NUMERICAL INVESTIGATION OF IMPELLER DESIGN VARIATION ON MECHANICAL BLOOD PUMP HEMODYNAMICS

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To my beloved family and friends...

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ABSTRACT

Mechanical heart assist device is an emerging treatment for end-stages of heart failure which is an alternative to heart transplant due the shortage of heart donors. Despite the clinical success of "Left Ventricular Assist Devices (LVAD)", the development still continue as new designs are progressively being tested to address the ever existing complications. Developing these blood pumps requires determining a balance in providing adequate pump performance while giving attention to possible occurrence of blood damage. This study utilized a proposed design concept of a hybrid bearing system and evaluate its' merits of adapting the concept from a perspective of computational fluid dynamic (CFD) approach. Two design parameters were chosen for this study; the conical shape of the impeller bottom that functions to provide both radial and axial stability and secondly, the inclusion of a groove profile intended to complement the system as a hydrodynamic bearing as well as improving washout flow. Four model variations were constructed from the design parameters for comparison with the number of mesh between 8.9 to 9.8 million nodes. Menter's Shear Stress Transport (SST) turbulent model was used to simulate 3 different operating speeds (2000 rpm, 3000 rpm, 4000 rpm) at 5 varying flowrate (3, 4, 5, 6, 7 $\mathrm{L/min}$). Evaluation involved assessing the model variants based on several performance criteria. Ranked selection method was used to rate and select the better performing model variation with a good compromise between the level of blood damage potential (hemolysis index) and the pump performance although heavier emphasis on blood damage was chosen as a priority. In the analysis, CFD results showed that the inclusion of conical shape has negligible effect on pump head with a minor 0.8 percent difference, however it does present a potential area of stagnant flow, reducing washout by 28.3 percent. The groove profile along with conical shaped impeller present high shear stress region at the impeller bottom area that caused an increase in hemolysis index by an average of 15.4 percent. Ranking and selection of the model variants resulted in the flat groove configuration scored as the best performing configuration that gives the good compromise of pump performance and hemolysis.

ABSTRAK

Alat bantu jantung mekanikal adalah rawatan terkini untuk peringkat akhir penyakit jantung yang merupakan alternatif kepada transplantasi jantung kerana kekurangan penderma jantung. Walaupun dengan kejayaan klinikal pengunaan “Left Ventricular Assist Devices (LVAD)”, penyelidikan masih diterusan dengan pelbagai reka bentuk baru yang diuji sehingga hari ini untuk menangani komplikasi rawatan tersebut. Fabrikasi pam darah memerlukan keseimbangan dalam menyediakan tekanan pam yang mencukupi sambil memberi perhatian kepada berlakunya kerosakan darah. Kajian ini menggunakan konsep reka bentuk sistem galas hibrid dan menilai merit penyesuaian konsep ini dari perspektif perkomputeran dinamik bendalir. Dua parameter reka bentuk dipilih untuk kajian ini; bentuk kon di bahagian bawah impeler yang berfungsi menyediakan kestabilan radial dan axial. Parameter kedua ialah profil alur yang membantu sistem pam sebagai galas hidrodinamik serta meningkatkan aliran darah dibawah impeler. Daripada parameter reka bentuk tersebut, empat variasi model dibandingkan dengan jumlah jaringan antara 8.9 hingga 9.8 juta nod. Model turbulen “Shear Stress Transport Menter (SST)” dipilih bagi mensimulasikan 3 kelajuan operasi yang berbeza (2000 rpm, 3000 rpm, 4000 rpm) pada 5 kadar aliran (3, 4, 5, 6, 7 $\mathrm{L/min}$). Penilaian varian model berdasarkan beberapa kriteria prestasi. Kaedah pemilihan mengikut pemarkahan digunakan untuk menilai prestasi parameter reka bentuk untuk mendapatkan konfigurasi model yang mempunyai kompromi terbaik antara tahap potensi kerosakan darah (indeks hemolisis) dan prestasi pam dengan penekanan markah yang lebih tinggi diberi ke atas indeks hemolisis. Dalam analisis ini, keputusan perkomputeran dinamik bendalir menunjukkan bahawa bentuk kon impeler tidak mempunyai kesan negatif yang ketara terhadap prestasi pam yang hanya mempunyai perbezaan 0.8 peratus. Bagaimanapun ia berisiko menyebabkan kawasan aliran bertakung dan mengurangkan aliran di bawah impeller sebanyak 28.3 peratus. Kombinasi bentuk kon impeler dan profil alur menyebabkan tegasan ricih yang tinggi di kawasan bawah impeler dan peningkatan indeks hemolisis sebanyak 15.4 peratus. Pemilihan variasi model menunjukkan konfigurasi alur rata sebagai konfigurasi yang mempunyai prestasi terbaik yang memberikan kompromi yang baik pada prestasi pam dan hemolisis.

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LIST OF ABBREVIATIONS

LVAD	-	Left Ventricular Assist Device
RVAD	-	Right Ventricular Assist Device
BIVAD	-	Bi-ventricular Assist Device
TAH	-	Total Artificial Heart
CFD	-	Computational Fluid Dynamics
CHF	-	Congestive Heart Failure
HF	-	Heart Failure
VAD	-	Ventricular Assist Device
BTT	-	Bridge to Transplant
DT	-	Destination Therapy
CVD	-	Cardiovascular Disease
SST	-	Shear Stress Transport
ACC	-	American College of Cardiology
AHA	-	American Heart Association
NYHA	-	New York Heart Association
SGB	-	Spiral Groove Bearing
BDI	-	Blood Damage Index
HI	-	Hemolysis Index
BEP	-	Best Efficiency Point
NIH	-	Normalized Index of Hemolysis

LIST OF SYMBOLS

α	-	Spiral groove angle
α_v	-	Volute angle
η	-	Hydraulic efficiency
ω	-	Operating speed
τ	-	Shear stress
θ	-	Impeller blade angle
A_{th}	-	Volute throat area
D	-	Impeller diameter
D_v	-	Volute base circle diameter
P	-	Pressure
Q	-	Volumetric flowrate
T	-	Torque
b_v	-	Volute width
h	-	Spiral Groove Depth
r_θ	-	Groove Radius
r_{ig}	-	Spiral groove inner radius
t	-	shear stress exposure time
t_1, t_2	-	Impeller blade thickness

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CHAPTER 1

INTRODUCTION

1.1 Background of the Problem

Congestive heart failure (CHF) is a type cardiovascular disease that causes ventricular dysfunction and a reduction in cardiac output (Hunt and Frazier (1998); Wood et al. (2005)). CHF is fatal and is increasing in major urban areas of developing countries and developed countries alike where it is a leading cause of mortality globally. The fatality rate is one in five patients died within the first year and fewer than 60 percent survives to five years (Lloyd-Jones et al. (2010)).

There are many therapies for treating patients with heart failure (HF). For early stages of HF includes lifestyle changes, medications, transcatheter interventions and surgery. However, for patients with the advanced stage of HF, heart transplantation or Ventricular Assist Device (VAD) is the only treatment options. Heart transplant remains the best treatment to date but due to the limited number of donor hearts, only a minor percentage of patients benefit from this treatment (Porepa and Starling (2014)).

Mechanical heart assist device is an emerging treatment for end-stages of heart failure which is an alternative to heart transplant due the shortage of heart donors. The Left Ventricular Assist Device (LVAD) has evolved with decades of improvements, currently is the third generation of LVAD with the highlighted feature of utilizing electromagnets drive system, magnetic and/or hydrodynamic levitations principles for improved durability and reliability as blood pump. The advancements in LVAD technology has facilitated sequential approval for clinical use either as a temporary bridge to transplant (BTT) and as a permanent support, destination therapy (DT) (Porepa and Starling (2014)).

Decades of development have aimed to make the LVADs even smaller and less cumbersome devices. However, such an improvement results in some drawbacks; as the pump reduces size, a higher impeller speeds is required to provide the adequate pressures, and blood damage and platelet activation will become a more apparent issue (Fraser et al. (2011)). Therefore, determining a balance between better performance and pump size with acceptable hemo-compatibilty.

Despite the clinical success of LVADs, the development stills continues as new designs are progressively being tested to address the ever existing complications. Developing these blood pumps requires certainties in providing adequate pump performance while giving attention to possible occurrence of blood damage. Solutions in solving these complications is a multidisciplinary task employing numerical modeling, in-vitro models, animal trials, and clinical trials. Computational fluid Dynamics (CFD) forms the bulk of numerical modeling since LVADs are essentially blood pumps where fluid flow is involved as in many fields of engineering. CFD is a versatile tool for design development of LVAD as numerous design configurations could be characterized for virtually functional performance before fabricating the physical device (Fraser et al. (2011)).

1.2 Statement of the Problem

The main challenge faced developing rotary blood pump is the potential damage to blood cells. Hemolysis and platelet activation are a function of both level of shear stress and the exposure time of blood particles traversing through the blood pump. Blood damage is affected by the blood flow within the pump and varying geometries of the pump is hypothesized to contribute to this effect. Therefore, evaluation the effects of varying geometric parameters are the focus of this study. Numerical simulation is used to assess the effects of the design factors on the potential for blood damage and also blood pump performance.

1.3 Objectives of the Study

The objective of this research comprise of the following:

1. To construct and evaluate the numerical models of blood pump in performance and blood damage potential
2. To determine the best model configuration with acceptable compromise of overall performance

1.4 Scope of the Study

The scope of this study is focused on steady state numerical simulation. Evaluation of blood pump model variations is based on selected design factors. Ranked selection method is used for rating and comparison of selecting the best model configuration with the best compromise of key performance criteria.

1.5 Significance of the Study

This study expands the works of adapting a blood pump design based on established pump design principles. Numerical simulation approach is utilized in evaluating the pump design to function as a blood pump which puts emphasis on indications for blood damage and thrombosis In addition to common performance measures like generated pressure and efficiency. The benefit of this research is in providing a comprehensive estimation of overall performance at design stage that would eventually pave way to devising a physical working prototype of the blood pump design.

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