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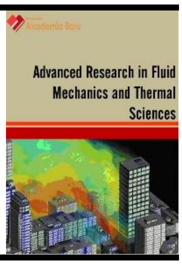

Reducing of Thrombosis in Mechanical Heart Valve through the Computational Method: A Review

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ABSTRACT

Thrombosis is formation of a blood clot, known as a thrombus within a blood vessel. This review paper discussed thrombosis which associated with the malfunction of the heart valve based on computational method to investigate the causes of blood clotting. The non-physiological flow is the causes of trapped platelet and the formation of blood clotting in the mechanical heart valve (MHV). Besides that, it is found that the hinge design, leaflet material and flow control can reduce blood clot formation. Furthermore, a specific method to reduce thrombosis through vortex generator design on the leaflet is also discussed. Finally, the review paper provides an important critical assessment regarding the method to reduce thrombosis in mechanical heart valve for engineers, mathematician, medical doctor and scientist.

1. Introduction

Since the last few decades, the issues of malfunction heart valve (MHV) with the replacement of either bioprosthetic or MHV have been of subject intense debated [1]. The nature of the MHV material that has outstanding durability which made from pyrolytic-carbon [2], but strongly thrombogenic which the patient will have to take anti-coagulation that leads to life-threatening hemorrhage. The risk of thromboembolism is partly due to non-physiological hemodynamics parameters such as turbulence, shear stress and flow separation which can cause trapped platelet and also through blood-material reactivity [3]. This complex flow through the valve indicates to blood damage which connected to thrombosis related outcomes [4]. Furthermore, shorter valves and distant fluid dynamic conditions may increase the blood damage profile that one of the important complications in prostheses designed for pediatric applications [5].

Computational fluid dynamics (CFD) is a benefit tool in the evolution of such heart valve prostheses [6]. In this regard, CFD can be used to create and analyses the behavior of the blood flow

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through MHV [7]. Computational studies can access to damage potential up to point particle tracking in prostheses flows [8]. Furthermore, the risk of thrombosis can be optimized to reduce energy loss by showing velocity vectors and pressure profiles [9]. Therefore, this review paper discussed the thrombosis in MHVs based on computational perspectives.

The section of this paper is organized as follows: Sect. 2 starts with a brief about MHVs flow physics that contribute to thrombosis. Besides that, Sect. 3 determine the criteria of thrombosis in MHVs. Then, Sect. 4 discusses on the method to reduce the risk of thrombosis with vortex generator of the MHVs that can control the blood clotting. Finally, the conclusion of this paper along with recommendation are summarized in Sect. 5 and Sect. 6, respectively.

2. Mechanical Heart Valve Implantation and Configuration

The prosthetic heart valve is commonly used to replace damaged heart valve [10]. Figure 1 shows the major development of prosthetic heart valves since the 1962s, concentrate on the most commonly used heart valves and the valves that have made beneficial contributions to heart valve replacement. The first heart valve introduces in 1962 which is Starr–Edwards (SE) caged-ball valve. The design of the valve includes a ball within a metal cage and the ball obstructs the valve orifice which prevents the backflow of blood. The high blood pressure pushes the ball downstream when blood forward flows thus the orifice opens whereas the metal cage holding the ball distal to the orifice. The SE valve has through the massive modification since 1960 that raise the performance of the valve which the development focused on construction techniques and materials.

In 1977s, St Jude Medical (SJM) Inc. (Minneapolis, MN, USA) introducing the bileaflet mechanical heart valve (BMHV). The valve consists of two semi-circular occluders called leaflets. The leaflet ear is an extension region of the leaflet which pivots about a recessed hinge [11]. The heart valve consists of two semi-circular lateral orifices and the blood flow through central rectangular orifice when the leaflet opens. The leakage will happen when the leaflet fully closed. The hinge region will occur during the leakage during blood flow. Figure 2 shows the SJM 23 mm Regent valve for forwarding flow phase. During the evolution of the SJM valve, the heart valve features which are a length to diameter already invented close to the native heart valve. The design of the heart valve using smoothed pivots that can allow the leaflet open at an angle of 90° and a two-point landing mechanism during valve closure. The BMHV is most demand MHV which is approximately 80% of a patient implanted with MHV [11]. The anticoagulant complications, embolism, endocarditis, structural failure and thrombosis is the effect of using MHV.

In 2002, the implantation of transcatheter valve replacement by Cribier-Edwards is using the balloon-expandable valve which consist equine pericardium and stainless-steel frame are the first transcatheter aortic prosthesis. In order to enhance sealing a polyethylene terephthalate fabric skirt are introduced which represents the first Edwards SAPIEN model in 2006 [12]. Then, the SAPIEN XT are introduced in 2009 by using lower-profile tubular cobalt-chromium stent that increase the function of the transfemoral approach. The SAPIEN 3 is the last evolution of the SAPIEN valve which an additional outer skirt is added to increase sealing and expandable 14/16 F sheet are design to reduce femoral invasiveness [13]. Then, the Medtronic Corevalve was represented in 2005 with the prototype of self-expandable valves. The valve consists of pericardial leaflets which mounted on a nitinol frame. The previous material of leaflet is made by bovine pericardium but change to porcine pericardium which allows the development of lower profile device. The developments made the device resheathable, repositionable, recapturable and the height with diameter of the delivery system was reduced [13]. After that, the Caisson was introduced in 2016 that used to treat mitral regurgitation in native valves [14]. To conclude that, the majority of heart valve design has most prone to blood clotting during replacement which is Chitra valve (1.6$\pm$0.5 % patient-years) incidence and Medtronic-hall valve (1.1$\pm$0.3 % patient-years) incidence [15].

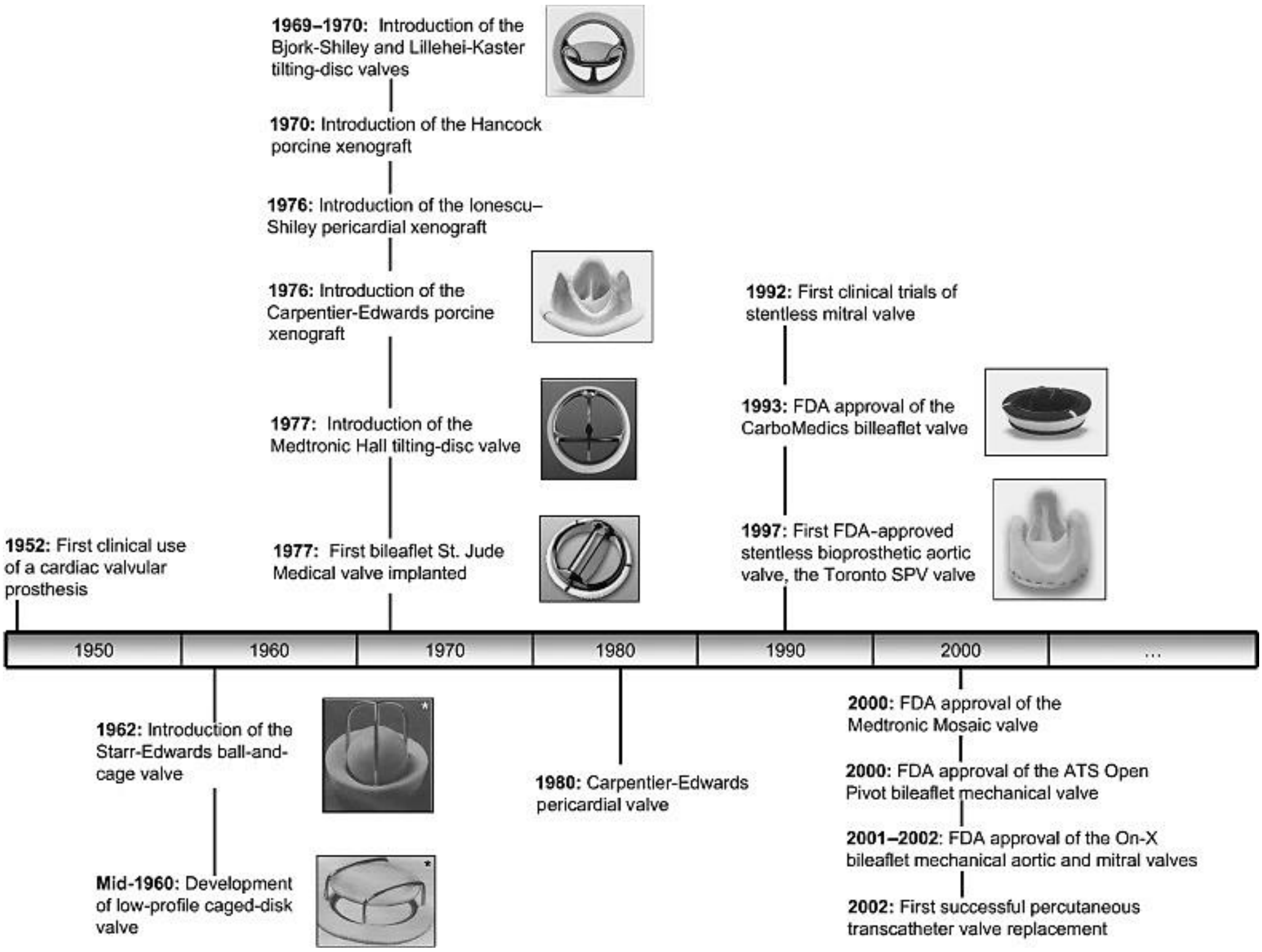


Fig. 1. Major development of prosthetic heart valves [11]

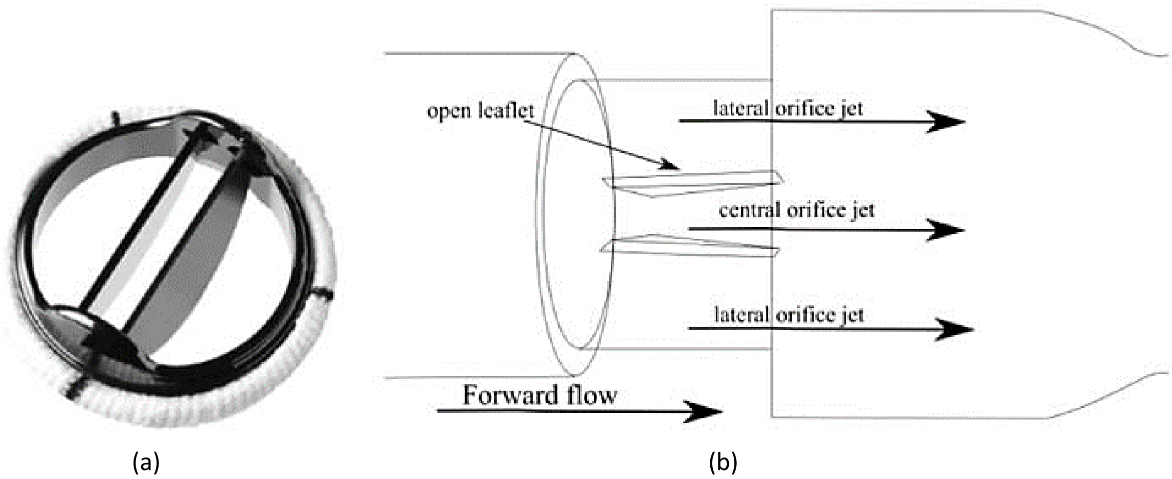


Fig. 2. SJM valve showing (a) Geometry of the SJM valve, (b) The forward flow characteristic [12]

2.1 Leaflet Material

The development of a prosthetic heart valve has been years to fit suitable materials which are blood compatible and biocompatible. Basically, The material of MHV are made from synthetic origin such as metals, ceramics and polymers [15]. The structural factor is one of the heart valve properties that need to focus when chose a related material because it will cause fatigue and wear resistance where not just depend on heart valve configuration. The first caged ball valve is the SE valve which using silicon rubber ball as a leaflet material. The most problem material is silicon rubber because it can incursion of body fluids especially liquids resulting in cracking and swelling of the balls [15]. The problem of modification on silicon rubber was later solved by the previous study to increase the post-curing characteristic [13,14]. For the Bjork–Shiley tilting disc valve, the material for the valve design is polyacetal (Delrin) disc. Delrin is produced by polymerization of formaldehyde. However, delrin material are devours moisture during steam sterilization which causes an obstacle to the proper functioning of the valve [15]. Then, the failure of polymeric occulders tends to development of LTI carbon (pyrolytic carbon) that use as the most preferred biomaterial for leaflet. The benefits of LTI carbon is good wear resistance that can improve hemodynamic as well as fatigue resistance. However, the LTI carbon is constitutionally brittle and easily crack when subject to delayed fracture failure mode due to high stress concentrations.

2.2 Hinge Design

Since its debut in1978s, the BMHVs has geometrical improvements but still can cause a serious complication such as thromboembolic events, platelet activation and hemolysis [16]. The non-physiological shear stress levels are one of the major complication which imposed on complex flows of blood elements through BMHVs in particular hinge region. The hinge region of BHMVs has been shown by previous studies which lead to shear stress above an acceptable threshold limit of blood damage [4,16,17]. The hinge region has intricate geometry in which the blood will flow extremely complex and unsteady. The clot formation will develop when the hinge region has low flow and recirculating flow. The lateral corners of BMHV hinges have a strong forward flow which moving correlation to the forward flow. The formation of blood clotting is due to the strong flow jet that effectively fails blood elements which restrain blood cell build up in the hinge region [18,19]. Besides that, the hinge region has leakage during mid-diastole between close leaflet and valve including the central b-datum plane. The hinge region also produces the formation of strong leakage jets which can be induced at large cross-valvular pressure gradients (see Figure 3(a)). The design of hinge incorporated at the leakage jet to reduce the propensity for clot formation, dislodge possible blood and prevent flow stasis. The large shear stress necessitates with jet which known to cause hemolysis and initiate the coagulation cascade [20]. The recirculating flow region is present in the hinge during mid-diastole leakage flow which develops to large shear stresses and formation of blood clotting. Figure 3(b) shows the larger hinge gap width between the leaflet ear and hinge recess could result in the failure of blood elements from the hinge region, thus reducing blood clot complications [21]. Simon *et al.,* investigated the hinge flow dynamics under aortic pulsatile conditions and found that the hinge geometry is a main parameter in influencing platelet activation, hemolysis and thrombus formation. The high fluid velocity and shear stress in the hinge region was characterized by the leakage mid-diastole phase. Otherwise, the cause of thromboembolic complications is during recirculation flow at the hinge region which leads to longer residence times than at leakage jets at another region of the valve during mid-diastole [21]. Otherwise, the existence of recirculation regions during the forward flow phase has been characterized through hinge flow fields. The recirculation flow is the primary location where the blood begins to clots.

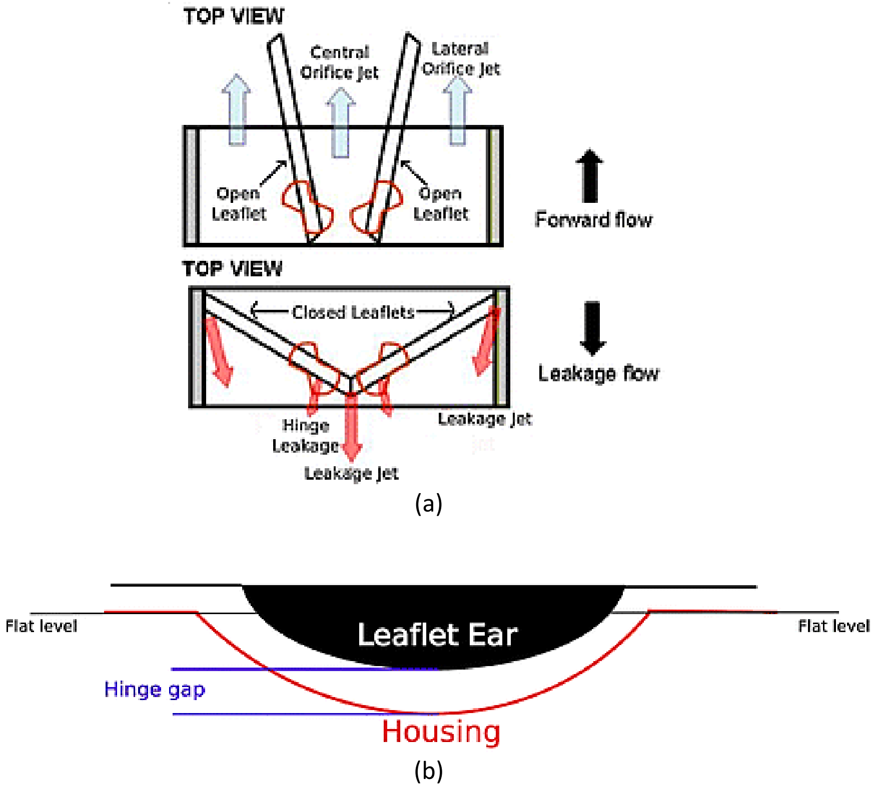


Fig. 3. Schematics of SJM valve (a) The SJM valve for forwarding flow and leakage flow and (b) Diagram of leaflet ear at the hinge recess housing [21]

Figure 4 shows that the qualitative of the flow phases within the hinge designs such as BMHV, SJM, CarboMedics, Medtronic parallel and Medtronis Advantage based on publish article [11,16,20,21].

The four hinge design, the Medtronic Parallel was ended due to inspection of the uncompromising clot formation within hinge region during the clinical investigations. The presence of recirculation region during the forward flow phase are characterized by all the hinge flow fields [22]. The recirculation region is the basic location where blood clot starting to form by increasing cell to cell contact time [23]. Then, it is crucial to note that the hinge design shows important role in formation of thrombosis. Besides that, the hinge region of the Medtronic Parallel during closed phase was potential for blood clots formation when at highly convoluted flow although more streamlined flow is present in the other hinges [24].

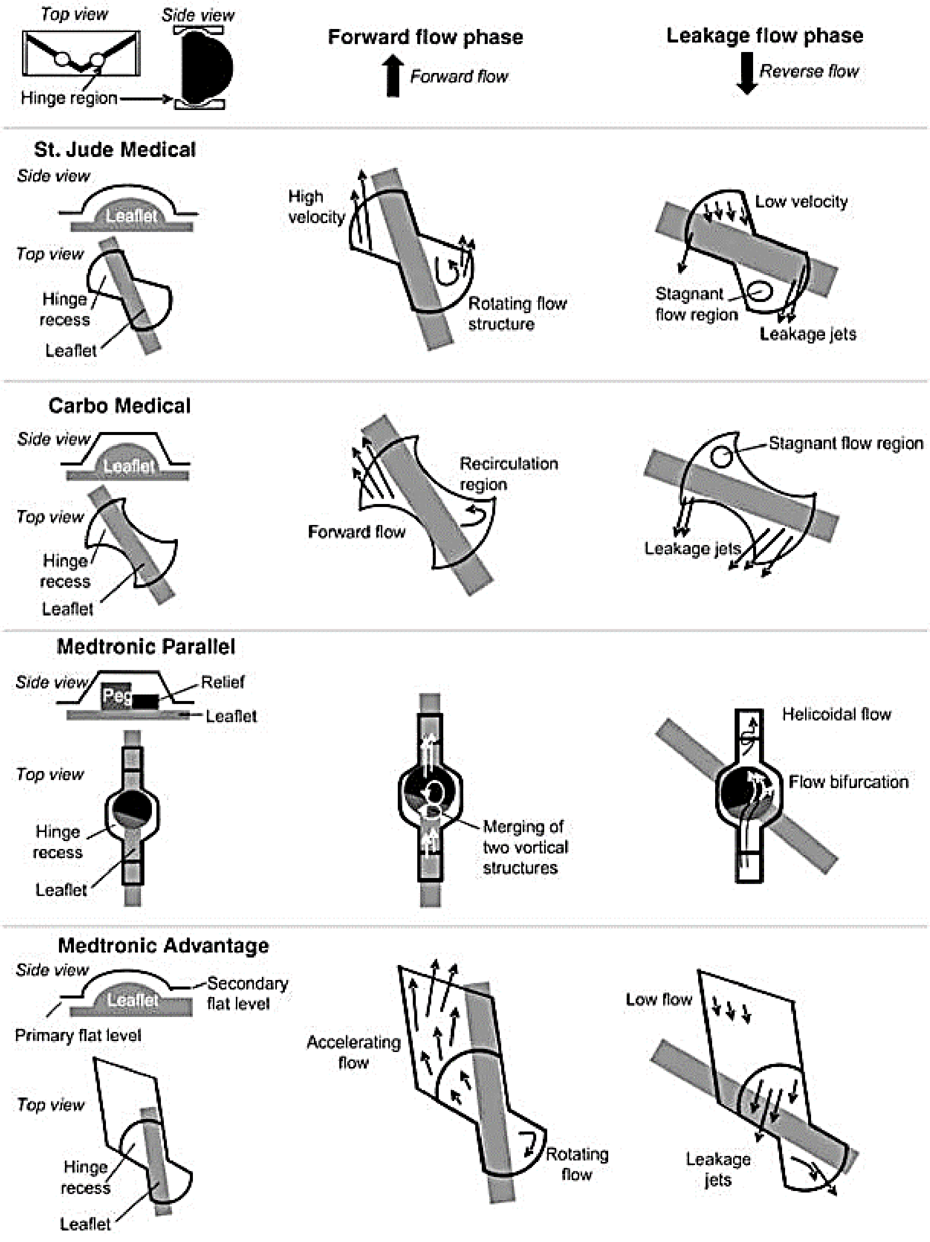


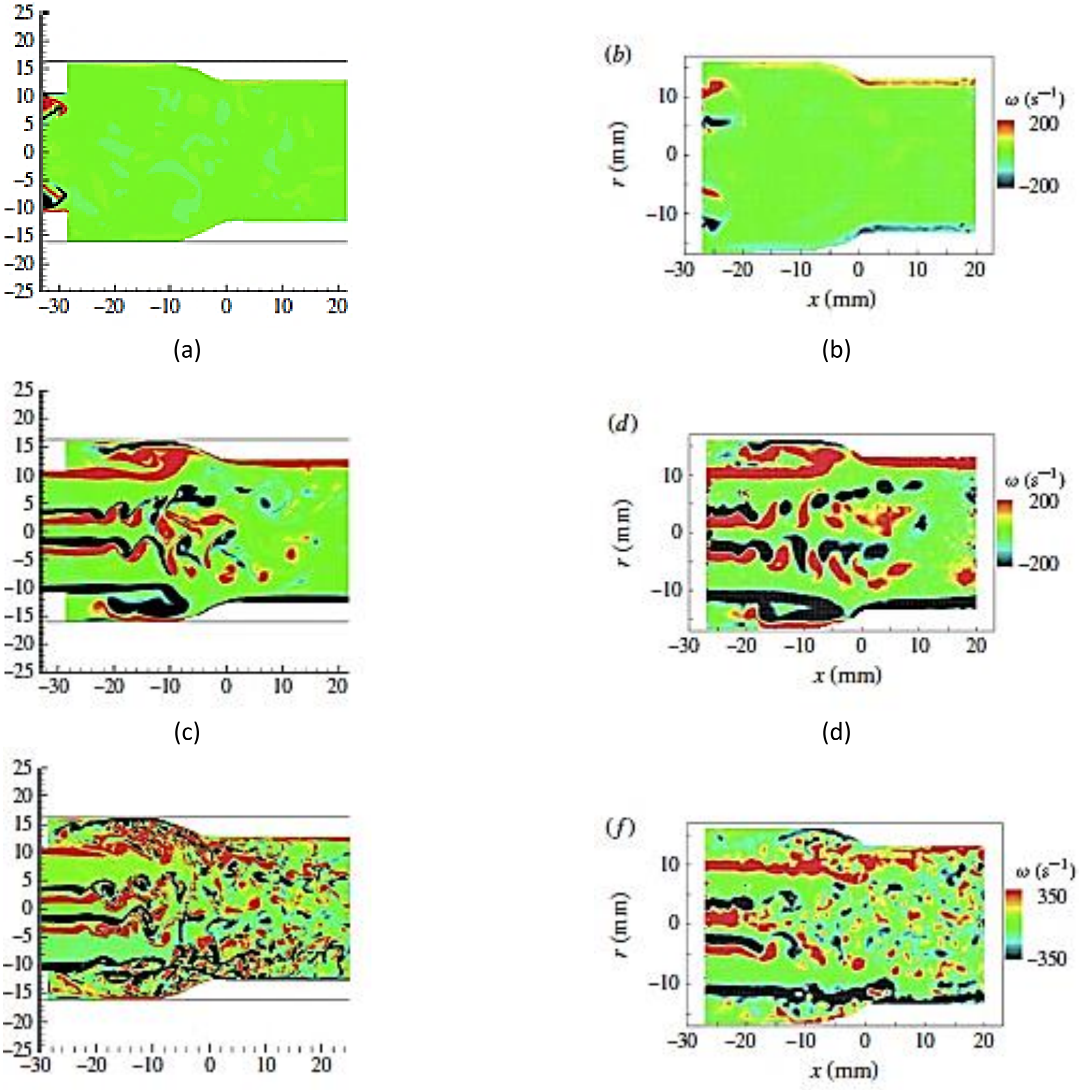
Fig. 4. The convolution flow fields in four hinge designs [11]

2.3 Flow Characterization

The investigation of blood flow characteristics such as vortex formation, velocity, turbulent stresses and wall shear stress are important to recognize potential blood cell damage [25]. The pressure drop over the valve and energy loss is related to velocity. The study of Sievers *et al.,* examines the flow velocity decrease when inflow diameters increasing. This could cause a positive effect on blood clotting generation [26].

Besides that, higher velocities at the central and lateral orifices were accompanied by a higher level of velocity gradient in the vicinity of leaflet surfaces [27]. The higher viscous shear stresses will increase the velocity gradient as it is directly related to viscous shear stresses. Otherwise, the angular velocity of the leaflets decreases linearly with time when the leaflet at a fully open position [2]. Figure 5 shows that the vorticity magnitude comparison between simulation and experiments for BMHV flow at opening, acceleration and peak flow phases [28]. Figure 5(a) shows the shear layer from the flow of separation at the edge of the valve housing to the sudden sinus expansion region and Figure 5(b) has the flow of at the tip of the leaflet for opening phase with Reynold Number (*Re*) is 240.

The geometry of the valve affects the vorticity flow through the sinus expansion region. Then, Figure 5(c), (d) shows the (Re = 2070) at the accelerating phase when the leaflet is fully open and increasing when flow rate past the valve. The recirculation vortices can be seen at the sinus expansion region which it happens two coherent von Karman vortex wakes at the flow past of leaflet tips [28]. Figure 5(e), (f) shows the peak flow (Re = 5780) for recirculation vortices and vortex shedding wakes due to a higher Reynold number that makes the flow unstable. The coherent structures indicate the vortices completely break apart into small scale at downstream which eventually wiped out due to viscous dissipation [29].



(a) (b)

(c) (d)

(e) (f)

Fig. 5. The comparison of 2D vorticity magnitude between the simulation and experiment of BMHV flow: (a) opening, computational; (b) opening, experimental; (c) acceleration, computational; (d) acceleration, experimental; (e) peak, computational; (f) peak, experimental [28]

The development of red blood cell damage and platelet activation because of high levels of shear stresses created at the near wake of the valve and the small-scale turbulence downstream whereas both of them depend on the flow separation at the leaflets [30]. In aeronautical applications (dynamic stall), the flow separation is utterly steady or moving bodies. The low-pressure transient is created when the valve at the closing phase which indicates to platelet activation [31]. Furthermore, the vortex shedding form at the trailing edge of the leaflet which refers to a mechanism for free emboli formation [32,33]. The most risk area is a fixed leaflet that can combine blood cells which elevated the level of shear stress and different material that indicates sublethal damage.

The blood elements with finite volume at wall shear stress (WSS) is simulate to accomplish a platelet suspended in simple shear flow while tracking maximum surface shear stress [34]. The low WSS and highly oscillatory patterns of WSS can cause intimal wall thickening that can be studied by in vitro and in vivo [34]. The blood stagnation can develop low WSS when residence time increase of blood particles. The area that disordered endothelial cells may lead highly oscillatory WSS that will establish gaps and allow penetration of atherogenic particles in the intimal layer of the aorta [35]. Figure 6 shows that the mechanical loading state of aortic tissue in the aortic wall [36].

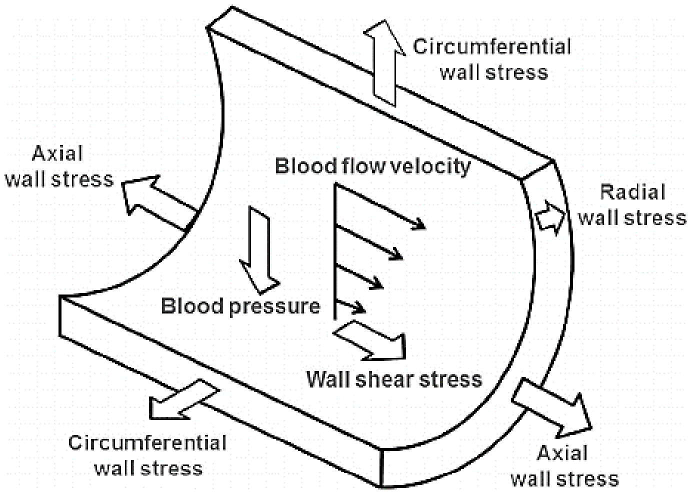


Fig. 6. The loading state of aorta tissue in the aorta wall [36]

The mechanosensitive processes indicate the non-physiological flow patterns and shear stress that interfere with wall weakening also wall remodeling whereas the rupture or dissection will occur when mechanical stresses in the wall surpass the strength of the wall tissue. The effect on endothelial cell synthetic happens at higher shear stress which the leaflet produces profound and preventing blood clotting [37]. The higher shear stress indicates to higher the capability of red cells and platelets damage in a blood vessel [38]. The main activator is blood damage which leads to blood clotting formation and leads to flow stagnation.

2.4 Hemodynamic of the Blood Flow

Hemodynamics is the study of blood flow, blood pressure and the physical properties of the blood which help to better understanding of flow characteristics of blood [39]. The pressure gradient also illustrates as the transvalvular pressure gradient (DP) which is the main important of the hemodynamics parameter because of the resistance of the valve t orifice area against the bloodstream when blood flows through the valve [40]. Avrahami *et al.,* examined the tilting-disk mechanical heart valves cavitation during valve closure. The vortices observe at the center has a higher pressure drop. The pressure changes in the closing phase during the valve movement would drive the blood pressure below vapor pressure. The pressure drop on the upper side of the valve surpasses of the lower tip which the upper tip is chosen location for cavitation inception [41]. The closing speed of the leaflet for the hemodynamic at closure time is very dependent where any development in the closing speed could dramatically change the pressure drops [42]. The formation and collapse of cavitation bubbles due to local disturbance and blood damage. Besides that, the cavitation is a rapid formation of vapor filled bubbles that cause by the transient reduction in local pressure under the vapor pressure of blood. The implosion of bubbles occurs due to damage of blood cell in the vicinity along with activating platelets [13,38]. The study for a variety of mechanical heart valves has been revealed by the University of Iowa, the USA which relates to the kind of material used for disc fabrication and capacity of the valve to produce cavitation damages on the development of blood elements [43].

The complication of thrombosis due to non-physiological flow patterns in the vicinity of heart valves. Figure 7 shows the mechanical heart valve in the aortic position throughout the leakage flow phase. The leakage flow leading to rupture or activation of platelet which one of the first steps towards the inception of the coagulation response [44].

The area of high velocity gradient is promptly distal to the valve leaflets has high turbulent shear stresses [45]. The further downstream of the valve during movement it will make the flow become more disturbance. The centreline plane at peak systole produces high turbulent shear stresses along with 1500 dyn/cm^2 downstream of the valve [46]. The BMHV model provide the leakage flow especially through the b-datum gap (the line of two leaflets touch each other) and periphery gap which mostly occur at the hinge region.

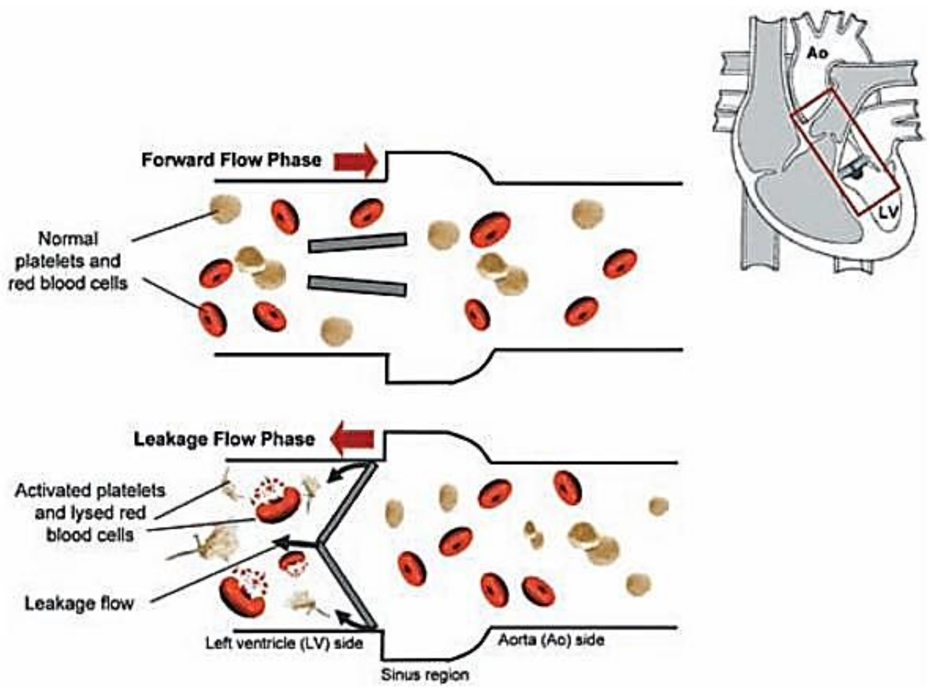


Fig. 7. The BMHV schematic throughout the leakage flow phase [44]

3. Thrombosis Criteria

Thrombosis associated with localized clotting of the blood that can occur in the arterial or the venous. There are several methods to quantified the level of thrombosis such as hemolysis index, blood damage index, power-law and Q criterion.

3.1 Hemolysis Index

The estimation of blood cell during the blood cell damage which causes by mechanical stress need to consider using hemolysis index, HI (%). It is also describing as the ratio between whole hemoglobin contained in a sample of blood (H_b) and increasing in plasma free hemoglobin (ΔH_b) which resolved to the reaction of flow shear stress [46]. The power-law model is proposed by [47] which objective for having preliminary quantification of potential hemolysis. Then, the hemolysis index can be calculated for one single transition through a mechanical heart valve as shown in Eq. (1).

$$HI\% = \frac{\Delta H_b}{H_b}100 = 3.62.10^{-5}.t_{exp}^{0.785}.\tau^{2.416} \quad (1)$$

where, t_{exp} is the duration of the exposure to the 'active' shear stress τ. Table 1 shows the list of hemolysis index that contributing to the hemolysis [48]. The hemolysis will occur during HI is more than 300 which the hemoglobin is released into the surrounding plasma following damage of the cell membrane [49].

Table 1
The list of hemolysis based on HI and gross appearance [48]

HI	Appearance of serum	Degree of hemolysis
<20	Clear	No hemolysis
20-100	Pink tinged	Slight hemolysis
100-300	Red	Moderate hemolysis
>300	Dark red	Marked hemolysis

3.2 Blood Damage Index

The blood damage index (BDI) or platelet activation has been developing in an empirical model for the first approximation by the means of the power law of the form which can be calculated [50] shown in Eq. (2).

$$BDI = C\tau^{\alpha}t^{\beta} \quad (2)$$

where τ (shear stress); t (exposure time); and C, α, and β model constants. A nonlinear mathematical formula and exponential formula are suggested by [51-53]. The power of law is modified to explain the effects of shear-stress development [53].

3.3 Power-Law

The characteristic trajectories of blood elements crossing the hinge and evaluation of the flow fields are used to track particle algorithm. The model of weightless point particles is blood elements that affected to be indifferently adverted by the velocity field. The study of power-law model to respectively quantify the amount of cytoplasm enzyme (LDH) which proportional to activate the platelet along with the quantity of hemoglobin (H_b) that discharge by red blood cell [38]. It is can measure the platelet activation and hemolysis level which accumulated to blood damage in Eq. (3) and Eq. (4).

$$BDI_P^{PL} = \sum_i 3.31 \; x \; 10^{-6} \Delta t_i^{0.77} t_i^{3.075} \tag{3}$$

$$BDI_P^{H} = \sum_i 3.62 \; x \; 10^{-5} \Delta t_i^{0.785} t_i^{2.416} \tag{4}$$

The blood damage index is BDI^{PL} which equivalent to platelet activation, thus BDI^{H} refers to hemolysis and time points along the trajectory of particle P indicates to i. The cardiac cycle is divided into 10 000 time steps which dominating to an exposure time of about 3 m/s. The capability of computational has disadvantage and lagrangian analysis for the flow is concentrate on the first part of the cardiac cycle which accurately from the first systole to after valve closure (from 0 to 520 ms). Then, the power-law formula is mostly used however the main issue with these empirical models is the model coefficients that depending on the set of experimental data that suitable for fitting only [54]. The constant shear-stress model is found that not fit with the dynamic shear stress condition [55]. Then, dynamic shear stress along with the sensitization of platelets is been proposed to the more complicated model [56].

3.4 Q Criterion

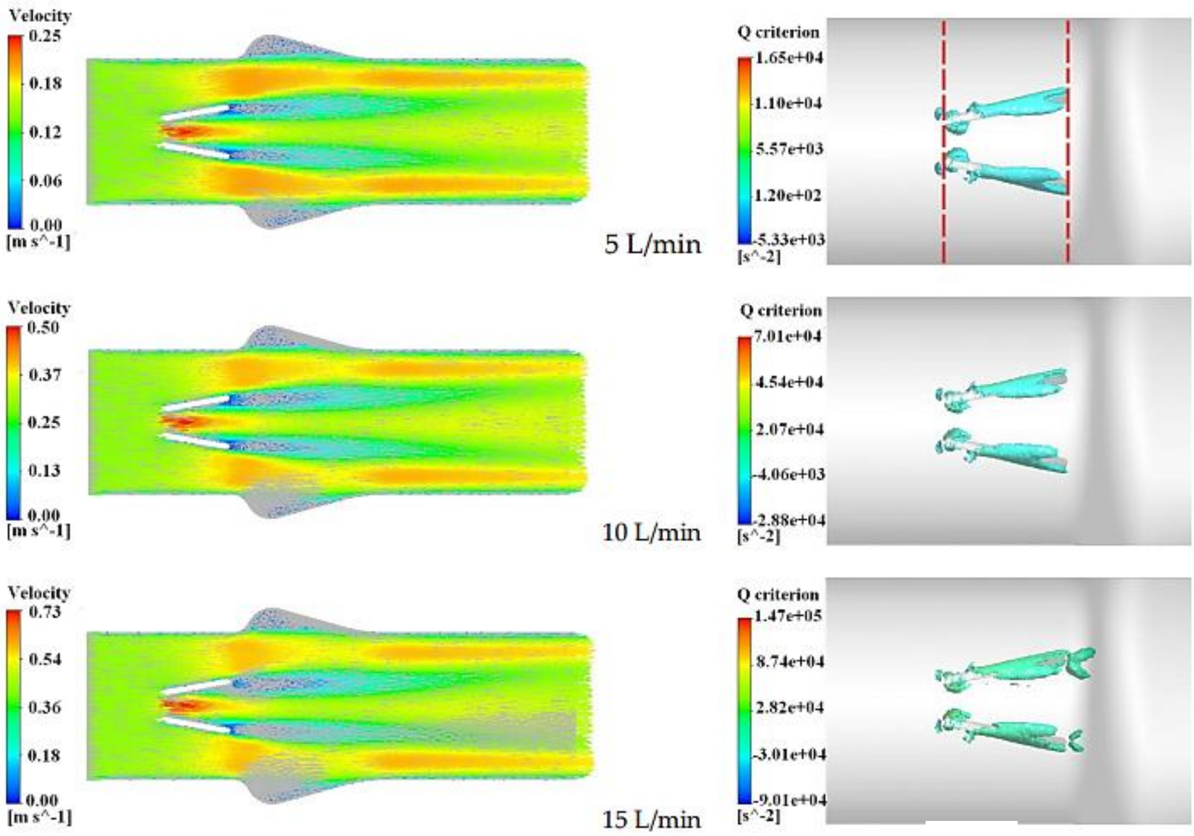
A connection of fluid area with a positive second invariant of ∇u are defined as Q-criterion when Q>0 [57]. Then, the Q criterion accumulates a secondary condition on the pressure which needs to be reduced than ambient pressure in the vortex. The definition of the second variant where the Q represents the local balance between shear strain rate and vorticity magnitude thus the vorticity magnitude is larger than the magnitude of strain rate [58]. The identification of vortices can be defined by using Q criteria from Jacobian Matrix J shown in Eq. (5) and Eq. (6).

$$S = \frac{1}{2} \; x \; (J + J^T) \text{ and } \Omega = \frac{1}{2} \; x \; (J + J^T) \tag{5}$$

$$Q = \frac{1}{2} \; x \; (\| S^2 \| + \| \Omega^2 \|) \text{ with } \| G \| = [\, tr(GG^T)]^{1/2} > 0 \tag{6}$$

The characterization of vortex center with Q-criterion when Q > 0 for the spatial area where fluid strain rate is dominated by the Euclidian norm of the vorticity tensor [59,60]. The Q criterion can be seen as a substitute for vortices detection and also can determine the spatial area of minimum pressure in two-dimensional plane for Navier-Stokes flows [61]. Figure 8(a) shows the blood flow pattern by velocity vector distribution of a BMHV at different flow rate condition [62]. The opening degree of leaflet at 80° for all flow rate develop the same flow pattern due to non-physiologic geometric of mechanical valve, a three-jet configuration through the central and lateral orifices can show a relatively higher velocity and low velocity region located at the whole surfaces and trailing edges of both leaflet [63]. The trailing edges of the leaflet at the spread region are increases with the flow rate. The maximum velocity occurs when the flow rate at 15 L/min about 0.75 m/s in the central orifices. The higher level of velocity gradient is accompanied by higher velocity at the central orifices in the vicinity of leaflet surfaces [25,61].

Figure 8(b) shows the vortex structure of the flow fields where the color represents the value of the Q criterion of the vortex core region. The vortex core region is developing due to low velocity region near both leaflet edges. As the flow rate increasing, the value of the Q criterion in the vortex core region increased rapidly. The flow rate increase more than 15 L/min will increase the velocity of the mainstream region and vortices shed downstream from the trailing edges of the leaflets. The Figure 8(b) shows the study of pressure pulsation characteristics in the vicinity of the leaflet under different flow conditions by monitoring lines perpendicular to the flow direction (Y direction) were set at the leading edge and trailing edge of the leaflets of the BMHV. As the result, the influence of pressure pulsation decrease when the flow rate increase and the velocity near the edges of the leaflets increase [63].



(a) (b)

Fig. 8. Velocity distribution and Q criterion of the vortex core region of BMHV. (a) Velocity vector distribution and (b) Q criterion of the vortex core region [62]

4. Methods for Reduction Thrombosis

The MHV has a major complication which knowns as thrombosis and bleeding [64]. The bleeding or blood clot itself could affect the brain and other organ body malfunction due to abnormal flow [65–68] In medical treatment, the malfunction of the valve can be prevented by using blood thinner or warfarin at the right dosage every day with periodic blood tests and dietary restrictions [69]. Then, the blood thinner will give the high impact of bleeding if not control the usage of dosage when he injured or requires surgery [70]. The risk of anticoagulant or antiplatelet drug regimens which increase the bleeding risk has resulted in a drop of the patient receiving MHV [71,72].

Besides that, if thrombosis resistant material is made by a durable valve it will affect the hemodynamic and less aggressive anticoagulant or antiplatelet therapies will be required. Then, the material surface needs to be modified by minimizing the defence reaction or provide localized antithrombotic activity [73]. In engineering, a particular method has been widely used to coat the surface of medical implants with a more biocompatible material that can reduce the risk of device rejection and improve the hemocompatibility [74]. Besides the, the blood material interactions can result in thrombosis [75]. The various synthetic valve has been designed to exhibit similar hemodynamic to bioprosthetic and native heart valves even though they still suffer from thrombotic complications [76]. The various material treatment is being developed to prevent thrombosis complications by approach interaction of cell and protein adhesion to surface by using hydrophilic surface or unreactive protein surface [77]. After that, the various pathways involved in thrombosis through the release of agents such as heparin but the issues with degrading the thrombo-resistive properties of the surface over time [78]. Superhydrophobic (SH) surfaces are repel to water which provides an alternative approach to minimize the thrombotic risk associated with blood material interactions [79]. The surfaces produced by the lotus leaf in nature which fabricated by combining materials at low solid surface energy (typically γ_{sv} <15 mN m^{-1}) and texture at low solid surface energy make the surface hydrophobic and control by chemical composition [80]. Minimize the blood material reactions which surfaces based on Cassie-Baxter can alter hemodynamics since fluid slip can exist along the surface and potentially reducing the risk for hemolysis and platelet activation [81–83] The potential of Superhydrophobic (SH) surfaces can reduce the thrombosis properties of the current pyrolytic carbon based valve leaflet.

4.1 Application of Vortex Generators

The Automotive industry, the vortex generator (VG) is used to make velocity decrease and lead to reduce fuel consumption. The instability of boundary layers and their potential separation are associated with an energy distribution that contributing to the flow control [84]. The separation of the flow near the rear end of the roof of an automobile is one of the causes of aerodynamic drag [85]. Then, the flow separation needs to be controlling for increasing the system performance by resulting in the energy conservation as well as weight and space savings. The vortex generator is having small-aspect ratio airfoils that assemble perpendicularly to the surface. For the presence of adverse pressure gradient, the flow separation occurs and the fluid particle is slowdown which adequates to energy losses. Vortex generators are simple to resolve the problem of flow separation by generating simple trailing streamwise vorticities and adding energy to the boundary layer. The re-energizing of the boundary layer is known as the process of adding momentum to the region near the surface [86]. The lower drag of the coefficient gives a better result in reducing fuel consumption and significant to the environment protection [85].

The vortex generator also uses in the biomedical applications which is to reduce blood clotting complication. Vortex generator has been analysed by the researcher to improve the hemodynamic of the valve and reduce the excessive level of mechanical stresses. Bark *et al.,* studied the blood material interactions and hemodynamic using SJM bileaflet mechanical heart valve (BMHV) with superhydrophobic (SH) coating to reduce thrombosis complications. The superhydrophobic coating can be used to reduce cell adhesion when putting into contact with blood which indicating a reduction in thrombosis [87]. Lakshmi P. Dasi *et al.,* demonstrated the passive flow control technique could reduce the procoagulation in a bileaflet mechanical heart valve without altering large scale designs of the valve. The study was conducted with different vortex generator which is a rectangular and hemisphere vortex generator to optimize the leakage flow hemodynamic at length scales relevant to blood damage. Hatoum and Dasi conducted high resolution particle image velocimetry measurement to improve the pressure gradient and reducing turbulence on bilealflet mechanical heart valve. The co-rotating vortex generator was applying at leaflet of heart valve to delayed flow separation and streamlined transition of flow. The vortex generator can reduce thrombosis at mechanical heart valve which indicates for further study in different arrangement and geometry of vortex generator. The function of the vortex generator has been used by many sectors of the industry to improve the quality or performance of the device. For a comprehensive summary of vortex generator uses in engineering and medical field is shown in Table 2.

4.2 Vortex Generator in Mechanical Heart Valve

The previous studies are promoting for passive flow control surface features such as vortex generators on the leaflet surface to reduce turbulence and platelet activation correlated with the regurgitant jet [94]. The surface of the valve leaflet with a vortex generator can manipulate flow to confine damaging effects and promote the advantages ones [89]. The major issue of the vortex generator is to lag and restrain flow separation over transport momentum from the free stream into the boundary layer to assist the strong local streamwise opposed pressure gradient [88,90]. The studys of various vortex generator configurations on pressure gradient with turbulent Reynold shear stresses (RSS) to recognize the passive flow control for turbulent issues [91-105].

The model of vortex generator is mounted on the downstream side of the BMHV has shown in Figure 9; (a) with four co-rotating equally distant vortex generator, (b) with counter-rotating eight closely spaced vortex generator, (3) with counter-rotating 4 far spaced vortex generators, and (d) with counter-rotating 4 closely spaced vortex generators are study by Hotum and Dasi. Vortex generator heights were chosen to be 1 mm, length 2.8 mm, the spacing 5 mm and set at an angle of incidence of 23˚ based on Bradbury *et al.,* [106]. Leaflets length is 20 mm. These 4 vortex generator configurations and arrangements were specifically chosen as addition of previous studies [84].

The main indicator of the velocity and vorticity state of the flow is the flow velocity field. Figure 10 shows the root mean square (RMS) of the variation in velocity (V'_x and V'_y) at peak systole for the particular valve cases. The co-rotating VGs case shows the shear layer is widely elongated at the exit from the leaflet. The information from the RMS result has described the characterization of growth during an interruption in the shear layer when co-rotating will contribute to the lower turbulence which clarifies the reduction in pressure gradient along with Reynold shear stress (RSS) [81,84]. The y-direction shows unsteadiness of the streamwise component for velocity and vorticity area which more steady performance for the co-rotating VGs and more homogenized along with the streamlined transition of flow [89,107]. The efficient moment transfers of vortices only on the close arrangement which also ensures that there is no discontinuity.

Table 2
Application of vortex generator

Reference	Vortex generators design	Application	Finding	Scope
[88]	Bump-shaped vortex generators	Automotive (Car models Sedan and Hatchback)	Reduce both the drag and lift coefficients.	GAMBIT and FLUENT
[89]	Rectangular shape vortex generators	Medical (Prosthetic Heart Valves)	Establish pressure gradients and reduce turbulence	PIV experiment
[90]	Triangle shape vortex generator	Aerospace (Airfoil)	Increase the skin friction which use passive device	PIV experiment
[91]	Vane-type VGs in rectangular and curve-edge vortex generator	Aeronautics (Airfoil)	The peak lift coefficient is accomplished when the VGs are fixed nearer to the separation point	Experimental and simulation (FLUENT 6.3)
[84]	Curve-edge vortex generator and triangle vortex generator	Aeronautics (Airfoil)	The regulating of low-speed separated flows in adverse pressure gradient and supersonic shock-induced separation	Experimental
[92]	Triangle and rectangular shape vortex generator	Solar (solar air heater)	Vortex-flows that can generate impingement jets on the wall (absorber plate), which demonstrate faster fluid mixing between the warmer near-wall fluid and the colder bottom-wall fluid regions	Numerical simulation and experimental
[86]	Rectangular shape vortex generators	Medical (b-Datum Bileaflet Mechanical Heart Valves)	The existence of vortex generators necessarily diminished the blood propensity for thrombus formation	PIV experiment and in-vitro experiment
[93]	Triangle shape vortex generator	Aeronautics (Airfoil)	Vortex intensity is proportional to the average kinetic energy of the fluid in the height range of the VG.	FLUENT method
[94]	Rectangular and hemispherical vortex generator (VG)	Medical (b-datum leaflet edge bileaflet mechanical heart valve)	An important diminution of turbulence stresses, particularly with the rectangular VG configuration	PIV experiment
[85]	Triangle shape vortex generator	Automotive (Car)	Decrease the aerodynamic drag of the car with low coefficient of drag	Numerical simulation (CFD simulation)
[95]	Triangle shape vortex generator	Aviation aircraft (Piper Arrow)	Development of a boundary layer downstream of a VG with a laminar inlet boundary layer	PIV experiment
[96]	Rectangular shape vortex generators	Jet impingement	The stream wise velocity of the jet expansion with the cross-flow while the wall-normal velocity and turbulent kinetic energy are reduced close to the target wall	PIV experiment and Liquid Crystal Thermography (LCT)
[97]	Delta wing, rectangular of vortex generator	Lithium ion battery	Heat transfer enhancement is due to bulk fluid mixing, boundary layer modification and flow destabilization by VGs	Numerical method
[98]	Triangle shape vortex generator	Scramjet (supersonic combustion ramjet)	Reducing of the mixing length, the maximization of the penetration depth and the minimization of the stagnation pressure losses	Numerical method

[99]	Delta winglet vortex generator	Circular tube (heat exchanger)	A smaller pitch ratio results in a higher Nusselt number and a higher friction factor	Experimental and CFD simulation
[100]	Rectangular shape vortex generator	Plate-fin channel (heat exchanger)	The channel with the rectangular wings increases the heat transfer performance of the PFHE	CFD simulation
[101]	Triangle shape vortex generator	Aircraft (Edge Aerodynamix Conformal Vortex Generator (CVG)	CVG is extremely low profile, it can generate coherent structures that persist downstream and reduce fuel costs for aircraft (reduce drag) without the adverse side effects	PIV experiment
[102]	Delta winglet vortex generator	Diesel exhaust exergy (heat exchanger)	Vortex generators with optimum dimensions and angle of attack are located in the exhaust to reach more exergy recovery as well as low pressure drop	Experimental
[103]	Delta-winglet vortex generator	Solar water heater	Can minimize the demand for electric energy and, consequently, decrease the electrical bill	CFD simulation
[104]	Vane-Type Vortex Generators	Aeronautics (Tiltrotor Wings)	The optimization eliminated the separation experienced by the clean geometry (from 11.1% to 0%), whilst reducing the drag obtained from the best Latin Hypercube sample by 7%	CFD simulation
[108]	Delta Wing vortex generator	Aerospace	The vortices present advantages to increase the lift via high fields of suction above the delta wing	Experimental and CFD simulation
[109]	Winglet vortex generator	Heat exchanger	Increase in the rate of heat exchange by generating vortex and reverse flow which in turn increases the efficiency of the thermal process	CFD simulation

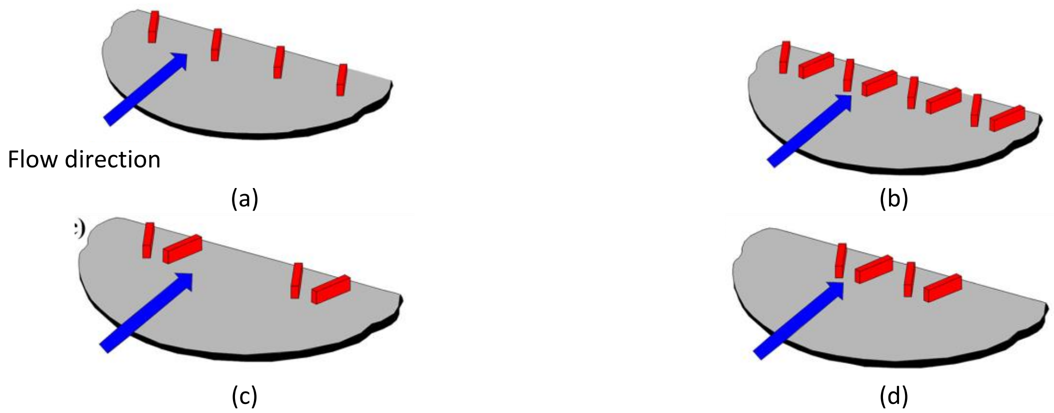


Fig. 9. The schematic of vortex generator arrangement: (a) co-rotating, (b) 8 equally spaced counter-rotating vortex generator, (c) 4 far spaced counter-rotating VGs and (d) 4 closely spaced counter-rotating VGs [89]

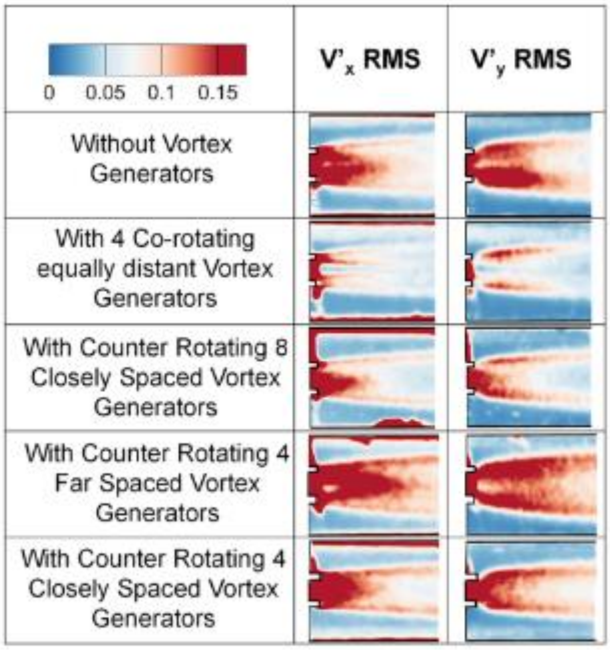


Fig. 10. RMS of the variation in velocity (V'_x and V'_y) at peak systole for the particular valve cases [89]

The study of significance turbulence post disinformation stems to understand the effect of platelet activation, hemolysis and pressure drop. Besides that, the VG arrangement for the mechanical heart valve application has not been completely covered especially for the type of applications and this research contributes to further studies towards the target. The characteristics of VGs indicate low drag which significantly important for many applications specifically to heart valve engineering [84].

5. Recommendation

The SH coating method is used on the leaflet of the mechanical heart valve for reducing blood clotting. The SH coating is advantages technology that can be valuable for various blood contacting medical devices. The SH coating that has been analysed were 2D and limited to downstream.

Therefore, heart valve performance for the long term when it was implanted in 3D needs further investigation. The investigation can capture the flow in leakage gaps.

The vortex generator is demonstrated the passive flow control technique that could reduce the procoagulation in a BHMV without changing large scale models of the valve. It is asserted that the VGs studied will not enhance clinical outcomes as the bulk forward flow hemodynamic is likely to be debated considering the minimization in effective orifice area induced by the existence of the generator [94]. The effect of non-newtonian blood on VG at the mechanical heart valve leaflet could predict the complex hemodynamics of the valve, especially in regions of leaflet.

Furthermore, the different VGs arrangement is not fully cover in the previous study so need further investigation to optimize the best geometry, dimension and distribution. The investigation for reducing blood clotting with SH coating and VGs as a method can improve the hemodynamic whereas reducing any increase in blood cell damage due to fluid stress.

6. Conclusions

In conclusion, CFD modeling is one of the alternatives that can approach for accurate assessment of thrombosis. The review focused on the investigation of reducing thrombosis at the MHVs for better understanding of complex flow. Furthermore, the leaflet of MHVs tends to generate higher shear layers than in natural valve flows. The shear layers are correlated with larger shear stresses and platelet damage, thus lead to increase thromboembolic complexity for abnormal MHVs flows. Besides that, the MHVs designs will help in reducing recirculation zones for abnormal flows by reconstruct the geometric of valve. Then, the method of reducing thrombosis such as coating and vortex generator on leaflet could prevent any increase in blood cell damage due to fluid stress. This also would provide that elevated platelet damage for abnormal MHVs flows are not worsened by the formation of risky recirculation zones near valves. The previous studies on reducing thrombosis have been conducted to prevent from blood clotting but still need to improve the hemodynamic results in MHVs. The studies give a significant work on reducing blood clotting to give a better life for patients that use MHV.

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