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Evaluation of CFD based hemolysis prediction methods

Oyuna Myagmar

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Evaluation of CFD based Hemolysis Prediction Methods

By

Oyuna Myagmar

A Thesis Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

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Abstract

Accurate quantitative evaluation of shear stress-related hemolysis (destruction of red blood cells) could be used to improve blood handling devices, including left ventricular assist devices (LVAD). Computational Fluid Dynamics (CFD) predicts the fluid dynamics of complex pump geometry and has been used to track the shear stress history of red blood cells as they travel through these devices. Several models that predict the relationship between hemolysis, shear stress and exposure time have been used to evaluate the hemolysis in the pumps. However, the prediction accuracy has not reached the satisfactory level. The goal of my thesis is to investigate the application of CFD in determining hemolysis using different hemolysis prediction methods.

This approach is two-fold. First it is done on a simplified geometry designed to produce known and controllable shear stresses. This device is known as the mag-lev shearing device and was designed using CFD in order to study erythrocyte damage in terms of the effects of shear stress. This mathematical solution for annular shearing device will be used to verify computational data.

Secondly, I applied the same methods to the LEV-VAD pump, currently under development at RIT. The grid independent mesh was obtained for RIT axial pump and was utilized for further studies. In Characteristic curve (Pressure vs. Flow), the experimental pressure rise data was compared with the pressure difference data from CFD simulation of the RIT mini pump.

Hemolysis was estimated for both geometries using four different hemolysis analysis methods, referred to as: Threshold Value, Mass-Weighted Average, Eulerian and Lagrangian approaches. The pump numerical hemolysis predictions are compared with the previous in vitro hemolysis data using bovine blood. The numerical simulation of flow field for mag-lev shearing device was compared with the analytical solution of the fluid dynamics inside the gap regions of the device. In the future, the mag-lev shearing device will be used with animal and human blood to empirically evaluate the hemolysis and this empirical data may be used to validate the numerical methods presented here.
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**List of Symbols**

RIT – Rochester Institute of Technology
FDA – Food and Drug Administration
VAD - ventricular assist device
LVAD - left ventricular assist device
RVAD - right ventricular assist device
BiVAD - bi-ventricular assist device
CFD - computational fluid dynamics
RBC - red blood cell
LEV-VAD – RIT pump magnetically levitated axial flow pump
MAG-LEV – RIT shearing device
3D – three dimensional
CAD – computer aided program
EDR - energy dissipation rate
Ta – Taylor number
Re – Reynolds number
Ta-Re – Taylor-Reynolds number
MRF - Moving Reference Frame
NIH – Normalized index of hemolysis
lpm – Liters per minute (flow rate)
rpm – radians per minute (rotating speed)
Pa – Pascal (shear stress)
ms – Millisecond (time)
cP – centipoises =0.001 Pa-sec
s\(^{-1}\) – inverse second (shear rate)
\(\tau\) - Shear stress (tau)
\(I_{\text{exp}}\) - Exposure time
D – blood damage
\(\tau\) - Damage index
\(I\) - Damage source term
\(\sigma_{SS}\) - Scalar 1-D stress
\(\sigma_{xx}, \sigma_{yy}, \sigma_{zz}\) - normal stress components
\(\tau_{xy}, \tau_{yz}, \tau_{zx}\) - shear stress components
$y^+$ - Y plus
$y^*$ - Y star
$u_i$ - Fluid velocity at node i
$u_i^p$ - Particle velocity at node i
$F_D^i$ - Drag force
$g_i$ - Gravity at node i
$F_i$ - Additional force at node i
$t$ - Time
$x$ - Location
$a$ - Acceleration
$u$ - Fluid velocity
$u_p$ - Particle velocity
$\tau_p$ - Particle shear stress
$u_p^{n+1}$ - Particle velocity at new location
$u_p^n$ - Particle velocity at old location
$u_p^e$ - Fluid velocity at old location
$x_p^{n+1}$ - Particle location at new location
$x_p^n$ - Particle location at old location
$L$ - Length Scale
$\Delta t$ - Integration time step
$\lambda$ - Step Length Factor
$\Delta t^*$ - Estimated transit time
1. Introduction

Importance and Background

Heart disease has been the leading cause of death in the United States since 1960’s [1]. (Figure 1.1) The human heart is one of the most vital organs we depend on to survive. Therefore, it is essential to keep this organ functionally operative at an optimal rate throughout its lifetime. A cardiac muscle pumps oxygen, and nutrient-rich blood throughout a body to sustain life [2]. If a heart is not properly maintained through adequate diet and exercise the probability of having a heart disease increases.

Figure 1-1: Death rates for selected leading causes of death in the U.S. (1958-2007) [1]

There are many types of heart diseases such as coronary artery disease, cardiomyopathy, arrhythmia, and heart failure. Each type of heart disease accompanies different symptoms and conditions. An easy indicator of heart disease is inadequate blood circulation. Once a condition has been properly detected through various medical diagnostics devices such as Electrocardiogram, stress test, Holter monitor, chest X-ray, Echocardiogram, Cardiac CT and Cardiac Catheterization the method of treatment can be assessed. Depending on the severity of the heart disease, the treatments can range from medicines that help to lower blood pressure, heart rate and cholesterol levels to angioplasty, bypass surgery, heart transplants or mechanical assist devices.

For severe cases of heart disease such as a heart failure; there are only two options available for treatment. Traditionally, heart transplant is the only proven, approved, and long-term
treatment for heart failure; however, transplants are often limited by factors such as biological matches and lack of donors. The limitations of heart transplants paved ways for mechanical devices, which provide a competitive alternative.

One such mechanical device is a ventricular assist device (VAD) which is a blood pump. VAD is a surgically implantable mechanical circulatory device that assists the heart to pump blood efficiently. There are three types of VADs: left ventricular assist device (LVAD), right ventricular assist device (RVAD) and bi-ventricular assist device (BiVAD), which simultaneously supports both sides. A LVAD supports the pumping function of the left ventricle, which is a heart's main pumping chamber. Blood enters the pump though an inflow conduit connected to the left ventricle and exits through an outflow conduit into the body's arterial system as shown in Figure 1.2.

![Figure 1-2: LVAD System](image)

Not only do LVADs have to deliver adequate hydraulic performance to assist physiological pumping, moreover, they need to provide good blood compatibility or hemocompatibility. Hemocompatibility is crucial for a blood pump because high blood damage can potentially decrease its useful life [4].

The history of VADs is divided into three generations of advancement [4]. First generation VADs were displacement pumps, which created a pulsatile flow [5]. Their approximate design
conditions met a flow rate of 5 L/min and pressure of 100 mmHg. An example of 1st generation VAD was created by World Heart and called Novacor (Figure 1.3). The Novacor weighs 160 grams and is made out of titanium and plastic.

Although effective, the 1st generation pumps had durability and hemocompatibility issues. Moreover, to utilize these devices many patients were required to take blood thinners to reduce the risk of stroke [7].

The 2nd generation of LVADs improved upon many of the shortcomings of the 1st generation devices. The 2nd generations LVADs were rotating pumps with mechanical bearings and seals. 1st generation LVADs assumed pulsatile flow was a required condition for optimal functionality, however, 2nd generation LVADs contradicted this assumption [4]. The Heartmate II, Jarvik 2000, Deakey, Impella, Streamliner are all examples of 2nd generation pumps and are commercially available for short-term use. The Heartmate II LVAD (Figure 1.4) pump can generate flows up to 10 L/min at physiologic pressures. It measures 4 cm in diameter and 6 cm in length with a mass of approximately 375 gram and it has ceramic bearings that can rotate from 6000-13000 rpm. It uses external electronic controller that modulates pumps speed based on physical demands [5].
VADs have proven to be effective as temporary life-sustaining system for end-stage heart failure patients but they still needed improvement for long-term usage. In order to reach this goal, third generation LVAD eliminated some of the major concerns regarding these mechanical devices. The newer axial LVADs such as the Streamliner use magnetic bearings. This magnetic bearing allows the impeller inside the housing to be suspended by magnetic forces due to permanent magnets and electromagnetic forces. This design eliminates friction that was created by mechanical bearings and decrease blood damage making the pump possible to last for long periods of time.

By eliminating the wearing parts, developers were able to increase the lifespan and durability of the device. In July 1998 The Streamliner (Figure 1.5), was the first magnetic bearing LVAD to reach animal testing. Its CFD based design was developed by the McGowan Center for Artificial Organ Development at the University of Pittsburgh School of Medicine [9]. Similar to its predecessors, the Streamliner had stability issues and is not currently being used or studied. Although some of its design was incorporated into the PediaFlow pump which is used for infants.
Currently, a 3rd generation LVAD called LEV-VAD is under development at RIT. The RIT magnetically levitated axial pump has been under development at the Kate Gleason College of Engineering, Rochester, NY. This pump has an impeller with four helical blades rotating inside cylindrical pump housing. In this axial flow pump, the magnetically suspended single moving impeller pushes the blood with its helical blades. The inflow cannula is attached to the housing surface and the outflow cannula is attached horizontally to the pump casing. Under typical operating conditions, the RIT pump produces a flow of 6 L/min against 80 mmHg pressure at a rotating speed of 4000-5000 rpm. Blood flows freely through a 250-1600 µm (micrometer) gap at high rotation speeds causing blood damage.

Figure 1-6: Current RIT LEV-VAD pump (above) as compared to Thoratec HMII (below)
Scope of Thesis Project

Although the methods for evaluating blood damage from CFD data have been used to on rotary pumps, no studies have quantified the accuracy of these methods with a comparison to empirical data. The standard techniques to determine hemolysis (Methods 1-4) are based on empirical results found from a simple Couette viscometer [10], [11], [12].

Four methods that have been used for hemolysis analysis are Threshold Value Approach, Mass-Weighted average approach, Eulerian and Lagrangian approaches. Threshold Value Approach compares shear stress with the critical shear stress value while the Mass-Weighted average approach finds assumes percentage of hemolysis from percentage of high shear stress region. Eulerian approach numerically calculates blood cell damage using damage parameter. Lastly, Lagrangian approach tracks particles along pathlines and finds the cumulative blood damage.

In the past, all four of these methods has been extensively used however, each one of the other methods also has their limitations. Even though first three methods give accurate shear stress results, Lagrangian method is the only method that calculates both the shear stress and exposure time. Unfortunately to be effective, a sufficient number of particles need to be tracked which requires extensive amount of computational resources. As a result, it is not enough to just rely on one of these methods as each one individually does not provide an accurate technique to analyze hemolysis.

The goal of this research is to evaluate the effectiveness of these hemolysis prediction methods on two different geometries. First, a complex geometry (LEV-VAD pump), which is representative of any axial flow blood pump and a simple concentric cylinder geometry (mag-lev shearing device), which reduced the flow complexity because it has no blades. The RIT LEV-VAD pump geometry will be used to determine if current methods of evaluating hemolysis are appropriate for complicated pump geometry. The mag-lev shearing device geometry is designed to test the validity of these techniques for simple geometry. Due to complexity of hemolysis analysis, all four methods were used collectively in my thesis in order to accurately predict hemolysis. The following objectives were accomplished to fulfill thesis goal.

Objective 1

Perform CFD analysis to obtain a grid independent solution for the following geometries:

1. LEV-VAD pump geometry. CFD results will be compared with experimental performance data.
2. Mag-lev shearing device geometry

**Objective 2**

Use CFD solution to guide the design refinement of a mag-lev shearing device using the grid independent solution obtained from Objective 1. Select a suitable geometry to generate shear rate in close range of shear rate of the LVAD. There are two ways that can change the shear rate inside concentric cylinder in order to achieve shear rate in similar magnitude as that of pump while avoiding areas of recirculation and stagnation. If time allows, it will be assembled and sent to (FDA) for testing.

**Objective 3**

Create a Matlab code to estimate hemolysis from the Fluent solution data for simple and complex flow fields. Compare numerical hemolysis results of LEV-VAD pump that are calculated by using Threshold Value, Mass-Weighted average, Eulerian and Lagrangian methods with its experimental data.
Literature Review

Blood

Blood properties

Blood is a connective tissue that carries oxygen and nutrients to the cells while removing waste products from other parts of the body. Blood consists of cellular material (red blood cells, with white blood cells and platelets making up the remainder), water, amino acids, proteins, carbohydrates, lipids, hormones, vitamins, electrolytes, dissolved gases, and cellular wastes. Plasma constitutes 54.3% of the blood while red blood cells make up 45% and white blood cells only 0.7%. Moreover, plasma is mostly 92% water along with some nutrients and waste products. Red blood cell (RBC) or erythrocyte is a disc shaped cell that is hollow in both sides. RBCs are constantly produced in the bone marrow and live for four months. There are approximately 25 trillion erythrocytes in a human body. Hemoglobin, a protein pigment in red blood cells, is responsible for transporting oxygen to the tissue and carbon dioxide from them. Red blood cells can withstand large normal deformations but it ruptures easily in small shear. White blood cell or leukocyte is a part of immune system and it defends the body against foreign bacteria, viruses and other microorganisms. Platelets are disc shaped fragments that control bleeding through hemostasis and are also produced in the bone marrow [13].

The blood density is a constant value of 1050 kg per cubic meters in most literatures. Blood viscosity is a function of temperature and blood hematocrit and it is shear-thinning (viscosity decreases as shear stress increases). At high shear rates (above 100s⁻¹), the viscosity of a normal human blood reaches a constant value. Therefore, the analysis is simplified assuming the blood as a Newtonian fluid. Constant value of 3.5 cP is more commonly used for blood viscosity [14],[16],[17],[18],[19],[20],[21],[22],[23].

Blood damage

The main concern for blood pumps is to determine the level of blood damage occurring inside a device due to its flow field. The two main types of blood damage are known as thrombosis and hemolysis. Both types of blood damage are strongly influenced by the fluid shear in the flow field, in particular at the wall regions [24],[25]. Low shear and flow stagnation can influence in platelet deposition and thrombosis. On the other hand, high shear and high velocity can result in hemolysis and platelet activation [26].
Thrombosis is the formation of a blood clot and it is initiated by the body’s hemostatic mechanisms to prevent unnecessary bleeding. It can be triggered by three main factors, which are sometimes described as Virchow’s Triad: alteration in blood flow (regions of high shear stress, recirculation, or stagnation), abnormalities of the vascular wall and alterations in the constitution of blood [27]. Due to complexity and lack of experimental knowledge of thrombosis formation, further studies will need to be conducted in order to accurately predict thrombosis. Primarily, this paper will focus on the following type of blood damage known as hemolysis.

Hemolysis is the premature rupture of erythrocytes or red blood cells. When red blood cells burst and rupture the hemoglobin content leaks out from the erythrocyte into the plasma. When erythrocytes are deprived of hemoglobin content, the ability to transport oxygen through the body is reduced. This can trigger other organ dysfunctions. Increased release of hemoglobin can result in decreased oxygen and carbon dioxide content as well as it can cause kidney saturation as free hemoglobin is toxic. It is found that a kidney can clear 14 grams of hemoglobin a day in a healthy person [28].

One of the primary causes of hemolysis is fragmentation of red blood cells due to shearing. Red blood cells deform and rupture under high shear stress and/or long exposure time. Therefore, hemolysis is mainly a function of shear stress and exposure time to this stress [27]. For rotating axial pump, high fluid stress levels arise due to high rotational speeds and narrow clearances between the stationary and rotating parts of the pump.

Assuming hemolysis is only function of shear stress and exposure time to this stress, hemolysis can be determined. The rupture of red blood cells is usually determined by concentration of free hemoglobin in the blood stream.

**CFD Studies on Blood pump**

**CFD Software**

Due to complex flow field, computational fluid dynamics (CFD) is used widely in design of rotary blood pumps. CFD helps to quantify the prediction of hemolysis and to identify areas where blood clotting is most likely to occur. Therefore, various CFD solver packages have been developed and utilized over the years [27]. TASCflow which a hybrid finite volume/finite element method that solves control volume around the nodes and describe the solution variation within each element, was used by Bludszuweit [29], Apel [30], Throckmorton [31], Song [23] and Arvand, [32]. Fluent, a finite volume method, has been used by Yu [33], Chan [34], Zhang
Other CFD packages such as STAR-CD (finite volume method), SMAC (finite difference method) have been used Wu [37], Yamane [38].

**Numerical vs. Experimental results**

In 2004, Song et al. analyzed a magnetically levitated axial blood pump by a CFD software titled TASCflow. The computer simulation was both steady meaning it was not dependent on time and transient which was dependent on time. The transient simulation was done to model a pulsatile flow inlet flow condition. The pulsatile flow condition was thought to be necessary to simulate the “pulsing” feature of the heart. His CFD results were compared with in vivo testing of plastic axial blood pump, LEV-VAD, in which velocity and pressure could easily be measured. The flow field was also studied by using Particle Image Velocimetry (PIV). Due to the transparent nature of the plastic blood pump the PIV was utilized. The discrepancy between steady numerical and experimental performance was less than 10% while the discrepancy between CFD and PIV results at a flow rate of 4L/min and 6000 rpm were less than 20% [23].

In 2005, Untaroiu did a similar CFD simulation using steady flow condition and his CFD predictions was compared with the same plastic prototype of the LEV-VAD. Untaroiu’s numerical estimations agreed within 10% of the experimental flow performance so that a quasi-steady assumption is validated [39].

**Turbulence**

Moving impeller blades cause highly disturbed turbulent flows. For turbulent flow, Reynolds stress is introduced and this stress is due to random fluctuation in fluid momentum [40]. It can strongly contribute to blood mechanical trauma such as hemolysis [41].

Therefore, finding an accurate turbulent model is crucial. Two turbulent models that are mostly used are: “k-ε” and “k-ω”. Both models utilize the eddy viscosity assumption to relate the Reynolds stress to the mean velocity [40].

Apel et al. found that the standard (linear/logarithmic) wall functions become more flawed due to the increasing dominance of the viscous sublayer. Therefore, “k-ω” turbulence model was used due to the low Reynolds number. The “k-ω” model is known for the viscous sublayer and this model allows for a more accurate description of the near wall region in high grid resolution.
In dealing with computed shear stress and turbulence Apel emphasized the importance of refinement near wall grid [2].

Song et al. compared “k-ε” model and “k-ω” model in Fluent. He found that “k-ω” model is in better agreement with PIV experimental data near the wall. He agreed with Apel and concluded that “k-ω” model is more accurate near wall region whereas “k-ε” model is better compared with PIV results away from the wall [6]. Therefore for my pump model which has a narrow blade gap, I will be utilizing the “k-ω” turbulence model.

**Empirical studies**

Concentric cylinder viscometer is a relatively simple device compared to blood pumps because it creates a known, uniform shear stress. Concentric cylinder viscometer allows researchers to study erythrocyte damage in terms of the effects of shear stress.

In 1972, Leverett and Hellums conducted tests on a concentric cylinder viscometer to study the effects solid surface interaction, centrifugal force, air interface interaction, mixing of sheared and not sheared layers, cell-ell interaction, and viscous heating. They concluded that solid surface interaction effect was most important and determined that threshold shear stress for concentric cylinder geometry was 150 Pa. They have summarized the effect of exposure time on threshold shear stress as well as the effect of shear stress on hemolysis for different flow regimes [42].

![Figure 1-9: The Effect of Exposure time on Shear stress [42]](image-url)
In 1975, Sutera and Mehrajardi found critical shear stress of 250 Pa with 4 minutes of exposure time in turbulent shear flow [43]. In 1980, Heuser and Orbits measured hemolysis of porcine blood in Couette device. Furthermore, they made a comprehensive review table of shear stress and exposure time for literature before 1980 [44].

<table>
<thead>
<tr>
<th>Type of exposure</th>
<th>Order of magnitude of exposure time</th>
<th>Threshold level of damage</th>
<th>References and comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent jet</td>
<td>$10^{-4}$</td>
<td>40,000</td>
<td>Forstrom (1969) and Blackshear (1971)</td>
</tr>
<tr>
<td>Oscillating wire</td>
<td>$10^{-4}$</td>
<td>5600</td>
<td>Williams et al. (1970) (human and canine)</td>
</tr>
<tr>
<td>Oscillating bubble</td>
<td>$10^{2}$</td>
<td>4500</td>
<td>Rooney (1970) (human and canine)</td>
</tr>
<tr>
<td>Capillary flow</td>
<td>$10^{-3}$</td>
<td>5000</td>
<td>Bacher and Williams (1970) (bovine blood)</td>
</tr>
<tr>
<td>Capillary flow</td>
<td>$10^{-3}$</td>
<td>4500–7000</td>
<td>Keshaviah (1990) and Blackshear (1971) (canine blood)</td>
</tr>
<tr>
<td>Concentric cylinder, maximum stress, 600 dynes/cm²</td>
<td>$10^{9}$</td>
<td>Relatively little hemolysis per unit time</td>
<td>This work</td>
</tr>
<tr>
<td>Concentric cylinder, maximum stress, 250 dynes/cm²</td>
<td>$10^{9}$</td>
<td>Relatively little hemolysis per unit time</td>
<td>Shapiro and Williams (1970) (surface effects dominate)</td>
</tr>
<tr>
<td>Concentric cylinder, maximum stress, 600 dynes/cm²</td>
<td>$10^{9}$</td>
<td>Relatively little hemolysis per unit time</td>
<td>Knapp and Yarborough (1969) (surface effects dominate)</td>
</tr>
</tbody>
</table>

Figure 1-10: The Effect of Shear stress on Hemolysis [42]

In 1986, Wurzinger took experimental hemolysis data of human blood using the same Couette viscometer [45]. In 1990, Giersiepen utilized Wurzinger’s experimental data and found an empirical power law correlation between shear stress and exposure time in determining hemolysis [11]. Giersiepen came up with his power law model of hemolysis (Equation 2) and this correlation was plotted by Arora in 2005 [46].

![Figure 1-11: Heuser (1980) Literature Review [44]](image-url)
In 2003, Paul et. al performed experiments for wider range of shear stress and exposure time (25ms < t_{exp} < 1,238 ms) under constant shear stress (0 < \tau < 450 Pa). The results revealed that a measurable damage increase is not detectable below \( \tau = 425 \) Pa and \( t_{exp} = 620 \) ms. For the operational range of the device, the measured maximum index of hemolysis is 3.5%. The porcine blood that was used for this experiment correlated closely with human blood properties rather than bovine blood [12].
Taylor Vortices

Taylor vortices occur for annuli with the rotating inner cylinder with the stationary outer cylinder. In 1923, Taylor offered a non-dimensional Taylor number, Ta, to determine the critical relative rate of rotation between the cylinders. The critical Taylor number is predicted to be 1708 for narrow annuli with the rotating inner cylinder with the stationary outer cylinder. Beyond the critical Taylor’s number, Taylor vortices occur. The critical Taylor number increases with gap width from 1708 to 3020 when the gap width equals the radius.

In 1958, Kaye and Elgar distinguished by hot-wire velocity measurements four regimes on a Taylor - Reynolds map [47]. Ta-Re map includes four regions: laminar flow with and without vortices and turbulent flow with and without vortices. The critical value of Taylor number is 1708 when axial Reynolds number is zero. The critical number of axial Reynolds number is 2300 when rotational Taylor number is zero.

![Schematic representation of modes of flow](image)

Figure 1-14: Schematic representation of modes of flow in an annulus with an axial flow (Kaye & Elgar) [47]

The Ta-Re map four modes of flow was experimentally validated by Elgar [48]. But Reynolds number decreased from 2300 to 2000 and Taylor’s number significantly reduced from 1708 to around 50 or 60.
Published Threshold Value

In 1984, Sallam and Hwang established that the threshold shear stress with turbulent shear stress to be 400 Pa with 1 ms exposure time [49]. In 1999, Grigioni argued that the peak turbulence shear stress for hemolysis should be at least 600 Pa with the same exposure time [50]. In 2004, Song et. al found this value was found to be too high, thus the threshold value of shear stress was reduced to 500 Pa for exposure time of 100 ms [23]. In 2007, Chua et al. found that turbulent shear stress less than 250 Pa is acceptable and anything higher than 500 Pa is catastrophic through the pump [7].

Table 1.1 summarizes the published threshold stress values found from all literature review. These stress threshold values are graphed in Figure 1.16.
Figure 1-16: Threshold values of shear stress in term of exposure time
<table>
<thead>
<tr>
<th></th>
<th>Flow condition</th>
<th>Blood Type</th>
<th>Exposure Time [s]</th>
<th>Shear Stress [Pa]</th>
<th>Name</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Concentric Cylinder</td>
<td></td>
<td>1.00E+03</td>
<td>25</td>
<td>Knapp and Yarborough</td>
<td>1969</td>
</tr>
<tr>
<td>2</td>
<td>Concentric Cylinder</td>
<td></td>
<td>1.00E+02</td>
<td>60</td>
<td>Steinbach</td>
<td>1970</td>
</tr>
<tr>
<td>3</td>
<td>Concentric Cylinder</td>
<td></td>
<td>5.50E+02</td>
<td>60</td>
<td>Shapirot and Williams</td>
<td>1970</td>
</tr>
<tr>
<td>4</td>
<td>Concentric Cylinder</td>
<td></td>
<td>1.00E+02</td>
<td>150</td>
<td>Leverett</td>
<td>1972</td>
</tr>
<tr>
<td>5</td>
<td>Concentric Cylinder</td>
<td></td>
<td>6.00E-01</td>
<td>700</td>
<td>Heuser</td>
<td>1980</td>
</tr>
<tr>
<td>6</td>
<td>Concentric Cylinder</td>
<td>human</td>
<td>7.00E-01</td>
<td>255</td>
<td>Wurzinger</td>
<td>1985</td>
</tr>
<tr>
<td>7</td>
<td>Concentric Cylinder</td>
<td></td>
<td>6.00E-01</td>
<td>400</td>
<td>Hasenkam</td>
<td>1988</td>
</tr>
<tr>
<td>8</td>
<td>Concentric Cylinder</td>
<td>porcine</td>
<td>6.20E-01</td>
<td>425</td>
<td>Paul</td>
<td>2003</td>
</tr>
<tr>
<td>9</td>
<td>Concentric Cylinder</td>
<td>porcine</td>
<td>1.20E+00</td>
<td>350</td>
<td>Paul</td>
<td>2003</td>
</tr>
<tr>
<td>10</td>
<td>Concentric Cylinder</td>
<td>porcine</td>
<td>2.40E+02</td>
<td>250</td>
<td>Sutera and Mehrajardi</td>
<td>1975</td>
</tr>
<tr>
<td>11</td>
<td>Concentric Cylinder</td>
<td>human</td>
<td>1.00E+00</td>
<td>250</td>
<td>Giersiepen</td>
<td>1990</td>
</tr>
<tr>
<td>12</td>
<td>Capillary</td>
<td>bovine</td>
<td>1.00E-03</td>
<td>500</td>
<td>Bacher</td>
<td>1970</td>
</tr>
<tr>
<td>13</td>
<td>Capillary</td>
<td>canine</td>
<td>1.00E-03</td>
<td>575</td>
<td>Bacher</td>
<td>1970</td>
</tr>
<tr>
<td>14</td>
<td>Oscillating Wire</td>
<td>human and canine</td>
<td>1.00E-04</td>
<td>560</td>
<td>Williams</td>
<td>1970</td>
</tr>
<tr>
<td>15</td>
<td>Oscillating Wire</td>
<td>human and canine</td>
<td>1.00E-03</td>
<td>450</td>
<td>Rooney</td>
<td>1970</td>
</tr>
<tr>
<td>16</td>
<td>Turbulent Jet</td>
<td></td>
<td>1.00E-05</td>
<td>4000</td>
<td>Blackshear</td>
<td>1970</td>
</tr>
<tr>
<td>17</td>
<td>Turbulent Jet</td>
<td>human</td>
<td>1.00E-03</td>
<td>400</td>
<td>Sallam and Hwang</td>
<td>1984</td>
</tr>
<tr>
<td>18</td>
<td>Turbulent Jet</td>
<td></td>
<td>1.00E-03</td>
<td>800</td>
<td>Lu</td>
<td>2001</td>
</tr>
<tr>
<td>19</td>
<td>Pump</td>
<td></td>
<td>1.00E-03</td>
<td>600</td>
<td>Grigioni</td>
<td>1999</td>
</tr>
<tr>
<td>20</td>
<td>Pump</td>
<td></td>
<td>1.00E-01</td>
<td>500</td>
<td>Song</td>
<td>2004</td>
</tr>
<tr>
<td>21</td>
<td>Pump</td>
<td></td>
<td>1.00E-03</td>
<td>1000</td>
<td>Mitoh</td>
<td>2003</td>
</tr>
<tr>
<td>22</td>
<td>Pump</td>
<td></td>
<td>3.00E-03</td>
<td>300</td>
<td>Apel</td>
<td>2001</td>
</tr>
</tbody>
</table>

In 2006, Day et al. distinguished the viscous and turbulent stress threshold values in exposure time vs. shear stress graph shown in Figure 1.16 [51].
Predictive Relationships of Hemolysis

Scalar Shear Stress

Bludszuweit attempted to relate the 3D flow effects to steady shear loading though single scalar parameter which is an instantaneous 1D stress obtained from the six components of the stress tensor [52]. Bludszuweit’s equation is based on Von Mises criterion:

Equation 1-1: Bludszuweit’s equation

\[
\sigma_{SS} = \left( \frac{1}{6} \left[ (\sigma_{xx} - \sigma_{yy})^2 + (\sigma_{yy} - \sigma_{zz})^2 + (\sigma_{zz} - \sigma_{xx})^2 \right] + (\tau_{xy}^2 + \tau_{yz}^2 + \tau_{zx}^2) \right)^{1/2}
\]

\(\sigma_{SS}\) - Scalar 1-D stress
\(\sigma_{xx}, \sigma_{yy}, \sigma_{zz}\) - Normal stress components
\(\tau_{xy}, \tau_{yz}, \tau_{zx}\) - Shear stress components

Hemolysis Power Law Models

Assuming that shear stress (\(\tau\)) and exposure time (\(t_{exp}\)) are the only two factors in determining hemolysis, a few empirical power law models were formulated to determine the correlation among shear stress, exposure time and blood damage (D). D is also defined as a
percent change of hemoglobin content in the plasma

In 1986, Wurzinger obtained data for hemolysis in a rotating viscometer. A viscometer is a shearing device that produces a constant shear stress. He documented that his shear stress was less than 250 Pa with exposure time below 700 ms \[45\]. In 1990, Giersiepen came up with the Power law model based on Wurzinger’s experimental data. Giersiepen assumed that Reynolds stresses due to turbulent flow dominated the viscous stresses due to friction occurring in the pump. Therefore, he only accounted for Reynolds stresses \([53]\).

### Equation 1-2: Giersiepen Power Law model

\[
D = \frac{\Delta Hb}{Hb} = 3.62 \times 10^{-7} \tau^{2.416} \Delta t^{0.785}
\]

- \(\tau\) - Viscous stress
- \(\Delta t\) - Exposure time
- \(D\) - Blood damage

On the other hand, Apel et. al discovered that on average turbulent stress was lower than viscous stress in the pump gap region and concluded that the viscous stresses are more important than the turbulent stresses for the microaxial blood pump \([30]\).

In 1980, Heuser obtained constants for Power law model by regression analysis of experimental data taken with an exposure time of 0.0034 to 0.6 seconds for shear stresses between 40 and 700 Pa in a Couette viscometer \([10]\). The experiment was conducted on Couette viscometer in a laminar flow regime.

### Equation 1-3: Heuser Power Law model

\[
D = \frac{\Delta Hb}{Hb} = 1.8 \times 10^{-6} \cdot \tau^{1.991} \cdot \Delta t^{0.765}
\]

- \(\tau\) - Viscous stress
- \(\Delta t\) - Exposure time
- \(D\) - Blood damage

Heuser model is based on experimental data that is in the range of shear stress, which is comparable to the flow conditions in blood pumps while shear stress in Giersiepen model experimental model ranges below 250 Pa. Therefore, I will be employing Heuser’s Power Law model because it includes a wider range of shear stress data.

Gu compared four published power law hemolysis models along with a model that he
developed using energy dissipation rate (EDR) as the damage function. The first model that he analyzed is the power law model developed by Giersiepen. The second model was proposed by Heuser while the third and fourth models used a differential form of the power law developed by Grigioni [54]. The constants for models 3 and 4 were the same as those used for the Giersiepen and Heuser models respectively. In model 5, the damage index was then defined as the EDR multiplied by the exposure time. Four test devices were used to evaluate the models, a hemoresistometer, a spinning disk, a capillary tube, and a concentric cylinder. Between 50 and 500 streamlines were created for the flow fields of each device. The shear stress or energy dissipation rate and exposure time were integrated over the length of each streamline, for each blood damage model. He established that CFD result had better agreement to the experiments by using the modified shear stress models [55].

Arora et. al developed a tensor based hemolysis model, which estimated the deformation of the red blood cells using steady shear flow experiments. Arora determined that catastrophic hemolysis occurs at an approximate strain rate of 42,000 s\(^{-1}\). Below this level, RBC will gradually return to its original shape when the shearing force is reduced. His strain based model predicted much less hemolysis than the stress based model and had better agreement with his experimental hemolysis data [56]. Similar to Arora, Hentschel used strain-based method for RBC deformation. They have utilized the time rate of hemolysis model and cumulated blood damage along pathline [57].

In 2001, Wu et. al designed and optimized a blood shearing instrument that can generate shear stress upto 1500 Pa with exposure time ranging from 0.0015 to 0.2 seconds. This shearing device had a gap between 0.127-1.27 mm and a rotor which rotates from 1000 to 10000 rpm. Blood damage was predicted by Lagrangian method using 4 particles and was reduced in the optimized model [37].

**Hemolysis Evaluation in Devices**

There are four methods that were used to determine hemolysis. In this thesis, these are referred to as: 1) Threshold Value, 2) Mass-Weighted average, 3) Eulerian and 4) Lagrangian approaches. These methods have been previously used to conduct similar experiments on axial and centrifugal heart pumps.

**Method 1: Threshold Value Approach**

This approach is based on the fact that red blood cell will damage when a critical value of
shear stress is reached. This approach is common for many biological systems.

The Threshold Value approach assumes that blood is ruptured in the regions where shear stress exceeds the critical shear stress or threshold value. Even though Method 1 only depends on the highest shear stress and does not account for the exposure time, the critical threshold value for blood hemolysis shear stress is varied depending on the exposure time as mentioned previously in literature. This method is not a very accurate way of estimating hemolysis because hemolysis is a function of both shear stress and exposure time. Additionally, a very small region of high stress is found in the literature.

The advantages of this method are that it is quick and easy to evaluate hemolysis. The disadvantage is that Method 1 solely depends on variable threshold values that are found from previous studies. Regarding estimating hemolysis, Method 1 only provides a binary output where hemolysis is only determined whether blood damage exists or not.

**Method 2: Mass-Weighted Average Approach**

The Mass-Weighted average approach finds the mass data distribution of stresses within the pump. This method can be used to calculate what percentage of the mass is affected by velocity and shear stress. The Mass-Weighted average approach assumes that the percentage of high shear stress region will correlate to the percentage of hemolysis that will occur inside the pump.

In 2001, Apel used this method to compare the ratio between Reynolds and Viscous shear stresses within the pump. This allowed him to find out what percentage of shear stresses were higher or lower than the critical shear stress. He also plotted the mass distribution of shear stress and exposure time [58].

In 2003, Mitoh applied Mass-Weighted average approach to calculate shear stress value inside the pump. Based on the percentage of shear stress above critical shear stress, he assessed how much blood damage will occur within the pump [59].

In 2006 and 2007, Chua also used this method for analyzing axial LVAD and created a Mass-Weighted average shear stress table for different regions of the pump [18],[22].

Overall, Method 2 is similar to Method 1 where shear stress is compared to critical shear stress. However, Method 2 provides blood damage percentage from the percentage of mass distributed shear stress ranges.
**Method 3: Eulerian Approach**

Eulerian approach has been used by Garon and Farinas in 2004 [60] and Zhang in 2006 [61]. Fourgeau and Garon proposed a mathematical model to assess hemolysis by assuming the rate of hemolysis depended upon the instantaneous stress, exposure time, and damage history. A hyperbolic advection equation was developed by the authors to assess a linearized damage function [26]. The authors used Giersepen power law constants (Equation 2). The Eulerian approach determines hemolysis by using a single damage index parameter independent of exposure time.

Hemolysis Power law model has the following general form.

**Equation 1-4: Blood damage model**

\[ D = C \tau^{\beta} t^{\alpha} \]

This blood damage model is non-linear with respect to time. Garon and Farinas introduced linear damage, \( D_t \) [60].

**Equation 1-5: Linearized blood damage model**

\[ D_t = D^{1/\alpha} = C^{1/\alpha} \tau^{\beta/\alpha} t \]

The blood damage can be formulated as a partial differential equation discretized on Navier-Stokes computational cells. Time derivative along a streamline of the linear blood damage is constant and given by source term, \( I \).

**Equation 1-6: Damage source term**

\[ I = \frac{D}{Dt} [D_t] = C^{1/\alpha} \tau^{\beta/\alpha} \]

The authors made following three assumptions:

1. The equation of blood damage source term applies outside the interval of definition of Giersiepen (\( 1<t_{exp}<700\text{ms} \) and \( 0<\tau<255 \text{ Pa} \)).
2. The equation of blood damage source term applies to a material volume along a streamline and describes the blood damage evolution inside this material volume.
3. It applies to any material volume.

A hyperbolic transport equation can be derived from the previous equation.

**Equation 1-7: Hyperbolic transport equation**

\[ I = \left( \frac{\partial}{\partial t} + \vec{u} \cdot \nabla \right) D_t \]

This hyperbolic equation can estimate blood damage over the whole domain. Assuming that the flow field was time independent, hyperbolic equation is simplified. Thus, a time independent
average linear damage index \( (\bar{D}_I) \) with flow rate \( (Q) \) was obtained as

\[
\text{Equation 1-8: Average linear damage index}
\]

\[
\bar{D}_I = \frac{1}{Q} \int_{V} I\,dV
\]

Finally, the average damage was then obtained from average linear damage index by the following equation,

\[
\text{Equation 1-9: Time independent average damage}
\]

\[
\bar{D} = \bar{D}_I^a
\]

Zhang in 2006 conducted computational and experimental study of CentriMag centrifugal blood pump. His CFD analysis showed good agreement with experimental hemolysis and no significant hemolysis was observed in a model with gap of 1.5mm using Eulerian approach [61].

**Method 4: Lagrangian Approach**

The Lagrangian approach tracks and treats those particles in a fluid flow. This method is used to sum up the hemoglobin leakage along streamlines. Hemolysis rate is integrated along each pathline to calculate blood damage for individual red blood cells. It is assumed that the corpuscles in the blood do not deviate from the flow path of the plasma [58].

In Method 4, the rate of hemolysis is integrated along the pathlines in a flow with an instantaneous scalar measure of stress and exposure time to compute accumulated hemolysis. By taking the average over a sufficiently high number of pathlines, it is possible to calculate the hemoglobin release in the blood pump. This analysis provides a statistical estimate of damage to cells flowing through the pump.

Lagrangian method was previously used by Apel (2001) [58], Chan (2002) [34], Yano (2003) [62], Song (2004) [63][64] and Arora (2006) [56].

Apel (2001) used Lagrangian method by tracking 1000 particles inside the Impella microaxial pump in order to determine hemolysis. His study revealed that average shear stress inside the axial blood pump was 200 Pa with an average exposure time approximately 5 ms. Highest shear stress was found to be 1000 Pa although the exposure time was significantly short [58].

Chan (2002) compared five different blade designs for centrifugal pump while demonstrating particle tracking method by releasing 100 particles from pump inlet. He concluded that the more particles will give more accurate shear stress and exposure time results [32].

Yano (2003) used the Giersiepen power law relationship to evaluate the hemolysis occurring
inside a rotary LVAD. The scalar stress values were computed at each computational node and blood element shear stress histories were determined along 937 streamlines released at the inlet of the domain. Finally, equation along with the data from the particle traces related the shear stress and exposure time to an estimate of level of hemolysis [62].

Song (2004) applied a Lagrangian approach to assess the stress distribution and related exposure time inside centrifugal blood pump by tracking 388 particles. The accumulation of shear and exposure time is integrated along the pathlines to evaluate the levels of blood damage index or blood trauma. The mean residence time found to be 0.34 ms with mean blood damage index of 0.21%. Damage indices were reasonably correlated with hemolysis levels of clinically in vitro tested pumps [63][64].

Arora (2006) had traced 100 uniformly distributed particles over the inlet section for following them up to 1s or until they exit the device. He found 78% of the particles reach the outflow, while the rest either remain in the pump or hit the walls due to approximate errors. By using equation of NIH values per single pass though the pump [56].

To get an accurate result using Lagrangian method is to trace a sufficient number of particles inside the pump to represent an accurate shear stress and exposure time values inside the pump.

This calculation requires extensive amount of computational resources. Sometimes particles can be trapped inside one region for a long time and this is called recirculation zone. Hemolysis information from these trapped particles is not reliable because the exposure time is extremely long.

Comparison of Methods

Four primary methods that were utilized for hemolysis analysis are Threshold Value Approach, Mass-Weighted average approach, Eulerian and Lagrangian approaches.

Threshold Value Approach assumes that blood is ruptured in the regions where shear stress exceeds the critical shear stress or threshold value. While the Mass-Weighted average approach assumes that the percentage of high shear stress region will correlate to the percentage of hemolysis that occurs inside the pump. On the other hand, the Eulerian approach identifies potential blood cell damage using a single damage parameter. The Lagrangian approach finds blood damage by tracking particles along pathlines through the pump and finding shear stress and exposure time for each particle. All four methods share their similarities and differences but the Lagrangian method is the most unique.

The Lagrangian approach utilizes all the techniques from the other three methods and more. It considers exposure time of the particles as part of its analysis. Exposure time is critical because
the threshold value of shear stress varies with exposure time. It is important to realize that hemolysis is dependent on both.

All four of these methods have been extensively used before. However, the first three methods do not consider exposure time. Lagrangian method is the only method that calculates both the shear stress and exposure time into consideration during its study of hemolysis. Unfortunately in order for Lagrangian method to be effective, a sufficient number of particles need to be tracked. This requires extensive amount of computational resources.

Each one of the other methods also has their limitations. The Threshold Value Approach depends solely on the threshold shear stress value. The Mass-Weighted average approach only gives information about percentage of shear stress. The Eulerian approach eliminates the need to track the particle paths as can be seen in the Lagrangian Approach requiring less computational effort but still does not account for the exposure time.

Consequently, it is not enough to just rely on one of these methods as each one individually does not provide an accurate technique to analyze hemolysis. The complexity of hemolysis requires careful investigation that is only incorporated by utilizing all four methods. Therefore, all four of these methods were used collectively in this study in order to better predict hemolysis.

In my thesis, Heuser’s blood damage model (Equation 1.3) was used for both Eulerian and Lagrangian approach due to its wider range of shear stresses. However, the developers of Eulerian approach used Giersiepen’s blood damage model (Equation 1.2) for their work. Therefore, both Heuser and Giersiepen blood damage models were used for Method 3 (Eulerian Approach).
Fluent Theory

CFD Simulation

CFD simulation is based on balance among realistic physical model, needed accuracy, computational resource, appropriate turbulent model and optimal mesh.

Figure 3.1: CFD Simulation Process

Navier-Stokes (NS) equations

The Navier-Stokes (NS) equations are conservations of momentum and mass equations. These equations are solved to give fluid flow parameters such as velocities and pressure.

Before adding the turbulent terms, the NS equations are in the following format.

Equation 1-10: Navier-Stokes equation with turbulent terms

\[
\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \mu \frac{\partial u_i}{\partial x_i} \right)
\]
Equation 1-11: Continuity equation
\[ \frac{\partial u_i}{\partial x_i} = 0 \]

Turbulence Model
Before using Fluent, we must determine flow regime whether flow is laminar or turbulent. Laminar flow is dominated by object shape and dimension in a large scale whereas turbulent flow is dominated by object shape and dimension in a large scale and by the motion and evolution of small eddies in a smaller scale. The flow regime depends on flow Reynolds number, which is the ratio between the inertial forces and the viscous forces. Reynolds number measures the relative importance of convection and diffusion mechanisms. Fluid in a pipe becomes turbulent for a Reynolds number above 2300 whereas fluid in an annulus reaches its turbulence at Reynolds number above 2000.

The turbulent equations can be solved by direct numerical simulation (DNS) method or Reynolds Averaged Navier-Stokes (RANS) method. The first method solves the NS equations resolving all eddies for a sufficient time interval so that fluid properties reach a statistical equilibrium. DNS method needs a very strong computational power because of the very fine mesh and transient solution. Due to these reasons, DNS method is the most expensive and time consuming and is generally not used for real life problems. RANS method uses time-averages of the instantaneous velocities as a sum of the mean and a fluctuation. There are four mean flow equations and 10 unknowns. This is referred to as the “closure problem”. Typically, this system is closed, by approximations for the stress caused by turbulence, which is called the Reynolds stress tensor. Reynolds stress tensor in RANS is not a stress tensor, rather an average effect of turbulent convection.

Equation 1-12: RANS Turbulent instantaneous velocity
\[ u_i(x_k,t) = U_i(x_k) + u'(x_k,t) \]

Equation 1-13: RANS mean instantaneous velocity
\[ U_i(x_k) = \lim_{T \to \infty} \frac{1}{T} \int_0^T u(x_k,t) dt \]

Equation 1-14: Reynolds stress tensor
\[ R_{i,j} = \bar{u_i}'\bar{u_j}' \]

Substitute RANS quantities and add Reynolds stress tensor and NS equations for steady flow
becomes:

**Equation 1-15: Navier-Stokes equation with Reynolds stress term**

\[
U_j \frac{\partial U_i}{\partial x_j} = -\frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i} \left( \frac{\mu}{\rho} \frac{\partial U_i}{\partial x_j} \right) + \frac{\partial (-\overline{u_i' u_j'})}{\partial x_j}
\]

**Equation 1-16: Continuity equation**

\[
\frac{\partial U_i}{\partial x_i} = 0
\]

**k – ω Model**

The k – ω model is an empirical model based on model transport equations for the turbulent kinetic energy (k) and specific dissipation rate (ω), ratio of turbulent energy dissipation rate (ε) to turbulent kinetic energy (k). This model is a two equation model to solve turbulent eddy viscosity in RANS equations. There are two kinds of models available: standard and shear-stress transport (SST). SST k – ω model is better for most applications since it uses standard k – ω model inside boundary layer and high Reynolds number k – ε model outside boundary layer [65].

**Grid Adaption in Fluent**

From a physical point of view, accurate modeling near wall region is important because solid walls are the main source of vortices and turbulence. In engineering applications, flow separation and reattachment are largely dependent on a correct prediction of the turbulence near wall regions. Three different meshes (Mesh 1, Mesh 2, and Mesh 3) were adapted using three adaption methods (Boundary Adaption, Yplus/Ystar Adaption, Gradient Adaption) in Fluent.

**Boundary Adaption**

Boundary adaption allows marking or refining cells in the proximity of the selected boundary zones. The ability to refine the grid near one or more boundary zones is provided because important fluid interactions often occur in these regions. It creates more cells near boundary for applications such as velocity boundary layer [65].

**Yplus/Ystar Adaption**

The approach is to compute \( y^+ \) or \( y^* \) for boundary cells on the specified viscous wall zones, define the minimum and maximum allowable \( y^+ \) or \( y^* \) and mark and/or adapt the appropriate
cells. Cells with $y^+$ or $y^*$ values below the minimum allowable threshold will be marked for coarsening and cells with $y^+$ or $y^*$ values above the maximum allowable threshold will be marked for refinement [65].

**Gradient Adaption**

Solution-adaptive grid refinement is performed to efficiently reduce the numerical error in the digital solution, with minimal numerical cost. Unfortunately, direct error estimation for point-insertion adaption schemes is difficult because of the complexity of accurately estimating and modeling the error in the adapted grids. A comprehensive mathematically rigorous theory for error estimation and convergence is not yet available for CFD simulations. Assuming that maximum error occurs in high-gradient regions, the readily available physical features of the evolving flow field may be used to drive the grid adaption process. In Gradient approach, Fluent multiplies the Euclidean norm of the gradient of the selected solution variable by a characteristic length scale.

**Discrete Phase Model (Particle Tracing)**

The Discrete Phase Model utilizes a Lagrangian approach to derive the equations for the underlying physics which are solved transiently. The phases are divided into two phases: fluid phase and dispersed phase. The main assumption is that dispersed phase occupies a low volume fraction than the fluid phase. In steady-state discrete phase modeling, particles do not interact with each other and are tracked one at a time in the domain. Fluid phase is treated as a continuum and is initially solved using Navier-Stokes equation. The fluid is assumed to be single phase, incompressible and Newtonian fluid.

Then, dispersed phase is injected into the fluid phase and is solved by tracking particles throughout the calculated flow field. Fluent predicts the trajectory of a discrete phase particle by integrating the force balance equation on the particle in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle, and can be written as:

**Equation 1-17: Force Balance equation**

$$\frac{du_i^p}{dt} = F_D(u_i - u_i^p) + \frac{g_i(\rho_p - \rho)}{\rho_p} + F_i$$

- $u_i$ - Fluid velocity at node i
- $u_i^p$ - Particle velocity at node i
- $F_D(u_i - u_i^p)$ - Drag force per unit particle mass
- $g_i$ - Gravity at node i
$F_i$ - Additional force per unit particle mass at node $i$

First term is drag force and it is a function of the relative velocity. Second term is gravity force. The last term accounts for additional forces such as pressure gradient, thermophoretic, rotating reference frame, Brownian motion, Saffman lift for and other user-defined forces. Rotating forces created due to rotation of the reference frame. The additional force term includes forces on particles that arise due to rotation of the reference frame. These forces arise when modeling flows in rotating frames of reference.

The trajectory equations, and any auxiliary equations describing mass transfer to/from the particle, are solved by stepwise integration over discrete time steps. Integration of time yields the velocity of the particle at each point along the trajectory, with the trajectory itself predicted by the following.

**Equation 1-18: Trajectory equation**

\[
\frac{dx}{dt} = u_p \\
\]

- $t$ - Time
- $x$ - Location
- $u_p$ - Particle velocity

Equation 1.17 and 1.18 are a set of coupled ordinary differential equations. The equation 1.17 can be cast into the following general form.

**Equation 1-19: General form of Force Balance equation**

\[
\frac{du_p}{dt} = \frac{u - u_p}{\tau_p} + a \\
\]

- $a$ - Acceleration
- $u$ - Fluid velocity
- $u_p$ - Particle velocity
- $\tau_p$ - Particle shear stress

In this equation, the term $a$ includes accelerations due to all other forces except drag force. This set can be solved for constant $u$, $a$ and $\tau_p$ by analytical integration. The particle velocity at the new location ($u_p^{n+1}$) is defined by Equation 1.20.
Equation 1-20: Particle velocity at the new location

\[ u_p^{n+1} = u_p^n + e^{-\eta}(u_p^n - u^n) - a \tau(e^{-\eta} - 1) \]

- \( u_p^{n+1} \): Particle velocity at new location
- \( u_p^n \): Particle velocity at old location
- \( u^n \): Fluid velocity at old location

Similarly, the new location (\( x_p^{n+1} \)) can be computed by the following relationship.

Equation 1-21: Particle location at the new location

\[ x_p^{n+1} = x_p^n + \Delta t(u^n + a \tau_p) + \tau_p(1 - e^{-\eta})(u_p^n - u^n - a \tau_p) \]

- \( x_p^{n+1} \): Particle location at new location
- \( x_p^n \): Particle location at old location

In setting up DPM mode, there are two tracking parameters to control the time integration of the particle trajectory equations: max number of steps and step length scale. The maximum number of time steps is the maximum number of time steps used to compute a single particle trajectory.

The step length factor or length scale is used to set the time step for integration within each control volume.

Equation 1-22: Length scale

\[ \Delta t = \frac{L}{u_p + u_c} \]

- \( L \): Length Scale
- \( \Delta t \): Integration time step

The integration time step is computed by Fluent based on a characteristic time that is related to an estimate of the time required for the particle to traverse the current continuous phase control volume. The integration time step (\( \Delta t \)) is defined by the following equation.

Equation 1-23: Integration time step

\[ \Delta t = \frac{\Delta t^*}{\lambda} \]

- \( \lambda \): Step Length Factor
Δt* - Estimated transit time

With Track in Absolute Frame enabled, you can choose to track the particles in the absolute reference frame. All particle coordinates and velocities are then computed in this frame. The forces due to friction with the continuous phase are transformed to this frame automatically.

In rotating flows, it might be appropriate for numerical reasons to track the particles in the relative reference frame. If several reference frames exist in one simulation, then the particle velocities are transformed to each reference frame when they enter the fluid zone associated with this reference frame [65].
2. Methods

In order to properly analyze hemolysis, a given geometry is modeled using three-dimensional (3D) computer aided design (CAD) software. The fluid dynamics inside the pump can only be solved by using CFD due to the complex geometry of the pump. The primary softwares that were utilized for CFD analysis are SolidWorks, Gambit and Fluent.

The four methods that were used to determine hemolysis are Threshold Value Approach, Mass-Weighted average approach, Eulerian and Lagrangian approaches. In this section, these approaches are explained in greater detail.

CFD Analysis

CFD analysis consists of modeling the LEV-VAD pump and mag-lev shearing device using SolidWorks. Then, they were meshed in Gambit and simulated using Fluent. Fluent provides visual fluid flow information along with numerical data that were used in Matlab for the four different hemolysis evaluating approaches. The results from the Fluent software were analyzed using Hemolysis code that were written in Matlab program.

Modeling – SolidWorks

Solidworks is a mechanical 3D CAD program. It has been used extensively to model the various components of the devices for this paper. The pump geometry was modeled using Solidworks 2009.

LEV-VAD pump

A 3D axial blood pump (Figure 2.1A) that was created at RIT was used. The section between inducer and diffuser was considered. The pump consists of 4 blades, each with a chord length of 95 mm. The blades are located approximately 9.6 mm (measured from the leading edge) from the center of rotation. The model is axisymmetric, thus full 3D model was used for my model. Figure 2.1B shows a 2D view on the transverse plane through the axis of rotation. The radius of the outer wall is 9.85 mm while the impeller wall is 8.2 mm. Detailed drawing of the pump impeller is shown in Figure 2.2. The fillets around the blade edges were removed to avoid small faces and to reduce the number of faces that will be exported. A fluid volume was created inside pump housing from inducer to diffuser as shown in Figure 2.7. Then, a true fluid volume region was created by subtracting solid volumes such as inducer, impeller and diffuser from the total fluid volume using Mold/Cavity feature. This volume was saved as a part and exported as a Binary Parasolid file with .x_b extension.
Figure 2-1: A) RIT LEV-VAD pump (3D isometric view)

B) RIT LEV-VAD pump (2D section view)
**MAG-LEV Shearing Device**

The Mag-lev shearing device will utilize the current magnetic levitation system that is being used for the LEV-VAD pump. Unlike the RIT pump this device has bladeless inducer (inlet), diffuser (outlet), and impeller. The new impeller was created first by removing all blades. Then a 10 mm extruded section was created around the middle of the impeller to create same shear stress that is created by LEV-VAD pump. This extruded section is called a “bump”. All components in the MAG-LEV device are shown below. (Figure 2.3)

**Mag-lev shearing device Components**
1. Magnetic system from LEV-VAD pump
2. Outside housing
3. Impeller housing
4. Impeller rear
5. Bump
6. Inlet pipe with inner diameter of 0.25in/ 6.35mm
7. Outlet pipe with inner diameter of 0.25in / 6.35mm

In order to properly calculate shear stress through the device, one of the crucial sections to analyze is the bump. In the device, the bump is the portion where the highest shear stress is estimated to occur.

To determine the shear stress properly through the bump, specific dimensional changes to that section have been made. Changes regarding the MAG-LEV device are highlighted in Figure 2.4 by green lines. The red lines indicate the constrained sections. By adjusting the dimensions of the bump, we can control shear stress. In addition, exposure time can be controlled by changing axial
flow rate while shear stress depends mostly on rotating speeds. Table 2.1 contains the dimensions and flow variables of the constrained and adjustable sections of the MAG-LEV shearing device.

![Image](image-url)

**Figure 2-4: Fixed (red) and Adjustable (green) Geometry**

<table>
<thead>
<tr>
<th>Constrained Geometry</th>
<th>Adjustable Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rin=8.2mm</td>
<td>Hgap=0.125mm</td>
</tr>
<tr>
<td>Rout=9.85mm</td>
<td>Lgap=10.00mm</td>
</tr>
<tr>
<td>Lin=51.55mm</td>
<td>0&lt;θ&lt;90 deg</td>
</tr>
</tbody>
</table>

*Table 2-1: Summary of Constrained and Adjustable variables*

The extruded section was later streamlined or aerodynamically modified in order to avoid stagnation point and recirculation area. Moreover, the impeller nose was changed. The changes that are made to the bump are shown in Figure 2.6.

![Image](image-url)

**Figure 2-5: The impeller (blue) with this bump (LEV-VAD)**

**Figure 2-6: The impeller (blue) with streamlined bump (LEV-VAD)**

The volume inside the housing and impeller was created using Cavity/Mold feature in
Initially, three different designs were created and design 3 was further analyzed. From Design 1 to Design 2, the bump height was changed from 0.25mm to 0.125mm to reach the desired shear stress value. From Design 2 to Design 3, the bump length was changed from 10mm to 22mm to create the desired exposure time. This design was the only model out of first three initial designs which was capable of reaching the desired shear stress value with a given exposure time. The extensive numerical simulation was done on Design 3.

Design 4 was created because the bump length depends on the distance away the center of rotational axis. More details can be found in “Determining Bump Length” section. For manufacturing purposes, the design 4 will be used as the final design.
Determining Bump length

In order for Mag-lev shearing device to levitate, the impeller tip can be 0.5 mm distance away from the center of rotational axis. The rotation angle, $\theta$, will be determined by dividing 0.5 mm distance by the overall length of the impeller (106.7 mm) as shown in Figure 2.13.

$$\theta = \sin \theta = \frac{0.5\text{mm}}{106.7\text{mm}} = 0.004686\text{rad}$$

Gap H=0.25mm: \[ L = \frac{0.25\text{mm}}{\sin \theta} = \frac{0.25\text{mm}}{0.004686} = 53.35\text{mm} \] minimum length of the bump.

Gap H=0.125mm: \[ L = \frac{0.125\text{mm}}{\sin \theta} = \frac{0.125\text{mm}}{0.004686} = 26.7\text{mm} \] minimum length of the bump.

Therefore the bump length will be 27mm for the gap of 0.125mm.
Volume Minimization

The volume from Design 1 decreased from 15.3 ml (Figure 2.14) to 5.8 ml (Figure 2.15) in Design 4. This was done in order to reduce the cost because human blood was the test fluid.

Meshing – Gambit

The SolidWorks geometry in Parasolid format was imported into grid generating software (Gambit, v2.2.30, Fluent Inc., Lebanon, NH, U.S.A) for meshing by the 3D Tet/ Hybrid TGrid and Hex/Wedge Cooper elements.
LEV-VAD pump

Figure 2-16: Overall view of Mesh 1 (100,800 elements)

Table 2-2: The setting of the mesh 1 in Gambit

<table>
<thead>
<tr>
<th>Mesh Elements</th>
<th>Mesh Type</th>
<th>Interval Size</th>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 1</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>0.5</td>
</tr>
<tr>
<td>Volume 2</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>0.5</td>
</tr>
<tr>
<td>Volume 3</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Since all three volumes had an irregular shape with empty holes, they were meshed by Tet/Hybrid TGrid elements in Mesh 1 (Figure 2.17). Table 2.2 summarizes mesh type and number of elements for each volume. For typical geometry such as cylinders, cooper mesh is typically utilized. For irregular shapes with an impeller hole can only be meshed with TGrid with tetrahedral shape elements.

Figure 2-17: Overall view of Mesh 2 (138,150 elements)

Table 2-3: The setting of the mesh 2 in Gambit

<table>
<thead>
<tr>
<th>Mesh Elements</th>
<th>Mesh Type</th>
<th>Interval Size</th>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 1</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>0.5</td>
</tr>
<tr>
<td>Volume 2</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>0.5</td>
</tr>
<tr>
<td>Volume 3</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>1</td>
</tr>
</tbody>
</table>

In Mesh 2, volume 1 and volume 3 were cylinder shape geometries and meshed by
Hex/Wedge Cooper mesh. Volume 2 contained impeller vacuum and was meshed by all Tet/Hybrid TGrid elements with interval size 0.5.

![Figure 2-18: Overall view of Mesh 3 (350,000 elements)](image)

### Table 2-4: The setting of the mesh 3 in Gambit

<table>
<thead>
<tr>
<th>Mesh Elements</th>
<th>Mesh Type</th>
<th>Interval Size</th>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 1</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>0.5</td>
</tr>
<tr>
<td>Volume 2</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>0.2</td>
</tr>
<tr>
<td>Volume 3</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>0.5</td>
</tr>
</tbody>
</table>

In Mesh 3, volume 1 and volume 3 were the same as Mesh 2. Boundary layer was added near wall regions at both inlet (volume 1) and outlet faces (volume 3). Then, those volumes were meshed by Hex/Wedge Cooper mesh with interval size 0.5. Volume 2 which contained impeller vacuum was meshed by all Tet/Hybrid TGrid elements with interval size 0.2 which is smaller than Mesh 2.

**Mag-lev shearing device**

Mag-lev shearing device was divided into 9 volumes. Volumes at the inlet (Volume 1) and outlet (volume 9) and concentric cylinders at the wide gap (Volume 3 and 7) and thin gap (Volume 5) were meshed by Hex/Cooper mesh. TGrid was used for the rest of the volumes with an irregular shape (Volume 2, 4, 6 and 8). The overall mesh view can be seen in Figure 2.20 and details of the Mesh 1 can be seen in Figure 2.21. Table 2.5 summarizes mesh type and number of elements for each volume.

![Figure 2-19:Overall view of Mesh 1 (30,000 elements)](image)
Figure 2-20: Detailed view of Mesh 1

Table 2-5: The setting of the Mesh 1 in Gambit

<table>
<thead>
<tr>
<th>Volume</th>
<th>Mesh Elements</th>
<th>Mesh Type</th>
<th>Interval Size</th>
<th>Number of Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 1</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>1</td>
<td>1581</td>
</tr>
<tr>
<td>Volume 2</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>1</td>
<td>12,389</td>
</tr>
<tr>
<td>Volume 3</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>1</td>
<td>2688</td>
</tr>
<tr>
<td>Volume 4</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>1</td>
<td>1227</td>
</tr>
<tr>
<td>Volume 5</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>1</td>
<td>2812</td>
</tr>
<tr>
<td>Volume 6</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>1</td>
<td>1226</td>
</tr>
<tr>
<td>Volume 7</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>1</td>
<td>3956</td>
</tr>
<tr>
<td>Volume 8</td>
<td>Tet/Hybrid</td>
<td>TGrid</td>
<td>1</td>
<td>2842</td>
</tr>
<tr>
<td>Volume 9</td>
<td>Hex/Wedge</td>
<td>Cooper</td>
<td>1</td>
<td>1224</td>
</tr>
</tbody>
</table>
In addition, swirling flows often involve steep gradients in the circumferential velocity and require a fine grid for accurate resolution. Rotating boundary layers may be very thin inside the pump model; therefore, sufficient resolution grid near a rotating wall is needed.

In order to refine grid resolution near the rotating wall, boundary layer was created. Four rows of boundary layer of size 0.01 with growth rate of 1.2 were added at the four edges of the thin gap. Four rows of boundary layer of size 0.1 with growth rate of 1.2 were added at the inlet and outlet boundary edges. The overall mesh 5 can be seen in Figure 2.23 and Table 2.6 summarizes mesh type and number of elements for each volume.
Analyzing flow field – Fluent

An unstructured-mesh finite-volume based commercial CFD package, (Fluent, v12.0, Fluent Inc., Lebanon, NH, U.S.A), was used to solve the incompressible steady Navier-Stokes equations. A velocity boundary condition was specified at the inlet and a pressure-outlet condition was set at the outlet. Steady laminar flow was simulated in all cases.

The rotational motion was modeled by the Multiple Reference Frame (MRF) provided in Fluent CFD package. For this model, one moving part (impeller walls) is rotating at a prescribed angular velocity (3000-6000 rpm), and the stationary walls (outside walls) are anchored with absolute zero velocity. Second order discretization was used for solving Navier-Stokes and turbulence equations and the SIMPLE scheme was used for pressure-velocity coupling. Convergence criteria was set at 1e-3 to 1e-5.

**LEV-VAD pump**

In Fluent, the uniform velocity that was found from flow rate was set at the inlet (blue) while constant pressure of 200 kPa was set at the outlet (red). The impeller is magnetically levitated which means the impeller is suspended inside the pump housing without touching walls. Inlet and outlet diameters are 14 mm and 10 mm, respectively. The inlet area is 1.54e-4 m². The blades are rotating with an angular velocity (3000-6000 rpm). Therefore, the flow is assumed to be turbulent. The velocity at the inlet is found to be 0.05 m/s for a flow rate of 0.1 lpm and the flow discharges to ambient conditions (gauge pressure = 200 kPa). Uniform velocity set at the inlet depending on the flow rate (Table 2.7).
Figure 2-23: Fluent Boundary Conditions

Table 2-7: Inlet velocity and exposure time for different flow rates

<table>
<thead>
<tr>
<th>Flow Rate [lpm]</th>
<th>Flow Rate [m³/s]</th>
<th>Velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.00E+00</td>
</tr>
<tr>
<td>1</td>
<td>1.667E-05</td>
<td>1.08E-01</td>
</tr>
<tr>
<td>2</td>
<td>3.333E-05</td>
<td>2.17E-01</td>
</tr>
<tr>
<td>3</td>
<td>5.000E-05</td>
<td>3.25E-01</td>
</tr>
<tr>
<td>4</td>
<td>6.667E-05</td>
<td>4.33E-01</td>
</tr>
<tr>
<td>5</td>
<td>8.333E-05</td>
<td>5.41E-01</td>
</tr>
<tr>
<td>6</td>
<td>1.000E-04</td>
<td>6.50E-01</td>
</tr>
</tbody>
</table>

Volume 1 and 3 were stationary fluid zone whereas Volume 2 was set as a moving fluid zone with a given rotational speed (Table 2.8)

Table 2-8: Fluid volume conditions for LEV-VAD pump

<table>
<thead>
<tr>
<th></th>
<th>Max. Diameter [mm]</th>
<th>Length [mm]</th>
<th>Cell Zone Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 1</td>
<td>7</td>
<td>10</td>
<td>Stationary</td>
</tr>
<tr>
<td>Volume 2</td>
<td>9.85</td>
<td>92.5</td>
<td>Moving Reference Frame</td>
</tr>
<tr>
<td>Volume 3</td>
<td>5.65</td>
<td>116.5</td>
<td>Stationary</td>
</tr>
</tbody>
</table>

No slip stationary relative to adjacent cell zone boundary condition was set at the outside walls of Volume 1 and 3 (Wall 1 and 3). No slip absolute stationary boundary condition was set at the outside wall of Volume 2 (Wall 2) while impeller wall is set as a moving wall rotating at the same speed as Volume 2. (Table 2.9)

Table 2-9: Wall Conditions for LEV-VAD pump

<table>
<thead>
<tr>
<th>Wall</th>
<th>Fluid</th>
<th>Cell Zone</th>
<th>Wall Motion</th>
<th>Reference Frame</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name</td>
<td>Volume</td>
<td>Condition</td>
<td>Relative to</td>
<td>[rpm]</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>--------</td>
<td>--------------------</td>
<td>---------------------------</td>
<td>-------</td>
<td></td>
</tr>
<tr>
<td>Impeller Wall</td>
<td>2</td>
<td>Moving Reference Frame</td>
<td>Moving wall Relative to Adjacent Cell Zone</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Wall 1</td>
<td>1</td>
<td>Stationary</td>
<td>Stationary Wall Relative to Adjacent Cell Zone</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Wall 2</td>
<td>2</td>
<td>Moving Reference Frame</td>
<td>Moving wall Absolute</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Wall 3</td>
<td>3</td>
<td>Stationary</td>
<td>Stationary Wall Relative to Adjacent Cell Zone</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

**Turbulent model SST \( k - \omega \) model**

Literatures stated that Shear Stress Transport (SST) \( k - \omega \) model uses standard \( k - \omega \) model inside boundary layer and high Reynolds number \( k - \varepsilon \) model outside boundary layer. The standard \( k - \omega \) model predicts turbulent flow better near the wall region while high Reynolds number \( k - \varepsilon \) model calculates turbulent flow better away from the wall region. My model contains thin boundary layers inside thin gap region between the tip of the blades and outside housing as well as regions outside these thin boundary layers. Therefore, SST \( k - \omega \) model is better suited for my pump model. Default setting of SST \( k - \omega \) model is shown in Figure 2.25.

![Figure 2-24: Turbulent model set up](image)
The Mag-lev bump creates 2 concentric cylinder regions (Region 1 and 2) inside the device. Flow enters from inlet with constant velocity through a cylinder with 6.35mm diameter. Then, fluid travels through annular wide and narrow gap regions. Region 1 is narrow gap with height of 0.125mm whereas Region 2 has a wider gap of 1.6mm. The outside walls are stationary and inside impeller wall is rotating with constant speeds of 3000rpm, 6000rpm and 9000 rpm.

**Axial Flow Rate**

A Harvard Apparatus syringe pump (Model #4200017) with 140 ml Monoject syringes can achieve up to flow rate of 220 ml/min but 1ml/min was little bit too low. Therefore, I chose the following 4 flow rates: 50, 100, 150 and 200 ml/min. Even with the highest flow rate, exposure time below 20 ms may not be reached. This is due to the bump which is required for the Mag-lev shearing device to levitate.

Mag-lev shearing device and LEV-VAD pump share similar Fluent setup. The uniform velocity that was found from flow rate was set at the inlet (blue) while constant pressure of 200kPa was set at the outlet (red). Uniform velocity set at the inlet depending on the flow rate (Table 2.10). The inlet radius is 3.175 mm and the area is 3.17e-5 m².
Table 2-10: Inlet velocity and exposure time for different flow rates

<table>
<thead>
<tr>
<th>Flow Rate [lpm]</th>
<th>Flow Rate [m^3/s]</th>
<th>Velocity [m/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>8.33 E-07</td>
<td>2.63E-02</td>
</tr>
<tr>
<td>0.1</td>
<td>1.67E-06</td>
<td>5.26E-02</td>
</tr>
<tr>
<td>0.15</td>
<td>2.5 E-06</td>
<td>7.89E-02</td>
</tr>
<tr>
<td>0.2</td>
<td>3.33E-06</td>
<td>1.05E-01</td>
</tr>
</tbody>
</table>

Volume 1 and 9 were stationary fluid zones whereas Volumes 2-8 were set as moving fluid zones with a given rotational speed (Table 2.11).

Table 2-11: Fluid volume conditions for mag-lev shearing device

<table>
<thead>
<tr>
<th></th>
<th>Max. Diameter [mm]</th>
<th>Length [mm]</th>
<th>Cell Zone Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume 1</td>
<td>5</td>
<td>18</td>
<td>Stationary</td>
</tr>
<tr>
<td>Volume 2</td>
<td>9.85</td>
<td>45</td>
<td>Moving Reference Frame</td>
</tr>
<tr>
<td>Volume 3</td>
<td>9.85</td>
<td>56</td>
<td>Moving Reference Frame</td>
</tr>
<tr>
<td>Volume 4</td>
<td>9.85</td>
<td>62</td>
<td>Moving Reference Frame</td>
</tr>
<tr>
<td>Volume 5</td>
<td>9.85</td>
<td>84</td>
<td>Moving Reference Frame</td>
</tr>
<tr>
<td>Volume 6</td>
<td>9.85</td>
<td>88</td>
<td>Moving Reference Frame</td>
</tr>
<tr>
<td>Volume 7</td>
<td>9.85</td>
<td>99.5</td>
<td>Moving Reference Frame</td>
</tr>
<tr>
<td>Volume 8</td>
<td>9.85</td>
<td>125.7</td>
<td>Moving Reference Frame</td>
</tr>
<tr>
<td>Volume 9</td>
<td>5</td>
<td>144.8</td>
<td>Stationary</td>
</tr>
</tbody>
</table>

No slip stationary relative to adjacent cell zone boundary condition was set at the outside walls of Volume 1 and 3 (Wall 1 and 3) No slip absolute stationary boundary condition was set at the outside wall of Volumes 2-8 (Wall 2) while cylinder wall is set as a moving wall rotating at the same speed as Volumes 2-8 (Table 2.12).
Table 2-12: Wall Conditions for mag-lev shearing device

<table>
<thead>
<tr>
<th>Wall Name</th>
<th>Fluid volume</th>
<th>Cell Zone Condition</th>
<th>Wall Motion</th>
<th>Reference Frame Relative to</th>
<th>Speed [rpm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylinder Wall</td>
<td>2</td>
<td>Moving Reference Frame</td>
<td>Moving wall</td>
<td>Adjacent Cell Zone</td>
<td>0</td>
</tr>
<tr>
<td>Wall 1</td>
<td>1</td>
<td>Stationary</td>
<td>Stationary Wall</td>
<td>Relative to Adjacent Cell Zone</td>
<td>0</td>
</tr>
<tr>
<td>Wall 2</td>
<td>2</td>
<td>Moving Reference Frame</td>
<td>Moving wall</td>
<td>Absolute</td>
<td>0</td>
</tr>
<tr>
<td>Wall 3</td>
<td>3</td>
<td>Stationary</td>
<td>Stationary Wall</td>
<td>Relative to Adjacent Cell Zone</td>
<td>0</td>
</tr>
</tbody>
</table>

**Fluid Material:**

Blood was treated as an incompressible Newtonian fluid with a viscosity of 0.0035 Pa-s and density 1050 kg/ m³ (Figure 2.26A). For inert particle material, custom “blood-particle” was added with constant blood density of 1050 kg/m³ (Figure 2.26B).

*Setting up the DPM model*

LEV-VAD pump
Figure 2-27: Injection properties for injection 0, 1 and 2 (number of particles=18000, 500,500)

Figure 2.27 display the properties of three injections that are released from the inlet. Injection 0 was a surface type. There was 18,000 particles tracked and 5000 completed. Though the binary file was too large to process (500MB) in Matlab. Custom “blood particle” with the density equal to blood was used as the particle material. Injection 1 and 2, a group of 500 particles are released from y=-5 mm to y=5 mm and x=-5 mm to y=5 mm at the inlet. However, injection 1 and 2 did not get out of the domain when the particle data was graphed in Matlab.

The maximum number of time steps (1e9) was set in order to complete the particles. Particles did not escape. Therefore, pathline data were used to export residence time, velocity and strain rate. 200 particle that are released from inlet rakes (equally spaced line) y=-5 mm to y=5 mm and x=-5 mm to y=5 mm. These pathlines were tracked and 93 particles are escaped out of 200. Therefore, the pathline data for the LEV-VAD pump is used for hemolysis analysis using Lagrangian approach.

Mag-lev Shearing Device

Figure 2-28: Injection properties for injection 1 and 2 (total number of particles=200)

Figure 2.28 displays the properties of two injection that are released from the entrance of the thin gap (z=62 mm). Both injections are group inert type particles with linear diameter
distribution. Custom “blood particle” with the density equal to blood was used as the particle material. Injection 1 releases 100 particles from \( y=9.73 \) mm to \( y=9.83 \) mm whereas Injection 2 releases 100 particles from \( x=9.73 \) mm to \( y=9.83 \) mm. The maximum number of time steps was set as 20,000 in order to complete the particles (Figure 2.31).

![Figure 2-29: The setting of DPM model for MAG-LEV shearing Device.](image)

**Evaluating data – Matlab**

Matlab (v2009, Mathworks Inc., Natick, MA, U.S.A) was used to get analytical solution for Mag-lev shearing device as well as for Hemolysis model codes.

**Hemolysis Analysis**

Four methods to evaluate hemolysis are Threshold Value, Mass-Weighted Average, Eulerian and Lagrangian approaches. These methods have been previously used to conduct similar experiments on axial and centrifugal heart pumps.

**Method 1: Threshold Value Approach**

The Threshold Value Approach assumes that blood is ruptured in the regions where shear stress exceeds the critical shear stress or threshold value. Even though Method 1 only depends on the maximum shear stress, the critical threshold value for blood hemolysis shear stress varies depending on the exposure time as mentioned previously in literature.

**Calculations:**

Step 1 – Solution of velocity and pressure
The velocity field is solved from Navier-Stokes equation in Fluent.

Step 2 – Calculation of 1-D scalar shear stress
The three-dimensional (3D) shear stresses are calculated from the CFD numerical simulations of the blood flow in the pump. Using flow field information, scalar stress defined by Bludszuweit
(Equation 1) for every node is calculated. Through my analysis, I construed that the total strain rate data from Fluent provides identical shear stress value as Bludszuweit’s 1-D scalar shear stress.

Step 3 – Comparison to the critical Threshold shear stress

Calculated scalar stress is then compared to the published threshold values in order to predict the hemolysis. If the scalar shear stress is higher than the critical shear stress value, it is considered that shear stress may damage the erythrocytes.

**Method 2: Mass-Weighted Average Approach**

The Mass-Weighted average approach finds the mass distribution of stresses. Method 2 assumes that the percentage of high shear stress region will correlate to the percentage of hemolysis that will occur inside the pump.

**Calculations:**

Step 1 – Solution of velocity and pressure
Step 2 – Calculation of 1D scalar shear stress
Step 3 – Categorize the stresses

In Mass-Weighted average approach, it is important to initially classify elements by magnitude of stress and then sum up masses of element for each class. Shear stress is categorized in bin fashion from low to high. The primary goal of this is to see shear stresses above the threshold value. It is important because it helps to figure out how much percentage of shear stress is above certain level. The example of this bar graph is done by Mitoh [66].

![Figure 2-30: Example of Bar graph for shear stress [59]](image)
The Mass-Weighted average approach assumes that the percentage of high shear stress region will correlate to the percentage of hemolysis that will occur inside the pump.

Using method 2, it is easier to find out range of shear stress inside the pump because it outputs mass distributed shear stress ranges. Once again, this approach only depends on the shear stress and does not account for the exposure time. Therefore, it is also not very accurate method to estimate hemolysis.

**Method 3: Eulerian Approach**

The Eulerian approach determines hemolysis by using a single damage index parameter independent of exposure time.

**Calculations:**
Step 1 – Solution of velocity and pressure
Step 2 – Calculation of 1D scalar shear stress
Step 3 – Calculation of average blood damage

For my study, I defined two damage source terms, $I$, with both Giersiepen and Heuser power law models:

1. Source term with constants from Giersiepen model (the authors used this relationship for their model) $I_{GIERSEIPE} = G = (3.62 \times 10^{-7})^{1/0.785} \tau^{2.416/0.785}$

2. Source term with constants from Heuser model (I used this relationship for Lagranagian approach my thesis) $I_{HEUSER} = H = (1.8 \times 10^{-6})^{1/0.765} \tau^{1.991/0.765}$

These terms are defined as Custom Field Functions in Fluent and were solved as a post-processing procedure after the flow field solution converged. These functions are shown in Table 2.13.

<table>
<thead>
<tr>
<th>Fluent Custom Defined Functions</th>
<th>Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_{total} = 3.5 \times 10^{-3} \times \varepsilon_{total}$</td>
<td></td>
</tr>
</tbody>
</table>
Method 4: Lagrangian Approach

The Lagrangian approach tracks particles and sums up the hemoglobin leakage along streamlines. This analysis provides a statistical estimate of damaged cells through the pump.

Calculations:

Step 1 – Solution of velocity and pressure (same as prior methods)

Step 2 - Discrete Phase Model must be turned on in Fluent to acquire flow pathline flow field information for all particles. The Discrete Phase Model treats the particles as a dispersed phase and tracks individual particles along pathline.

Step 3 – Calculation of 1-D scalar shear stress

Step 4 – Calculation of Damage along pathline using Matlab

\[ \sigma = (3.62 \times 10^{-7})^{1/0.785} \tau^{2.416/0.785} \]

\[ \sigma = (1.8 \times 10^{-6})^{1/0.765} \tau^{1.991/0.765} \]
3. Results and Discussion

**LEV-VAD Pump Model**

**Experimental Results**

There experimental results are collected from two studies: Study 1 includes 4000 rpm and 5000 rpm data and Study 2 includes 5000 rpm and 6000 rpm. Table 3.1 summarizes experimental results for LEV-VAD pump for 4000, 5000 and 6000 rpm. Mini refers to miniaturized RIT pump or LEV-VAD pump. Two studies were combined in Figure 3.1. Performance results for 5000 rpm from two studies match very closely. Therefore, all performance data for 4000 rpm, 5000 rpm and 6000 rpm are used to compare with the numerical performance results.

<table>
<thead>
<tr>
<th>Study #1</th>
<th>Study #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow [lpm]</td>
<td>ΔP [mmHg]</td>
</tr>
<tr>
<td>Flow [lpm]</td>
<td>ΔP [mmHg]</td>
</tr>
<tr>
<td>Mini 5000</td>
<td>Mini 6000</td>
</tr>
<tr>
<td>0</td>
<td>91</td>
</tr>
<tr>
<td>1</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
</tr>
<tr>
<td>3</td>
<td>64</td>
</tr>
<tr>
<td>4</td>
<td>57</td>
</tr>
<tr>
<td>5</td>
<td>51</td>
</tr>
<tr>
<td>5.8</td>
<td>45</td>
</tr>
<tr>
<td>Flow [lpm]</td>
<td>ΔP [mmHg]</td>
</tr>
<tr>
<td>Flow [lpm]</td>
<td>ΔP [mmHg]</td>
</tr>
<tr>
<td>Mini 4000</td>
<td>Mini 5000</td>
</tr>
<tr>
<td>0.8</td>
<td>53</td>
</tr>
<tr>
<td>1.8</td>
<td>46</td>
</tr>
<tr>
<td>2.7</td>
<td>39</td>
</tr>
<tr>
<td>3.7</td>
<td>33</td>
</tr>
<tr>
<td>4.8</td>
<td>25</td>
</tr>
<tr>
<td>5.4</td>
<td>22</td>
</tr>
<tr>
<td>7.2</td>
<td>65</td>
</tr>
</tbody>
</table>

Table 3-1: Summary of in vitro Experimental Studies for LEV-VAD pump
Figure 3-1: Characteristic Curve for experimental studies LEV-VAD pump (Mini)

**Numerical Solutions**

**Grid Independence Study**

Mesh independence studies analysis shows mesh parameters and quantify the error associated with spatial discretization.

Three different meshes (Mesh 1, Mesh 2, and Mesh 3) were adapted using three adaption methods (Boundary Adaption, Yplus/Ystar Adaption, Gradient Adaption) in Fluent. Boundary adaption increased cells around the wall boundary regions while Yplus/Ystar adaption increased the number of cells based on \( y^+ \) or \( y^* \) values on the specified viscous wall zones. In Gradient adaption, the strain rate value was computed and used as refining criteria. Then, the refined meshes were compared in order to find grid independent solution for the LEV-VAD pump.

Next, the pressure data for all mesh conditions were plotted in Figure 3.2. In Figure 3.2, it can be seen that all adapted meshes are converging to similar pressure difference, 71-73 Pa. Mesh 3 was chosen because it was converging to the pressure value faster. The summary of pressure results for all mesh case conditions can be found in Appendix C.
Pressure is converging to a value as the different meshes are refined and the number of mesh elements increase. Mesh3b was chosen as a grid independent mesh.

Three different transects were created inside the LEV-VAD pump geometry to compare velocity and strain rate data for refinement of Mesh 3.

Table 3-2: Summary of Transect coordinates

<table>
<thead>
<tr>
<th>Transect 2</th>
<th>Transect 1</th>
<th>Transect 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0=0</td>
<td>x0=0</td>
<td>x0=0</td>
</tr>
<tr>
<td>x1=0</td>
<td>x1=0</td>
<td>x1=0</td>
</tr>
<tr>
<td>y0=9.85 mm</td>
<td>y0=9.85 mm</td>
<td>y0=9.85 mm</td>
</tr>
<tr>
<td>z0=25 mm</td>
<td>z0=50 mm</td>
<td>z0=75 mm</td>
</tr>
<tr>
<td>x1=8.2 mm</td>
<td>x1=8.2 mm</td>
<td>x1=8.2 mm</td>
</tr>
<tr>
<td>z1=25 mm</td>
<td>z1=50 mm</td>
<td>z1=75 mm</td>
</tr>
</tbody>
</table>
The strain rate and velocity distributions on Transect 1, 2 and 3 were shown in Figure 3.4 – 3.6. Strain rate unit is inverse second [s\(^{-1}\)] while velocity is meter per second [m/s]. It is observed that the variation of strain rate has decreased from Mesh3b (Mesh11b in Figure 3.4A, 3.5A and 3.6A) to Mesh3c (Mesh11c in 3.4A, 3.5A and 3.6A). The variation of velocity has decreased from Mesh3b (Mesh11b in Figure 3.4B, 3.5B and 3.6B) to Mesh3c (Mesh11c in Figure 3.4B, 3.5B and 3.6B).

The mass flow rate of the LEV-VAD pump was checked for validity. The mass flow rate difference between inlet and outlet was found to be 4.5e-6 kg/s which is an acceptable difference (Figure 3.7).
Figure 3-7: The mass flow rate difference between inlet and outlet

Comparison between CFD and Experimental performance data (Characteristic Curve)

In Characteristic curve, the experimental pressure rise data was compared with the pressure difference data from CFD simulation of the LEV-VAD pump. The data points were for flow rates of 0 to 7 lpm for rotating speeds of 4000 rpm, 5000 rpm and 6000 rpm. The percent errors were 12%, 13% and 10% for 4000rpm, 5000 rpm and 6000 rpm, respectively. The average percent error was 11.5% which is a little higher than the expected 10% error between the experimental and CFD predicted results, however, these CFD results were used for the numerical hemolysis analysis. For all rotating speeds, percent error between the CFD prediction and experimental results is decreased as the flow rate is increased. All the data for three different rotating speeds are available in Appendix C.
Evaluation of Device Damage

The sample case simulation is for fluid flow rate of 6 lpm with rotating speed of 6000 rpm. Flow field solution data from Fluent was saved and analyzed using Matlab code.

Method 1: Threshold Value Approach

Step 1 – Solution of velocity and pressure

From the Pressure contour plot in Figure 3.9, the pressure rise can be seen on the transverse plane along the z-axis and impeller walls. The pressure difference that is used for the grid independence study was calculated by subtracting the mass weighted average pressure at the inlet from that at the outlet. All pressure is given in units of Pascal [Pa].

![Contour plot of Pressure data [Pa] (LEV-VAD)](image)

Figure 3-9: Contour plot of Pressure data [Pa] (LEV-VAD)

The contour plot of velocity magnitude in Figure 3.10 and 3.11 agrees with the prediction that the high velocity region is around the rotating impeller and blade regions. In Figure 3.12, velocity vector plot reveals the magnitude and direction of velocity. From Figure 3.13, the flow can be seen that it is rotating counter clockwise direction as positive x-axis is pointing into the paper.
Figure 3-10: Contour plot of Velocity Magnitude [m/s] (LEV-VAD)

Figure 3-11: Detailed view of velocity [m/s] around the impeller blade region

Figure 3-12: Vector plot of Velocity Magnitude [m/s] (LEV-VAD)
Axial velocity distribution can be seen in Figure 3.14. The axial velocity is zero at the all stationary wall as well as rotating impeller walls. The flow of 6 lpm enters the pump with axial velocity of 0.65 m/s through a circular inlet with radius of 7 mm. The axial velocity at the outlet is higher than the uniform axial velocity at the inlet. At this center plane along the z-axis, a high axial velocity region can be observed near the impeller front while a low axial velocity can be seen behind the impeller tip.

From Figure 3.15, contour plot of strain rate inside pump revealed that there was higher strain rate near the impeller wall, impeller blades and the gaps between the impeller blades and outside housing. The strain rate has a linear dependence with shear stress.
Contour plot of Total Strain Rate \([s^{-1}]\) (LEV-VAD)

Contour plot of shear stress on the impeller surface wall and midline section plane is shown in Figure 3.16. In addition, Figure 3.17 shows the detailed contour plot of shear stress around the gap between the blade tip and outside housing.

Contour plot of Shear Stress [Pa] (LEV-VAD)

Detailed view of shear stress [Pa] around the blade region
Step 2 – Calculation of 1-D scalar shear stress

Bludszuweit 1D scalar shear stress is calculated from these six stress components which were found from the strain rate tensor. Total shear stress was computed from the total strain rate. Then the total shear stress (blue) was compared with Bludszuweit 1D scalar shear stress (red) in Figure 3.18. Through this analysis, I construed that the total strain rate data from Fluent provides identical shear stress value as Bludszuweit’s 1-D scalar shear stress. Additionally, the six components of stress are plotted separately in Figure 3.18. Total stress from Fluent does not include both viscous and Reynolds stress terms. The total stress should not account for Reynolds stress term since Reynolds stress is not physical stress rather convection that affects bulk flow.

![Shear stress along the z-axis in the fluid region](image)

**Figure 3-18: Shear stress along the z-axis in the fluid region**

Step 3 – Comparison to the Threshold shear stress value

It is established that the threshold value of shear stress changes with exposure time from Published Threshold shear stress values (Figure 1.17). Therefore, to find critical shear stress value average exposure time is used. The estimated residence time is found by dividing the pump volume (12.15 ml) by flow rate (6 lpm). Table 3.3 summarizes the average exposure time estimation for different flow rates inside LEV-VAD pump.
The average exposure time for this flow rate is 0.12 seconds. The calculated scalar shear stress in the pump is generally below 200 Pa. Compared to Threshold value of viscous shear stress line in Figure 3.22, erythrocytes will not rupture. However, comparing the same shear stress and exposure time with Giersiepen 1% and Heuser 1% blood damage line, Method 1 predicts 1% hemolysis for 6lpm at 6000rpm.

Method 2: Mass-Weighted Average Approach

Step 1 – Solution of velocity and pressure
Velocity (3 components), pressure (3 components) and strain rate (6 components) have been
solved and solution data was exported from Fluent to Matlab binary data.

Step 2 – Calculation of 1-D scalar shear stress
Step 3 – Categorize the stresses
The mass – weighted average of shear stress have been graphed as a bar plot in Matlab in Figure 3.20. The relative mass percentage of shear stresses above 200 Pa is 1e-2%. Hence, Method 2 predicts 0.01% of hemolysis for 6 lpm at 6000rpm.

![Figure 3-20: Relative mass ratio of Scalar Shear Stress](image)

**Table 3-4: Summary of Mass-Weighted Scalar Stress**

<table>
<thead>
<tr>
<th>Shear Stress [Pa]</th>
<th>Relative Mass</th>
<th>Relative Mass [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>0.6249</td>
<td>62.49%</td>
</tr>
<tr>
<td>50-100</td>
<td>0.3003</td>
<td>30.03%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.0711</td>
<td>7.11%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0036</td>
<td>0.36%</td>
</tr>
<tr>
<td>200-250</td>
<td>0.0001</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

**Method 3: Eulerian Approach**
Step 1 – Solution of velocity and pressure
Step 2 – Calculation of 1-D scalar shear stress
Step 3 – Hemolysis analysis
The damage indices with Giersiepen and Heuser models were calculated in Table 3.5. The equation 1.9 was used to define custom field function.
Table 3-5: Custom Field Functions results (6 lpm 6000rpm)

<table>
<thead>
<tr>
<th>Values</th>
<th>Fluent Setup</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giersiepen</td>
<td></td>
<td>Total Volume Integral</td>
</tr>
<tr>
<td>Heuser</td>
<td></td>
<td>giersiepen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fluid2 3.825943e-09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fluid3 7.162252e-10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fluid4 3.9567688e-12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Net 4.187122e-09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>heuser</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fluid2 1.835970e-09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fluid3 3.484808e-10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>fluid4 4.4358559e-12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Net 2.1888867e-09</td>
</tr>
</tbody>
</table>

Hemolysis prediction by Eulerian approach for the case of 6 lpm with 6000 rpm was given in Table 3.6. The Eulerian approach with Giersiepen and Heuser model predicts 3.63e-2% and 2.72e-2% hemolysis, respectively. Appendix D includes comprehensive data for all cases. These cases include flow rates of 4 lpm, 5lpm and 6lpm at rotating speeds of 4000 rpm, 5000 rpm and 6000 rpm.

Table 3-6: Hemolysis Analysis for LEV-VAD pump using Eulerian approach

<table>
<thead>
<tr>
<th></th>
<th>Giersiepen</th>
<th>Heuser</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 LPM with 6000 RPM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Q [m^3/s]</td>
<td>I</td>
<td>D</td>
</tr>
<tr>
<td>total vol</td>
<td>1.000E-04</td>
<td>4.15E-09</td>
</tr>
<tr>
<td>vol 1</td>
<td>1.000E-04</td>
<td>3.96E-12</td>
</tr>
<tr>
<td>vol 2</td>
<td>1.000E-04</td>
<td>3.43E-09</td>
</tr>
<tr>
<td>vol 3</td>
<td>1.000E-04</td>
<td>7.16E-10</td>
</tr>
</tbody>
</table>

**Method 4: Lagrangian Approach**

Step 1 – Solution of velocity and pressure (same as prior methods)

Step 2 - Discrete Phase Model must be turned on in Fluent

Step 3 – Calculation of 1-D scalar shear stress

Step 4 – Calculation of Damage along pathline using Matlab

**LEV-VAD pump Results for one particle (1)**

In particle tracking, exposure time, velocity and strain rate values were saved along the particle pathline (pathlength). In Figure 3.21A, the pathlength was correlated with z position. All
aforementioned variables were plotted along the z-axis in Figure 3.21 B-G, except Figure 3.21F. In Figure 3.21F, the relation between shear stress and exposure time was graphed. The following graphs (Figure 3.21 A-G) were plotted for only one particle at one design condition with flow rate of 6lpm running at speed of 6000 rpm. The particle took approximately 0.12 seconds (Figure 3.21B) to travel through the pump reaching the highest shear stress 82 Pa (Figure 3.21E). Integration of Lagrangian damage model shows very little hemolysis index, 6.074e-4 (from Figure 3.21G)). To get a meaningful conclusion, statistically sufficient particles will need to be analyzed. In the next step, 200 particles are traced.

![Pathlength vs. Z](image1.png)

**Figure 3-21: A) Pathlength vs. Z**

![Exposure time vs. Z](image2.png)

**B) Exposure time vs. Z**

![Velocity Magnitude vs. Z](image3.png)

**C) Velocity Magnitude vs. Z**

![Total Strain rate vs. Z](image4.png)

**D) Total Strain rate vs. Z**
The following graphs (Figure 3.22A-G) were plotted for 200 particles at the same design condition with flow rate of 6lpm running at speed of 6000 rpm. In Figure 3.22A, the pathlengths were correlated with z positions. All exposure time, shear stress and blood damage values were graphed along the z-axis in Figure 3.22 B-G except Figure 3.21F. In Figure 3.21F, the relation between shear stress and exposure time was plotted. For these 200 particles, the exposure time varies from 0.12 seconds to 2.6 seconds (Figure 3.22B) while the maximum shear stress ranged from 120-275 Pa (Figure 3.22E). The integrated value of Lagrangian damage model for 200 particles was 1.6e-4. This equals a blood damage value of 1.6e-2%. The relationship between exposure time and shear stress (Figure 3.22F) reveals that the particles with high shear stress had short exposure time while the particles with the long exposure time had relatively low shear
stress. As a result, hemolysis inside the LEV-VAD pump will be relatively low because the particles in the pump will not be exposed to high shear stress for a long time.

**Figure 3-22:**

A) Pathlength vs. Z  
B) Exposure time vs. Z  
C) Velocity Magnitude vs. Z  
D) Total Strain rate vs. Z  
E) Shear Stress vs. Z  
F) Shear Stress vs. Residence Time
Comparison of 4 methods

Flow rate affect pump exposure time whereas rotating speed mainly affect pump’s shear stress. Table 3.7 is the comparison of blood damage (D) for all 4 methods. Method 3 and 4 are more consistent than Method 1 and 2. General trend is that damage increases with rotating speed and decreases with increasing flow rate. This makes sense because exposure time is reduced when flow rate increases. Shear stress increases as rotating speed increases. Method 3 was calculated with two blood damage models: 1) Giersiepen blood damage model (Equation 1.2) and 2) Heuser blood damage model (Equation 1.3). In Table 3.7, Eulerian approach with Giersiepen model overpredicts that with Heuser model. This is consistent with the literature [55].
Table 3-7: Damage (D) found by all four methods

<table>
<thead>
<tr>
<th>LPM</th>
<th>Method 1</th>
<th>Method 2</th>
<th>Method 3 (G)</th>
<th>Method 3 (H)</th>
<th>Method 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 LPM</td>
<td>1.00E-02</td>
<td>1.25E-05</td>
<td>2.07E-04</td>
<td>1.87E-04</td>
<td>2.40E-04</td>
</tr>
<tr>
<td>5 LPM</td>
<td>1.00E-02</td>
<td>8.40E-03</td>
<td>3.57E-04</td>
<td>2.89E-04</td>
<td>4.60E-04</td>
</tr>
<tr>
<td>6 LPM</td>
<td>1.00E-02</td>
<td>1.51E-02</td>
<td>5.37E-04</td>
<td>3.93E-04</td>
<td>4.90E-04</td>
</tr>
</tbody>
</table>

Comparison between CFD and Experimental hemolysis

Experimental Results

The experimental data for hemolysis at typical operating conditions of the RIT axial pump are reported in Figure 3.23 and 3.24 with bovine blood. 1 liter of blood was circulated at three flow rates (3, 5, 6 lpm) with a rotating speed of 5000 rpm. The test was conducted on bovine blood with 31% hemoglobin content that is collected from a local cow slaughter house. All tests were carried out for 150 minutes. Figure 3.24 illustrates the LEV-VAD pump experimental results.
Equation 3-1: Experimental Normalized Index of Hemolysis

\[ NIH(g/100L) = \Delta fHb \times \frac{V}{Q} \times (1 - Hct) \times 100 \]

\( \Delta fHb \) - Free haemoglobin in the plasma (g/L)

\( V \) - Total volume that was tested (\( V = 1L \))

\( Q \) - Blood flow rate

\( Hct \) - Hemoglobin content of the blood

(\( Hct = 31\% \) for the experimental test)

The calculated NIH was plotted in Table 3.8 for all three flow rates.

Table 3-8: Experimental Hemolysis data for LEV-VAD pump (Rig 3)

<table>
<thead>
<tr>
<th>Pump</th>
<th>Blood</th>
<th>Purpose</th>
<th>Flow Rate</th>
<th>Pressure</th>
<th>( \Delta fHb )</th>
<th>NIH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rig 3</td>
<td>bovine</td>
<td>Low Flow</td>
<td>3</td>
<td>63</td>
<td>0.072</td>
<td>0.0164</td>
</tr>
<tr>
<td>Rig 3</td>
<td>bovine</td>
<td>Norm Flow</td>
<td>5</td>
<td>49</td>
<td>0.067</td>
<td>0.0092</td>
</tr>
<tr>
<td>Rig 3</td>
<td>bovine</td>
<td>High Flow</td>
<td>6</td>
<td>41</td>
<td>0.071</td>
<td>0.0084</td>
</tr>
</tbody>
</table>

Figure 3-24: Experimental results for LEV-VAD pump (LEV-VAD)

**Eulerian Results**
The normalized index of hemolysis (NIH) is used to compare against global blood damage indices obtained by in vitro hemolysis measurements and evaluated by the following equation:

**Equation 3-2: Analytical Normalized Index of Hemolysis**

\[ NIH = (1 - Hb) \times D \times 100 \]

\[ Hb \] - Hemoglobin concentration [g/dl]

Table 3.9 showcases the estimated hemolysis by Eulerian approach with Giersiepen and Heuser power law models at 5000 rpm for flow rates of 4, 5 and 6 lpm. All cases used rotating speeds of 4000 and 6000 rpm can be found from Eulerian Approach section in the Appendix D.

**Table 3-9: Eulerian Hemolysis results for LEV-VAD pump (Rig 3)**

<table>
<thead>
<tr>
<th>Pump</th>
<th>Flow Rate LPM</th>
<th>Pressure mmHg</th>
<th>( \Delta Hb/Hb ) (Giersiepen)</th>
<th>NIH g/100L (Giersiepen)</th>
<th>( \Delta Hb/Hb ) (Heuser)</th>
<th>NIH g/100L (Heuser)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rig 3</td>
<td>4</td>
<td>62</td>
<td>3.5737E-04</td>
<td>0.024658</td>
<td>2.8895E-04</td>
<td>0.019938</td>
</tr>
<tr>
<td>Rig 3</td>
<td>5</td>
<td>51</td>
<td>2.8200E-04</td>
<td>0.019458</td>
<td>2.3175E-04</td>
<td>0.015991</td>
</tr>
<tr>
<td>Rig 3</td>
<td>6</td>
<td>41</td>
<td>2.3734E-04</td>
<td>0.016376</td>
<td>1.9613E-04</td>
<td>0.013533</td>
</tr>
</tbody>
</table>

**Lagrangian Results**

Table 3.10 displays the estimated hemolysis by Lagrangian approach at 5000 rpm for flow rates of 4, 5 and 6 lpm. Appendix D includes the data for other cases. These cases include flow rates of 4 lpm, 5 lpm and 6 lpm at rotating speeds of 4000 rpm, 5000 rpm and 6000 rpm.

**Table 3-10: Lagrangian Hemolysis results for LEV-VAD pump (Rig 3)**

<table>
<thead>
<tr>
<th>Pump</th>
<th>Flow Rate LPM</th>
<th>Pressure mmHg</th>
<th>( \Delta Hb/Hb )</th>
<th>NIH g/100L (Lagrangian)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rig 3</td>
<td>4</td>
<td>62</td>
<td>4.6000E-04</td>
<td>0.031740</td>
</tr>
<tr>
<td>Rig 3</td>
<td>5</td>
<td>51</td>
<td>2.1000E-04</td>
<td>0.014490</td>
</tr>
<tr>
<td>Rig 3</td>
<td>6</td>
<td>41</td>
<td>8.8727E-05</td>
<td>0.006122</td>
</tr>
</tbody>
</table>

**Result Comparison:**

In Figure 3.25, the experimental data (black) were compared with the numerical results that are found from Eulerian (red, green) and Lagrangian (blue) approach. Eulerian approach was modeled with both Giersiepen (red) and Heuser (green) power law hemolysis prediction models. The authors who developed the Eulerian approach used the Giersiepen correlation model.
However, I have used Heuser model throughout my thesis due to its wide range of validity. Therefore, I have decided to use both models for Eulerian approach for comparison.

As it can be seen in Figure 3.25, most numerical results expect higher value of hemolysis inside the LEV-VAD pump. The hemolysis NIH predicted by Lagrangian approach decreases faster with increasing flow rates. The Lagrangian method overpredicts hemolysis compared to Eulerian approach for lower flow rates. The Eulerian approach has the similar slope as the experimental hemolysis results. Heuser model (green) is the closer to the empirical hemolysis with percent error ranging from 22-73%. The percent error comparisons for all methods at all rotating speeds can be found from Percent Error Comparison section in the Appendix D.

In Figure 3.26 and 3.27, all three numerically predicted NIH were compared at rotating speeds of 4000 and 6000 rpm. Unfortunately, the empirical data at these speeds were not available at the moment. From Figure 3.25-3.27, NIH values increase with increasing rotating speeds. Moreover, a negative slope of NIH means the hemolysis caused by the flow decreases with increasing flow rates at the same rotating speed.

![Comparison of NIH for 5000 RPM](image)

*Figure 3-25: Comparison for Experimental and Numerical Results at 5000 rpm*
From Figure 3.28, the bar graph of NIH slopes for different rotating speed are compared for clarity. Compared to Lagrangian approach, Eulerian approach has similar trend as the experimental hemolysis data. Therefore, it can be concluded that Eulerian method calculates hemolysis more precisely than Lagrangian method. It is also possible that Lagrangian method
gave an erroneous result. This can be a result of low number of particles being utilized. This means that 200 particles that were used for this thesis were not significant enough to justify the use of Lagrangian method in the LEV-VAD pump.

Figure 3-28: Comparison of NIH Slope
Mag-lev Shearing Device Model

Analytical Solutions

Analytical solution for Circular Couette flow was found using first, second order and Bessel solution for rotating concentric flows with axial flow. Circular Couette flow was shown in Figure 3.29.

**Couette Flow**

![Couette flow in an annulus with rotating inner wall](image)

**First order**

One-dimensional viscous incompressible fluid with rotating cylinder with the gap of 0.125-0.25 mm and bump length of 10mm. Blood is flowing at a rate of 108mL/min. This problem was solved using simple first order solution.

**Equation 3-3: First order Solution**

\[ u_\phi(r) = \Omega r \]

\[ \tau_{r\phi} = \mu \left( \frac{\Delta u_\phi}{\Delta r} \right) \]

**Second order**

Two-dimensional viscous incompressible flow for the same problem was solved by Navier-Stokes equations and Navier-Stokes equations are reduced to ordinary differential equations. Matlab code was written in order to solve the equations.
Equation 3-4: Second order solution

\[ u_\theta(r) = (\Omega \cdot r) \left[ 1 - \left( \frac{R_2}{r} \right)^2 \right] \left[ 1 - \left( \frac{R_2}{R_1 + H} \right)^2 \right] \]

where \( H(z) = \begin{cases} 0, & z < d_1 \text{ and } z > d_2 \\ H, & d_1 \leq z \leq d_2 \end{cases} \)

\[ \tau_{r\theta} = -\frac{2 \mu \Omega}{r^2} \frac{R_2^2 (R_1 + H)^2}{R_2^2 - (R_1 + H)^2}; \quad \tau_{rz} = \mu \frac{\partial u_z}{\partial r}; \]

\( H = \text{gap} \quad u_\theta = \text{angular velocity} \)
\( R_1 = \text{inner radius} \quad \tau_{r\theta} = \text{shear stress} \)
\( R_2 = \text{outer radius} \quad \mu = 3.5 \times 10^3 \text{ Pa} \cdot \text{s} \)
\( r = \text{position in radial direction} \quad \Omega = \text{rotating speed} \)

Figure 3-30: A) X-velocity vs. Z  
B) Z-velocity vs. Z  
C) Velocity Magnitude vs. Z
Comparison of analytical and numerical solution for mag-lev shearing device (bump gap=0.25mm) with flow rate of 6 lpm rotating with 6000 rpm was shown in Figure 3.33. In Figure 3.33A, tangential velocity profiles were compared. This comparison showed that the tangential flow rate (x velocity) profile was linear due to large flow rate. Thus, Couette flow assumption for the previous 1st and 2nd order analytical solution was invalidated. The research to find a correct analytical solution for tangential velocity profile led to Astill’s paper in 1968 [67]. That is why Astill’s analytical solution for tangential velocity was added to analytical Matlab code. In Figure 3.33B, axial velocity profiles were compared and there was a very close correlation between the analytical and numerical axial velocity profiles. In Figure 3.33C, total velocity magnitude solutions were compared. The difference between the analytical and numerical velocity profiles was due to nonlinear tangential velocity profile.

However, axial flow rate was later given by FDA to be 0.05-0.2 lpm. For this range of low axial flow rates, the tangential velocity has almost linear velocity profile. In this case, previous Couette flow assumption was validated and first and second order solutions were used. Nevertheless, the analytical solution to find the correct nonlinear tangential velocity for high axial flow rates was explored in this research. This analytical equation is discussed in the next section.

**Bessel Solution**

In 1968, Astill obtained an analytical solution to estimate tangential velocity profile in rotating concentric cylinders with axial flow [67]. His analytical solution utilizes combination of Bessel functions of first and second kind. For convenience, this solution will be called Bessel solution. This equation can predict a tangential velocity profile in rotating cylinders with high axial flow.

Non dimensional tangential velocity is given by the following equation:

\[
\text{Equation 3-5: Bessel solution}
\]

\[
v = \frac{r_1}{r} \left(1 - \frac{r^2}{1 - r_1^2}\right) \sum_{n=1}^{\infty} \left\{ \frac{(2r_1/\alpha_n)\ell_0(\alpha_n r_1)}{[\ell_0(\alpha_n r_1)]^2 - [r_1 \ell_0(\alpha_n r_1)]^2} \right\} \ell_1(\alpha_n r_1) \exp\left(\frac{0.5}{Re_L} - M_n z\right)
\]

Therefore, dimensional tangential velocity equals:

\[
\text{Equation 3-6: Tangential velocity}
\]

\[V = vR\]
Please see Astill’s equation in the Appendix B.

Fin Figure 3.31, the grids on transverse plane and impeller walls can be seen. These grids were divided into two regions of interest. Region 1 is in an annulus region with the thinnest gap whereas Region 2 is in an annulus region with a wider gap.

![Figure 3-31: Region 1 and 2 in transverse plane](image)

I used the equations to find axial Reynolds number and rotational Taylor’s number given by Dong [68] and Cannellas [69].

**Equation 3-7: Rotational Taylor’s number**

\[ Ta_{rot} = Re_{rot}^2 \left( \frac{1}{\eta} - 1 \right) \]

**Equation 3-8: Rotational Reynolds number**

\[ Re_{rot} = \frac{U_{rot}d}{\nu} \]

**Equation 3-9: Gap distance**

\[ d = R_2 - R_1 \]

- \( R_2 \) - Outer radius
- \( R_1 \) - Inner radius

**Equation 3-10: Radius ratio**

\[ \eta = \frac{R_1}{R_2} \]

From Table 3.11, axial Reynolds number for all flow rates are low indicating flow is laminar. From Table 3.12, Taylor’s number in thin gap (region 1) is below critical Taylor’s number 1708 when the Taylor vortices start to develop. Taylor’s number in wide gap region is much higher than the critical Taylor’s number. Therefore, it can be concluded that there will be a large Taylor’s vortices in the wide gap.
Table 3-11: Summary of Axial Reynolds numbers

<table>
<thead>
<tr>
<th>Inlet region</th>
<th>Flow [lpm]</th>
<th>Flow [m³/s]</th>
<th>v_ax [m/s]</th>
<th>Re_ax</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>8.333E-07</td>
<td>2.631E-02</td>
<td>50.1</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>1.667E-06</td>
<td>5.263E-02</td>
<td>100.3</td>
<td></td>
</tr>
<tr>
<td>0.15</td>
<td>2.500E-06</td>
<td>7.894E-02</td>
<td>150.4</td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td>3.333E-06</td>
<td>1.053E-01</td>
<td>200.5</td>
<td></td>
</tr>
</tbody>
</table>

Wide gap region (Region 2)

<table>
<thead>
<tr>
<th>Flow [lpm]</th>
<th>Flow [m³/s]</th>
<th>v_ax [m/s]</th>
<th>Re_ax</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>8.333E-07</td>
<td>4.283E-02</td>
<td>17.3</td>
</tr>
<tr>
<td>0.1</td>
<td>1.667E-06</td>
<td>8.566E-02</td>
<td>34.7</td>
</tr>
<tr>
<td>0.15</td>
<td>2.500E-06</td>
<td>1.285E-01</td>
<td>52.0</td>
</tr>
<tr>
<td>0.2</td>
<td>3.333E-06</td>
<td>1.713E-01</td>
<td>69.4</td>
</tr>
</tbody>
</table>

Thin gap region (Region 1)

<table>
<thead>
<tr>
<th>Flow [lpm]</th>
<th>Flow [m³/s]</th>
<th>v_ax [m/s]</th>
<th>Re_ax</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.05</td>
<td>8.333E-07</td>
<td>7.058E-01</td>
<td>26.5</td>
</tr>
<tr>
<td>0.1</td>
<td>1.667E-06</td>
<td>1.412E+00</td>
<td>52.9</td>
</tr>
<tr>
<td>0.15</td>
<td>2.500E-06</td>
<td>2.117E+00</td>
<td>79.4</td>
</tr>
<tr>
<td>0.2</td>
<td>3.333E-06</td>
<td>2.823E+00</td>
<td>105.9</td>
</tr>
</tbody>
</table>

Table 3-12: Summary of Rotational Reynolds and Taylor numbers for different speeds

<table>
<thead>
<tr>
<th>Rotational Speed [rpm]</th>
<th>3000</th>
<th>6000</th>
<th>9000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotational Speed [rad/s]</td>
<td>314.2</td>
<td>628.3</td>
<td>942.5</td>
</tr>
<tr>
<td>Wide Gap</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re_rot</td>
<td>1081.5</td>
<td>2163.0</td>
<td>3244.5</td>
</tr>
<tr>
<td>Ta_rot</td>
<td>185,764</td>
<td>743,058</td>
<td>1,671,880</td>
</tr>
<tr>
<td>Thin Gap</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re_rot</td>
<td>114.6</td>
<td>229.1</td>
<td>343.7</td>
</tr>
<tr>
<td>Ta_rot</td>
<td>168.7</td>
<td>674.9</td>
<td>1518.5</td>
</tr>
</tbody>
</table>

Numerical Solutions

Grid Independent Solution

In Figure 3.32, the grids on transverse plane and impeller walls can be seen. In order to find grid independent solution, three sections on transverse plane were used. The results on these sections were then compared for all different mesh cases. Transect 1 was at the center of thin gap region. Axial velocity, tangential velocity and total strain rate results at Transect 1 had negligible
change for refined mesh cases. Therefore, the comparison of results at Transect 2 and 3 were shown in Figure 3.33-35. Transect 2 and 3 locations are summarized in Table 3.13.

Figure 3-32: Sections on Transverse plane

Table 3-13: Summary of Transect Dimensions

<table>
<thead>
<tr>
<th>Transect 2</th>
<th>Transect 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>x0=0</td>
<td>x1=0</td>
</tr>
<tr>
<td>y0=9.85mm</td>
<td>y1=9.85mm</td>
</tr>
<tr>
<td>z0=43mm</td>
<td>z1=43mm</td>
</tr>
<tr>
<td>x1=8.5mm</td>
<td>x1=8.5mm</td>
</tr>
<tr>
<td>y1=9.85mm</td>
<td>y1=9.85mm</td>
</tr>
<tr>
<td>z1=43mm</td>
<td>z1=43mm</td>
</tr>
</tbody>
</table>

Figure 3.33 shows that the axial velocity difference on Transect 2 and 3 for different meshes are decreasing as the mesh refined.

Figure 3-33: A) Axial velocity [m/s] on Transect 2

Figure 3-34: B) Axial velocity [m/s] on Transect 3

Figure 3.34 displays that the tangential velocity difference on Transect 2 and 3 for different meshes are decreasing as the mesh refined.
Figure 3-34: A) Tang. velocity [m/s] on Transect 2  
B) Tang. velocity [m/s] on Transect 3

Figure 3.35 shows that the strain rate difference on Transect 2 and 3 for different meshes are decreasing as the mesh refined. It was concluded that the changes from Mesh5c to Mesh5d is very little. Therefore, Mesh5c was chosen as a grid independent mesh and used to acquire the solution.

Figure 3-35: A) Strain Rate [s^{-1}] on Transect 2  
B) Strain Rate [s^{-1}] on Transect 3

Mass flow rate from the inlet and outlet were checked validity of Mesh5c.

<table>
<thead>
<tr>
<th>Mass Flow Rate</th>
<th>(kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>inlet</td>
<td>0.0017213445</td>
</tr>
<tr>
<td>outlet</td>
<td>0.0017108201</td>
</tr>
<tr>
<td><strong>Net</strong></td>
<td>8.3143406e-06</td>
</tr>
</tbody>
</table>

Figure 3-36: The mass flow difference between inlet and outlet was found to be 8.3e-6 kg/s which is an acceptable difference.

It is assumed that there is a Couette flow condition inside the thin gap region (gap=0.125mm). This assumption was validated in the numerical simulation. The axial velocity profile was parabolic (Figure 3.37A). The tangential velocity profile was linear (Figure 3.37B). Due to much smaller axial velocity, the total velocity magnitude distribution looks similar to the tangential velocity profile (Figure 3.37C).
C) Total velocity (thin gap)

The axial velocity profile in the wider gap region was sinusoidal (Figure 3.38A) due to possible Taylor vortices in this wide gap region. In the wide gap region (gap=1.35mm), the tangential velocity profile is nonlinear (Figure 3.38B). Due to much smaller axial velocity, the total velocity magnitude distribution looks similar to the tangential velocity profile (Figure 3.38C).
C) Total velocity (wider gap)

To prove the existence of Taylor vortices, the axial velocity was plotted in cross-sectional plane in mag-lev shearing device model. Figure 3.39 displays the overall contour plot of axial velocity. In Figure 3.39B, negative and positive axial velocities can be seen. This indicates that the velocities in the wider gap region were circulating and there could be Taylor vortices. These CFD findings are consistent with the analytical results.

\[ \text{Particle Tracking in Discrete Phase Model} \]

The particles were injected from the inlet region \((z=0\text{mm})\) and traced through the outlet. Figure 3.40 demonstrates that about half of the particles escape though the outlet. Figure 3.41 illustrates that particles are trapped due to the vortices created in the wider gap region. The Taylor vortex region inside the wide gap region was previously predicted from the mathematical calculation and numerical results. Therefore, the particles were injected from the thin gap entrance region \((z=62\text{mm})\) in order to track particles only inside the thin gap region in Figure 3.42. These particles were used for Model 4 for mag-lev shearing device Hemolysis analysis.
Comparison between Analytical and CFD results

| Region 1: Sample velocity and shear stress graphs | Region 2: Sample velocity and shear stress graphs |
Fluent angular velocity is 0.2 m/s and shear stress is 20 Pa smaller than both 2\textsuperscript{nd} order and Bessel solution for 3000 rpm at the centerline of region 1.

At the wall ends, Fluent shear stress is 20 Pa higher than both 2\textsuperscript{nd} order and Bessel solution for 3000 rpm at the centerline of region 2.

Fluent angular velocity is 0.35 m/s and shear stress is 20 Pa smaller than both 2\textsuperscript{nd} order and Bessel solution for 6000 rpm at the centerline of region 1.

At the wall ends, Fluent shear stress is 40 Pa higher than both 2\textsuperscript{nd} order and Bessel solution for 6000 rpm at the centerline of region 2.
Fluent angular velocity is 0.6 m/s and shear stress is 40 Pa higher than both 2\textsuperscript{nd} order and Bessel solution for 9000 rpm at the centerline of region 1.

Comparison between the analytical and CFD solutions revealed that the analytical solution of the velocity profile largely differed from the CFD solution of the velocity profile inside the wider gap region. Since the tangential velocity profile is not linear, it is evident that the flow inside that wider gap is not Couette flow.

As found from the Taylor number calculation, Taylor number inside the wider gap region exceeds the critical Taylor’s number, 1708. Then from the CFD simulation, it was shown that the axial velocity had an irregular velocity profile. CFD solution confirmed there will be a possible Taylor vortices inside wider gap region making the flow harder to predict.

**Hemolysis Models**

The sample simulation case for 0.1 lpm with 6000 rpm.

**Method 1: Threshold Value Approach**

Step 1 – Solution of velocity and pressure
Mag-lev shearing device geometry was solved in Fluent and solution data was saved as ASCII binary file to analyze in Matlab. Three components of velocity vectors were graphed.

The contour plot of velocity magnitude (Figure 3.43 and 3.44) agrees with the prediction that the high velocity region is around the rotating impeller and thin gap regions. In Figure 3.45, velocity vector plot reveals the magnitude and direction of velocity. From Figure 3.46, the flow can be seen that it is rotating counter clockwise direction as positive x-axis is pointing into the paper.
Figure 3-43: Contour plot of Velocity Magnitude inside the mag-lev device

Figure 3-44: Contour of Velocity detailed around the bump region

Figure 3-45: Vector plot of Velocity Magnitude inside the mag-lev device
Figure 3.46: Contour plot of X-Velocity inside the mag-lev device

Axial velocity distribution is seen in Figure 3.47. Axial velocity is zero at the all stationary wall as well as rotating impeller walls. The flow of 0.1 lpm enters the shearing device with axial velocity of 0.05 m/s through a circular inlet with diameter of 5 mm. The axial velocity at the outlet is higher than the uniform axial velocity at the inlet. At this center plane along the z-axis, a high axial velocity region can be observed near the impeller front while a low axial velocity can be seen behind the impeller tip.

Figure 3.47: Contour plot of Axial Velocity inside the mag-lev device

From Figure 3.48, contour plot of shear stress inside the mag-lev shearing device reveals shear stress distribution. The areas with highest shear stress are most prone to hemolysis. More detailed view inside the bump region can be seen in Figure 3.49 and max shear stress is around 200Pa.
Figure 3-48: Contour plot of Shear Stress inside the mag-lev device

Figure 3-49: Contour plot of stress detailed view around the impeller blade region

Step 2 – Calculation of 1D scalar shear stress

The six components of stress data was graphed from the Fluent solution data. Then the total stress was found from the total strain rate which is also equal to Bludszuweit’s 1D scalar shear stress was graphed along the z in Figure 3.50.
Step 3 – Comparison to the critical Threshold shear stress

Threshold stress value changes with exposure time. Therefore, average exposure time is estimated to find critical shear stress value. The estimated residence time is found by dividing the pump volume (6.33E-6 m³) by flow rate (0.1 lpm). The average exposure time for this flow rate is 3.79 seconds. Table 3.14 summarizes the average exposure time estimation for different flow rates inside mag-lev shearing device.

From Figure 3.51, the proposed viscous threshold shear stress for approximately 3.8 seconds will be around 200 Pa. The scalar shear stress for mag-lev device in Figure 3.64 ranges from 100 Pa to 270 Pa, therefore, it will cause hemolysis 100%.
Method 2: Mass-Weighted Average Approach

Step 1 – Solution of velocity and pressure
Step 2 – Calculation of 1-D scalar shear stress
Step 3 – Categorize the stresses

The mass – weighted average of shear stress have been graphed as a bar plot in Matlab in Figure 3.52. The relative mass percentage of shear stresses above 200 Pa is 0.35%. Hence, Method 2 predicts 35% of hemolysis for 0.1 lpm at 6000rpm.
Table 3-15: Summary of Mass-Weighted Scalar Stress

<table>
<thead>
<tr>
<th>Shear Stress [Pa]</th>
<th>Relative Mass</th>
<th>Relative Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>0.7882</td>
<td>78.82%</td>
</tr>
<tr>
<td>50-100</td>
<td>0.1714</td>
<td>17.14%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.0303</td>
<td>3.03%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0065</td>
<td>0.65%</td>
</tr>
<tr>
<td>200-250</td>
<td>0.0033</td>
<td>0.33%</td>
</tr>
<tr>
<td>250-300</td>
<td>0.0002</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

Method 3: Eulerian Approach

Step 1 – Solution of velocity and pressure
Step 2 – Calculation of 1-D scalar shear stress
Step 3 – Hemolysis analysis

After evaluating Equation 6 from Fluent, evaluation of Equation 7 was found from the volume integral of the source term. Then, Equation 8 and 9 were calculated in Table 3.6.

Table 3-16: Custom field function results

<table>
<thead>
<tr>
<th>Values</th>
<th>Fluent Setup</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Giersiepen</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heuser</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Hemolysis prediction by Eulerian approach for the case of 0.1 lpm with 6000 rpm was given in Table 3.18. The Eulerian approach with Giersiepen and Heuser model predicts 1.41% and 0.91% hemolysis, respectively.

Appendix D includes comprehensive data for all cases with flow rates of 0.05 lpm, 0.1 lpm, 0.15 lpm and 6 lpm at rotating speeds of 4000 -9000 rpm.

Table 3-17: Hemolysis analysis using Eulerian Approach (0.1 lpm 6000rpm)
### Method 4: Lagrangian Approach

Step 1 – Solution of velocity and pressure (same as prior methods)

Step 2 - Discrete Phase Model must be turned on in Fluent

Step 3 – Calculation of 1-D scalar shear stress

Step 4 – Calculation of Damage along pathline using Matlab

**MAG-LEV Results for one particle (1)**

In particle tracking, exposure time, velocity and strain rate values were saved along the particle pathline (pathlength). In Figure 3.53A, the pathlength was correlated with z position. All aforementioned variables were plotted along the z-axis in Figure 3.53 B-G, except Figure 3.53F. In Figure 3.53F, the relation between shear stress and exposure time was graphed. The following graphs (Figure 3.53A-G) were plotted only for one particle at one design condition with flow rate of 6lpm running at speed of 6000 rpm. This particle took approximately 0.09 seconds (Figure 3.53B) to go through the thin gap region inside the mag-lev device reaching the highest shear stress 175 Pa (Figure 3.53D). Integral of Lagrangian damage model shows very little hemolysis index, 3.58e-3. To get a meaningful conclusion, statistically sufficient particles had to be analyzed. In the next step, 200 particles were traced.
Figure 3-53: A) Pathlength vs. Z
B) Exposure time vs. Z
C) Velocity vs. Z
D) Total Strain rate vs. Z
E) Shear Stress vs. Z
F) Shear Stress vs. Residence Time
G) Lagrangian Damage model Distribution along Z (D1=3.58e-3)

**MAG-LEV Results for all particle (200)**

The following graphs (Figure 3.54A-G) are plotted for 200 particles at the same design point. In Figure 3.54A, the pathlengths were correlated with z positions. All exposure time, shear stress and blood damage values were graphed along the z-axis in Figure 3.54B-G except Figure 3.54F. In Figure 3.54F, the relation between shear stress and exposure time was plotted. The exposure time varies from 0.08 seconds to 0.21 seconds (Figure 3.54B) while the maximum shear stress ranged from 80-220 Pa (Figure 3.54D). In Figure 3.54C, there were three main groupings of velocity along z. I think the reason why this is because some particles followed a path around impeller blade wall region with high velocity where as some particles were near housing wall resulting in lower velocity. In Figure 3.54D, total strain rate is similar near both wall regions and that is why there is one main group for total strain along z. Integral of Lagrangian damage model was 3.54e-3. Therefore, Method 4 estimated 0.354% hemolysis. Each point is taken at a node. It is possible that scatter on the particle pathline could occur due to mesh inaccuracy and other numerical errors. Mesh independence study for particles were not included in my study.
Figure 3-54: A) Pathlength vs. Z  
B) Exposure time vs. Z  
C) Velocity vs. Z  
D) Total Strain rate vs. Z  
E) Shear Stress vs. Z  
F) Shear Stress vs. Residence Time
Comparison of 4 Methods

Table 3.18 is the comparison of blood damage (D) for all 4 methods. At flow rate of 0.1 lpm with 6000 rpm, Method 1 predicts D equal to 1 whereas Method 2 finds D value less than half around 0.35. Method 3 with Giersiepen and Heuser model determined D equaling 0.035 and 0.009, respectively. Method 4 gives blood damage value (D) of 3.5e-3 which is approximately 10 times smaller than Method 3 prediction. It might be due to the fact that particles were not traced in whole domain. The damage value found from Method 4 is the damage that is caused only in the thin gap region. Therefore, Lagrangian method was applied for only one case (0.1 lpm and 6000 rpm) These numerical results show that there will be definitely hemolysis at this rotating speed with the given flow rate. As expected, blood damage (D) value increases with increasing rotating speed in Methods 2 and 3.

Table 3-18: Damage (D) found using all 4 methods

<table>
<thead>
<tr>
<th>Mag-lev Shearing Device</th>
<th>Method 1</th>
<th>Method 2</th>
<th>Method 3 (G)</th>
<th>Method 3 (H)</th>
<th>Method 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 LPM</td>
<td>1.00E+00</td>
<td>1.3E-01</td>
<td>1.60E-02</td>
<td>4.00E-03</td>
<td>NA</td>
</tr>
<tr>
<td>3000 rpm</td>
<td>1.00E+00</td>
<td>3.50E-01</td>
<td>3.53E-02</td>
<td>9.00E-03</td>
<td>3.50E-03</td>
</tr>
<tr>
<td>9000 rpm</td>
<td>1.00E+00</td>
<td>3.00E+00</td>
<td>8.10E-02</td>
<td>2.20E-02</td>
<td>NA</td>
</tr>
</tbody>
</table>
Comparison between CFD and Literature hemolysis

Lagrangian approach cannot be used due to difficulty with particle tracking. From previous results, it was observed that there is a Taylor vortex region inside the wider gap between the impeller and the outside housing in the shearing device. Therefore, Eulerian approach was used to estimate hemolysis inside the mag-lev shearing device. Giersiepen power law model was compared with Heuser power law model. As observed from the LEV-VAD pump hemolysis results, Giersiepen power law model predicted more hemolysis than Heuser. Numerical hemolysis results predicted by Method 3 are shown in the following graphs. Blood damage (D) was displayed Figure 3.55 and 3.56 while NIH was displayed in Figure 3.57 and 3.58.

![D for Mag-Lev (Eulerian - Giersiepen)](image)

Figure 3-55: D predicted by Eulerian approach (Giersiepen model)
Figure 3-56: D predicted by Eulerian approach (Heuser model)

Figure 3-57: NIH predicted by Eulerian approach (Giersiepen model)
NIH for Mag-Lev (Eulerian - Heuser)

Figure 3-58: NIH predicted by Eulerian approach (Heuser model)
4. Discussion and Conclusion

Hemolysis was estimated analyzing fluid dynamics of the LVAD by CFD. The numerical simulation of flow field and hemolysis was conducted for LEV-VAD pump and mag-lev shearing device using commercially available CFD software: SolidWorks 2009, Fluent 12.0, Gambit 2.4 and Matlab 2009.

Four different methods for estimating hemolysis have been investigated: Threshold Value approach compares measured scalar stress with the critical value of shear stress. Eulerian method calculates the production of plasma free haemoglobin in terms of a single linearized damage parameter. Lagrangian methods estimate hemolysis by tracking particles along streamlines and integrating the calculated blood damage.

**LEV-VAD pump**

The RIT pump domain was discretized with three types of mesh and then was refined by three kinds of adaption. The pressure rise within these meshes was compared to find a grid independent solution for the LEV-VAD pump. This solution was utilized for further hemolysis studies.

In Characteristic curve, the experimental pressure rise data was compared with the pressure difference data from CFD simulation of the LEV-VAD pump. The data points were for flow rates from 0 to 7 lpm with accompanying rotating speeds of 4000 rpm, 5000 rpm and 6000 rpm. For all rotating speeds, percent error between CFD prediction and experimental results has decreased as the flow rate has increased.

The experimental NIH comparison at 5000 rpm reveals that Lagrangian method over predicts hemolysis at lower flow rates. However, the Eulerian approach with Heuser model predicted NIH close to the experimental data than any other methods. Heuser model (green) is closest to the empirical hemolysis with an average percent error of 50%. This method is preferred because it have similar trend line to the experimental hemolysis results.

Flow rate affects pump exposure time whereas rotating speed mainly affects pump’s shear stress. General trend is that damage increases with rotating speed and decreases with increasing flow rate. This makes sense because exposure time is reduced when flow rate increases. Shear stress increases as rotating speed increases. Eulerian and Lagrangian method predicted damage values with average percent error of 40%. In general, Eulerian approach with Giersiepen model over predicts that with Heuser model and this correlates with literature [55]. Giersiepen’s and Heuser’s models were used to find blood damage while the fit that was proposed by Dr. Day was
used to find critical shear stress and exposure time values that might cause blood damage for all four methods.

**Mag-lev shearing device**

Mag-lev shearing device was designed at RIT with collaboration with Food and Drug Administration in order to better study Hemolysis models that are used to predict red blood cells rupture. These hemolysis models are based on the empirical data of concentric cylinder geometry models. Therefore, mag-lev shearing device will have concentric cylinder geometry. It was assumed that mag-lev shearing device has a Couette flow condition which creates a constant shear stress. These analytical solutions will be used to verify numerical data.

Taylor number inside the wider gap region exceeds the critical Taylor’s number, 1708 and it was hypothesized that there will be a possible Taylor vortex region in the wider gap region of the mag-lev shearing device. CFD solution confirmed the analytical prediction of possible Taylor vortices inside wider gap region.

Due to the Taylor vortices in the wide gap region, the particles were not traced from the inlet of the device. The particles were injected at the entrance of thin gap region and these data were used to get hemolysis using the Lagrangian approach.

The comparison of blood damage (D) for all 4 methods showed that there was a wide variation of D values amongst them. At flow rate of 0.1 lpm with 6000 rpm, these numerical hemolysis results showed that hemolysis will occur. The damage value found from Method 4 is caused only in the thin gap region as opposed to the overall damages throughout the device indicated by the other methods. Therefore, due to the limiting spread of the damage indicated by method 4 it cannot be compared with the other three methods. Therefore, hemolysis damage analysis was done using Eulerian approach with 2 power models for flow rates of 0.05, 0.1, 0.15 and 0.2 lpm at rotating speeds ranging from 3000 to 9000 rpm.

**Completed Work**

**Objective 1**

Grid independent solutions for both geometries (RIT LEV-VAD pump and mag-lev shearing device) were obtained.

1. RIT LEV-VAD pump geometry

   Grid independent solution was tested in operating condition for flow rate of 2 L/min and rotating speeds of 6000 rpm. Calculations of pressure head were compared with experimental measurements and the mean percent error was 12%.

2. Mag-lev shearing device geometry
Grid independent solution was tested in operating condition for flow rate of 0.1 L/min and rotating speeds of 6000 rpm. The numerical simulation of flow field for mag-lev shearing device was compared with the analytical solution of the fluid dynamics inside the gap regions of the device.

**Objective 2**

Four different impeller designs were considered for mag-lev shearing device using CFD simulations in Fluent and quoted for manufacturing. A new inducer, diffuser and impeller rear were modeled and are being manufactured by RIT Brinkman Lab. The prototype of mag-lev device, a bladeless impeller with brass ring, was tested on Test Rig 3 as a design approval process.

**Objective 3**

Hemolysis was estimated on both geometries using Threshold Value approach, Mass-Weighted average approach, Eulerian and Lagrangian approaches. Numerical prediction of LEV-VAD at 5000 rpm was compared with experimental results at 5000 rpm. Predictions at 4000 and 6000 rpm are presented in the Appendix.

**Future Work**

There are various ways to improve CFD evaluation for predicting hemolysis. The following are just a few suggestions that can be improved upon.

First, the discrepancies between flow CFD simulation results and the experimental data for LEV-VAD pump should be decreased to progress hemolysis prediction. In my work, the percent error of CFD prediction and experimental result of flow performance is around 11.5% which is higher than the acceptable 10%. This percentage can be improved by refining CFD model or finding a better way to calculate the pressure rise inside the pump.

Second, Lagrangian method should to be studied further to accurately predict hemolysis. Each point is taken at a node. It is possible that scatter on the particle pathline could occur due to mesh inaccuracy and other numerical errors. The mesh independence was done for bulk flow comparing pressure rise. Mesh independence study for particles should be conducted in my study. Currently, only the particles that go through the outlet are counted into the analysis. However, all the particles including the ones that do not travel through the outlet should be accounted for. Moreover, in order to make this model accurate, all particles need to be tracked from inlet to outlet. For particle tracking to complete, more refined mesh size will be required. This sort of calculation, requires computers with higher capabilities. RIT has Research Computing group that can assist with computing needs.
Third, vacant shear stresses and exposure times in literature review for both concentric cylinder geometry as well as pump geometry should be expanded. CFD result and experimental data should be conducted for both geometries.

Fourth, it may be necessary to redesign shearing device in order to eliminate Taylor vortices. Taylor vortices create a flow condition that is not easily predicted. In addition, particle tracking in this region is difficult to manage. Concentric shearing device with very thin gap would be ideal. But with current maglev technology, the overall length of the magnets within the rotor cannot be reduced any further than it is now. If we were to make a constant length, this simple design would have to be very long, thus producing long exposure times. Nonetheless, this is true that the device needs to be redesigned and the benefit of eliminating these vortices may be worth longer exposure times, which could be compensated by using a higher flow rate.

Lastly, once the mag-lev shearing device is redesigned, impeller housing will need to be manufactured. Other components are already manufactured in RIT Brinkman center. Ultimately, this device will need to be assembled and sent to FDA for their hemolysis experiment.
Works Cited


Canellas M., 2008, “NONLINEAR DYNAMICS OF MODE COMPETITION IN ANNULAR FLOWS.”
Appendix

Appendix A

Second Order Analytical Solution

Assumptions

\[ u_r = u_z = 0, \quad \frac{\partial u_\theta}{\partial \theta} = 0, \quad \frac{\partial p}{\partial \theta} = 0, \quad g_z = -g \]

Continuity Equation

\[ \frac{1}{r} \frac{\partial}{\partial r} (ru_r) + \frac{1}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{\partial u_z}{\partial z} = 0 \]

\( r \)-Momentum

\[ \rho \left( \frac{\partial u_r}{\partial t} + u_r \frac{\partial u_r}{\partial r} + \frac{u_\theta}{r} \frac{\partial u_r}{\partial \theta} - \frac{u_\theta^2}{r} + u_z \frac{\partial u_r}{\partial z} \right) = -\frac{\partial p}{\partial r} + \mu \left[ \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial (ru_r)}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_\theta}{\partial \theta^2} - \frac{2}{r^2} \frac{\partial u_\theta}{\partial \theta} + \frac{\partial^2 u_r}{\partial z^2} \right] + \rho g_r \]

\[ \Rightarrow \frac{\partial p}{\partial r} = \frac{\rho}{r} u_\theta^2 \]

\[ \Rightarrow \text{It suggests that the centrifugal force on an element force of fluid balances the force produced by the radial pressure gradient.} \]

\( \theta \)-Momentum

\[ \rho \left( \frac{\partial u_\theta}{\partial t} + u_r \frac{\partial u_\theta}{\partial r} + \frac{u_\theta}{r} \frac{\partial u_\theta}{\partial \theta} + u_z \frac{\partial u_\theta}{\partial z} \right) = -\frac{1}{r} \frac{\partial p}{\partial \theta} + \mu \left[ \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial (ru_\theta)}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 u_\theta}{\partial \theta^2} + \frac{2}{r^2} \frac{\partial u_\theta}{\partial \theta} + \frac{\partial^2 u_\theta}{\partial z^2} \right] + \rho g_\theta \]

\[ \Rightarrow \frac{\partial}{\partial r} \left( \frac{1}{r} \frac{\partial (ru_\theta)}{\partial r} \right) = 0 \quad \text{(eq.1)} \]

\( z \)-Momentum

\[ \rho \left( \frac{\partial u_z}{\partial t} + u_r \frac{\partial u_z}{\partial r} + \frac{u_\theta}{r} \frac{\partial u_z}{\partial \theta} + u_z \frac{\partial u_z}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left[ \frac{1}{r} \frac{\partial (ru_z)}{\partial r} + \frac{1}{r^2} \frac{\partial^2 u_z}{\partial \theta^2} + \frac{\partial^2 u_z}{\partial z^2} \right] + \rho g_z \]

\[ \Rightarrow \frac{\partial p}{\partial z} = -\rho g \]

\[ \Rightarrow \text{It represents the standard hydrostatic expression.} \]
\[ p = -\rho gz + C(r, z) \] because \( \frac{\partial p}{\partial r} \) is not function of \( t \).

Stress tensor in cylindrical coordinate:

\[
T = \begin{bmatrix}
\sigma_r & \tau_{r\theta} & \tau_{rz} \\
\tau_{\theta r} & \sigma_\theta & \tau_{z\theta} \\
\tau_{zr} & \tau_{z\theta} & \sigma_z
\end{bmatrix}
\]

\[
\sigma_r = 2\mu \frac{\partial u_r}{\partial r}, \quad \tau_{r\theta} = \tau_{\theta r} = \mu \left[ r \frac{\partial}{\partial r} \left( \frac{u_\theta}{r} \right) + \frac{1}{r} \frac{\partial u_r}{\partial \theta} \right]
\]

\[
\sigma_\theta = 2\mu \left( \frac{1}{r} \frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r} \right), \quad \tau_{rz} = \tau_{zr} = \mu \left[ \frac{\partial u_z}{\partial r} + \frac{\partial u_r}{\partial \theta} \right]
\]

\[
\sigma_z = 2\mu \frac{\partial u_z}{\partial z}, \quad \tau_{z\theta} = \tau_{\theta z} = \mu \left[ \frac{\partial u_\theta}{\partial z} + \frac{1}{r} \frac{\partial u_z}{\partial \theta} \right]
\]

Nonzero components of stress tensor are shear stresses,

1. \( \tau_{r\theta} = \tau_{\theta r} = \mu r \frac{d}{dr} \left( \frac{u_\theta}{r} \right) \)

\( \theta \)-component gives differential equation to find shear stress

\[
\tau_{r\theta} = \mu r \frac{d}{dr} \left( \frac{C_2}{r^2} \right)
\]

The general solution for shear stress \( \tau_{r\theta} = \tau_{\theta r} \) is:

\[
\tau_{r\theta} = -2\mu \frac{C_2}{r^2}
\] \hspace{1cm} \text{(eq.2)}

**General Solutions**

\[
u_\theta (r) = C_1 r + \frac{C_2}{r}
\] \hspace{1cm} \text{(eq.1)}

\[
\tau_{r\theta} = -2\mu \frac{C_2}{r^2}
\] \hspace{1cm} \text{(eq.2)}

\[
p = \rho \left( \frac{C_1^2 r^2}{2} + 2C_1 C_2 \ln r - \frac{C_2^2}{2r^2} \right) - \rho gz + C
\] \hspace{1cm} \text{(eq.3)}

**Boundary Conditions**

1. \( u_\theta = \Omega R_i \) at \( r = R_i \)

2. \( u_\theta = 0 \) at \( r = R_z \)
3) \( u_\theta = v_1 \) at \( z = 0 \)

4) \( u_\theta = v_2 \) at \( z = d \) where \( d \) is the distance where hump exists.

Solutions:

**Equation 1**

By substituting boundary conditions 1 and 2 into eq.1:

1) \( u_\theta (r = R_1) = C_1R_1 + \frac{\Omega}{R_1} = \Omega R_1 \Rightarrow C_1R_1^2 - \Omega R_1^2 + C_2 = 0 \) (1)

2) \( u_\theta (r = R_2) = C_1R_2 + \frac{\Omega}{R_2} = 0 \Rightarrow C_1R_2^2 + C_2 = 0 \) (2)

Subtract (2) from (1) and solve for \( C_1 \):

\[
C_1(R_1^2 - R_2^2) - \Omega R_1^2 = 0 \Rightarrow C_1 = \frac{\Omega R_1^2}{R_1^2 - R_2^2} \Rightarrow C_1 = \frac{\Omega}{1 - \left(\frac{R_2}{R_1}\right)^2} \] (3)

Substitute (3) into (2) and solve for \( C_2 \):

\[
C_2 = -C_1R_2^2 \Rightarrow C_2 = -\frac{\Omega R_2^2}{1 - \left(\frac{R_2}{R_1}\right)^2} \Rightarrow C_2 = \frac{\Omega}{1 - \left(\frac{1}{R_1}\right)^2} - \left(\frac{1}{R_2}\right)^2 \] (4)

In eq.1 replace \( C_1 \) and \( C_2 \) with (3) and (4):

\[
u_\theta (r) = \frac{\Omega}{R_2^2 - R_1^2} \left[ -R_1^2 \cdot r + \frac{\Omega R_2^2}{R_2^2} \right] \Rightarrow u_\theta (r) = \frac{\Omega R_1^2}{R_2^2 - R_1^2} \left[ R_2^2 - \frac{r}{R_1^2} \right] = 0
\]

\[
u_\theta (r) = \frac{\Omega r}{1 - \left(\frac{R_1}{R_2}\right)^2} \left[ 1 - \left(\frac{R_1}{r}\right)^2 \right]
\]

\[
u_\theta (r) = \frac{\Omega \cdot r}{1 - \left(\frac{R_1}{r}\right)^2} \left[ 1 - \left(\frac{R_1}{r}\right)^2 \right] \text{ where } R_1 \leq r \leq R_2
\]

Similarly we can write velocity equation for the region with
\[ u_\theta(r) = \frac{\Omega \cdot r}{1 - \left( \frac{R_2}{R_1 + H} \right)^2} \left[ 1 - \left( \frac{R_2}{r} \right)^2 \right] \text{ where } R_1 + H \leq r \leq R_2 \]

**Equation 2**

Substitute (4) into eq.2:

\[
\tau_{r\theta} = -\frac{2\mu}{r^2} \left( \frac{\Omega}{1 - \left( \frac{R_2}{R_1 + H} \right)^2} \right)^2 \Rightarrow \tau_{r\theta} = -\frac{2\mu \Omega}{r^2} \frac{R_2^2 (R_1 + H)^2}{R_2^2 - (R_1 + H)^2}
\]

**Equation 3**

We can neglect the gravity term since there is no change in the z direction:

Since \( C \) is the initial pressure, gauge pressure can be found by subtracting from pressure term on the left.

\[
p = \rho \left( \frac{C_1^2 r^2}{2} + 2C_2 \ln r - \frac{C_2^2}{2r^2} \right)
\]

Substitute (3) and (4) into eq.3:

\[
p = \frac{\rho \Omega^2}{2} \left[ \frac{r^2}{1 - \left( \frac{R_2}{R_1} \right)^2} + \frac{4 \ln r}{\left( \frac{1}{R_1} \right)^2 - \left( \frac{1}{R_2} \right)^2} - \frac{1}{r^2 \left( \frac{1}{R_1} \right)^2 - \left( \frac{1}{R_2} \right)^2} \right]
\]

At this point we can express \( v_2 \) in terms of \( v_1 \) using Continuity equation:

\[
\rho v_1 A_1 = \rho v_2 A_2 \Rightarrow v_2 = v_1 \frac{A_1}{A_2}
\]

(5)

If cross sectional area of the region without hump \( A_1 \) is:

\[
A_1 = \pi (R_2^2 - R_1^2)
\]

(6)

If cross sectional area of the region with hump \( A_2 \) is:

\[
A_2 = \pi (R_2^2 - (R_1 + H)^2) \text{ where } H \text{ is the height of the hump}
\]

(7)

By using (10) and (11) in (9), \( v_2 \) can be found:

\[
v_2 = v_1 \frac{\pi (R_2^2 - R_1^2)}{\pi (R_2^2 - (R_1 + H)^2)} \Rightarrow v_2 = v_1 \frac{(R_2 - R_1)(R_2 + R_1)}{(R_2 - R_1 - H)(R_2 + R_1 + H)}
\]

(8)
Summary

We can change this piecewise function into 1 equation where $H$ is the gap and a function of $z$:

$$H(z) = \begin{cases} 
0, & z < d_1 \text{ and } z > d_2 \\
H, & d_1 \leq z \leq d_2 
\end{cases}$$

Tangential velocity is given by the following equation:

$$u_\phi(r) = (\Omega \cdot r) \left[ \frac{1 - \left( \frac{R_2}{r} \right)^2}{1 - \left( \frac{R_2}{R_1 + H} \right)} \right]$$

Shear stress related to tangential velocity is given by the following equation:

$$\tau_{r\phi} = -\frac{2\mu \Omega}{r^2} \frac{R_2^2 (R_1 + H)^2}{R_2^2 - (R_1 + H)^2}$$
Bessel Function Analytical Solution

\[
v = \frac{r_1}{r} \left( 1 - r^2 \right) - \sum_{n=1}^{\infty} \left\{ \frac{(2r_1 / \alpha_n) \ell_0(\alpha_n r_1)}{[\ell_0(\alpha_n r)]^2 - [\ell_1(\alpha_n r_1)]^2} \right\} \ell_1(\alpha_n r_1) \exp\left[ (0.5 \text{Re}_L - M_n) z \right]
\]

- \(v\) - tangential velocity
- \(R\) - radial coordinate
- \(R_1\) - outer radius of inner cylinder
- \(R_2\) - inner radius of outer cylinder
- \(r\) - dimensionless radial coordinate; \(r = \frac{R}{R_2}\)
- \(r_1\) - dimensionless radius of inner cylinder; \(r_1 = \frac{R_1}{R_2}\)
- \(Z\) - axial coordinate
- \(z\) - dimensionless axial coordinate; \(z = \frac{Z}{L}\)
- \(\alpha_n\) - eigenvalue order \(n\); \(\alpha = \frac{k}{S}\)
- \(k\) - separation parameter
- \(S\) - dimensionless duct length; \(S = \frac{L}{R_2}\)
- \(L\) - characteristic duct length
- \(\ell_m\) - Combination of Bessel functions; \(\ell_m(\alpha_n r_1) = J_m(\alpha_n r) - \frac{J_1(\alpha_n r_1)}{Y_1(\alpha_n r_1)} Y_m(\alpha_n r)\)
- \(\text{Re}_L\) - Reynolds number based on the duct length; \(\text{Re}_L = \frac{WL}{\nu}\)
- \(\nu\) - fluid kinematic viscosity
- \(\bar{W}\) - mean axial velocity; \(\bar{W} = -\frac{1}{8\mu} \frac{\partial p}{\partial z} \left[ (R_2^2 + R_1^2) - \frac{R_2^2 - R_1^2}{\ln(R_2 / R_1)} \right]\)
- \(\frac{\partial p}{\partial z}\) - axial pressure gradient
- \(\mu\) - fluid dynamic viscosity
- \(M_n\) - exponent order of \(n\); \(M = \left( \frac{\text{Re}_L^2}{4} + k^2 \right)^{1/2}\)
Appendix B

Matlab Code 1: Solve analytical solution

% Oyuna Myagmar
% find hub length and height in concentric cylinder
clear all; clc;
mu=3.5e-3; % blood viscosity [Pa*s]
ro=1050; % blood density [kg/m^3]

%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Variable parameters
% Variable parameters
w=11000*2*pi/60; % rotational speed [rad/s]
h=1.51e-3; %height of current blade =1.35e-3
L=10e-3; % length of hump [m]
R1=8.20e-3; % inner radius [m]
R2=9.80e-3; % outer radius [m]
R=5e-3; % inlet radius [m]
A1=pi*R1^2; % inner area [m^2]
A2=pi*R2^2; % outer area [m^2]
A=pi*R^2; % clearance area [m^2]
flow= 6; % volume flow rate [L/min]
flow_m3= flow*0.001/60; % volume flow rate [m^3/s]
uz=flow_m3/A; % axial velocity [m/s]

Z=51.5e-3; %m real length of impeller is 51.55mm
d1=20.7e-3 ; %starting point [m]
d2=d1+L ; % ending point [m]

K=10; % factor to increase element number
del_r=1e-4/K; % change delta r
del_z=1e-3/K; % change delta z

%%%%%%%%%%%%%%%%%%%%%%%%%% SOLUTION 1 %%%%%%%%%%%%%%%%%%%%%%%%%%
% Simplified determination of shear stress(tau) and exposure time (texp)
% assuming linear relationship of rotating velocity
% 1 - impeller area without hump
    tau1=-w*mu*R1/(R2-R1);
    v1=(A/(A2-A1))*uz;
    texp1=(Z-L)/v1;
    u_theta1=R1*w;
    dam1=3.62e-7*(-tau1)^2.416*texp1^0.785;  % to be developed
% 2 - impeller area with hump
    R3=R1+h;
    v2=v1*(R2^2-R1^2)/(R2^2-R3^2);
    tau2=-w*mu*R3/(R2-R3);
    texp2=L/v2;
    u_theta2=R3*w;
    dam2=3.62e-7*(-tau2)^2.416*texp2^0.785;  % to be developed

fprintf(1, 'PART1: SIMPLIFIED ANALYTICAL SOLUTION\n');
fprintf(1, 'Impeller area without hump\n');
fprintf(1, '   Velocity    Shear Stress    Exposure Time Damage\n');
fprintf(1, '%12.4f m/s %18.4f Pa %18.3e sec %18.4f microPa-s\n', u_theta1, tau1, texp1, dam1*1e6);
fprintf(1, 'Impeller area with hump\n');
fprintf(1, '   Velocity    Shear Stress    Exposure Time Damage\n');
fprintf(1, '%12.4f m/s %18.4f Pa %18.3e sec %18.4f microPa-s\n', u_theta2, tau2, texp2, dam2*1e6);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% SOLUTION 2 %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Determination of shear stress and exposure time over whole cylinder
% Define constants
    N=ceil((R2-R1)/del_r+1);  % dimension of r
    M=ceil((Z)/del_z);        % dimension of z
    M1=ceil((d1)/del_z);
    M2=ceil((d2)/del_z);
    N1=ceil((h)/del_r);
% initialize matrix
\[
\begin{align*}
\text{utheta_ro} &= \text{zeros}(N,M); \\
u_z &= \text{zeros}(N,M); \\
tau_ro &= \text{zeros}(N,M); \\
\text{press} &= \text{zeros}(N,M); \\
r &= \text{zeros}(N,1); \quad r(1)=R1; \\
z &= \text{zeros}(M,1); \\
texp_1 &= 0; \\
texp_2 &= 0; \\
\end{align*}
\]

% creating \(R-Z\) coordinate system

% create \(z\) coordinate
for \(j=2:M+1\)
\[
z(j) = z(j-1) + \text{del}_z;
\]
end

% create \(r\) coordinate
for \(i=2:N+1\)
\[
r(i) = r(i-1) + \text{del}_r;
\]
end

% starting solution loop
for \(j=1:M+1\) \% \(z\)-direction
\[
\text{if} \quad j \geq M1 \text{ \& } j \leq M2 \\
\quad H=h; \\
\text{else} \quad H=0; \\
\text{end}
\]
for \(i=1:N+1\) \% \(r\)-direction
\[
\text{\% VELOCITY \%} \\
\text{\% finding circumferential velocity} \\
\text{if} \quad (j \geq M1) \& (j \leq M2) \& (i \leq N1-1) \\
\quad \text{utheta_ro}(i,j)=0; \\
\text{else} \\
\quad \text{utheta_ro}(i,j)=w*r(i)*(1-(R2/r(i))^2)/(1-(R2/(R1+H))^2); \\
\text{end}
\]
% finding axial velocity
\[
\text{if} \quad (j \geq M1) \& (j \leq M2) \& (i \leq N1-1)
\]
\begin{verbatim}

u_z(i,j)=0;
else u_z(i,j)=v1*(R2^2-R1^2)/(R2^2-(R1+H)^2);
end

%% EXPOSURE TIME %%
if (j>M1)&(j<=M2)&(i<=N1-1)
    texp(i,j) = 0;
elseif (j>M1)&(j<=M2)&(i>=N1-1)
    texp(i,j) = del_z/v2; texp_2=del_z/v2;
else
    texp(i,j)= del_z/v1; texp_1=del_z/v1;
end

%% SHEAR STRESS %%
if (j>M1)&(j<=M2)&(i<=N1-1)
    tau_ro(i,j)=0;
else
    tau_ro(i,j)= -2*mu*w/r(i)^2*(R2*(R1+H))^2/(R2^2-(R1+H)^2);
end

texp_1=texp_1*(M-(M2-M1));
texp_2=texp_2*(M2-M1);
utheta_1=utheta_ro(1,1);
utheta_2=utheta_ro(N1,M1);
tau_1=mean(tau_ro(:,1));
% tau_2=mean(tau_ro(N1:N,M1));
tau_2=min(min(tau_ro));

fprintf(1, 'PART2: GRAPHICAL ANALYTICAL SOLUTION in R-Z plane\n');
fprintf(1, 'Impeller area without hump\n');
fprintf(1, '      Velocity             Shear Stress        Exposure Time \n');
fprintf(1, '%12.4f m/s %18.4f Pa %18.3e sec \n', utheta_1, tau_1, texp_1);
fprintf(1, 'Impeller area with hump\n');
end
\end{verbatim}
\n');
fprintf(1, '%12.4f m/s %18.4f Pa %18.3e sec \n', utheta_2, tau_2, texp_2);

figure (1)
subplot(2,1,1)
contourf(z,r,utheta_ro); colorbar;
xlabel('z [m]');
ylabel('r [m]');
zlabel('u [m/s]');
title('u_r_o  Circumferential Velocity');

% Shear Stress - Positive value of shear stress for ease of visualization
subplot(2,1,2)
contourf(z,r,-tau_ro); colorbar;
xlabel('z [m]');
ylabel('r [m]');
zlabel('tau_r_o [Pa]');
title('Tau_r_o Shear Stress');

Matlab Code 2: Solve Method 1 and Method 2

% Matlab code to analyze the tracked particle data found from Fluent
% Oyunaa Myagmar, 01/15/11
% $Revision:4   $Date: 05/25/11
clear all; clc;
n=65512;
% n=45000;
% load the data from Excel
All = importdata('pump10b_5_5000_kw.txt');
% All = importdata('pump10b_5_6000_kw.txt');
for k = 1:31
    disp(All.colheaders{1, k});
    disp(M.data(:, k))
end
A = All.data;

% Assign values
    node=A(:,1);
    Xpos=A(:,2);
    Ypos=A(:,3);
    Zpos=A(:,4);
    pressure=A(:,5);
    press_coef=A(:,6);
    press_dyn=A(:,7);
    press_abs=A(:,8);
    press_total=A(:,9);
    vel=A(:,10);
    Xvel=A(:,11);
    Yvel=A(:,12);
Zvel = A(:,13);
vel_ax = A(:,14);
vel_rad = A(:,15);
vel_tan = A(:,16);
wall = A(:,17);
Xwall = A(:,18);
Ywall = A(:,19);
Zwall = A(:,20);
m = 1050 * A(:,21);
strainrate = A(:,22);
dudx = A(:,23);
dvdx = A(:,24);
dwdx = A(:,25);
dudy = A(:,26);
dvdy = A(:,27);
dwdy = A(:,28);
dudz = A(:,29);
dvdz = A(:,30);
dwdz = A(:,31);

% for i = 2:1:n
%  X(i-1) = Xpos(i);
%  Y(i-1) = Ypos(i);
%  Z(i-1) = Zpos(i);
%  velX(i-1) = Xvel(i);
%  velY(i-1) = Yvel(i);
%  velZ(i-1) = Zvel(i);
%  strain(i-1) = strainrate(i);
% end

% Velocity along Z-axis (Cartesian Coordinate)
figure(1)
% Plotting xvelocity along Z-axis
subplot(2,2,1)
plot(Z, velX); grid on
xlabel('Z-axis (m)');
ylabel('Velocity (m/s)');
title('X velocity');
% Plotting yvelocity along Z-axis
subplot(2,2,2)
plot(Z, velY); grid on
xlabel('Z-axis (m)');
ylabel('Velocity (m/s)');
title('Y velocity');
% Plotting zvelocity along Z-axis
subplot(2,2,3)
plot(Zpos, Zvel); grid on
xlabel('Z-axis (m)');
ylabel('Velocity (m/s)');
title('Z velocity');

% Finding Shear Stress along Z-axis (Cartesian Coordinate)
mu = 3.5e-3; % [Pa] Blood Viscosity
for i = 2:1:n
% Finding Normal Stress
  tau_xx(i-1) = 2 * mu * dudx(i);
  tau_yy(i-1) = 2 * mu * dvdy(i);
  tau_zz(i-1) = 2 * mu * dwdz(i);
% Finding Viscous Shear Stress
tau_xy(i-1)=mu*(dvdx(i)+dudy(i));
tau_xz(i-1)=mu*(dudz(i)+dwdx(i));
tau_yz(i-1)=mu*(dvdz(i)+dwdy(i));
end

% 3-D scalar shear stress (multiplying matrixes)
eultau=sqrt(((tau_xx-tau_yy).^2+(tau_yy-tau_zz).^2+(tau_zz-tau_xx).^2)/6+(tau_xy.^2+tau_yz.^2+tau_xz.^2));
tau=mu*strain;
figure(2)
subplot(3,3,1) % Plotting Tau_xx along Z-axis
plot(Z,tau_xx); grid on
xlabel('Z-axis (m)');
ylabel('Shear Stress (Pa)');
title('Tau_x_x ');
subplot(3,3,2) % Plotting Tau_yy along Z-axis
plot(Z,tau_yy); grid on
xlabel('Z-axis (m)');
ylabel('Shear Stress (Pa)');
title('Tau_y_y ');
subplot(3,3,3) % Plotting Tau_zz along Z-axis
plot(Z,tau_zz); grid on
xlabel('Z-axis (m)');
ylabel('Shear Stress (Pa)');
title('Tau_z_z ');
subplot(3,3,4) % Plotting Tau_xy along Z-axis
plot(Z,tau_xy); grid on
xlabel('Z-axis (m)');
ylabel('Shear Stress (Pa)');
title('Tau_x_y ');
subplot(3,3,5) % Plotting Tau_xz along Z-axis
plot(Z,tau_xz); grid on
xlabel('Z-axis (m)');
ylabel('Shear Stress (Pa)');
title('Tau_x_z ');
subplot(3,3,6) % Plotting Tau_yz along Z-axis
plot(Z,tau_yz); grid on
xlabel('Z-axis (m)');
ylabel('Shear Stress (Pa)');
title('Tau_y_z ');
subplot(3,3,[7 9]) % Plotting Tau along Z-axis
plot(Z,eultau,'b',Z,tau,'r'); grid on
xlabel('Z-axis (m)');
ylabel('Shear Stress (Pa)');
title('Tau along Z-axis');

% Mass Weighted Approach
tau_pump=(M_ind*tau_ind+M_gap*tau_gap+M_rotor*tau_rotor+M_dif*tau_dif)/(M_ind+M_gap+M_rotor+M_dif)
M=sum(M(2:n)); % total mass
nbin=9;
Mf=zeros(nbin,1);
mf=zeros(nbin,1);
Vf=zeros(nbin+1,1);
vf=zeros(nbin+1,1);
% for j=1:nbin
  for i=2:n-1
    if eultau(i)<50 & eultau(i)>0
      Mf(1)=Mf(1)+m(i);
    end
    if eultau(i)<100 & eultau(i)>=50
      Mf(2)=Mf(2)+m(i);
    end
    if eultau(i)<150 & eultau(i)>=100
      Mf(3)=Mf(3)+m(i);
    end
    if eultau(i)<200 & eultau(i)>=150
      Mf(4)=Mf(4)+m(i);
    end
    if eultau(i)<250 & eultau(i)>=200
      Mf(5)=Mf(5)+m(i);
    end
    if eultau(i)<300 & eultau(i)>=250
      Mf(6)=Mf(6)+m(i);
    end
    if eultau(i)<350 & eultau(i)>=300
      Mf(7)=Mf(7)+m(i);
    end
    if eultau(i)<400 & eultau(i)>=350
      Mf(8)=Mf(8)+m(i);
    end
    if eultau(i)>=400
      Mf(9)=Mf(9)+m(i);
    end
  end
% end
mf=Mf/M;

for i=2:n-1
  if vel(i)<1 & vel(i)>0
    Vf(1)=Vf(1)+m(i);
  end
  if vel(i)<2 & vel(i)>=1
    Vf(2)=Vf(2)+m(i);
  end
  if vel(i)<3 & vel(i)>=2
    Vf(3)=Vf(3)+m(i);
  end
  if vel(i)<4 & vel(i)>=3
    Vf(4)=Vf(4)+m(i);
  end
end
if vel(i)<5 & vel(i)>=4
    Vf(5)=Vf(5)+m(i);
end

if vel(i)<6 & vel(i)>=5
    Vf(6)=Vf(6)+m(i);
end

if vel(i)<7 & vel(i)>=6
    Vf(7)=Vf(7)+m(i);
end

if vel(i)<8 & vel(i)>=7
    Vf(8)=Vf(8)+m(i);
end

if vel(i)<9 & vel(i)>=8
    Vf(9)=Vf(9)+m(i);
end

if vel(i)>=10
    Vf(10)=Vf(10)+m(i);
end

ev=Vf/M;
figure(3)
subplot(2,1,1), bar(50:50:450,mf,1), colormap(cool)
ylabel('Relative mass ratio');
xlabel('Scalar Shear Stress [Pa]');
title('Bar plot of Scalar Shear Stress');
subplot(2,1,2), bar(1:1:10,vf,1)
ylabel('Relative mass ratio');
xlabel('Velocity Magnitude [m/s]');
title('Bar plot of Velocity Magnitude');
Matlab Code 3: Read particle tracking data

% Matlab code to read the tracked particle data found from Fluent
%   Oyuna Myagmar, 01/15/11
%   $Revision:5   $Date: 06/30/11

clear all; clc;

pathFiles = [ ...
    'part_0.1_6000_time.txt' 0 0 0;
    'part_0.1_6000_strain.txt' 0;
    'part_0.1_6000_vel.txt' 0 0 0 0;
    'part_0.1_6000_z.txt' 0 0 0 0 0 0;
];

j=0;
maxNumDataPoints = 0;
data=ones(200,5,1000)*NaN;

for filestr=pathFiles'
    j=j+1;
disp(filestr');
    file = fopen(filestr');
    %file = fopen('path_6_6000_vel.txt');
    fgets(file);%read in title
    fgets(file);%read in labels
    while not( feof(file) )
        fgets(file);%read in empty line
        particle = fscanf(file, '%g
',2);
Matlab Code 4: Track single particle

% Matlab code to trace single particle data found from Fluent
%   Oyuna Myagmar, 01/15/11
%   $Revision:5   $Date: 06/30/11
mu=3.5e-3; % [Pa] Blood Viscosity
n=200;
i=3;
for i=1:n
    path(i,:)=data(i,1,:);
time(i,:)=data(i,2,:);
strain(i,:)=data(i,3,:);
vel(i,:)=data(i,4,:);
z(i,:)=data(i,5,:);
end
tau=mu*strain;

figure (1) % z
plot( z(i,:), path(i,:)); hold on; grid on;
ylabel('Path length [m]')
xlabel('Z position [m]')
title('Pathlength vs. Z')
figure (2) % exposure time
plot(z(i,:), time(i,:)); hold on; grid on;
xlabel('Z [m]')
ylabel('Exposure time [sec]')
title('Exposure time along Z')

figure (3) % velocity
plot(z(i,:), vel(i,:)); hold on; grid on;
xlabel('Z [m]')
ylabel('Velocity [m/s]')
title('Velocity along Z')

figure (4) % strain rate
plot(z(i,:), strain(i,:)); hold on; grid on;
xlabel('Z [m]')
ylabel('Strain [1/s]')
title('Strain Rate along Z')

figure(5) % Shear Stress
plot(z(i,:),tau(i,:),'b'); grid on; hold on;
xlabel('Z [m]');   ylabel('Shear Stress [Pa]');
title('Particle Shear Stress');

figure(6) % Threshold limit of Hemolysis
plot(time(i,:),tau(i,:),'b'); grid on; hold on;
xlabel('Residence Time [s]');   ylabel('Shear Stress [Pa]');
title('Shear Stress vs. Time');

figure(7) % Hemolysis model
for j=1:length(data)-1
    t(i,j)=time(i,j+1)-time(i,j);
    LA(i,j)=1.8e-6*(tau(i,j).^1.991).*(t(i,j)).^0.765;
end
plot(z(1,1:length(data)-1),abs(LA(1,:))); hold on; grid on;
xlabel('Z [m]');   ylabel('Blood Damage');
title('Lagrangian Approach along Z');
D=0; % integration of blood damage
for j=1:length(data)-1
    if isnan(LA(i,j))
        LA(i,j)=0;
    end
    D=D+abs(LA(i,j));
end

Matlab Code 5: Track all particles

% Matlab code to trace all particles found from Fluent
%   Oyuna Myagmar, 01/15/11
% $Revision:5   $Date: 06/30/11
mu=3.5e-3; % [Pa] Blood Viscosity
n=200;

figure (1) %z
for i=1:n
    path(i,:)=data(i,1,:);
    plot(z(i,:), path(i,:)); hold on; grid on;
end
xlabel('Z [m]')
ylabel('Path length[m]')
title('Pathline vs. Z')

figure (2) % exposure time
for i=1:n
    z(i,:)=data(i,5,:);
    time(i,:)=data(i,2,:);
    plot(z(i,:), time(i,:)); hold on; grid on;
end
xlabel('Z [m]')
ylabel('Exposure time [sec]')
title('Exposure time along Z')

figure (3) % velocity
for i=1:n
vel(i,:)=data(i,4,:);
plot(z(i,:), vel(i,:)); hold on; grid on;
end
xlabel('Z [m]')
ylabel('velocity [m/s]')
title('Velocity along Z')

figure (4) % strain rate
for i=1:n
strain(i,:)=data(i,3,:);
plot(z(i,:), strain(i,:)); hold on; grid on;
end
xlabel('Z [m]')
ylabel('Strain Rate[s^-1]')
title('Strain Rate along Z')

figure(5) % Shear Stress
tau=mu*strain;
for i=1:n
    plot(z(i,:),tau(i,:),'b'); grid on; hold on;
end
xlabel('Z(m)');
ylabel('Shear Stress (Pa)');
title('Scalar Shear Stress');

figure(6) % Threshold limit of Hemolysis
for i=1:n
    plot(time(i,:),tau(i,:),'b'); grid on; hold on;
end
xlabel('Residence Time (s)');
ylabel('Shear Stress (Pa)');
title('Shear Stress vs. Time');

figure(7) % Hemolysis model
for i=1:n
    for j=1:length(data)-1

\[ t(i,j) = \text{time}(i,j+1) - \text{time}(i,j); \]
\[ \text{LA}(i,j) = 1.8 \times 10^{-6} \times \text{abs(\text{tau}(i,j)^{1.991}) \times (t(i,j)^{0.765});} \]

end

plot(z(i,1:length(data)-1), abs(LA(i,:))); hold on; grid on;

end

xlabel('Z (m)');
ylabel('Blood Damage');
title('Lagrangian Approach along Pathline');

D=0;  \% integration of blood damage
for i=1:n
    for j=1:length(data)-1
        if isnan(LA(i,j))
            LA(i,j)=0;
        end
        D=D+abs(LA(i,j));
    end
end
D=D/n;
Appendix C

Grid Independent Study

Mesh 1 was refined by using Boundary Adaption.

<table>
<thead>
<tr>
<th>Number of Elements</th>
<th>File Name</th>
<th>Previous Name</th>
<th>Flow [lpm]</th>
<th>Inlet P [Pa]</th>
<th>Outlet P [Pa]</th>
<th>Δ P [Pa]</th>
<th>Δ P [mmHg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>100,800</td>
<td>Mesh1</td>
<td>Mesh1</td>
<td>2</td>
<td>185,775</td>
<td>200,000</td>
<td>14225</td>
<td>107</td>
</tr>
<tr>
<td>311,800</td>
<td>Mesh1a</td>
<td>Mesh1a</td>
<td>2</td>
<td>187,332</td>
<td>200,000</td>
<td>12668</td>
<td>95</td>
</tr>
<tr>
<td>1,775,000</td>
<td>Mesh1b</td>
<td>Mesh1b</td>
<td>2</td>
<td>189,632</td>
<td>200,000</td>
<td>10368</td>
<td>78</td>
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<tr>
<td>4,000,000</td>
<td>Mesh1c</td>
<td>Mesh1c</td>
<td>2</td>
<td>190,555</td>
<td>200,000</td>
<td>9445</td>
<td>71</td>
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</tbody>
</table>

Mesh 2 was refined by using Yplus/Ystar Adaption.

<table>
<thead>
<tr>
<th>Number of Elements</th>
<th>File Name</th>
<th>Previous Name</th>
<th>Flow [lpm]</th>
<th>Inlet P [Pa]</th>
<th>Outlet P [Pa]</th>
<th>Δ P [Pa]</th>
<th>Δ P [mmHg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>138,150</td>
<td>Mesh2</td>
<td>Mesh4</td>
<td>2</td>
<td>186,425</td>
<td>200,000</td>
<td>13575</td>
<td>102</td>
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<tr>
<td>605,421</td>
<td>Mesh2a</td>
<td>Mesh4a</td>
<td>2</td>
<td>189,066</td>
<td>200,000</td>
<td>10934</td>
<td>82</td>
</tr>
<tr>
<td>1,055,318</td>
<td>Mesh2b</td>
<td>Mesh4b</td>
<td>2</td>
<td>189,888</td>
<td>200,000</td>
<td>10112</td>
<td>76</td>
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<tr>
<td>2,095,455</td>
<td>Mesh2c</td>
<td>Mesh4c</td>
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<td>190,486</td>
<td>200,000</td>
<td>9514</td>
<td>71</td>
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<tr>
<td>2,372,919</td>
<td>Mesh2d</td>
<td>Mesh4d</td>
<td>2</td>
<td>190,240</td>
<td>200,000</td>
<td>9760</td>
<td>73</td>
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</table>

Mesh 3 was refined by using Gradient Adaption.

<table>
<thead>
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<th>File Name</th>
<th>Previous Name</th>
<th>Flow [lpm]</th>
<th>Inlet P [Pa]</th>
<th>Outlet P [Pa]</th>
<th>Δ P [Pa]</th>
<th>Δ P [mmHg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>350,000</td>
<td>Mesh3</td>
<td>Mesh11</td>
<td>2</td>
<td>187,654</td>
<td>200,000</td>
<td>12346</td>
<td>93</td>
</tr>
<tr>
<td>564,000</td>
<td>Mesh3a</td>
<td>Mesh11a</td>
<td>2</td>
<td>188,628</td>
<td>200,000</td>
<td>11372</td>
<td>85</td>
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<tr>
<td>1,157,725</td>
<td>Mesh3b</td>
<td>Mesh11b</td>
<td>2</td>
<td>190,060</td>
<td>200,000</td>
<td>9940</td>
<td>75</td>
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<tr>
<td>1,313,209</td>
<td>Mesh3c</td>
<td>Mesh11c</td>
<td>2</td>
<td>190,149</td>
<td>200,000</td>
<td>9851</td>
<td>74</td>
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<tr>
<td>1,815,000</td>
<td>Mesh3d</td>
<td>Mesh11d</td>
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<td>190,317</td>
<td>200,000</td>
<td>9683</td>
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</table>
### Characteristic Curve

**Experimental vs. CFD results for speed 4000rpm**

<table>
<thead>
<tr>
<th>Mini 4000</th>
<th>CFD 4000</th>
<th>Interpolated num data</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (lpm)</td>
<td>ΔP (mmHg)</td>
<td>Flow (lpm)</td>
<td>ΔP (mmHg)</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>0.84</td>
<td>53</td>
<td>1</td>
<td>64</td>
</tr>
<tr>
<td>1.8</td>
<td>47</td>
<td>2</td>
<td>49</td>
</tr>
<tr>
<td>2.75</td>
<td>39</td>
<td>3</td>
<td>37</td>
</tr>
<tr>
<td>3.67</td>
<td>33</td>
<td>4</td>
<td>29</td>
</tr>
<tr>
<td>4.76</td>
<td>25</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>5.41</td>
<td>22</td>
<td>6</td>
<td>11</td>
</tr>
</tbody>
</table>

**Experimental vs. CFD results for speed 5000rpm**

<table>
<thead>
<tr>
<th>Mini 5000</th>
<th>CFD 5000</th>
<th>Interpolated num data</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (lpm)</td>
<td>ΔP (mmHg)</td>
<td>Flow (lpm)</td>
<td>ΔP (mmHg)</td>
</tr>
<tr>
<td>0</td>
<td>91</td>
<td>0</td>
<td>114</td>
</tr>
<tr>
<td>1</td>
<td>82</td>
<td>1</td>
<td>101</td>
</tr>
<tr>
<td>2</td>
<td>72</td>
<td>2</td>
<td>87</td>
</tr>
<tr>
<td>3</td>
<td>64</td>
<td>3</td>
<td>72</td>
</tr>
<tr>
<td>4</td>
<td>57</td>
<td>4</td>
<td>62</td>
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<tr>
<td>5</td>
<td>51</td>
<td>5</td>
<td>51</td>
</tr>
<tr>
<td>5.75</td>
<td>45</td>
<td>6</td>
<td>41</td>
</tr>
<tr>
<td>6.93</td>
<td>33</td>
<td>7</td>
<td>30</td>
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</table>

**Experimental vs. CFD results for speed 6000rpm**

<table>
<thead>
<tr>
<th>Mini 6000</th>
<th>CFD 6000</th>
<th>Interpolated num data</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow (lpm)</td>
<td>ΔP (mmHg)</td>
<td>Flow (lpm)</td>
<td>ΔP (mmHg)</td>
</tr>
<tr>
<td>0</td>
<td>141</td>
<td>0</td>
<td>156</td>
</tr>
<tr>
<td>1</td>
<td>125</td>
<td>1</td>
<td>142</td>
</tr>
<tr>
<td>2</td>
<td>111</td>
<td>2</td>
<td>128</td>
</tr>
<tr>
<td>3</td>
<td>101</td>
<td>3</td>
<td>114</td>
</tr>
<tr>
<td>4</td>
<td>92</td>
<td>4</td>
<td>101</td>
</tr>
<tr>
<td>5</td>
<td>85</td>
<td>5</td>
<td>94</td>
</tr>
<tr>
<td>6</td>
<td>77</td>
<td>6</td>
<td>83</td>
</tr>
<tr>
<td>7</td>
<td>68</td>
<td>7</td>
<td>68</td>
</tr>
<tr>
<td>7.25</td>
<td>65</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix D

Hemolysis Results: Method 1 and 2

5 lpm 4000rpm $t_{exp}=0.15\text{s}$ $\tau=150\text{ Pa}$ $D=0.01\%$

<table>
<thead>
<tr>
<th>Shear Stress $[\text{Pa}]$</th>
<th>Rel Mass</th>
<th>Rel Mass $%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>0.734</td>
<td>73.40%</td>
</tr>
<tr>
<td>50-100</td>
<td>0.2617</td>
<td>26.17%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.0043</td>
<td>0.43%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0001</td>
<td>0.01%</td>
</tr>
<tr>
<td>200-250</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

5 lpm 5000rpm $t_{exp}=0.15\text{s}$ $\tau=150\text{ Pa}$ $D=0.09\%$

<table>
<thead>
<tr>
<th>Shear Stress $[\text{Pa}]$</th>
<th>Rel Mass</th>
<th>Rel Mass $%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>0.6548</td>
<td>65.48%</td>
</tr>
<tr>
<td>50-100</td>
<td>0.2984</td>
<td>29.84%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.0459</td>
<td>4.59%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0009</td>
<td>0.09%</td>
</tr>
<tr>
<td>200-250</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

5 lpm 6000rpm $t_{exp}=0.15\text{s}$ $\tau=150\text{ Pa}$ $D=0.75\%$

<table>
<thead>
<tr>
<th>Shear Stress $[\text{Pa}]$</th>
<th>Rel Mass</th>
<th>Rel Mass $%$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>0.6144</td>
<td>61.44%</td>
</tr>
<tr>
<td>50-100</td>
<td>0.302</td>
<td>30.20%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.0761</td>
<td>7.61%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0073</td>
<td>0.73%</td>
</tr>
<tr>
<td>200-250</td>
<td>0.0002</td>
<td>0.02%</td>
</tr>
</tbody>
</table>

6 lpm 4000rpm $t_{exp}=0.12\text{s}$ $\tau=180\text{ Pa}$ $D=1.25e-3\%$
### Table 1: Shear Stress Distribution

<table>
<thead>
<tr>
<th>Shear Stress [Pa]</th>
<th>Rel Mass</th>
<th>Rel Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>0.739086</td>
<td>73.91%</td>
</tr>
<tr>
<td>50-100</td>
<td>0.256971</td>
<td>25.70%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.003904</td>
<td>0.39%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0000125</td>
<td>0.12E-3%</td>
</tr>
<tr>
<td>200-250</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

### Table 2: Shear Stress Distribution

<table>
<thead>
<tr>
<th>Shear Stress [Pa]</th>
<th>Rel Mass</th>
<th>Rel Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>0.6654</td>
<td>66.54%</td>
</tr>
<tr>
<td>50-100</td>
<td>0.2933</td>
<td>29.33%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.041</td>
<td>4.10%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0003</td>
<td>0.03%</td>
</tr>
<tr>
<td>200-250</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

### Table 3: Shear Stress Distribution

<table>
<thead>
<tr>
<th>Shear Stress [Pa]</th>
<th>Rel Mass</th>
<th>Rel Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td>0.7258</td>
<td>72.58%</td>
</tr>
<tr>
<td>50-100</td>
<td>0.2687</td>
<td>26.87%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.0521</td>
<td>5.21%</td>
</tr>
<tr>
<td>150-200</td>
<td>0</td>
<td>0.00%</td>
</tr>
<tr>
<td>200-250</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

### Table 4: Shear Stress Distribution

<table>
<thead>
<tr>
<th>Shear Stress [Pa]</th>
<th>Rel Mass</th>
<th>Rel Mass %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-120</td>
<td>0.6414</td>
<td>64.14%</td>
</tr>
<tr>
<td>120-200</td>
<td>0.304</td>
<td>30.40%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.0521</td>
<td>5.21%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0024</td>
<td>0.24%</td>
</tr>
<tr>
<td>200-250</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

### Table 5: Shear Stress Distribution

<table>
<thead>
<tr>
<th>Shear Stress [Pa]</th>
<th>Rel Mass</th>
<th>Rel Mass %</th>
</tr>
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<tbody>
<tr>
<td>0-120</td>
<td>0.6414</td>
<td>64.14%</td>
</tr>
<tr>
<td>120-200</td>
<td>0.304</td>
<td>30.40%</td>
</tr>
<tr>
<td>100-150</td>
<td>0.0521</td>
<td>5.21%</td>
</tr>
<tr>
<td>150-200</td>
<td>0.0024</td>
<td>0.24%</td>
</tr>
<tr>
<td>200-250</td>
<td>0</td>
<td>0.00%</td>
</tr>
</tbody>
</table>
Hemolysis Results: Eulerian Approach for LEV-VAD pump:

### 6 LPM

<table>
<thead>
<tr>
<th>Q [m^3/s]</th>
<th>Giersiepen</th>
<th>Heuser</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6000 RPM</td>
<td>total vol</td>
<td>1.000E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000 RPM</td>
<td>total vol</td>
<td>1.000E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 RPM</td>
<td>total vol</td>
<td>1.000E-04</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
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</tbody>
</table>

### 5 LPM

<table>
<thead>
<tr>
<th>Q [m^3/s]</th>
<th>Giersiepen</th>
<th>Heuser</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
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<tr>
<td>6000 RPM</td>
<td>total vol</td>
<td>8.333E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000 RPM</td>
<td>total vol</td>
<td>8.333E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4000 RPM</td>
<td>total vol</td>
<td>8.333E-05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>D</td>
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<td></td>
<td></td>
<td></td>
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</tbody>
</table>

### 4 LPM

<table>
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<tr>
<th>Q [m^3/s]</th>
<th>Giersiepen</th>
<th>Heuser</th>
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<tbody>
<tr>
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<tr>
<td>6000 RPM</td>
<td>total vol</td>
<td>6.667E-05</td>
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<td>total vol</td>
<td>6.667E-05</td>
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<td>6.667E-05</td>
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### Eulerian Approach - 4000 RPM

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<tr>
<th>Pump</th>
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<th>Flow Rate LPM</th>
<th>Pressure mmHg</th>
<th>ΔHb/Hb (Giersiepen)</th>
<th>NIH g/100L (Giersiepen)</th>
<th>ΔHb/Hb (Heuser)</th>
<th>NIH g/100L (Heuser)</th>
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<tr>
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<td>Low Flow</td>
<td>4</td>
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### Eulerian Approach - 5000 RPM

<table>
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<tr>
<th>Pump</th>
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<th>Flow Rate LPM</th>
<th>Pressure mmHg</th>
<th>ΔHb/Hb (Giersiepen)</th>
<th>NIH g/100L (Giersiepen)</th>
<th>ΔHb/Hb (Heuser)</th>
<th>NIH g/100L (Heuser)</th>
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### Eulerian Approach - 6000 RPM

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<th>ΔHb/Hb (Heuser)</th>
<th>NIH g/100L (Heuser)</th>
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Hemolysis Results: Lagrangian Approach for LEV-VAD pump

### Lagrangian Approach - 4000 RPM

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<th>Purpose</th>
<th>Flow Rate LPM</th>
<th>Pressure mmHg</th>
<th>ΔHb/Hb</th>
<th>NIH g/100L (Lagrangian)</th>
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### Lagrangian Approach - 5000 RPM

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<th>Pressure mmHg</th>
<th>ΔHb/Hb</th>
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### Lagrangian Approach - 6000 RPM

<table>
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<th>Pressure mmHg</th>
<th>ΔHb/Hb</th>
<th>NIH g/100L (Lagrangian)</th>
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## Hemolysis Results: Percent Error Comparison for LEV-VAD pump

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<th>NIH g/100L (Heuser)</th>
<th>% Error</th>
<th>Flow Rate LPM</th>
<th>NIH g/100L (Lagrangian)</th>
<th>NIH g/100L (Giersiepen)</th>
<th>% Error</th>
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Hemolysis Results: Method 1 and 2

0.1 lpm 3000rpm \( t_{\text{exp}} = 3.8 \text{s} \) \( \tau = 200 \text{ Pa} \) D=0.13%

<table>
<thead>
<tr>
<th>Shear Stress [Pa]</th>
<th>Rel Mass</th>
<th>Rel Mass %</th>
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<tbody>
<tr>
<td>0-50</td>
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<tr>
<td>50-100</td>
<td>0.028842</td>
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<tr>
<td>100-150</td>
<td>0.0037837</td>
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<tr>
<td>150-200</td>
<td>0.001466</td>
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<tr>
<td>200-250</td>
<td>0.0013335</td>
<td>0.13%</td>
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0.1 lpm 9000rpm \( t_{\text{exp}} = 0.38 \text{s} \) \( \tau = 200 \text{ Pa} \) D=3%

<table>
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<th>Shear Stress [Pa]</th>
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<tr>
<td>100-150</td>
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<td>150-200</td>
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<td>200-250</td>
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<td>250-300</td>
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<td>0.0033</td>
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<td>350-400</td>
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Hemolysis Results: Eulerian Approach for MAG-LEV Shearing Device

<table>
<thead>
<tr>
<th>Volume (mL)</th>
<th>$Q$ [m$^3$/s]</th>
<th>$D$ [g/100L]</th>
<th>$D^{0.785}$</th>
<th>NIH [g/100L]</th>
<th>$I$ [g/100L]</th>
<th>$D^{0.765}$</th>
<th>NIH [g/100L]</th>
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</thead>
<tbody>
<tr>
<td>3000 total vol</td>
<td>8.333E-07</td>
<td>1.15E-09</td>
<td>1.38E-03</td>
<td>1.73E-02</td>
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<td>5.46E-10</td>
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<tr>
<td>4000 total vol</td>
<td>8.333E-07</td>
<td>3.22E-09</td>
<td>3.87E-03</td>
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<td>1.29E-09</td>
<td>1.55E-03</td>
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<tr>
<td>5000 total vol</td>
<td>8.333E-07</td>
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<tr>
<td>6000 total vol</td>
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<td>1.48E-02</td>
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<table>
<thead>
<tr>
<th>Volume (mL)</th>
<th>$Q$ [m$^3$/s]</th>
<th>$D$ [g/100L]</th>
<th>$D^{0.785}$</th>
<th>NIH [g/100L]</th>
<th>$I$ [g/100L]</th>
<th>$D^{0.765}$</th>
<th>NIH [g/100L]</th>
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<tbody>
<tr>
<td>3000 total vol</td>
<td>1.667E-06</td>
<td>1.40E-09</td>
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### 0.15 LPM

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<th>Giersiepen</th>
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<th>Heuser</th>
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<tbody>
<tr>
<td></td>
<td>Q [m³/s]</td>
<td>I</td>
<td>D</td>
<td>D⁺0.785</td>
<td>NIH [g/100L]</td>
<td>I</td>
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<tr>
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### 0.2 LPM

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Appendix E

Design of MAG-LEV Shearing Device:
SECTION A-A

This radius is not critical as long as thickness is not reduced.

6x Drill Thru R0.113

Bottom Tap Right Hand 6-32
0.276 Deep Drill Depth
[0.352] 8.95

All inside surface is polished.

\[ \phi 0.776 \pm 0.001 \]
SECTION A-A

160°

Bottom Tap
6-32 Left Hand
0.276 (M)

R0.394

1.330
1.232
1.133
1.069
0.852

0.438
0.0005
0.0000

0.55 ±0.001

0.607
-0.0005

0.0000

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±0.1
ANGULAR: MACING ±3°
TWO PLACE DECIMAL ±0.001
THREE PLACE DECIMAL ±0.000

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL: 31655

NAME:

DRAWN:

CHECKED:

ENG APPR.:

MFG APPR.:

Q.A.:

COMMENTS:

TITLE:
Cap, Impeller, Rear

SIZE

DWG. NO.

Imp Rear 2501_V7

REV

A

2

SCALE: 2:1

WEIGHT:

SHEET 1 OF 2
SECTION A-A

Bump Length
1.063 ± 0.000
27 ± 0.013

Base OD
0.646 ± 0.000
Φ 16.400 ± 0.013

Blade OD
0.000
[0.752 - 0.000]
0
Φ 19.100 - 0.013

Fillets R3 [0.197]

[0.593]
Φ 6.060

[0.883]
Φ 6.205

[2.106]
53.500

[2.497]
63.416

[1.988]
50.500

[1.752]
44.500

Bottom Tap
Right Hand 6-32
0.236 Deep
Drill Depth [.288] 7.31

4x Chamfer ID
0.25mm @ 45

[0.0236]
6

55

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL 0.01
ANGULAR, RADIO, 0.001
THREE PLACE DECIMAL:

MATERIAL: stainless steel
FINISH:

PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <COMPANY NAME HERE> IS PROHIBITED.

DRAWN:
CHECKED:
END APPR.:
ENG. REV.

PROFESSIONAL

SIGNATURE

TITLE:
Impeller

SIZE: A
REV:

DRAW 2500_CYLINDER_fillet

SCALE: 1:1 WEIGHT:

SHEET 1 OF 1

154
Quote for Impeller housing:

Turbo Machined Products LLC
102 Industrial Drive
Frankfort NY 13340-1139

Cartmell@turbomp.com  Voice: (315) 896-3010
www.turbomp.com      Fax: (315) 896-3011

May 9, 2011           Quote 1104112

Oyuna Myagmar
Rochester Institute of Technology
James E. Gleason Building
76 Lomb Memorial Drive

Dear Oyuna,

Thank you for the opportunity to quote this project for RIT.

<table>
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<tr>
<th>Part</th>
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<th>Piece Price</th>
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The quote is good for thirty (30) days; the payment schedule is "NET 30" with 1.1/2% per month, and the prices are F.O.B., Frankfort, N.Y. If you have any questions, please do not hesitate to call or fax.

Best regards,

Mr. Robert J Cartmell
VP