Numerical study of solid particle erosion in butterfly valve

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Abstract. In the actual operation of butterfly valve, the butterfly valve is found severe erosion wear. A solid particle erosion analysis of butterfly valve based on the erosion theory is researched in this study. A CFD model has been built to simulate the flow erosion. Different parameters of butterfly valve including inlet velocity, particle mass fraction and solid particle diameter are separately analysed. The results show that erosion rate increase with the increase of inlet velocity, particle mass fraction and solid particle diameter. The peak erosion rate is up to 4.63E-5 (kg/m²/s) and erosion of valve disc mainly occurs around the upstream edge and the cylinder face.

1. Introduction
Butterfly valve has advantages of simple structure, small volume, light weight and low cost, which has been widely applied in the industry. In the nuclear power station, butterfly valve is usually used to the circulation water filtration system and is found serve erosion wear frequently which would lead to functional failures and threaten the cooling water supply of nuclear power station. So it is essential to study the influencing parameters on flow erosion of butterfly valve.

Erosion wear of valve is an important issue for the valve industry which causes the concern of researchers [1]–[3]. Solid particle erosion is one of main reasons of erosion wear [4]–[6] and studies of solid particle erosion of valves with different influencing parameters [7]–[9] are highly performed. However, Solid particle erosion of butterfly valve is rarely studied at present.

Since erosion flow features of butterfly valve, especially for erosion rate are highly difficult to obtain by experiment. In this study, a numerical model of butterfly valve based on the solid-liquid two-phase flow theory has been built to simulate the flow erosion in FLUENT and erosion rates under different parameters including inlet velocity, particle mass fraction and solid particle diameter are discussed separately.

2. Theoretical models
The Computational Fluid Dynamics (CFD) model of butterfly valve is simulated by FLUENT. The k-ε model and discrete phase model are used in numerical analysis and theories of these models are described as follows.

2.1. k-ε model
There are three k-ε models in FLUENT including standard k-ε model, RNG k-ε model realizable k-ε model. The standard k-ε model has characters of robustness, economy reasonable accuracy for a wide range of turbulent flows which leads to widely using in industrial flow simulations. In this study, the standard k-ε model [10] is usually used to simulate turbulent flow.

The turbulent viscosity equation can be written as
\[ \mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \]  

where \( \rho \) is the fluid density, \( C_\mu \) is a constant, \( k \) is the turbulent kinetic energy, \( \varepsilon \) is the dissipation rate of \( k \).

The turbulent kinetic energy and its rate of dissipation can be obtained from the following transport equations:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_j} (\rho k u_j) = \frac{\partial}{\partial x_j} \left( \left( \mu + \mu_t \right) \frac{\partial k}{\partial x_j} \right) + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_j} (\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left( \left( \mu + \mu_t \right) \frac{\partial \varepsilon}{\partial x_j} \right) + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_{3\varepsilon} G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon
\]

in which \( G_k \) is the generation of turbulence kinetic energy due to the mean velocity gradients, \( G_b \) is the generation of turbulence kinetic energy due to buoyancy, \( Y_M \) is the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, \( C_{1\varepsilon}, C_{2\varepsilon}, C_{3\varepsilon} \) are constants, \( \sigma_k \) and \( \sigma_\varepsilon \) are the turbulent Prandtl number for \( k \) and \( \varepsilon \), \( S_k \) and \( S_\varepsilon \) are user-defined source terms.

2.2. Discrete phase model

2.2.1. Equations of motion for particles. Fluent predicts the trajectory of a discrete phase particle by integrating the force balance on the particle, which is written in a Lagrangian reference frame. This force balance equates the particle inertia with the forces acting on the particle can be written as

\[
\frac{d\bar{u}_p}{dt} = F_D (\bar{u} - \bar{u}_p) + \frac{\bar{g} (\rho_p - \rho)}{\rho_p} + \bar{F}
\]

where \( \bar{F} \) is an additional acceleration term, \( F_D (\bar{u} - \bar{u}_p) \) is the drag force per unit particle mass, \( \bar{u} \) is the fluid phase velocity, \( \bar{u}_p \) is the particle velocity, \( \rho_p \) is the density of the particle.

2.2.2. Particle erosion and accretion theory [11]. Particle erosion and accretion rates can be monitored at wall boundaries. The erosion rate is defined as

\[
R_{erosion} = \sum_{p=1}^{N_{particles}} \frac{\dot{m}_p C(d_p) f(\alpha) v^{b(v)}}{A_{face}}
\]

in which \( \dot{m}_p \) is the particle mass flow, \( C(d_p) \) is a function of particle diameter, \( \alpha \) is the impact angle of the particle path with the wall face, \( f(\alpha) \) is a function of impact angle, \( v \) is the relative particle velocity, \( b(v) \) is a function of relative particle velocity \( A_{face} \) is the area of the cell face at the wall.

![Figure 1. Geometry model of butterfly valve.](image)

3. Numerical simulations
3.1. Geometry model
To accurately simulate the solid particle erosion of butterfly valve, the geometry model is built at real size and the upstream length and downstream length of butterfly valve are five times and ten times of pipe diameter, respectively. The geometry model of butterfly valve is shown in Figure 1.

3.2. Mesh model
Figure 2 shows the mesh model of butterfly valve at the opening angle 45°. Both tetrahedral element and hexahedral element are used to the mesh model. Around the valve disc, the velocity gradient has a drastic change when fluids flow through the butterfly valve. Therefore, this zone’s mesh is smaller than other zones and is mainly comprised of tetrahedral element. Finally, the mesh model owns 289,880 elements and 56,439 nodes, respectively.

3.3. Boundary conditions and solution method
Velocity inlet and pressure outlet boundary conditions are used for the inlet and outlet of the numerical model and valve opening angle is set to 45°. Inlet velocity, particle mass fraction solid particle diameter are variable to separately study the effects of different factors. All solid walls including piping wall and valve disc wall have no-slip boundary conditions fluid gravity is considered in simulation model.

The standard k-\( \varepsilon \) model and discrete phase model are used to simulate turbulent flow and particle trajectory. The SIMPLE algorithm is adopted to pressure-velocity coupling. The QUICK scheme is applied for volume fraction. The PRESTO! scheme is used for pressure.

4. Numerical results and discussion
The solid particle erosion model has been calculated in FLUENT. Different parameters including inlet velocity, particle mass fraction and solid particle diameter are discussed successively. At inlet, velocity is separately set to 10m/s, 20m/s and 30m/s to observe the effect of inlet velocity. Particle mass fraction is separately set to 1%, 2%, 3%, 4% and 5%. Solid particle diameter is separately set to 0.05mm, 0.07mm, 0.1mm, 0.12mm and 0.15mm. Simulation results of solid erosion rate with different values of inlet velocity, particle mass fraction and solid particle diameter are shown in Figure 3-7.

Figure 3 shows that erosion rate of valve disc obviously increases with the increase of inlet velocity when the solid particle diameter and particle mass fraction keep at a certain valve. With the increase of the particle mass fraction, the erosion rate rapidly increases and the peak erosion rate is up to 4.63E-5 (kg/m²/s) with inlet velocity \( v_{in}=30\) m/s, particle mass fraction \( \eta=5\% \) and solid particle diameter \( d_p=0.1\)mm. Effects of solid particle diameter and inlet velocity can be observed in Figure 4. Erosion rate regularly becomes larger with the increase of solid particle diameter shown in Figure 4.

Figure 5-7 vividly show the distribution of solid particle erosion and the erosion intensity of valve disc is highly enhanced with the increase of inlet velocity shown in Figure 5. Erosion mainly occurs around the upstream edge and the cylinder face of valve disc which can be seen in Figure 5. The same trend can be found in particle mass fraction and solid particle diameter shown in Figure 6-7.
Figure 3. Erosion rate of butterfly valve at different inlet velocity $v_{in}$ and particle mass fraction $\eta$ with solid particle diameter $d_p=0.1$ mm.

Figure 4. Erosion rate of butterfly valve at different inlet velocity $v_{in}$ and solid particle diameter $d_p$ with particle mass fraction $\eta=3\%$.

Figure 5. Erosion rate at different inlet velocity $v_{in}$ with solid particle diameter $d_p=0.1$ mm and particle mass fraction $\eta=3\%$.

Figure 6. Erosion rate at different particle mass fraction $\eta$ with inlet velocity $v_{in}=20$ m/s and solid particle diameter $d_p=0.1$ mm.

Figure 7. Erosion rate at different solid particle diameter $d_p$ with inlet velocity $v_{in}=20$ m/s and particle mass fraction $\eta=3\%$. 

$v_{in}=10$ m/s
$v_{in}=20$ m/s
$v_{in}=30$ m/s

$\eta=1\%$
$\eta=2\%$
$\eta=3\%$
$\eta=4\%$
$\eta=5\%$

$d_p=0.05$mm
$d_p=0.07$mm
$d_p=0.1$mm
$d_p=0.12$mm
$d_p=0.15$mm
5. Conclusions
In this paper, a solid particle erosion analysis of butterfly valve based on the erosion theory is investigated and a CFD model of butterfly valve has been built to simulate the solid particle erosion. Different parameters of butterfly valve including inlet velocity, particle mass fraction and solid particle diameter are separately analyzed. From the study above, the following conclusions can be drawn:

(i) With increase of inlet velocity, particle mass fraction and solid particle diameter, erosion rate of valve disc increases, regularly. The peak erosion rate is up to 4.63E-5 (kg/m²/s).
(ii) The erosion intensity is highly enhanced with the increase of inlet velocity, particle mass fraction and solid particle diameter.
(iii) Erosion of valve disc mainly occurs around the upstream edge and the cylinder face. To improve the erosion of butterfly valve, it can use the corrosion resistance of material at the specific location of valve disc and efficiently modified the parameters of valve.

Acknowledgments
The authors gratefully acknowledge the anonymous reviewers and associate editors for their suggestions to improve the article. This research was supported by China Nuclear Power Technology Research Institute.

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