# Turbulent Energy on Mechanical Heart Valve Equipped with Triangular Vortex Generator

**Mohamad Shukri Zakaria, Akhmal Irfan Abd Razak, Mohd Juzaila Abd Latif, Haslina Abdullah, and Adi Azriff Basri**

**Abstract** Heart valve failure is a prevalent cardiovascular condition worldwide, often necessitating the use of mechanical heart valves (MHV) as replacements. Nevertheless, patients with MHV still require lifelong anticoagulant therapy to prevent blood clotting. One contributing factor to blood clot formation is the presence of high turbulence, which can be quantified using Turbulent Kinetic Energy (TKE) and Turbulent Shear Stress (TSS). This study's objective is to analyze and propose a new heart valve design aimed at reducing complications related to blood clotting. The analysis was conducted using Computational Fluid Dynamics (CFD) with the Commercial ANSYS Fluent software. Specifically, the study focused on analyzing MHVs equipped with vortex generators (VGs) and compared their TKE levels with those of MHVs without VGs. The physiological condition considered was pulsatile flow at the inlet, with the analysis specifically focusing on the peak systole condition. The results indicated that MHVs equipped with VGs reduced TKE by 23.55% and TSS by 22.02% compared to MHV leaflets without VGs, supporting the hypothesis of reduced potential for blood clot formation.

**Keywords** Mechanical heart valve · Computational fluid dynamics · Turbulent · Blood clot

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# 1 Introduction

Turbulent blood flow is commonly associated with heart valve disorders. Heart valves play a crucial role in maintaining the unidirectional flow of blood through the heart chambers. Installation of prosthetics such as MHV can disrupt the normal flow pattern and lead to turbulence (Zakaria et al. 2017). Heart valve failure often necessitates prosthetic replacement, typically utilizing a mechanical heart valve (MHV). Despite being available in the market since the 1950s, the issue of thrombus formation still persists. The formation of thrombi is associated with various hemodynamic flow characteristics, including shear stress, recirculation, turbulence, and flow separation.

Turbulent blood flow is frequently linked to heart valve disorders. Heart valves play a vital role in maintaining the unidirectional flow of blood through the heart chambers. The introduction of prosthetic devices, such as MHV, can disrupt the normal flow pattern and give rise to turbulence (Zakaria et al. 2017; Salleh et al. 2020).

Elevated levels of turbulent blood flow can have significant clinical implications. Turbulence can result in pressure drops, energy losses, and alterations in the hemodynamics of the cardiovascular system. Over time, turbulent flow can place additional stress on the heart and blood vessels, potentially leading to complications such as heart murmurs, heart failure, or the formation of blood clots (Salleh et al. 2020; Basri et al. 2021).

This blood clot prediction can now be realized by utilizing Computational Dynamics (CFD) analysis that was long time known in solving engineering problems (Zakaria et al. 2013). Turbulent Kinetic Energy (TKE) is a measure of the energy associated with turbulence (Zakaria et al. 2014; Basri et al. 2016). The turbulent kinetic energy (TKE) is defined as

$$k = \frac{1}{2}\left[\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right] \tag{1}$$

where *u*' *v*' and *w*' is turbulent fluctuating velocity for *x*, *y*, and *z*, respectively.

There are multiple methods to decrease turbulent energy and shear stress in mechanical heart valves (MHVs), with one of these approaches involving the use of a vortex generator (VG). While VGs have been employed in aircraft wings since the 1940s, their application in MHVs is comparatively recent. Researchers have investigated the utilization of a vortex generator to enhance the hemodynamics of the valve and mitigate excessive mechanical stresses such as in (Hatoum and Dasi 2019; Wang et al. 2022).

In this study, we analyzed a new mechanical heart valve (MHV) leaflet equipped with a Vortex Generator (VG) with the goal of reducing Turbulent Kinetic Energy (TKE). To date, no study has investigated the impact of VGs on MHVs, particularly in terms of turbulent kinetic energy, especially in patient-specific aortas. Our hypothesis was that MHV leaflets equipped with triangular VGs would decrease turbulent energy, potentially reducing the risk of heart valve thrombosis.

## 2 Methodology

The model's geometry combines the MHV housing with a patient-specific aorta. The MHV used in this study follows the ST Jude MHV type, as shown in Figs. 1 and 2, as detailed in Dasi et al. (2007). The setup represents a flow chamber with an idealized geometry featuring an SJM valve. This chamber resembles a stiff, straight tube with a 25.4 mm diameter, and the valve itself has an inner diameter of 23.0 mm. Downstream of the valve, on the aortic side, an idealized aortic sinus root is enlarged to approximately 25 mm. The St. Jude Medical BMHV design follows the leaflet design in this configuration. Please note that only the model of the leaflet with VGs is presented here, as the model of the leaflet without VGs is considered intuitive and is not included.

For this study, we assume that the leaflets are fully open and inclined at a 5° horizontal angle, as indicated in Zhou et al. (2016) and (Hatoum and Dasi (2019). The leaflets have a thickness of 0.5 mm and are designed in a semi-circular shape. Their diameter is 18.6 mm, and the thickness remains consistent at 0.5 mm.

The boundary condition at the inlet is pulsatile (Fraser et al. 2008), with a maximum velocity of 1 m/s during systole, as illustrated in Fig. 3. At the outlet,

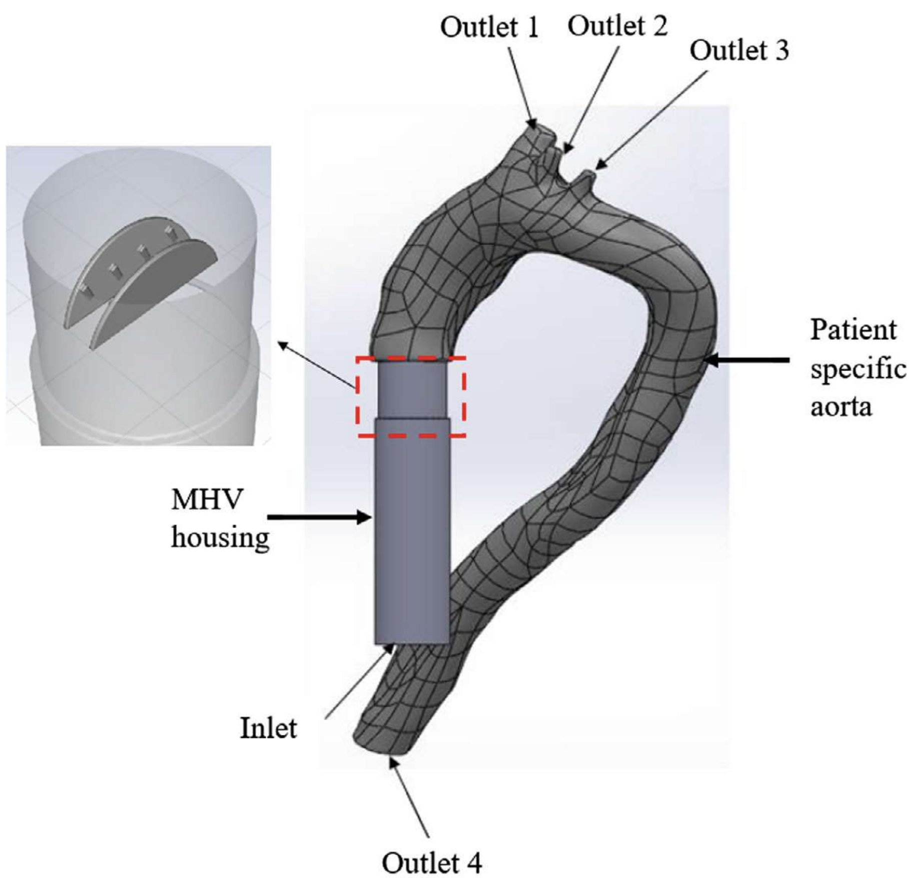


**Fig. 1** Geometry and boundary condition of the model

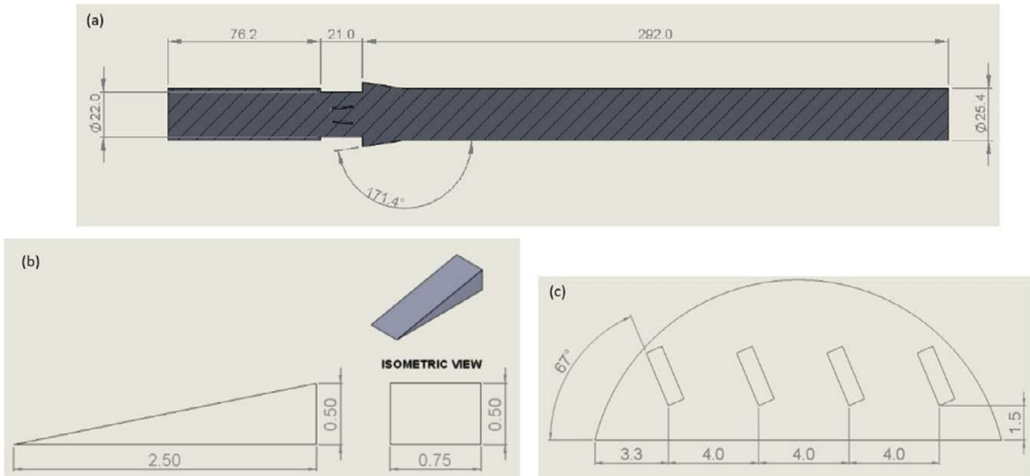


**Fig. 2** Geometry and dimension of MHV showing **a** cross section view of the tube, **b** vortex geometry **c** Vg attached to the leaflet

the pressure was set to 100 mmHg, which corresponds to a gage pressure of 13,332 Pa as despite in Table 1.

The properties of the blood are characterized by a density of 1060 kg/m$^3$ and a viscosity of 0.0035 kg/ms. An incompressible and Newtonian model was employed, a choice that has been used in many previous studies. This model is appropriate because the size of blood cells is considerably larger, at least three orders of magnitude, than a typical blood cell, which measures approximately 10 μm (Sotiropoulos et al. 2016).

The 3D incompressible Navier–Stokes equations are used to solve the problem, and the equations are given by:

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla p + \upsilon \nabla^2 \boldsymbol{u} \tag{2}$$

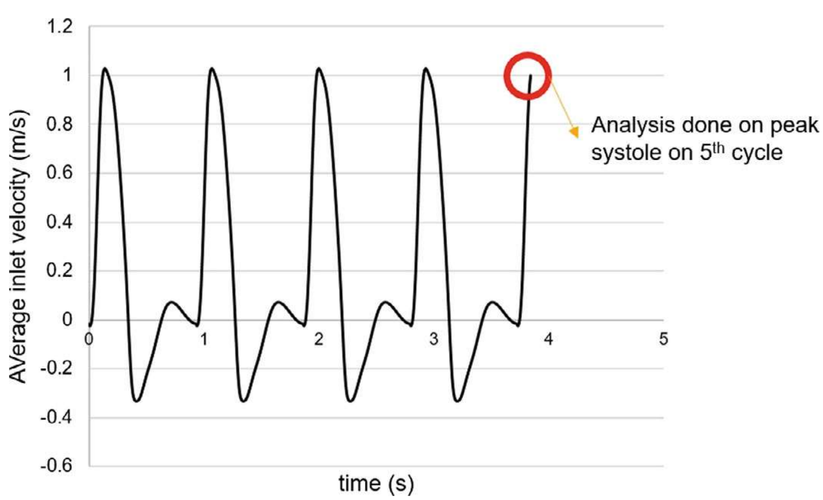


**Fig. 3** Pulsatile profile velocity at inlet

**Table 1** Boundary condition used in present study

| Boundary name | Properties |
|---|---|
| Inlet | Pulsatile inflow |
| Outlet 1 (Brachiocephalic artery) | 100 mmHg (13,332 Pa) |
| Outlet 2 (Left common carotid artery) | 100 mmHg (13,332 Pa) |
| Outlet 3 (Left subclavian artery) | 100 mmHg (13,332 Pa) |
| Outlet 4 (Thoracic aorta) | 100 mmHg (13,332 Pa) |
| Aorta wall | No slip |
| Leaflet wall | No slip |

$$\nabla \cdot \boldsymbol{u} = 0 \tag{3}$$

Equation (2) represents the momentum equation, and Eq. (3) represents the continuity equation, where $u$ **,** $\rho$, $p$, and $\nu$ are velocity vector field, blood density, pressure, and kinematic viscosity, respectively.

The $k - \omega$ SST turbulent model was selected in the present study because it is well-suited for a wide range of flow conditions and is not sensitive to the Y + value. It is also the most accurate turbulent model for complex geometries, although it can be challenging to achieve convergence. This turbulent model had previously been used in simulating blood flow through the MHV in previous studies such as in (Alemu and Bluestein 2007; Bluestein et al. 2002).

The Y + value was taken at a maximum of 4.0. Thus Y + value less than 5.0 ensures the flow resolves the viscous sublayer near the leaflets. The detail of Y + distribution is shown in Fig. 4. The simulation was conducted using ANSYS Fluent Software on the W-2255 Intel-Xeon processor on 128 GB RAM.

The grid-independent test was conducted on three grids as given in Tables 2 and 3. The finest grid was selected which is 3398556 cells for no VG case model, and 3,129,767 cells for VG case models since it produces the lowest discretization error. The detail of the finest mesh is shown in Fig. 5.

## 3 Result and Discussion

The data presented in this paper were analyzed both qualitatively and quantitatively using TKE and TSS parameters. To discuss the qualitative data, four vertical plane views were selected for each parameter: the center plane, 0.22R offset, 0.44R offset, and 0.66R offset, where R corresponds to the diameter of the leaflet, which is 18 mm. For the quantitative results, the peak TKE and TSS were determined for each plane, and comparisons were made between the VG and no VG case models in terms of percentage errors.

As depicted in Figs. 6 and 7, the TKE and TSS levels were higher for leaflets without vortex generators (VGs) compared to those with VGs. The result was also

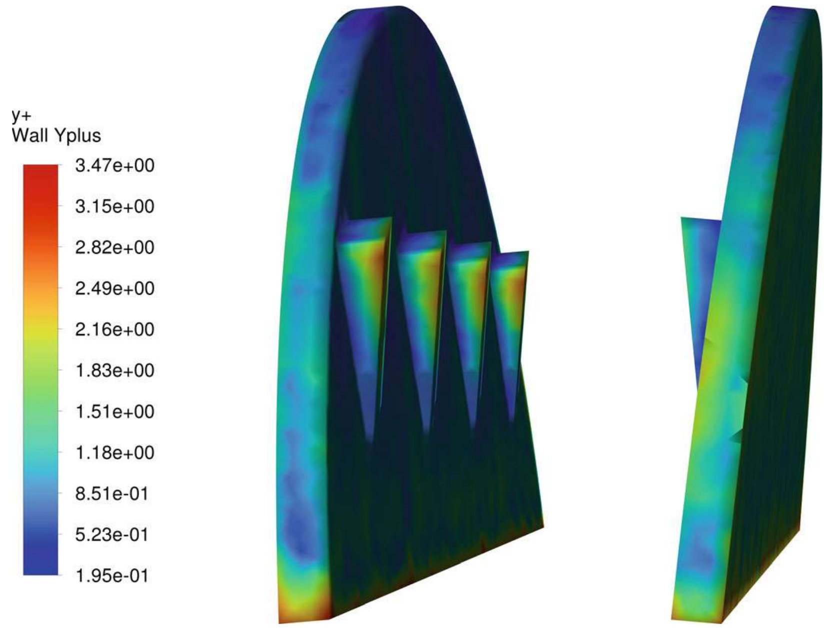


**Fig. 4** Y + contour plot of the leaflet

**Table 2** Detail of number elements and WSS for grid independent test for the model without VG

| Number of elements | Grid ratio | Max WSS | % error |
|---|---|---|---|
| 1,753,598 | | 26.74 | |
| 2,303,061 | 1.31 | 70.99 | 62% |
| 3,398,556 | 1.48 | 167.59 | 5% |

**Table 3** Detail of number elements and WSS for grid independent test for model with VG

| Number of elements | Grid ratio | Max WSS | % error |
|---|---|---|---|
| 1,334,985 | | 24.05 | |
| 1,777,770 | 1.33 | 71.86 | 66.5% |
| 3,129,767 | 1.76 | 77.10 | 6.78% |

quantitatively given in Tables 4 and 5. VGs function by controlling vortices, which help delay or reduce the separation of the boundary layer. This, in turn, can lead to a reduction in turbulence and an improvement in hemodynamic performance. The high intensity of TKE and TSS was observed in the aortic root region. This demonstrates that leaflets with VGs have lower turbulent energy and TSS levels, resulting in a reduction in blood clot formation. Lower TKE is preferable because it is directly related to TSS. High shear stress is undesirable since it can damage blood cells and activate platelets, leading to the formation of blood clots.

When comparing Figs. 6 and 7, the TKE contour plots closely resemble those of TSS. As blood flows through mechanical heart valves, it undergoes chaotic and irregular flow patterns, resulting in mechanical stress on the blood, a phenomenon

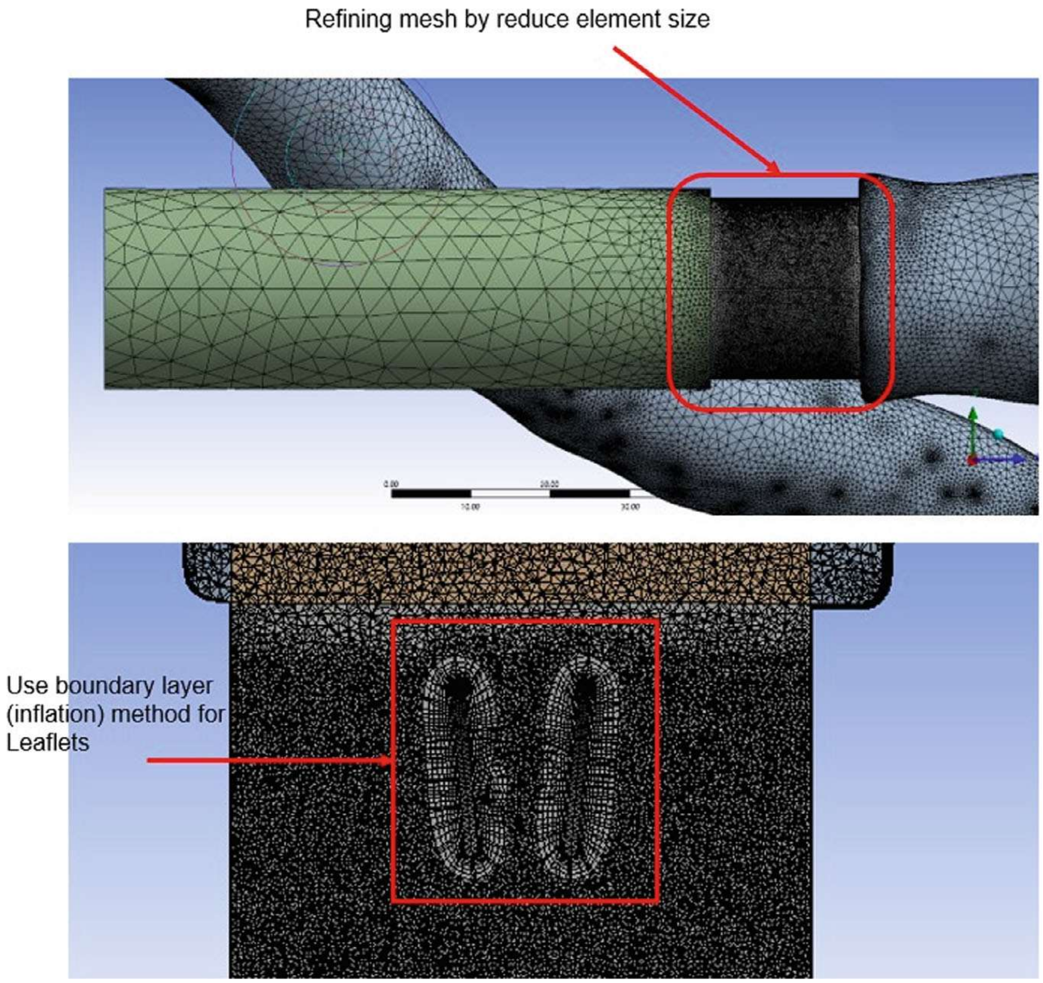


**Fig. 5** Mesh density of the model

referred to as turbulence shear stress (TSS). TSS is the product of the strain rate magnitude and the turbulent effective viscosity. It is widely associated with turbulence and the activation of platelets (Giersiepen et al. 1990; Hatoum et al. 2018; Dasi et al. 2013).

Excessive kinetic energy in prosthetic heart valves without VG installation increases the likelihood of blood clot formation. Higher TKE levels contribute to increased turbulence, resulting in elevated pressure within the prosthetic heart valve and an increased risk of thrombus formation. The TKE values presented indicate that VGs play a significant role in enhancing the performance of prosthetic heart valves. They effectively delay flow separation and reduce pressure within the prosthetic heart valve. Furthermore, decreased pressure within the valve leads to a lower probability of platelet activation. In addition, according to Wang et al. (2022), vortex generators generate small swirls of fluid that prevent smooth flow separation from the surface. These swirls also promote fluid mixing, thereby reducing Turbulent Kinetic Energy.

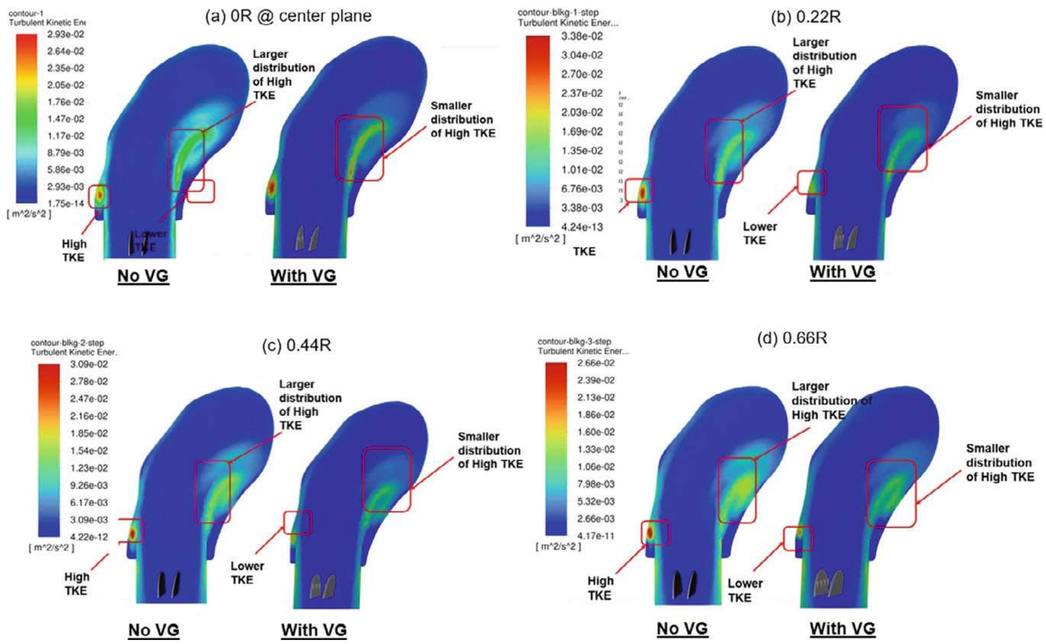


**Fig. 6** TKE Vg and no VG case at **a** center plane @ 0R, **b** 0.22R, **c** 0.44R, and **d** 0.66R, where R is the diameter of the leaflet

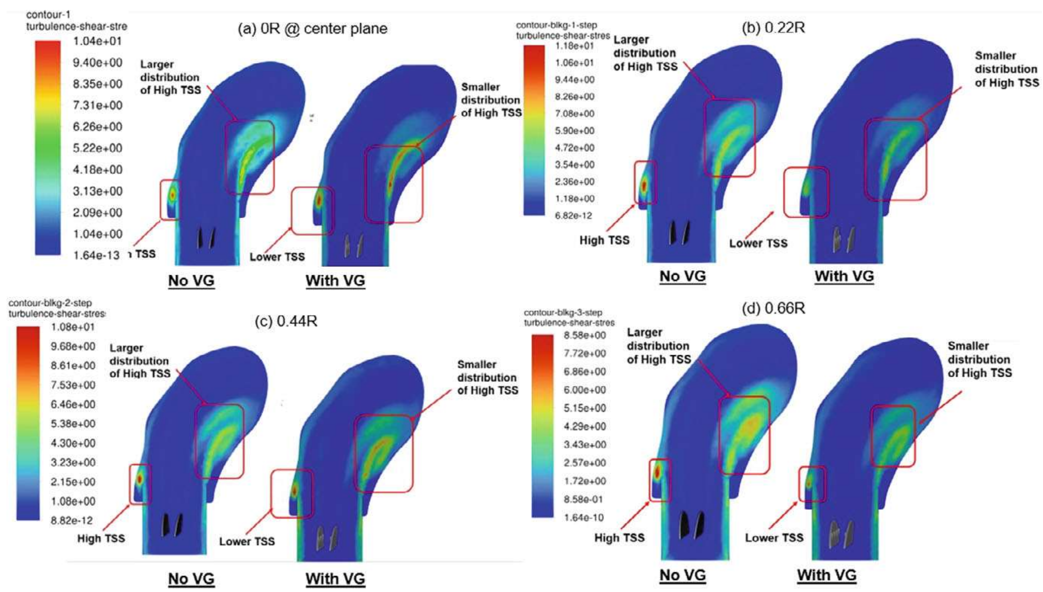


**Fig. 7** TSS Vg and no VG case at **a** center plane @ 0R, **b** 0.22R, **c** 0.44R, and **d** 0.66R, where R is diameter of the leaflet

**Table 4** Peak TKE comparison at different plane

| | No VG | VG | % error |
|---|---|---|---|
| 0R | 0.0293 | 0.0275 | 6.14% |
| 0.22R | 0.0338 | 0.0223 | 34.02% |
| 0.44R | 0.0309 | 0.0211 | 31.72% |
| 0.66R | 0.0266 | 0.0213 | 19.92% |
| average | 0.0302 | 0.0231 | 23.55% |

**Table 5** Peak TSS comparison at different plane

| | No VG | VG | % error |
|---|---|---|---|
| 0R | 10.44 | 9.83 | 8.84% |
| 0.22R | 11.8 | 7.95 | 32.85% |
| 0.44R | 10.76 | 7.63 | 29.09% |
| 0.66R | 8.58 | 7.03 | 18.06% |
| average | 10.40 | 8.11 | 22.02% |

# 4 Conclusion

The effectiveness of flow control concepts, which is the installation of VG applied to bi-leaflet prosthetic heart valve, was evaluated. Adding VG reduces the TKE and TSS compared to the case without adding VGs. From the study, it can be concluded that using a vortex generator on the leaflets could lower the TKE and TSS of the blood flow up to 23.55% and 22.02%, respectively. Therefore, a VG is a beneficial device to enhance the performance of hemodynamic factors in mechanical prosthetic heart valves to mitigate the risk of the formation of a thrombus.

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