International Research Journal of Innovations in Engineering and Technology (IRJIET)

ISSN (online): 2581-3048
Volume 7, Issue 7, pp 189-195, July-2023
https://doi.org/10.47001/IRJIET/2023.707029

Comparative Numerical Analysis of Three-Dimensional Flow in the Opening Process of the Single-Disc Butterfly Valves

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***Abstract* - The comparative numerical analysis of the butterfly valve is performed to simulate the fluid flow inside the pipe. In this study, the performance of the single-disc butterfly valve flow is investigated in the opening process. The flow separation for the turbulent case is also examined to observe the velocity and pressure distributions since the unsteady flow can be understood well with an examination of the velocity and pressure changes. The formations of the vortexes are considered. In addition, an optimization study is done to decrease the operational coefficient values. In the result of the study, the characteristic parameters of the conventional and optimized valves are compared including, flow coefficient; drag coefficients, and dynamic torque. The changes of the characteristic parameters at different opening angles are demonstrated as tables and graphs to evaluate the performance of the valves.**

Keywords: Single-disc butterfly valve; Numerical analysis; Flow coefficient; Disc Characteristics; Optimization; Fluid and solid interactions.

I. INTRODUCTION

The single-disc butterfly valves are generally operated for flow control in the oil, gas, and water transportation systems. The valves consist of three basic components, which are a body, shaft, and a circular disc. Therefore, the design of valves has an impact on the usage of the valve and interaction with the fluid flow. The advantages of butterfly valves are light structural weight and running in the high flow rate. This is because the disc of the valve has low resistance in the completely opened case.

Mostly, the flow and dynamic coefficients of the butterfly valves are significant parameters for on-off cases. That is why many researchers have investigated the performance of the valve by calculating of these values. Song and Park (2007) studied the flow and the characteristic values of the butterfly valve with various opening angles using moving grid method by CFX. The similar analyses were repeated using various computational methods and opening angles. For instance, the flow coefficients were investigated at 40o and 60^o opening angle via FLUENT by Said et al. (2016). Furthermore, Leutwyler and Dalton (2006) studied the computational analysis of the single-disc butterfly valve for 45o and 75o disc positions using FLUENT. However, some numerical analyses were provided quite close results to the experimental outcomes. Azad et al. (2014) examined the coefficients of the butterfly valve at the different opening angle by performing CFX and it was obtained that the accuracy of the numerical analysis was very close the experimental results. The effect of turbulence model is significant to predict the flow behavior in the pipe. The fluid flow in the butterfly type valve was examined by $k - \varepsilon$ turbulence model and simulated using FLUENT by Kumar et al. (2015).

Two-dimensional (2D) analyses of butterfly valves provide more practical and approximate solutions (Sarpkaya, 1961). However, the obtained results from 2D analyses are not close to actual cases as much as 3D ones. Therefore, the 3D mathematical modelling has begun to use for the analysis of the butterfly valves. Furthermore, the mathematical models of butterfly valves have been advanced by researchers. For instance, Park and Chung (2005) improved the mathematical analysis of 3D torque coefficient and this provides more accurate results than the conventional methods.

In this study, the 3D-incompressible flow analysis of the valves is completed by using FloEFD. In addition, the unsteady flow in the valve has been analyzed by using dynamic method rather than static to reach better values. Therefore, the dynamic analysis is performed by moving grids that are high mesh quality technique. The meshing process is very significant to obtain the good computational grid. Afterwards, the disc of the valve is redesigned to optimize the characteristic coefficients of the butterfly valve during the opening process. In order to simulate both conventional and

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optimized butterfly valves, the moving grid technique is performed to create the dynamic analysis of the valves in the opening process. In the dynamic analysis, the pressure and velocity distributions are calculated for turbulent fluid flow on the mid-symmetric planes of the valve discs. The operational parameters of the valves, which are flowrate, drag and dynamic torque coefficients are determined. As a result, the outcomes of numerical analyses for both conventional and optimized valves are compared.

II. MATHEMATICAL MODEL

2.1. Governing Equations

In this analysis, the k-ε standard turbulence model is applied. The turbulent eddy viscosity is expressed in Equation 4 using two turbulence parameters. These are turbulence kinetic energy, k, and turbulent dissipation, ε.

The physical predictions in the flow are expressed using the conservation of momentum. The incompressible unsteady fluid motion can be described basically using Equation 1.

$$\partial\rho/\partial t + (\rho u_i) = 0 \quad (1)$$

When the preliminary equation is advanced, the following expression is extracted and represented in Equation 2.

$$\partial\rho u_i/\partial t + \partial/\partial x_i(\rho u_i u_j) + \partial p/\partial x_i = \partial/\partial x_i(\tau_{ij} + \tau_{ij}^R) + S_i \quad (2)$$

Where u is the flow velocity, p is the density, S is the mass-distributed external force, and τ is the shear stress tensor. The Reynolds-Stress tensor is expressed in Equation 3.

$$\tau_{ij}^R = \mu_t(\partial u_i/\partial x_j + \partial u_j/\partial x_i - 2/3\,\delta_{ij}\,\partial u_k/\partial x_k) - 2/3\rho k\delta_{ij} \quad (3)$$

Here, δij is Kronecker delta function and μt is the turbulent eddy viscosity coefficient.

2.2.Turbulence Modelling

In this analysis, the k-ε standard turbulence model is applied. The turbulent eddy viscosity is expressed in Equation 4 using two turbulence parameters. These are turbulence kinetic energy, k, and turbulent dissipation, ε.

$$\mu_t = f_\mu + C_\mu \rho k^2/\varepsilon \quad (4)$$

Where f_μ is the turbulent viscosity factor and C_μ, C_ε1, C_ε2, σ_ε, σ_k are constants. The empirical values of these constants are given in Table 1.

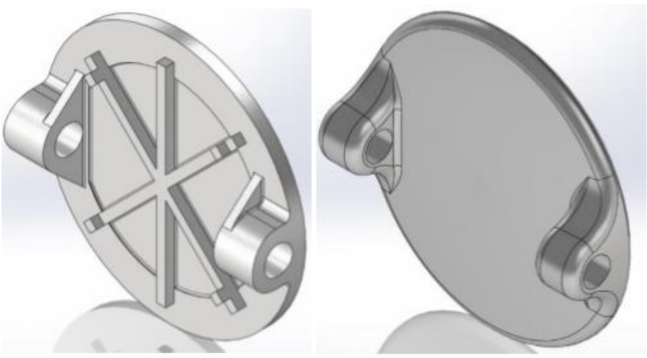
Table 1: Constants of k-ε turbulence model

C_μ	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	σ_ε	σ_k
0.09	1.44	1.92	1.30	1.00

III. OPTIMISATION

The butterfly valve conventional valves have major issues when utilizing. These are aerodynamically inconveniences, high operational force requirements, safety, strength and weighting. The flow separation occurs when the fluid passes throughout the valve. This separation causes undesired vortices behind the valve disc. The formation of the vortex is detailed in Result and Discussion section. However, the drag force is also another problem during the opening case and various operational angles. The shape and geometry of disc affect the flow characteristic and might cause high drag force.

The design criteria of the valve have a crucial impact on the other operational parameters. The required torque at opening process depends on geometrical property of the valve disc. Therefore, some improvements were necessary for conventional butterfly valve to make the on-off process easier. Furthermore, the weighting proportion of the valve components influences the working behaviors of the valve. In order to redesign weight of body assists to reduce excessive raw material usage.



(a) (b)

Figure 1: The discs of valves. (a) Conventional, (b) Optimised

When previous explanations and issues are considered, the shape and geometry of disc are improved to reduce the aerodynamically losses. In order to minimize the vortices, the proportion of the curvature height (H) and disc diameter (D) was accepted an optimization parameter for the drag coefficient. The following range supplies optimum drag values and optimizes flow separation.

$$0.04 < H/D < 0.075$$

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However, the quite reduction at the drag force cannot be obtained below 0.04. The H/D ratio of the optimised disc lies between the specified range.

Figure 2: Manufactured optimized valve

Another optimization is rearranging of the components weightings. The ratio of the disc-valve body was 0.25 for the conventional butterfly valves. This ratio has changed as 0.20 in the optimization process. Therefore, a lighter valve, which is seen in Figure 2, was manufactured.

IV. COMPUTATIONAL MODEL

In order to generate high-quality grid is one of the major subjects of the CFD studies. Much commercial software can be operated to create the tetrahedral or polyhedral, and block-hexahedral grid of the analyzed system and complete the numerical analysis.

The FloEFD can be used for all processing steps to simulate the case. The geometry-based FloEFD provides various mesh generation formats. The generation of the initial mesh is completed. The overall quality can be improved by using automatic smoothing algorithms. Also, manual re-meshing and automatic mesh editing can be used for local mesh editing.

The analyzed system, which consists of the butterfly valve and pipe, has a symmetrical geometry. That is why the half of the model can be taken for analysis. The flow area has been separated to three-part to create different mesh types. The tetrahedral/polyhedral or block-hexahedral mesh is generated for divided several different volumes. After meshing process, the CFD solver is run using the created nodes and elements with a good mesh quality. The generated grids are represented in Figure 3.

After inserting the meshed geometry in FloEFD pre-processor, the dynamic simulation, which bases on the disc rotation from completely closed to the opened position, is chosen as unsteady with time-steps of the analysis.

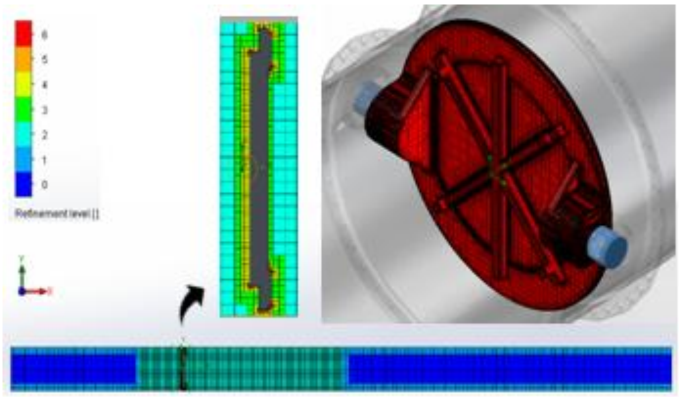

Figure 3: Computational grids of conventional valve

The fluid properties and type is also another significant computational domain. The fluid is supposed as incompressible and isothermal. As a result, the fluid is assumed water at 25oC. The fluid flow is modelled by using k – ε turbulence approach. The average inlet pressure of the water flow is detected 27.620 bars for the usual valve and 12.430 bars for the optimized valve when the disc is fully closed. The reference pressure for simulation is defined the 0-atmospheric condition.

V. RESULTS AND DISCUSSION

After results convergence in CFD solver software, the outcome files are created in the directory. However, in the transient simulation, different grid files are generated for each time steps. The parameters such as pressure, magnitude and vector of the velocity, and characteristic of the valve such as flow and drag coefficients, and dynamic torques are detected for each grid points. The results are demonstrated with contours, vectors, and streamlines.

The pressure contours on the discs show the pressure disturbance under the fluid flowing case at 0o angle. The pressure zones, which are red, yellow and blue colored, indicate the amount of the pressure. It can be investigated from Figure 4 that the pressure decreases in the gaps where are situated between the body of the valve and the disc. During opening process, the angle of the disc increases and the stagnation area occurs at the disc lower side before the other sides. Over stagnation area, the fluid goes up and accelerated and the pressure drops inversely proportional to the velocity. As the angle increases, the pressure on the discs drops. The pressure values with opening angles are given in Table 2.

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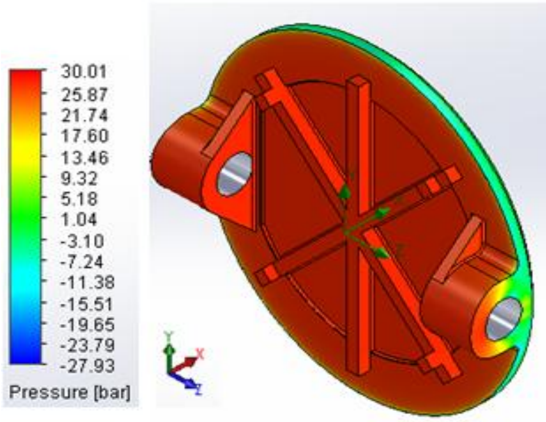
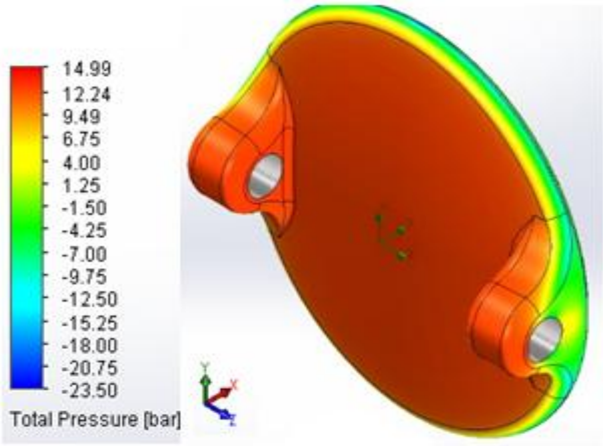


(a) Disc of conventional valve



(b) Disc of optimised valve

Figure 4: Pressure disturbance on the discs at 0° opening angle

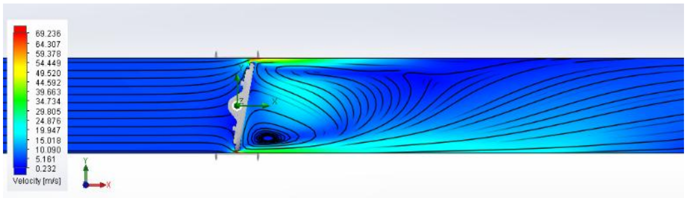
Table 2: Averaged inlet pressure at various angles

Opening Angle *θ(Degree)*	**Conventional Valve** *P(Bar)*	**Optimised Valve** *P(Bar)*
0	12.430	27.620
10	10.000	21.510
20	5.640	10.990
30	3.100	5.020
40	1.940	2.570
50	1.450	1.640
60	1.210	1.270
70	1.110	1.130
80	1.060	1.070
90	1.050	1.050

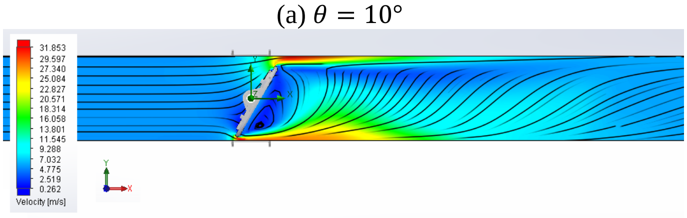
Beyond the stagnation area, the fluid speeds up and the pressure of the fluid becomes a negative value. Therefore, the boundary layer tends to separate and to compose a shear layer in the downstream region. In the field, where positive pressure gradient increases, the pressure value of the downstream becomes high as the opening angle is increased. In the negative pressure zone, the pressure decreases and it becomes negligibly small when the valve is fully opened.

After passing through the disc, the fluid velocity vectors begin to form the vortexes. Also, the fluid is assumed as incompressible so the fluid collides the disc surface and the fluid is stagnated there. Then, the flow starts to separate. During opening process, the fluid is separated into two branches and it flows in the gaps, where around the disc. The momentum in these gaps is not enough to push the boundary layer into the negative pressure gradient. Therefore, the boundary layer separates and forms a separated flow. After that, this separated flow creates the vortex. However, the fluid can flow easily from the upper gap because the lower side part of the disc blocks the flow. As a result, the vortex at the lower side is bigger and longer than the upper one.

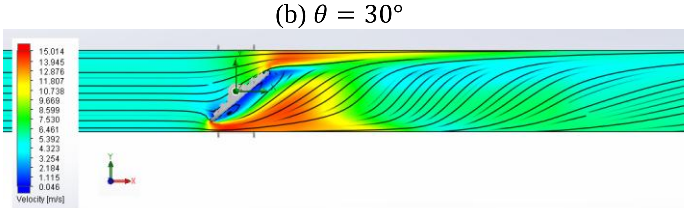
In the small opening angle, the fluid is flowing through the body of the valve and disc with high velocity but the flow velocity except in the gaps is very small. The fluid, which passed through the disc, flows from upper and lower side to center field and the clockwise direction vortexes take places due to upper side flow and the counter-clockwise vortexes are occurred by the lower downstream. When the opening angle increases, the turbulence existence around the disc becomes less. The velocity changes of both conventional and optimized valves at various opening angles are reflected in Figure 5 and Figure 6, respectively.



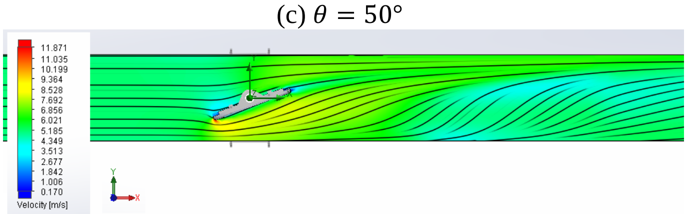
(a) $\theta = 10°$



(b) $\theta = 30°$



(c) $\theta = 50°$



(d) $\theta = 70°$

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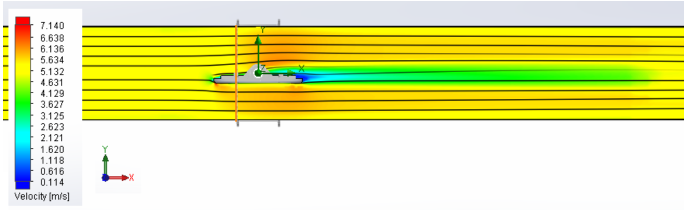
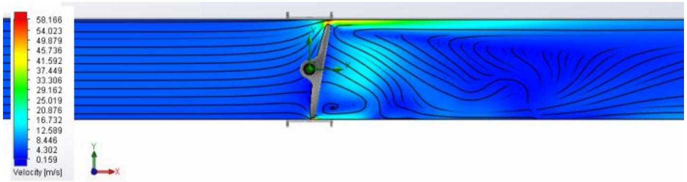
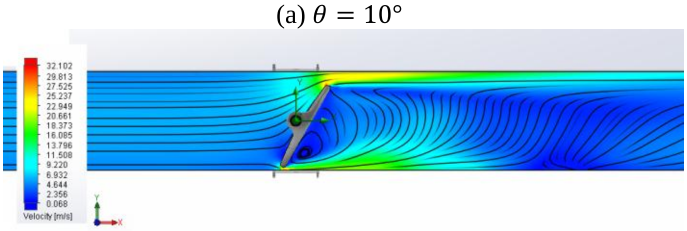


(e) $\theta = 90°$

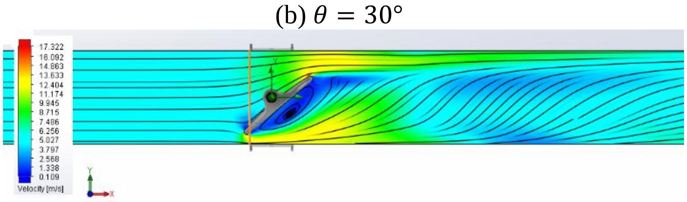
Figure 5: Velocity vectors of conventional valve disc mid-plane at various opening angles



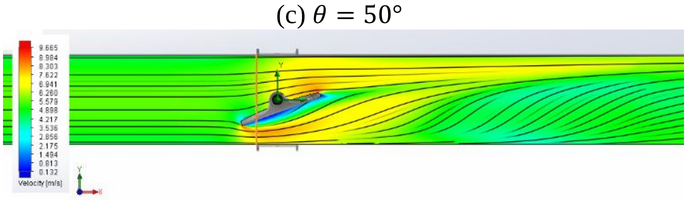
(a) $\theta = 10°$



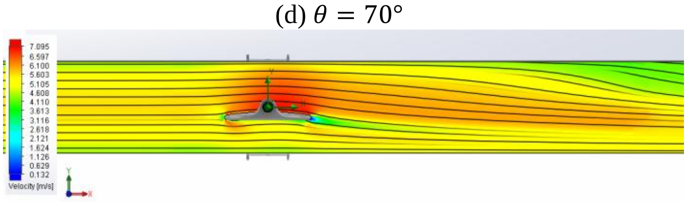
(b) $\theta = 30°$



(c) $\theta = 50°$



(d) $\theta = 70°$



(e) $\theta = 90°$

Figure 6: Velocity vectors of optimized valve disc mid-plane at various opening angles

The flow coefficient (Cv) also increases when the valve is opening. This coefficient is a mathematical expression of the disc design and the valve size. However, the dynamic torque of the valve decreases when the valve is opening. The other parameter is the drag force. When the valve is fully closed, the drag force depends on the upper and lower stream pressure differences and the diameter of the disc so the drag force can be detected at 0o opening angle. The drag force decreases quickly when the valve opening angle increases but the drag force begins to rise at 90^{o}. This is because, when the disc is fully opened, the viscous flow occurs around the disc.

Table 3: Monitored parameters

(a) Conventional valve

Opening Angle *θ(Degree)*	**Drag Coefficient** *(C_d)*	**Drag Force** *(N)*
0	229.119	8208082.634
10	178.33	6328703.566
20	89.958	3062758.132
30	38.383	1218505.854
40	16.405	466325.61
50	7.472	181758.824
60	3.582	70649.905
70	1.811	27154.672
80	0.998	10084.505
90	1.019	5737.088

(b) Optimized valve

Opening Angle *θ(Degree)*	**Drag Coefficient** *(C_d)*	**Drag Force** *(N)*
0	97.105	3477831.365
10	78.544	2765437.601
20	41.912	1413225.612
30	19.913	652884.018
40	9.711	273169.938
50	4.943	119760.096
60	2.579	51433.184
70	1.442	22154.024
80	0.837	8755.770
90	0.947	5884.148

As mentioned previous explanations, the fluid flow has various same physical behaviors due to the valve opening angle. However, the optimization has assisted to improve the flow coefficients when the flow passes through the valve disc. The data of both analyses of the conventional and optimized valves is monitored using FloEFD post-processor. The newly designed disc causes low drag coefficient at low opening angles. However, when the operation angle is increased, the almost equal values are detected for both valves. Furthermore, other monitored data has the same trend as the drag coefficient. The extracted data is indicated in Table 3.

When simulation results of conventional and optimized valves are compared, the operational values dramatically decrease. Figure 7 represents a comparison of drag coefficients of valves. The drag coefficient of the conventional butterfly valve is greater than optimized one at the low opening angle. However, the drag coefficients of both valves reduce and these values are almost equal at 60o. The inlet pressure changes due to the opening angles have the same trend as seen Figure 8.

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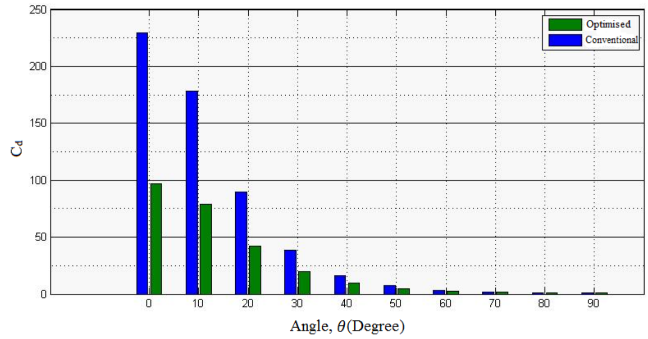

Figure 7: Cd vs Angle Change

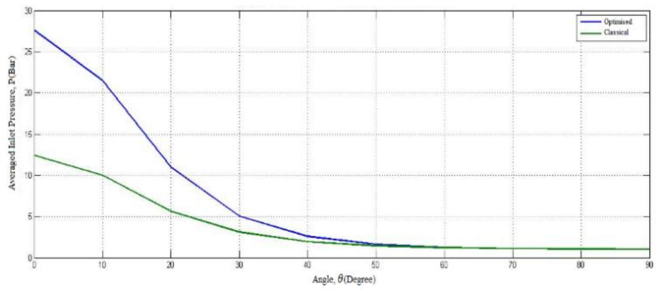

Figure 8: Averaged Inlet Pressure Change vs Angle

As a result, the conventional valves have some aerodynamically issues. Therefore, the flow physics is affected negatively due to existing drag, vortices, swirls, and so on. The operational parameters have lower values when the valve is optimized. Moreover, the new butterfly valve is manufactured by less raw material and weighting. This is also a positive effect on on-off operations.

VI. CONCLUSION

The analysis of the incompressible flow, where is passing through a single-disc butterfly valve, is studied as dynamically. In order to simulate dynamic movements, the moving grids are generated. Afterwards, the pressure differences on the disc surface and flow separation around the disc in the opening process is demonstrated. The pressure gradients occur and the boundary layers are separated around the edge of the disc. Therefore, the turbulence in the separated flow causes the vortexes but these swirls become weaker when the valve is opening. These characteristic parameters of the single-disc butterfly valve in a flow are studied. The conventional butterfly valve was analyzed using a numerical method. It is obtained that the valve affects the flow coefficients and the values are quite great. Therefore, an optimization was done for the disc of the valve to reduce the coefficients at various operational angles. As below;

1) The averaged inlet pressure, drag and flow coefficient, and torque values are improved.
2) The structure of valve optimized and lighter flow equipment designed.
3) The optimized butterfly valve was produced and tested.

Consequently, this study covers the dynamic and numerical analysis and optimization of the single-disc butterfly valve. The analysis was performed to provide the base data for the next valve improvement study.

ACKNOWLEDGEMENTS

This work is derived from the Master's thesis titled Optimization of butterfly valves and design of a new butterfly valve. I would like to thank the authors Hakan Gökmeşe and Mehmet Kayrıcı for their comments on the paper and contributions to the literature.

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Citation of this Article:

Onur GÖK, Hacı Ali ERTAŞ, Mehmet KAYRICI, Hakan GÖKMEŞE, "Comparative Numerical Analysis of Three-Dimensional Flow in the Opening Process of the Single-Disc Butterfly Valves" Published in *International Research Journal of Innovations in Engineering and Technology - IRJIET*, Volume 7, Issue 7, pp 189-195, July 2023. Article DOI https://doi.org/10.47001/IRJIET/2023.707029

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