



**COMPUTATIONAL STUDY OF BLOOD FLOW
THROUGH VORTEX GENERATOR INTEGRATED
MECHANICAL HEART VALVE**

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA
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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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Faculty of Mechanical Engineering



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GENERATOR INTEGRATED MECHANICAL HEART VALVE**

NURSYAIRA BINTI MOHD SALLEH

**A thesis submitted
in fulfilment of the requirements for the degree of Master of Science
in Mechanical Engineering**



UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2023

DECLARATION

I declare that this thesis entitled “Computational Study of Blood Flow through Vortex Generator Integrated Mechanical Heart Valve” is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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APPROVAL

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DEDICATION

A million praise towards my family, my respectful supervisor, lecturers and to all my friends for their support and cooperation in helping me to complete this thesis.

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ABSTRACT

Treatments for heart valve illness are being replaced by two types of prosthetics: bio-prosthetic heart valves (BHV) constructed from tissue material and mechanical heart valves (MHV) made of pyrolytic carbon. However, the replacement of the heart valve has several issues such as hemolysis, tissue overgrowth and thrombosis which still need improvement of the overall process. For MHV, the major complication is blood clotting, known as thrombosis and bleeding. MHV malfunction which lead to sudden death or stroke. The computational analysis was developed to study the blood flow through MHV equipped with VG. Thrombosis complications identified through non-physiological flow patterns such as pressure drop, recirculation, and wall shear stress (WSS). The result is validated with previous literature with percentage error of maximum velocity at central jet with 1.4% error. Results found that 1 mm triangular VG produced an optimum result with 25.13 % reduction of pressure drop compared to the absence of VG in laminar flow on idealized asymmetric aorta. Furthermore, three turbulence models, namely, Spalart Allmaras (SA), k - ϵ , and Large Eddy Simulation (LES), were used to analyze the blood clotting potential in MHV with and without VGs under turbulence effect. The results found the LES turbulent model most suitable to capture unsteady solutions with rich coherent vortex shedding and providing 33.4 % lower WSS compared to the MHV without VGs. This method was also used for the anatomic aorta model with the same solver and including the VGs. The implication of VGs on the leaflet of SJM valve produced lower 15.33 % WSS and small recirculation zones by 7 % associated with lower platelet to be trapped inside anatomic aorta compared to the absence of VGs.

KAJIAN PENGKOMPUTERAN ALIRAN DARAH MELALUI PENJANA VORTEKS BERSEPADU INJAP JANTUNG MEKANIKAL

ABSTRAK

Rawatan penyakit injap jantung digantikan oleh dua jenis prostetik iaitu injap jantung bio-prostetik (BHV) yang dibuat daripada bahan tisu dan injap jantung mekanikal (MHV) dibuat oleh karbon pirolitik. Walau bagaimanapun, penggantian injap jantung mempunyai beberapa masalah seperti hemolisis, pertumbuhan tisu dan darah beku yang masih memerlukan penambahbaikan proses keseluruhan. Bagi MHV, komplikasi utama adalah pembekuan darah yang dikenali sebagai trombosis dan pendarahan. MHV yang boleh menyebabkan kematian mengejut atau strok. Analisis pengkomputeran dijalankan untuk mengkaji kaedah mengurangkan kesan potensi trombosis. Komplikasi darah beku dapat dikurangkan dengan mengenal pasti corak aliran bukan fisiologi seperti pengurangan tekanan, peredaran semula dan tegasan ricih dinding (WSS). Data mendapati bahawa VG segitiga Imm menghasilkan kesan yang optimum dengan 25.13 % peratusan penurunan tekanan. Dalam kajian ini, tiga model gelora (SA, k-ε dan LES) digunakan untuk menentusah kesan gelora pada injap MHV yang dipasang VG dan tanpa VG. Hasil dapatan mendapati model gelora LES paling sesuai untuk memperoleh penyelesaian tidak mantap dengan perincian pusaran yang padat dan dapat menurunkan WSS sebanyak 33.4 % apabila VGs ini digunakan pada anatomi aorta. Implikasi VGs pada injap MHV pada anatomic aorta pula menghasilkan pengurangan zon pusaran sebanyak 7 % yang berkaitan dengan pengurangan platelet yang terperangkap berbanding dengan ketiadaan VGs.

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TABLE OF CONTENTS

	PAGE
DECLARATION	
APPROVAL	
DEDICATION	
ABSTRACT	i
ABSTRAK	ii
ACKNOWLEDGEMENT	iii
TABLE OF CONTENT	iv
LIST OF TABLES	vi
LIST OF FIGURES	vii
LIST OF APPENDICES	xii
LIST OF ABBREVIATIONS	xiii
LIST OF SYMBOLS	xiv
LIST OF PUBLICATIONS	xv
CHAPTER	1
1. INTRODUCTION	1
1.1 Background	1
1.2 Problem Statement	3
1.3 Objective	4
1.4 Scope of Study	5
1.5 Significance of Study	6
1.6 Outline of Thesis	6
2. LITERATURE REVIEW	8
2.1 Overview	8
2.2 Implantation and Configuration of Mechanical Heart Valve	11
2.2.1 Hinge Design	13
2.2.2 Flow Characterization	16
2.2.3 Hemodynamics of Blood Flow	21
2.3 Thrombosis criteria	22
2.3.1 Velocity	23
2.3.2 Pressure drop	26
2.3.3 Streamline	28
2.3.4 Wall shear stress (WSS)	32
2.4 Methods for reduction of thrombosis	34
2.4.1 Application of vortex generators	35
2.4.2 Vortex generator in Mechanical Heart Valve	41
2.5 Summary	45
3. METHODOLOGY	47
3.1 Overview	47

3.2	3D Modelling	47
3.2.1	Axisymmetric aorta with SJM valve	49
3.2.2	Vortex Generator	49
3.2.3	Anatomic aorta with SJM valve	51
3.3	CFD simulation process in axisymmetric aorta and anatomic aorta	52
3.3.1	Governing Equation	52
3.3.2	Blood properties and Boundary Condition	55
3.3.3	Meshing	58
3.3.4	Mesh sensitivity study	59
3.3.4.1	Axisymmetric aorta with non-VG and VGs with different height	60
3.3.4.2	Anatomic aorta with non-VG and VG	62
3.3.5	Solution Method	64
3.4	Summary	65
4.	RESULTS AND DISCUSSION	66
4.1	Overview	66
4.2	Validation of axisymmetric aorta	66
4.3	Selection of VGs	68
4.3.1	Type of VGs	69
4.3.2	Height of VGs	71
4.4	Effect of VGs on turbulent model and pulsatile with VG's installation	73
4.4.1	Velocity	73
4.4.2	Wall Shear Stress	85
4.5	Effect of anatomic aorta on VG's installation	87
4.5.1	Velocity	87
4.5.2	Wall shear stress	93
4.6	Summary	94
5.	CONCLUSION AND RECOMMENDATION	98
5.1	Overview	98
5.2	Conclusions	98
5.3	Recommendation for Future Work	100
	REFERENCES	102
	APPENDICES	112

LIST OF TABLES

TABLE	TITLE	PAGE
2.1	Application of Vortex Generator	37
3.1	The Triangular VGs Configurations	50
3.2	Mesh Sensitivity Error of Axisymmetric Aorta without VG	61
3.3	Mesh Sensitivity Error of Anatomic Aorta without Triangular VGs	63
3.4	Mesh Sensitivity Error of Anatomic Aorta with Triangular VGs	64
4.1	Data for Pressure Drop for Different Type of VG	70
4.2	Data of Pressure Drop with Different Triangular VGs Height	72
4.3	Simulation Run Summary of Axisymmetric Model for No VGs and Triangular VGs (Velocity Magnitude)	82
4.4	Simulation Run Summary of Aorta Model for No VGs and Triangular VGs (Velocity Vector)	84
4.5	Simulation Run Summary of Axisymmetric Model for No VGs and Triangular VGs (WSS)	86
4.6	Simulation Run Summary of Axisymmetric and Aorta Model	95

LIST OF FIGURES

FIGURE	TITLE	PAGE
2.1	Major Development of Prosthetic Heart Valve (Dasi et al.,2009)	11
2.2	SJM Valve showing (a) Geometry of the SJM Valve, (b) The Forward Flow Characteristic (Yun et al., 2014)	12
2.3	Schematics of SJM Valve (a) The SJM Valve for Forwarding Flow and Leakage Flow and (b) Diagram of Leaflet Ear at the Hinge Recess Housing (Yun et al., 2012)	15
2.4	Fields of Convolution in Four-Hinge Design (Dasi et al., 2009)	16
2.5	The Comparison of 2D Vorticity Magnitude between Simulation and Experiment of BMHV Flow: (a) Opening, Computational; (b) Opening, Experimental; (c) Acceleration, Computational; (d) Acceleration, Experimental; (e) Peak, Computational; (f) Peak, Experimental (Yun et al., 2014a)	18
2.6	Loading State of Aorta Tissue in Aorta Wall (Martufi et al., 2016)	20
2.7	BMHV Schematic during Phase of Leakage Flow (Dasi et al., 2009)	22
2.8	Downstream Flow Fields of BMHV Designs during the Forward Phase (left) and the Leakage Flow Phase (right) (Dasi et al., 2009)	23

2.9	Phase-Averaged Velocity Vectors and Vorticity Contours for the Different VG Arrangement Valves at Four Distinct Phases of the Cardiac Cycle (Hotoum et al., 2018)	25
2.10	The Illustration of Blood Flow through without and with VG (Murphy, 2009)	26
2.11	Pressure Drop between Inlet and Outlet at Various Degrees of Dysfunction (King et al., 1994)	27
2.12	Streamlines and the Movement of Leaflets in a Cycle (Li et al., 2020)	29
2.13	Velocity Time in Center of Model (Li et al., 2020)	31
2.14	Streamline Distribution after Valve Closing (Li et., 2020)	32
2.15	Types of VG Geometric (Shim et al., 2015)	41
2.16	Vorticity Contour at the Moment of Valve Closure: (a-c) No VG, (d-f) Rectangular VG and (d-i) Hemispherical VG (Dasi et al., 2008)	42
2.17	Schematic of VG Arrangement: (a) Co-Rotating, (b) 8 Equally Spaced Counter-Rotating VG, (c) 4 Far Spaced Counter-Rotating VGs and (d) 4 Closely Space Counter-Rotating VGs (Hotoum and Dasi, 2019b)	43
2.18	RMS of Variation in Velocity (V'_x and V'_y) at Peak Systole for Particular Valve Cases (Hotoum and Dasi, 2019b)	44
3.1	The Flowchart of Methodology	48
3.2	Computational Model of Axisymmetric Aorta with SJM valve	49

3.3	Leaflet of SJM Model with Triangular VGs	50
3.4	3D Aorta CT Scan Images (Basri et al., 2020)	51
3.5	Anatomic Aorta with SJM valve	52
3.6	Pulsatile Flow through SJM valve	57
3.7	The Meshing Configuration of SJM valve in Axisymmetric Aorta	58
3.8	The Meshing Configuration of SJM valve in Anatomic Aorta	59
3.9	Grid Dependency Test for Axisymmetric Aorta without VG	60
3.10	Grid Independent Test of Triangular VGs at Different Height	61
3.11	Grid Dependency Test for Anatomic Aorta without VG	62
3.12	Grid Dependency Test for Anatomic Aorta with Triangular VGs	63
4.1	Geometry of Axisymmetric Aorta for Three Different Location (F1-F3) at SJM valve	67
4.2	Velocity Profile Comparison between Previous Study and CFD Method for (a) $x = 0$ (b) $x = 0.3R$ mm (c) $x = 0.6R$ mm Plane Position	68
4.3	V_z Comparison between Different VG Types	69
4.4	Point of Inlet and Outlet Pressure	70
4.5	V_z Profile at Horizontal Centerline ($y = 0$) between Leaflets	71
4.6	Velocity magnitude of S-A method at the central plane of leaflet for (a) axisymmetric aorta without VG, AF (b) axisymmetric aorta with VG, AF (c) axisymmetric aorta	74

	without VG, PF (d) axisymmetric aorta with VG, PF (e) axisymmetric aorta without VG, DF (f) axisymmetric aorta with VG, DF	
4.7	Velocity magnitude of $k - \epsilon$ method at the central of leaflet for (a) axisymmetric aorta without VG, AF (b) axisymmetric aorta with VG, AF (c) axisymmetric aorta without VG, PF (d) axisymmetric aorta with VG, PF (e) axisymmetric aorta without VG, DF (f) axisymmetric aorta with VG, DF	75
4.8	Velocity magnitude of LES method at the central of leaflet for (a) axisymmetric aorta without VG, AF (b) axisymmetric aorta with VG, AF (c) axisymmetric aorta without VG, PF (d) axisymmetric aorta with VG, PF (e) axisymmetric aorta without VG, DF (f) axisymmetric aorta with VG, DF	76
4.9	Velocity vector of S-A method at the central of leaflet for (a) axisymmetric aorta without VG, AF (b) axisymmetric aorta with VG, AF (c) axisymmetric aorta without VG, PF (d) axisymmetric aorta with VG, PF (e) axisymmetric aorta without VG, DF (f) axisymmetric aorta with VG, DF	77
4.10	Velocity vector of $k - \epsilon$ method at the central of leaflet for (a) axisymmetric aorta without VG, AF (b) axisymmetric aorta with VG, AF (c) axisymmetric aorta without VG, PF (d) axisymmetric aorta with VG, PF (e) axisymmetric aorta without VG, DF (f) axisymmetric aorta with VG, DF	78
4.11	Velocity vector of LES method at the central of leaflet for (a) axisymmetric aorta without VG, AF (b) axisymmetric aorta with VG, AF (c) axisymmetric aorta without VG, PF (d) axisymmetric aorta with VG, PF (e) axisymmetric aorta without VG, DF (f) axisymmetric aorta with VG, DF	79

4.12	Velocity magnitude of LES method at the central of leaflet for (a) No VGs, AF (b) Triangular VGs, AF (c) No VGs, PF (d) Triangular VGs, PF (e) No VGs, DF (f) Triangular VGs, DF	88
4.13	Velocity streamline of LES method at the central of leaflet for (a) No VGs, AF (b) Triangular VGs, AF (c) No VGs, PF (d) Triangular VGs, PF (e) No VGs, DF (f) Triangular VGs, DF	89
4.14	Velocity Contour of LES Model at PF Phase (a) No VG (b) Triangular VGs	90
4.15	Streamline Velocity of LES Model (a) 2D Streamline No VG (b) 2D Streamline VGs (c) 3D Streamline No VGs (d) 3D Streamline VGs	91
4.16	V_z Profile at the Horizontal Centerline between the Leaflets during PF Phase	92
4.17	The Velocity Profile (V_x) at Vertical Line at Tip of Leaflet	93
4.18	WSS of LES Method for Anatomic Aorta (a) No VGs (b) Triangular VGs	94

LIST OF APPENDICES

APPENDICES	TITLE	PAGE
A	Parabolic Velocity Profile in UDF for Laminar Flow	112
	Pulsatile Velocity Profile in UDF for Turbulence Model	

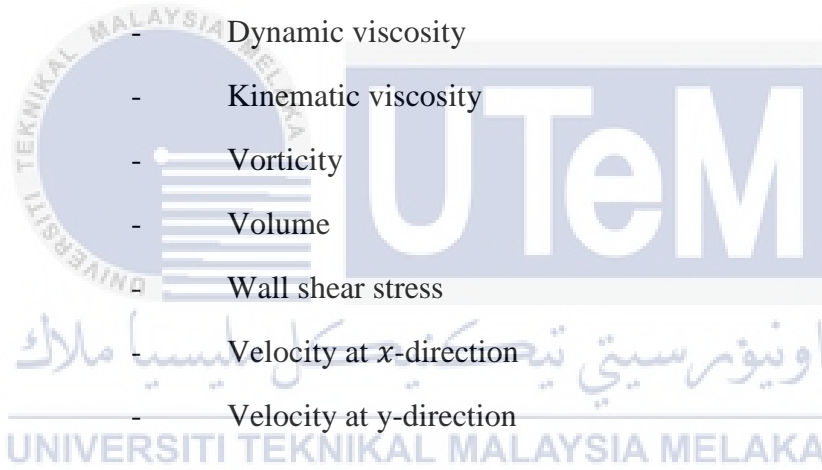


LIST OF ABBREVIATIONS

AF	-	Accelerating Flow
BDI	-	Blood Damage Index
BHV	-	Bioprosthetic Heart Valve
BMHV	-	Bileaflet Mechanical Heart Valve
CFD	-	Computational Fluid Dynamics
CT	-	Computed Tomography
DF	-	Decelerating Flow
IJN	-	Institut Jantung Negara (National Health Institute)
LES	-	Large Eddy Simulation
MHV	-	Mechanical Heart Valve
MRI	-	Magnetic Resonance Imaging
PF	-	Peak Flow
PIV	-	Particle Image Velocimetry
RBC	-	Red Blood Cell
RSS	-	Reynold Shear Stress
SA	-	Spalart Allmars
SJM	-	St. Jude Medical
WSS	-	Wall Shear Stress
PIV	-	Particle Image Velocimetry
SA	-	Spalart Almaras
SJM	-	St Jude Medical
WSS	-	Wall Shear Stress

LIST OF SYMBOLS

Re	-	Reynolds number
t	-	Time
v	-	Velocity
P	-	Pressure
D, d	-	Diameter
L_w	-	Recirculation length
ρ	-	Density
μ	-	Dynamic viscosity
ν	-	Kinematic viscosity
ω	-	Vorticity
V	-	Volume
τ_w	-	Wall shear stress
V_x	-	Velocity at x -direction
V_y	-	Velocity at y -direction
V_z	-	Velocity at z -direction



LIST OF PUBLICATIONS

1. Salleh, N.M., Zakaria, M.S. and Abd Latif, M.J., 2019. The vortex shedding for an inclined flat plate of thrombosis using CFD simulation. *Proceedings of Mechanical Engineering Research Day 2019*, pp. 152-154, August 2019.
2. Salleh, N.M., Zakaria, M.S. and Abd Latif, M.J., 2020. Reducing of Thrombosis in Mechanical Heart Valve through the Computational Method: A Review, *Journal of Advanced Research in Fluid Mechanics, and Thermal Sciences*, 2(2), pp. 178–200.
3. Salleh, N.M., Zakaria, M.S. and Abd Latif, M.J., 2020. The effect of vortex generator on bileaflet mechanical heart valve in anatomic aorta. *Proceedings of The International Conference of Science, Technology and Intedisciplinary Research*, 2020.
4. Salleh, N.M., Zakaria, M.S. and Abd Latif, M.J., 2020. CFD Simulation for Reduction Thrombosis in Bileaflet Mechanical Heart Valve using Vortex Generators, *Journal of Engineering Science and Technology*, 16(3), pp. 2736–2747.
5. Salleh, N.M., Zakaria, M.S. and Abd Latif, M.J., 2021. A Computational Study of a Passive Flow Device in a Mechanical Heart Valve for the Anatomic Aorta, *CFD Letters*, 13(4), pp. 69–79.

CHAPTER 1

INTRODUCTION

1.1 Background

Cardiovascular heart disease has remained the principal cause of death since the early 1980s and recorded 15% of total deaths in 2019 (Yun et al., 2014a). The heart valve's structure keeps blood flowing only in one direction through the heart. This structure or function is adversely affected by cardiovascular diseases. Stroke, chest pain, or even death due to heart attack is the consequence for people with heart valve disease. Severely damaged heart valve requires total replacement by either bio-prosthetic heart valve (BHV) or mechanical heart valves (MHV). This surgery involves patients that happen to have damaged heart valves due to some diseases, infections or accidents. In Malaysia, the main cause of heart valve diseases is due to infection coming from rheumatic fever, particularly in less develop region in country (Khoo et al., 2020). Replacement of heart valves is a common clinical procedure that accounts for 25% of all cardiac procedures (De Tullio et al., 2011).

The BHV is made from animal tissue and can get calcified over time. It requires another valve replacement for the next 10-15 years which is only suitable for young people. MHV on the other hand is made from the material which is extremely durable due to its pyrolytic carbon composition. It is the most preferable prosthetic heart valve among the patients as it is last long and only need to undergo replacement surgery once in a lifetime.

Unlike BHV, however, the MHV is highly thrombogenic (tend to generate blood clotting), necessitating anticoagulation medication to prevent life-threatening hemorrhage (Borazjani et al, 2010). Furthermore, thrombosis in MHV patients can harm the brain, resulting in a stroke or other organ failure. Non-physiological flow such as stagnation, high pressure drops, high wall shear stress (WSS); larger recirculation, and vortex dynamic could increase the risk of thromboembolism, which can lead to heart valve malfunction (Sun et al., 2009). The blood thinner usually warfarin can prevent from thrombosis of the MHV's patient, but the problem is when the patients are injured or require surgery, the blood thinner may encounter excessive bleeding during operation (Shoeb and Fang, 2013). This problem will put the patient at risk.

The risk of blood clotting can be minimized by adding a vortex generator (VG) to the MHV leaflet that can reduce pressure gradient and provide lower wall shear stress while controlling the flow separation. The function of VG is also to passively control the flow which improve the performance by reducing shear stresses through velocity magnitude and recirculation that are imposed to the blood cells during regurgitation (Yoganathan et al., 2005). The application of VGs are common in the aerospace industry in which the flow separation was controlled in order to provide better lift and drag force.

Computational fluid dynamics (CFD) have been proven as a powerful tool to tackle complex biomedical engineering challenges by visualizing blood flow characteristics (Yoganathan et al., 2005). As a result, CFD that uses mathematical equations and computing algorithm technology can be utilized to simulate and examine the blood flow behaviour through a MHV. The main contributor in this research area includes Yoganathan, et al. (2005), Yun et al. (2014a), Hotum and Dasi (2019b), among others. Beside that, the experimental work in this area is limited and expensive. CFD simulation provided the

visualization to the level of disease such as blood clotting in detail (Zakaria et al., 2018). Although the rich dynamic complex flow structure in pulsation and highly turbulent flow could capture the visualization of the blood flow characteristics in the heart valve using CFD (Zakaria et al., 2018), the debate over whether CFD data will enable insight to the specific level of disease will continue to rage in the literature (Zakaria, 2018; Yun et al., 2014a). Therefore, the information of CFD method in accessing the level of blood clotting still needs further research in medical field.

The installation of VGs on the surface leaflet to overcome blood clotting in MHV is a novel idea. It requires extensive numerical study, experimental testing, and also clinical trials to be conducted. To date, no numerical study has been done employed triangular shape VGs with turbulence and anatomic aorta mimicking real physiological of the human body. Therefore, this research aims to investigate the potential of reducing thrombosis by using VGs on the leaflet of MHV using CFD method.

1.2 Problem Statement

Artificial heart valves tend to disturb the flow and generate a turbulent flow. The turbulent stress of non-physiological flow is harm to the red blood cell (RBC) and platelets. This will lead to the occurrence of blood clotting. Given the potential for blood clotting complications, MHV recipients must take anticoagulant medication. Despite strong anticoagulation treatment, blood clotting is the most common complication linked with MHVs up to 5.7 % per patient per year.

The presence of VGs reduces thrombosis potential by removing the inflection point indicating the direction of the boundary layer separation. Beside that, the pressure drop at the peak systole is higher when VGs are not installed compared to the absence of the VGs. In order to reduce the pressure drop of the blood flow, VGs need to be attached to the valve's