Numerical investigation on cavitation in pressure relief valve for coal liquefaction

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Abstract. The pressure relief valve for regulating the level of the high-pressure separator works under a pressure difference up to 15 MPa in the temperature of 415 °C. Severe cavitation erosion and particle impact lead to the valve disc’s mass loss. In this paper, three-dimensional turbulent cavitating flows in the pressure relief valve are numerically simulated to reveal the mechanism of mass loss at valve disc. The RNG k-ε turbulence model and the mixture model with a mass transfer for cavitation are employed to simulate the cavitating flow in the pressure relief valve. The result shows that there is phase change in the pressure relief process and cavitation bubbles would be transported by high-velocity backflow to the head of valve disc. For the local pressure higher than the saturated vapor pressure, the bubbles collapse at the head of disc and cavitation erosion is formed at the head of the disc. By comparing the cases of opening of 40%, 50%, and 60%, backflow velocity and cavitation region in front of the disc decrease with the opening increase. Therefore, during the actual operation, the pressure relief valve should be kept to a relatively large opening.

1. Introduction

Cavitation, a general fluid mechanics phenomenon, would occur when the local pressure in liquid is below the saturated vapor pressure at the operating temperature [1]. The cavitation bubbles would collapse if they are transported to regions of higher pressure, generating extremely high temperatures, pressures and velocities [2-3]. If a bubble collapses near a wall, the high speed micro-jet, shock wave and pulse pressure produced may cause serious local damage [4-7].

The pressure relief valve studied is located at the bottom of high-pressure separator which is used for regulating liquid level in high-pressure separator. This type of valve is required to work under the most severe service conditions in Direct Coal Liquefaction Project. The pressure relief valve developed by the USA, which is tested on a 200-t/d H-Coal pilot unit, has a maximum service life of 693 hours. The pressure relief valve developed by Japan sintered diamond spool, which is tested on a 150-t/d pilot unit, has a maximum service life of 1008 hours. During the first commissioning of Direct Coal Liquefaction Demonstration Project, the service life of the pressure relief valve does not exceed 1 day at minimum and is not longer than 200 hours at maximum [8].

The pressure relief valve works under a pressure difference up to 15 MPa in the temperature of 415 °C in Direct Coal Liquefaction Demonstration Project which is the first megaton industrial scale.
demonstration project in the world [9]. Severe cavitation erosion and particle impact lead to the valve disc’ mass loss [10]. The surface of valve disc is treated by WC (tungsten carbide) which has a good performance resisting particle erosion, but the disc can’t bear severe cavitation erosion. The study on cavitation in pressure relief valve is of great engineering significance. Numerical simulation is a feasible choice to understand the flow characteristic compared to experiment for the severe operating condition.

In this paper, we simulate the three-dimensional turbulent cavitating flows in the pressure relief valve to reveal the mechanism of mass loss at valve disc and compare the difference of flow characteristic in the valve under different openings. Then, we analyze the mechanisms of cavitation formation and bubble collapse for various operation parameters.

2. Governing equations and numerical simulation
Numerical method is applied to study the cavitation flow in the pressure relief valve. The simulation model, governing equations, cavitation model, boundary conditions and discrete method are shown in the following part.

2.1. Geometrical model
The pressure relief valve is an angle type valve. Its flow channel and coordinate system are shown in Figure 1. The origin of coordinates is on the vertex of the valve disc when the pressure relief valve is closed (opening 0%). The media flows horizontally into the valve and gravity is in \(-y\) direction. The structure of valve disc is shown in Figure 2. The head of valve disc is a part of spherical surface with an elliptical surface after.

2.2. Governing equations
When cavitation occurs, the phase change from liquid to vapor happens. A multiphase model has to be employed to describe the flow. The governing equations for a multiphase flow are based on a single-fluid approach, regarding the mixture as one liquid. The flow field is solved for the mixture continuity and momentum equations:

\[
\frac{\partial}{\partial t} (\rho_m) + \nabla \cdot (\rho_m \mathbf{v}_m) = 0
\]  

(1)

\[
\frac{\partial}{\partial t} \rho_m \mathbf{v}_m + \nabla \cdot \left( \rho_m \mathbf{v}_m \mathbf{v}_m \right) = -\nabla p + \nabla \cdot \left[ \mu_m \left( \nabla \mathbf{v}_m + \nabla \mathbf{v}_m^T \right) \right] - \rho_m g
\]  

(2)

Here the mixture density \(\rho_m\) and \(\mu_m\) are defined as:

\[
\rho_m = \alpha \rho_v + (1 - \alpha) \rho_l
\]  

(3)

\[
\mu_m = \alpha \mu_v + (1 - \alpha) \mu_l
\]  

(4)

where the subscripts \(m\), \(v\), and \(l\) represent mixture, vapour and liquid phase respectively.
2.3. Cavitation model
The cavitation model employed here is developed by Schnerr & Sauer[11]. The liquid-vapor mass transfer is governed by the vapor transport equation:

\[
\frac{\partial}{\partial t}(\alpha, \rho_v) + \nabla \cdot (\alpha, \rho_v \mathbf{v}_v) = R_e - R_c
\]

where the mass transfer source terms \(R_e\) and \(R_c\) are connected to the growth and collapse of the vapor bubbles respectively.

The source terms are derived from the Rayleigh-Plesset equation and are defined as:

\[
R_e = \frac{\rho \rho_v}{\rho} \alpha (1-\alpha) \frac{3}{R_b} \left( \frac{2(p_v - p)}{3\rho_v} \right), \text{ when } p_v \geq p
\]

\[
R_c = \frac{\rho \rho_v}{\rho} \alpha (1-\alpha) \frac{3}{R_b} \left( \frac{2(p - p_v)}{3\rho_v} \right), \text{ when } p_v \leq p
\]

2.4. Discrete method
The numerical simulations are performed by using general CFD code Fluent. The RNG \(k-\varepsilon\) turbulence model and standard wall function are used in this study. The convective term is discretized by second-order upwind method and the diffusion term is approximated with central difference scheme. The PISO method is adopted to couple the pressure and velocity. The volume fraction is discretized by QUICK method.

2.5. Boundary conditions
The pressure boundary is chosen as the inlet and outlet condition. The inlet pressure is 18.7 MPa and outlet pressure is 2.9 MPa. Pipes and valve disc are set as wall boundary condition with no-slip. The inlet temperature is 415 °C and outlet temperature is 411.5 °C with variation of less than 1%. We consider the temperature in the valve is constant and ignore the effect of temperature variation. The rated travel of the pressure relief valve is 100 mm and normal opening is 40%~60%. In the numerical simulation, we compute the case of opening 40%, 50% and 60% to study its flow characteristic. The operating fluid property of the pressure relief valve is shown in Table 1.

### Table 1. Operating fluid property of the pressure relief valve.

| Property                        | Vapor | Liquid |
|---------------------------------|-------|--------|
| Saturated vapor pressure (MPa)  | 2.0   |        |
| Density (kg·m⁻³)                | 35.5  | 680.9  |
| Dynamic viscosity (kg·m⁻³·s⁻¹)  | 2.08×10⁻⁵ | 1.4×10⁻⁴ |

3. Results and analysis

3.1. Flow field under the opening 40%
The pressure energy is converted into kinetic energy when the high pressure media flow through the throttle. Phase change would occur where the pressure is lower than saturated vapor pressure. The throttle area is regulated by changing the opening of the valve and then the flow rate is adjusted correspondingly to maintain the liquid level of the high-pressure separator to be stable.

Figure 3 shows the contours of the mixture pressure from different views and from which we can obtain a three-dimensional impression of the flow field in the pressure relief valve. The pressure at the inlet is 18.7 MPa and it drops significantly in the throttle section. The minimum pressure on the surface near the head of the disc and downstream is under the saturated vapor pressure where the phase change takes place first. There is a region of high pressure in front of the disc and maximum pressure reaches 6 MPa. Thus, there exists a pressure gradient toward the head of valve. The pressure
on the head of valve disc is about 5 MPa which is much higher than the saturated vapor pressure, so the cavitation bubbles would collapse and cavitation erosion forms if they are transported to the head of valve disc.

**Figure 3.** Contours of mixture pressure (Pa): (a) z=0 plane from front view; (b) y=0 plane from top view.

Figure 4 shows the contours and streamline of mixture velocity on z=0 plane from front view and y=0 plane from top view. The results show that there is an obvious increase of velocity when the media flows through the throttle and the maximum velocity reaches 220 m/s. There exist vortices in front of disc and the backflow velocity ups to 75 m/s. The pressure gradient mentioned before speeds up the backflow velocity. The high-velocity backflow would not only transport the bubbles to the head of disc leading to cavitation erosion, but also promote the solid particles to impact the surface of disc.

**Figure 4.** Contours of mixture velocity (m/s): (a) z=0 plane from front view; (b) y=0 plane from top view.

**Figure 5.** Contours of liquid volume fraction: (a) z=0 plane from front view; (b) y=0 plane from top view.

Figure 5 shows the liquid volume fraction contours and streamline of mixture on z=0 plane from front view and y=0 plane from top view. As the sum of liquid volume fraction and vapour volume

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fraction is 1, we can also get information of vapour volume fraction in Figure 5. There exist cavitation regions at the head of disc and downstream of the valve. The throttle area decreases due to the cavitation which leads to the degradation of valve flow performance. The cavitation bubbles drown by the high-velocity backflow would impact the head of disc. As the pressure on the head of valve disc is much higher than the saturated vapor pressure, cavitation bubbles transported to the disc would severely collapse and cavitation erosion is formed.

3.2. Comparison of different opening

The velocity in front of the disc is nearly axisymmetric, so we use the x-velocity component on the centreline to analysis the backflow region and the variation of backflow velocity. Figure 6 shows the x-velocity component of mixture on the centreline for opening 40%, 50% and 60%. In order to clearly compare the backflow in front of disc, we move the coordinate system along x-axis to the vertex of disc during the post processing of the data. The sign of velocity means the flow direction and positive represents that the flow is along the x-axis. The starting point of backflow under opening 40%, 50% and 60% are about 14 mm, 8 mm and 3 mm from disc vertex respectively. The maximum backflow velocities are 75 m/s, 37 m/s and 21 m/s respectively. It is found that not only the backflow region, but also the magnitude of the velocity decreases with the opening increase. The velocity downstream becomes larger, because the increasing of opening leads to a larger flow rate.

Figure 6. X-velocity component of mixture on the centreline

Figure 7 shows the liquid volume fraction on the head of valve disc from left view. The vapor forms an annular on the head of valve disc. The volume fraction of vapor increases firstly and then decreases from outside to inside. It results from that cavitation initiates on the outside and then bubbles collapse on the inside. It is seen that cavitation on the disc is gradually reduced with the opening increase.

Figure 7. Liquid volume fraction on valve disc from left view: (a) opening 40%; (b) opening 50%; (c) opening 60%.
3.3. Damaged feature of the disc

Figure 8 shows the pictures of the damaged disc of high pressure relief valve from different views. Compared with the initial structure shown in Figure 2, the valve disc has a serious mass lose in the forepart and forms a concave shape surface where there are small pits on the concaved surface. The concave shape surface would not appear in the forepart without the high-velocity backflow. The high-velocity back flow that transports bubbles and particles to the head of disc is an important factor leading to cavitation erosion and particle erosion on the valve disc. The computation results have captured the cavitation erosion to the valve disc. According to these results, during the actual operation, the pressure relief valve should be kept to a relatively large opening to reduce the backflow and cavitation.

4. Conclusion

In this paper, we numerically investigate the three-dimensional turbulent cavitating flow in the pressure relief valve used in Direct Coal Liquefaction Demonstration Project and reveal the mechanism of cavitation erosion at valve disc. It is found that there exist cavitation regions at the head of disc and downstream of the valve disc. The high-velocity backflow in front of the disc drives the cavitation bubbles impacting the head of disc. For the local pressure higher than the saturated vapor pressure, the bubbles collapse at the head of disc and cavitation erosion is formed at the head of the disc. The computation results and analyses are accordance with the damaged feature of the disc found in actual operation. By comparing the cases of opening of 40%, 50%, and 60%, backflow velocity and cavitation region in front of the disc decrease with the increase of opening. Therefore, the pressure relief valve should be kept to a relatively large opening during the actual operation.

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