditions are highlighted on Table 2. Further reduction of tip gap height increased the WSS above the critical limit and hence not tabulated. A decrease in the tip volume corresponding to high WSS is significant.
Figure 4. WSS along polyline in ISO scheme geometries

Table 1. Max WSS corresponding to different normal tip

| Tip clearance (mm) | ISO Scheme | VAR Scheme |
|-------------------|------------|------------|
|                   | Max WSS (Pa) | High WSS span (mm) | Max WSS (Pa) | High WSS span (mm) |
| 0.3               | 373        | 4.57       | 343         | 3.83          |
| 0.2               | 385        | 4.79       | 358         | 3.91          |
| 0.1               | 396        | 5.57       | 377         | 4.25          |
| 0.09              | 405        | -          | 379         | 4.44          |
| 0.08              | -          | -          | 391         | 4.48          |
| 0.07              | -          | -          | 406         | -             |

Table 2. Tip clearance volume for ISO scheme

| Case    | Length | Area   | V=A*\(t_{av}\) |
|---------|--------|--------|-----------------|
| Iso 0.3 | 4.57   | 1.371  | 0.6855          |
| Iso 0.1 | 5.5754 | 0.55754| 0.27877         |
| Iso 0.1-0.08 | 5.4595 | 0.518653 | 0.259326       |

Now, another modification on the blade tip was done to further optimize the design. A linear variation of the tip gap along the length of the blade is introduced on the previously optimized geometries. This was done by varying the trailing edge gap of the previously optimized design. For both schemes, different LE-TE configurations were tried, i.e. 0.1-0.11, 0.1-0.9, 0.1-0.08. The results were analysed. Again optimization was done by maintaining maximum WSS below 400 Pa and the results are shown in Table 3 and 4. Using an average thickness, \(t_{av}\), for ISO scheme as 0.5mm and of VAR scheme as 0.57mm, the volume available at tip gap for leakage to occur was calculated.
Table 3. Tip clearance volume for VAR scheme

| Case   | Length | Area   | V=A*tav |
|--------|--------|--------|----------|
| Var0.3 | 3.8379 | 1.15137| 0.656281 |
| Var0.08| 4.4863 | 0.358904| 0.204575 |
| Var0.8-0.07 | 4.8424 | 0.377707 | 0.215293 |

It is found, out of the many LE-TE configurations, the linearly decreasing tip gap configurations lead to a decrease in the leakage flow, while linearly increasing tip gap increases leakage flow. The optimized design for ISO scheme (Iso0.1-0.08) has 62% lower tip clearance volume for leakage flow, while VAR scheme (Var0.8-0.07) has 67% lower tip clearance volume for leakage flow. The increase in pressure head, is 41.5% for ISO scheme while 66.7% for VAR scheme.

4. Conclusion

The WSS distribution along the blade of an axial LVAD was successfully simulated using the k-ω turbulence model. As the tip gap is reduced, for both the schemes, an increasing trend for WSS is observed, indicating the dependence of WSS on the clearance gap height. Higher WSS and leakage flow for ISO scheme compared to VAR scheme indicates strong dependence of both on the blade tip surface area also. Even though the WSS values increase as the tip gap reduces, the volume available for leakage flow decreases, which leads to a reduction in leakage flow, as leakage flow is a function of mass flow rate through clearance gap. The optimum clearance gap was found by keeping the maximum WSS as the limiting factor.

In any case, VAR scheme had a lower optimum clearance gap than that ISO scheme. This lead to lower leakage and hence higher efficiency in VAR scheme, also they had better pressure distribution along the pump. The study emphasises the importance of using a variable thickness blade designs for an LVAD, which commercially available devices have not considered. Such tip gap modifications are very effective in reducing blood damage and also bringing down the overall size of the pump and hence better implantability on the human body. Further experimental analysis can be done to validate these results. Further modifications involving blade tip rounding and parabolic clearance configurations can also be studied.

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