Numerical Study of Blood Flow Through Artificial Heart Valves

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Abstract. Analysis of blood flow through artificial heart valves (Titling disc valve) with different angles of valve inclination is numerically studied. Finite volume method was adopted to solve continuity, momentum, and energy equations by using k-e model. Six different angles of inclination of valve change of (30, 45, 60, 70, 80, 90) were considered with Reynolds number of laminar flow ranging 500, 750, 1000, and 1250 and Reynolds number of turbulent flow ranging 8000, 12000, 16000, and 20000. The results showed that the region of vortex formation before and after the artificial valve can clearly increase in recirculation zone after artificial valve has increased the Reynolds number. The maximum value of velocity was observed at the bottom side after valve was compared with top side of valve because the space of passage flow is larger than other side for all cases. The counter of velocity for turbulent range showed that the recirculation region is clearer and bigger after the valve was compared with laminar range. The best performance of artificial valve (Titling disc valve) was with greater opening angle of valve (90) compared with other cases. Generally, unsymmetrical blood flow for range opening angles valve were found to be (30, 45, 60, 70, 80,) while opening angle valve (90) for the blood flow was symmetrical and that demonstrated good performance for valve at angle (90). There can be seen a focus pressure of artificial valve (Titling disc valve) on one side in counter pressure and this may have harmful effect on aortas walls and lead to unnecessary aorta fatigue. The novelty of the present paper is to obtain new results for specific angle of valve since most papers focused on the standard angle.

Keywords. Blood flow, Artificial heart valve, CFD, Titling disc valve.

1. Introduction
One of the most important organs in human body is the heart which provides blood to all parts of the body by mechanisms in four main chambers. The heart is the organ that pumps blood around the body and contains valves to regulate blood flow in one direction. There are four valves for blood flow:

1. Tri-valve which regulates blood flow between right atrium and right ventricular.
2. The pulmonary valve which organizes blood flow of the right ventricular to the pulmonary arteries where blood transfers to the lungs to pick up oxygen.
3. The coronary valve which conveys oxidized blood from the left atrium to the left ventricle.
4. The aortic valve which opens to the oxidized blood to move from the left ventricle to the aortic and is the largest artery in the body.

There are some problems occurring in these types of valves affecting blood flow stoppage called heart valve diseases. Among these problems are the inability of the valve to open fully or the blood may...
stop backward due to the inability of the valve to close completely, which leads to cardiovascular disease. The reasons of valve diseases obtained by birth defects, old age, or other diseases and can be discovered using an echocardiogram. Due to these problems, the heart valve is replaced by an artificial valve and can be a single leaflet valve, bi-leaflet valve, or tri-leaflet valve. Many people die annually (approximately 26,000) due to problems in the aortic valve mechanics, and it is expected that in the coming years, that is, after 2020, cardiovascular disease will become highly prevalent in the world, and thus, heart valves are expected to be replaced in large numbers.

The Computer Aided Design (CAD) program was used to create the 3D model of the valve. The valve pressure was analysed by mechanical analysis, because the heart valve operates under blood pressure and the analysis shows that high pressure and deformation occurs at the prism joint [1]. Also, the investigations conducted on changing the valve of the patient by valve mechanism was affected by disturbances and to obtain mechanical information for the valve, a computer simulation of the aortic valve was used by Laura and Mohammad [2]. Further using computational modelling is required to understand the mechanics of the mitral valve and structural and semi-static analysis of the closed valve. The obtained findings showed that the function of the mitral valve cannot be fully evaluated without modelling the ventricular dynamics and the interaction of the fluid-structure (FSI) between the mitral valve, ventricles, and blood flow [3]. Model (2D) with different angles of the artificial heart valves were used to study the numerical investigation of how valve engineering (maximum opening angles) affects the speed of the pointer distribution behind the valve and blood flow presented by Bajgrowicz [4].

Polymeric heart valves (PHVS) can be used in place of the original valve because it combines the advantages of structural and dynamic valves [5]. Quanyu et al. [6] presented numerical study on viscous laminar model to know the velocity and constant pressure. The carotid artery was simulated in terms of blood flow with PC-MRI and it was found that blood velocity with PC-MRI was inaccurate near the arterial walls and that CFD simulation gave better results.

For the evaluation of cardiac functions, CFD and medical imaging tools were used. One of the evaluation tools is catheter, which is a medical device that measures blood flow or pressure and is done by inserting thin wires carrying minute tubes to reach the heart to inject a small amount of dye into the artery that is imaged through the X-ray. CFD is used to analyze blood flow using different computational techniques as CFD is useful in providing hematology which is useful in clinical evaluation of cardiac performance [7].

From the early investigations, there are very limited studies on the analysis blood flow through artificial heart valves, hence the aim of the current paper is to study blood flow for both range laminar and turbulent through the artificial heart valve (Titling disc valve) with six different angles of inclination of valve.

2. Geometry description

Geometry is considered in this simulation as presented in Fig. 1.

![Figure 1. Schematic of geometry.](image)
ANSYS 14.0 program (the workbench program) is used to draw the geometry represented by a pair of rectangles of two different sizes to stimulate the location of the valve presence inside the blood vessels. The length of the narrow vessel (H74) is 20 mm with entrance height (V78) of 19 mm while the wide vessel is 50 mm length (H60) with height (V45) of 28 mm. The position of valve is between narrow and wide vessel with dimensions of 0.5 mm length (L49) and 19 mm width (L84) in order to close the passage blood completely. In this paper cases are considered based on six different angles of inclination of valve change from (30,45,60,70,80,90) with Reynolds number of laminar flow varying 500,750,1000, and 1250 and Reynolds number of turbulent flow ranging 8000 ,12000,16000, and 20000.

2.1. Meshing process
The meshing process starts after completing drawing the geometry as in Fig.2. The independent procedures are used by three grids with different size to increase the accuracy of the results. Grid (2) was selected as grid independent in comparison to grid No.(1) and (3) due to the different results less than 1% as shown in figure 3 for comparison velocity profile between selected grids.

![Figure 2. Mesh of geometry.](image1)

![Figure 3. Grid independent.](image2)
3. Numerical procedure

Numerical simulation is carried out by using ANSYS Fluent 14 of computational fluid dynamics (CFD). The properties of liquid used for blood are shown in Table 1.

| Property | Value |
|----------|-------|
| Density  | 1055 kg/m³ |
| Viscosity| 0.0035 kg/m.s |
| Cp       | 4182 J/kg.K |
| K        | 0.6 W/m.K  |

Table 1. Properties of blood.

In this simulation, momentum, continuity, and energy equations are employed with k-ε model in two dimensions which can be written as below:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0
\]  
(1)

\[
\rho \left( \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right)
\]  
(2)

\[
\rho \left( \frac{\partial v}{\partial x} + u \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right)
\]  
(3)

\[
\rho \left( \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} \right) = \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right)
\]  
(4)

In this simulation, the standard k-ε turbulence model use is based on [8]. To compute turbulence kinetic energy k and dissipation rate \( \varepsilon \), equations 5 and 6 are respectively.

\[
\frac{\partial}{\partial x} (\rho k u) = \frac{\partial}{\partial y} \left( \left( \mu + \frac{\mu_f}{\sigma_k} \right) \frac{\partial k}{\partial y} \right) + G_k - \rho \varepsilon
\]  
(5)

\[
\frac{\partial}{\partial x} (\rho e u) = \frac{\partial}{\partial y} \left( \left( \mu + \frac{\mu_f}{\sigma_\varepsilon} \right) \frac{\partial e}{\partial y} \right) + C_{ie} \frac{\varepsilon}{k} \left( G_k + C_{3k} G_b \right) - C_{2e} \rho \frac{\varepsilon^2}{k}
\]  
(6)

Where \( G_K \) defines the generation of turbulence kinetic energy by turbulent viscosity and velocity gradients and is calculated using

\[
G_K = -\rho \frac{\partial u}{\partial x} \frac{\partial v}{\partial x}
\]  
(7)

\[
\mu_t = \rho Cp \frac{k^2}{\varepsilon}
\]  
(8)

The coefficients are employed in the simulation presented in Table 2.

| Value of coefficient | Value |
|----------------------|-------|
| \( C_{1e} \)        | 1.44  |
| \( C_{2e} \)        | 1.92  |
| \( C_{3e} \)        | 0.09  |
| \( \sigma_k \)      | 1.0   |
| \( \sigma_\varepsilon \) | 1.3   |
| \( Pr \)            | 0.71  |

Table 2. The coefficients in transport equations.

4. Results and discussion

Numerical study was carried out for blood flow through the artificial heart valve (Titling disc valve). Six different angles of inclination of valve change of (30,45,60,70,80,90) were considered with Reynolds number of laminar flow varying from 500,750,1000,and1250 and Reynolds number of turbulent flow varying from 8000,12000,16000, and 20000.
4.1. Distribution velocity for laminar range

Figure 4 shows the velocity counter of blood flow through artificial valve (Titling disc valve) with opening angle of 30 at different Reynolds number of 500, 750, 1000 and 1250 respectively. The results displayed the region of vortex formation before and after the artificial valve and increase in recirculation zone is clearly seen after the artificial valve increased the Reynolds number. The negative velocity found in the velocity counter refers to the velocity in the opposite direction which represent regions of vortexes before and after the artificial valve. The velocity was higher at the bottom side after the valve compared with top side of valve as the space of passage flow is larger than other side for all cases.

![Figure 4: Velocity counter with opening angle of 30 at different Reynolds number of 500, 750, 1000 and 1250 respectively.](image)

Velocities of blood flow are distributed at different positions before and after the artificial valve (Titling disc valve) with opening angle of 30 for Reynolds number of 1250 as presented in figures 5 and 6 respectively. The results showed that the separation region created before and after the artificial valve illustrating the velocity magnitude decreases at position near to the artificial valve for all cases.

![Figure 5: Distribution velocity before valve at different positions for Re =1250.](image)

![Figure 6: Distribution velocity after valve at different positions for Re =1250.](image)
4.2. Distribution velocity for turbulent range

Velocity counter of blood flow through artificial valve (Titling disc valve) with opening angle of 30 at different Reynolds number of (8000, 12000, 16000, 20000) are illustrated in Figure 7. In all cases, the trends of velocity counter are similar before and after the artificial valve and it shows that the recirculation regions increased after the valve with increasing the flow rate from the velocity counter of blood flow. The maximum value of velocity is observed at bottom side after the valve compared with top side of valve because the space of passage flow is larger than other side for all cases. The counter of velocity for turbulent range sowed that the recirculation region is clear and bigger after the valve compared with laminar range.

![Figure 7](image1.png)

Figure 7. Velocity counter with opening angle of 30 at different Reynolds number of 8000, 12000, 16000 and 20000 respectively.

Figures 8 and 9 display the velocity profile for Reynolds number of (8000,12000,16000,20000) with opening angle of 30 at different positions before and after the artificial valve (Titling disc valve). Reduction gradually in velocity is observed before the valve and suddenly deceases and increases after the valve. The vortex region created after the valve was higher than before the valve and can be seen clearly at position X=25.5 and 26.5 while in position X= 30.5, the profile of velocity was parabolic.

![Figure 8](image2.png)

Figure 8. Distribution velocity before valve at different positions for Re =20000.

![Figure 9](image3.png)

Figure 9. Distribution velocity after valve at different positions for Re =20000.
4.3. Effect angle of valve on distribution velocity

Figures 10 and 11 show the effect angle of valve on counter of velocity at Reynolds number of 1250 and 20000, respectively. It is clearly seen that by increasing the opening angle of valve, the velocity of blood flow increases and the higher velocity was found with opening angle 90 which gives a better flow distribution. The best performance of artificial valve (Titling disc valve) was with greater opening angle of valve (90) in comparison with other cases where the rate of blood flow was higher. This means all tissues in human body obtain the amount of blood then do their functions in the body.

Figure 10. Counter of velocity at Reynolds number of 1250 for different angles.
4.4. Counter pressure

Counter pressure for blood flow through artificial valve (Titling disc valve) with opening angle of 30° for laminar range (Re=1250) and turbulent range (Re=20000) are presented in figure 12. As can be seen, the maximum pressure drop was at turbulent range compared with laminar range due to increase in blood flow rate. Figures 13 shows that the effect angle of valve on counter of pressure is at Reynolds number of 1250. Generally, the results refer to focus pressure of artificial valve (Titling disc valve) on one side and may have harmful effect on aortas walls. This could lead to unnecessary aorta fatigue. Unsymmetrical blood flow was found in cases for range opening angles valve(30,45,60,70,80°), except opening angles valve (90°) where blood flow was symmetrical and that demonstrates good performance for valve at angle 90°. Generally, the results refer to focus pressure of artificial valve (Titling disc valve) on one side which may have harmful effect on aortas walls and leads to unnecessary aorta fatigue.

Figure 11. Counter of velocity at Reynolds number of 20000 for different angles.

Figure 12. Counter pressure for blood flow through artificial valve (Titling disc valve) with opening angle of 30° for laminar range (Re=1250) and turbulent range (Re=20000).
5. Conclusions
Six different angles of inclination of valve change from (30,45,60,70,80,90) were considered with Reynolds number of laminar flow varying from 500,750,1000, and1250 and Reynolds number of turbulent flow varying from 8000 ,12000,16000, and 20000. From the obtained results, the following main points can be concluded:

1. Increasing the Reynolds number leads to increase in region of vortex formation before and after the artificial valve for all cases.
2. Higher velocity is observed at the bottom side after the valve in comparison with top side of valve as the space of passage flow is larger than other side for all cases.

3. The effect of opening angle of valve on the velocity of blood flow was noticed and a higher velocity was found with opening angle 90 which gives a better flow distribution.

4. The maximum pressure drop was at the turbulent range compared with laminar range due to rises in blood flow rate.

5. The best performance for valve was found at angle 90 because blood flow was symmetrical and had less effect on aorta wall compared with others.

### Nomenclature

| $C_1\varepsilon$, $C_2\varepsilon$, $C_3\varepsilon$, $\sigma_k$, $\sigma_\varepsilon$ | Model constants |
| $C_p$ | Specific heat |
| $H$ | Width of channel at entrance |
| $K$ | Turbulent energy |
| $Nu$ | Nusselt number |
| $P$ | Pressure |
| $Pr$ | Prandtl number |
| $Re$ | Reynolds number |
| $T$ | Temperature |
| $u$, $v$ | Axial velocity |
| $X$, $y$ | Cartesian coordinates |

**Greek symbols**

| $\rho$ | Water density |
| $\varepsilon$ | Turbulent dissipation |
| $\mu$ | Dynamic viscosity |
| $\mu_t$ | Turbulent viscosity |

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