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The impact of inlet flash evaporation conditions on erosion damage characteristics of coal gasification black water angle valve and prevention strategies

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Abstract. In view of the three-stage flash evaporation system of the coal gasification plant, a combination of theoretical analysis and numerical simulation was used to establish the erosion damage evaluation model in the black water angle valve. The influence of the inlet flash evaporation ratio on the inlet velocity, the outlet flash evaporation ratio and the outlet velocity of the low-pressure black water angle valve are systematically studied, the mechanism of erosion damage to the carbon steel valve body by the solid medium in black water was analyzed according to the micro-cutting theory. The results show that the inlet velocity w_1, the outlet flash evaporation ratio x_2, the outlet velocity w_2 of angle valve have linear correlation with the inlet flash evaporation ratio x_1.The upstream volume erosion ratio of the angle valve at the inlet flash ratio $x_1 = 3$ wt.% is 114 times as much as that at zero inlet flash ratio. Meanwhile, the downstream volume erosion ratio of the angle valve at $x_1 = 3$ wt.% is only 2.7 times as much as that at zero inlet flash ratio. The prevention strategies to reduce the erosion damage to black water angle valve are proposed by inhibiting the inlet flash evaporation ratio and reducing the inlet flow rate etc. This study is expected to provide guidance for the erosion resistance design and operation of the black water angle valve.

Keywords: Coal gasification / the black water angle valve / inlet flash evaporation / erosion damage analysis / prevention strategies

The coal reserves is the most abundant resources among fossil fuels in China, which is much more than oil and natural gas, therefore, now coal chemical industry has entered into the process of large-scale industrialization under the overall layout of China energy strategy. Coal gasification is one of the key technologies of coal deep processing and has a significant influence on efficient and environment friendly use of coal resource. By the reaction between dry coal power or water coal slurry with oxidants, catalysts, etc. in the gasifier at high temperature and pressure, flammable gases such as CO, H_2 and CH_4 are generated and used in related fields like industrial chemicals, combined electricity generation and metallurgical reducing gas. The black water flash evaporation system of coal gasification process can efficiently handle the wastewater from gasifying wet wash and slag removal system [1,2]. Black water flash evaporation system often use black water angle valve to control the liquid level in flash tank; while flash evaporation system is constantly exposed in circumstance with high temperature, high pressure and high particle concentration [3,4]. Gas-liquid-solid multiphase flow during the flash evaporation process will cause not only seriously erosion to the inner components and rear pipe of the black water angel valve, but also noise and intense vibration [5–8], which strongly shorten the lifetime of the black water angel valve. With the consideration of listed problems, research works have been carried out by lot of scholars, representatives are: Yan Zhen et al. [9] simulated the inner flow field characteristic of the valve with k-ε standard turbulence model, and provided an improved structure solution based on the factor of the flash evaporation inside valve; since black water angel valve is similar to 90° pipe, and the velocity of inlet flow has a great impact on the pipe erosion, Peng and Cao [10] gained a sequence of factors(pipe diameter, inlet

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velocity, curvature radius, particle mass flow rate, particle diameter, average curvature radius/pipe diameter and bend direction etc.) that influence the erosion by numerical simulation methods, and also established the correlation between the Stoke number and the maximum erosion area with three collision mechanisms which explains how the Stoke number influence erosion area; Mansouri et al. [11] used an Eulerian–Lagrangian approach to perform the numerical erosion modeling of a 90° sharp bend in water–sand slurry flow. Standard wall-function and low-Re number approach were employed for resolving the near wall region, and the results showed that with low-Re number model, the accuracy of theerosion prediction resulting from small particle will be significantly improved; Guo-Fu et al. [12] did experimental research on the erosion appearance of austenitic stainless steel A182F347 under the SiO_2 and Al_2O_3 combined abrasive particle condition, hence the erosion mechanism of austenitic stainless steel A182 F347 under the liquid-solid two-phase flow system was revealed; Parsi et al. [13] pointed the fact that in H-H elbow, maximum erosion occurred at the top of the elbow's outer wall and highly related to parameters such as phase distributions, particle concentration and particle velocity under multiphase flow conditions.

In summation, this article starts with the erosion damage of low pressure black water angel valve that caused by three stage flash evaporation coal gasification system; by using a combination of theoretical analysis and numerical simulation, the effect of inlet flash evaporation conditions on erosion damage characteristics was studied, and with consideration of low pressure black water angle valve process connection method, the result shows the erosion damage mechanism of valve body. Furthermore, prevention strategy on the erosion damage of a black water angle valve is presented and numerical supports and guidance for the erosion resistance design and operation of the black water angle valveare provided.

1 Black water flash evaporation system process analysis and numerical model

1.1 Black water three-stage flash evaporation system

The black water 3-stage flash evaporation system of a dry pulverized coal gasifier (quench process) with a daily processing capacity of 2200 tons of coal is shown in Figure 1. Black water from gasification quench chamber, scrubber and separator flows into mid-pressure flash tank through mid-pressure black water angle valve LV-0101A. Low-pressure black angle valve LV-0301A and vacuum black angle valve LV-0401A are installed between mid-pressure flash tank, low-pressure flash tank and vacuum flash tank respectively to control the pressure gap and liquid level between different tanks. Meanwhile, the acid gas from flash evaporation will be split out. Then, concentrated black water flows through slag bath to separate fine slag, and reclaimed gray water will ensure an environmental friendly emission of the system.

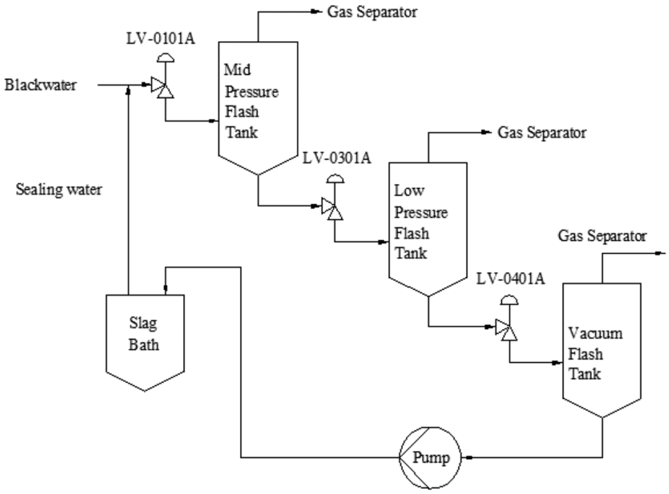

Fig. 1. The system of black water 3-stage flash evaporation.

1.2 Low pressure black water valve structure and working condition

Low pressure black water valve LV-0301A is a single-seat angel valve with the side entry and bottom exit of 10″-Class 150 (Inlet $d_1 = 254\,\text{mm}$, Outlet $d_2 = 254\,\text{mm}$). The valve body is made of carbon steel, and seat and spool are made of tungsten carbide. As shown in Figure 1, black water remains saturated at the bottom of mid-pressure flash tank, before entering the low-pressure black water angle valve, the pressure drop from connecting pipe may cause a partial flash evaporation, and accompanied with gas-liquid-solid multiphase flow. Table 1 shows the operation condition of a low-pressure black water angle valve LV-0301A, the inlet flash evaporation ration $x_1 \leq 3\text{wt.\%}$, solid content equals to 3wt.%, particle size $<200\,\mu\text{m}$. As assumption, the medium of the black water angle valve LV-0301A is considered as saturated water.

1.3 Numerical calculation model

Firstly, with computational fluid dynamics approach, a numerical simulation analysis of the gas-liquid two-phase flow inside the LV-0301A low-pressure black water angle valve is performed. According to the working conditions of the low-pressure black water angle valve, the average motion of the fluid is described by Reynolds averaged N-S equations (RANS), turbulence is described by the RNG k-ε model, and the phase change process between the liquid and gas phases is described by the evaporative condensation model. Where the transport equation for turbulent kinetic energy k and dissipation rate ε is:

$$\frac{\partial}{\partial t}(\rho k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M \quad (1)$$

Table 1. The condition of black water angle valve LV-0301A.

Parameters	Units	Condition 1	Condition 2	Condition 3
Mass flow/ W	kg/h	113609	162298	178528
Inlet pressure/ P_1	Barg	6.00	5.80	5.72
Pressure gap/ Δp	bar	3.43	3.20	3.12
Inlet Temp/ t_1	°C	164.94	163.781	163.307
Outlet Temp/ t_2	°C	139.88	139.88	139.59
Inlet liquid phase density/ ρ_{L1}	g/m^3	904.24	903.751	902.609
Inlet steam density/ ρ_{v1}	kg/m^3	3.526	3.566	3.666
Outlet liquid phase density/ ρ_{L2}	g/m^3	926.26	926.269	926.526
Outlet steam density/ ρ_{v2}	kg/m^3	1.958	1.958	1.933
Inlet liquid specific enthalpy/ h_1'	kJ/kg	690.16	692.24	697.32
Inlet steam specific enthalpy/ h_1''	kJ/kg	2761.5	2762.06	2763.29
Outlet liquid specific enthalpy/ h_2'	kJ/kg	588.71	588.71	587.43
Outlet steam specific enthalpy/ h_2''	kJ/kg	2733.6	2733.66	2733.27

$$\frac{\partial}{\partial t}(\rho\varepsilon) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right] + \rho C_1 S\varepsilon - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{\nu\varepsilon}} + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b \tag{2}$$

With: $C_1 = \max\left(0.43, \frac{\eta}{\eta+5}\right)$, $\eta = Sk/\varepsilon$, and σ_k, σ_ε are the turbulent Prandtl number of the turbulent kinetic energy and its dissipation rate, respectively; $C_{1\varepsilon}$, C_2, σ_k, σ_ε take values of 1.44, 1.9, 1.0, 1.2, respectively.

When the temperature changes, evaporation or condensation occurs in the gas and liquid phases, which leads to a mass transfer. The gas-liquid mass transfer process could be written as:

$$\frac{\partial(a_v\rho_v)}{\partial t} + \nabla\cdot(a_v\rho_v\boldsymbol{v}_v) = m_{l\to v} - m_{v\to l} \tag{3}$$

$$m_{l\to v} = coeff\cdot\alpha_l\rho_l\frac{(T - T_{sat})}{T_{sat}} \tag{4}$$

$$m_{v\to l} = coeff\cdot\alpha_v\rho_v\frac{(T - T_{sat})}{T_{sat}} \tag{5}$$

where α_ν and α_ι are gas- and liquid-phase fractions, respectively; ρ_ν and ρ_ι are gas- and liquid-phase densities, respectively; ν_ν is gas-phase velocity, $m_{l\to v}$ and $m_{v\to l}$ are masses that transformed by evaporation and condensation, respectively; T and T_{sat} are local temperature and vapor pressure corresponding temperatures, respectively. The Coeff factor represents the reciprocal of relaxation time, which is:

$$coeff = \frac{6}{d}\beta\sqrt{\frac{M}{2\pi RT_{sat}}}L\left[\frac{\rho_l}{\rho_l - \rho_v}\right] \tag{6}$$

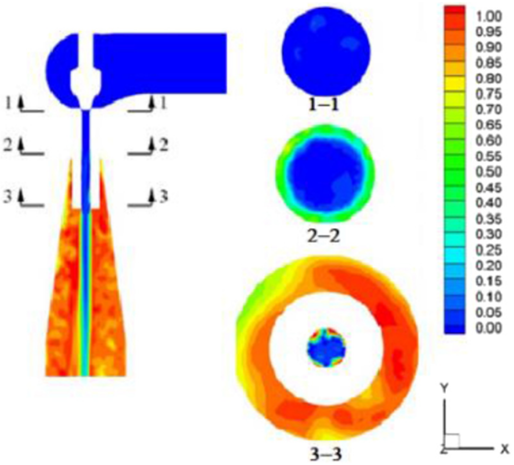

Fig. 2. The distribution of gas phase fraction in the internal flow field of black water angle valve.

where, d is the vacuolar diameter, β is a regulating factor which indicates the part of the vapor molecule that been absorbed when entering the liquid surface, M is the mass of the gas phase, R is the universal gas constant, and L is the latent heat of vaporization.

2 Low-pressure black water angle valve internal flow characteristics analysis

2.1 Gas phase fraction distribution in angle valves

The flow field gas phase fractions of a black water angle valve including a buffer tank is simulated, and the relevant parameters are as follows, $x_1 = 0$, $P_1 = 6.5$ bar, $\Delta p = 3.5$ bar, $W = 135636$ kg/h, and 40% opening, as shown in Figure 2.

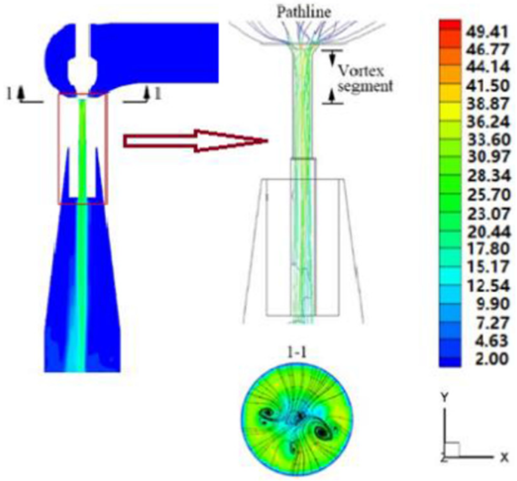

Fig. 3. The distribution of fluid velocity and motion pattern in black water angle valve.

Figure 2 shows a large amount of gas flash evaporate into venturi tube and buffer tanks downstream the valve. The cross-sections between the spool outlet and the valve outlet are divided into three, which are 1–1, 2–2 and 3–3 to show the changes of their flash evaporation rates. 1–1 is located at the spool outlet, where only the local gas phase is present in the flow field, and the maximum gas phase fraction is only 20%, with an overall flash evaporation ratio of 0.3 wt.%. The 2–2 is located upstream of the valve outlet, where the phase fraction increases and its maximum value shows around the tube, which can reach up to 70%, but the overall flash evaporation ratio is only 1.2 wt.%. The 3–3 cross section is located at the valve outlet with a maximum phase fraction of 90%, the overall flash evaporation ratio is increased to 5 wt.%.

2.2 Fluid velocity distribution in angle valves

The distribution of fluid velocity and motion pattern in black water angle valve is shown in Figure 3:

Figure 3 shows the distribution of fluid velocity in black water angel valve. As can be seen in the figure, high velocity area distributes from downstream of the spool outlet to the valve outlet section, with a low level of acceleration and an average speed of about 25 m/s. Flow rates are relatively low upstream of the valve and downstream of the valve outlet in the venturi pipe and buffer tank with intense evaporation. It can be concluded that high risk area of erosion is located from the spool to valve outlet section, where the calculation of the fluid velocity is particularly important. As can be seen from the local flow diagram as well as the flow diagram of the 1–1 cross section, there are apparently some unstable vortices near the downstream of the spool that can cause vibration and noise in the valve. Comparing with the gas phase fraction plotted in Figure 2, one can see the locations with higher gas phase fraction overlapped the center of the vortex, that is, the local flash evaporation ratio increased due to the pressure reduction caused by the vortex, which is a high risk area for erosion failure.

Fig. 4. The erosion damage morphology of upstream body of black water angle valve LV-0301A.

2.3 Anatomical validation of flow characteristic predictions

To verify the accuracy of the predicted results, a low-pressure black water angle valve was dissected after validated six months commissioning under typical operating conditions. As shown in Figure 4, the upstream body of the black water angle valve cavity is severely eroded, and the wall thickness is significantly thinner and even perforated.

Comparing Figures 2–4, it can be seen that the angle valve upstream body erosion failure area found by strip inspection is located in the narrow channel of the outlet throat of the spool, which corresponds to the area near cross-section 1–1 in Figures 2 and 3. Due to inlet flash evaporation and straight pipe throttling, the internal fluid velocity abruptly changed from nearly 9 m/s ($x_1 = 3$ wt.%) of inlet flow velocity to nearly 38 m/s of outlet flow velocity. The higher flow velocity and local vortex caused by flash evaporation are two of the main factors that cause the upstream body damage of the black water angle valve. The results of strip inspection remains consistent with numerical predictions.

2.4 Flow velocity characterization calculation

The above CFD-based numerical analysis described gives a good indication of the flow and flash characteristics in the black water angle valve, but the numerical calculations requires relatively longer time. For improving the efficiency of numerical calculation, the development of a more concise mathematical model to characterize the average flow velocity in the valve is critical for valve erosion failure analysis and erosion resistance optimization design and implementation. To facilitate the analysis, the gas-liquid two-phase flow is considered as a mixed single-phase medium, and the inlet medium mixed density ρ_{m1} of the angle valve is calculated by equation (7), while the velocity w_1 of the inlet gas-liquid mixed medium of the angle valve is calculated by equation (8).

$$\rho_{m1} = \frac{W}{\left[\dfrac{Wx_1}{\rho_{v1}} + \dfrac{W(1-x_1)}{\rho_{L1}}\right]} \tag{7}$$

$$w_1 = \frac{(W/3600)}{\left(\dfrac{\pi}{4}{d_1}^2\rho_{m1}\right)} \tag{8}$$

Assuming that the valve is isentropic throttling, with thermodynamic approach, the flash ratio of saturated liquid after throttling x_2 is calculated as shown in equations (9) and (10).

$$(1-x_1)h_1' + x_1h_1'' = (1-x_2)h_2' + x_2h_2'' \tag{9}$$

$$x_2 = \frac{[(1-x_1)h_1' + x_1h_1'' - h_2']}{(h_2'' - h_2')} \tag{10}$$

With inlet liquid specific enthalpy h_1'; inlet steam specific enthalpy h_1''; outlet liquid specific enthalpy h_2' and outlet steam specific enthalpy h_2''.

The mixing density ρ_{m2} of the outlet medium of the angle valve is calculated according to equation (11), and the velocity of the outlet gas-liquid mixing medium of the angle valve is calculated according to equation (12).

$$\rho_{m2} = \frac{W}{\left[\dfrac{Wx_2}{\rho_{v2}} + \dfrac{W(1-x_2)}{\rho_{L2}}\right]} \tag{11}$$

$$w_2 = \frac{(W/3600)}{\left(\dfrac{\pi}{4}{d_2}^2\rho_{m2}\right)} \tag{12}$$

Considering different inlet flash ratios x_1, the data in Table 1 are substituted by equations (7)–(12) separately, to obtain different inlet velocity w_1 and outlet velocity w_2 for the evaluation of the black water angle valve.

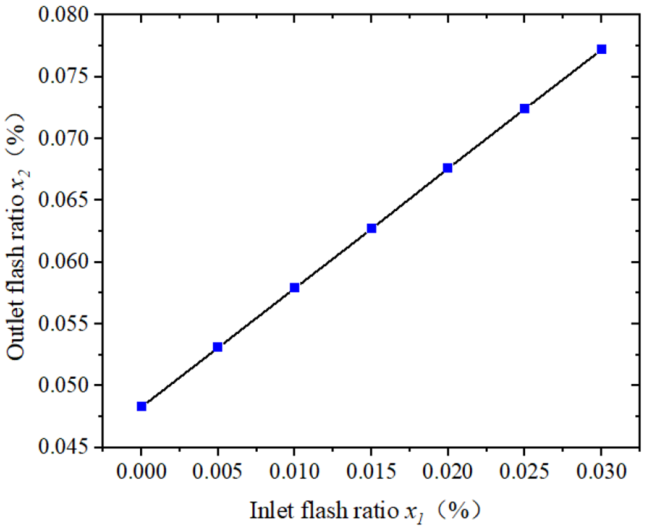

Fig. 5. The effect of inlet flash ratio x_1 on outlet flash ratio x_2.

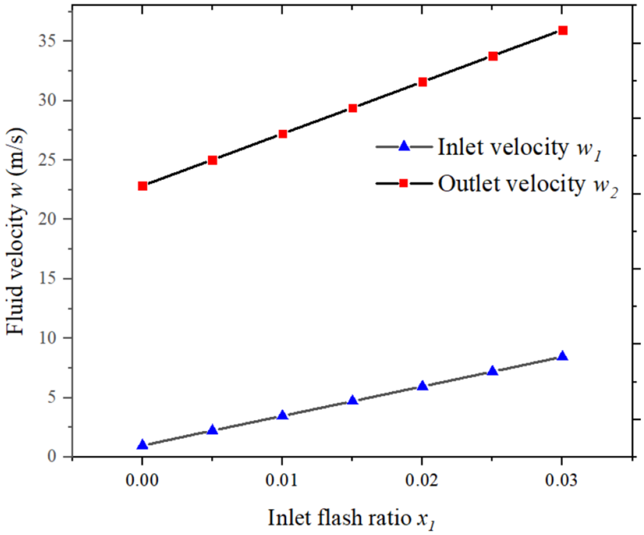

Fig. 6. The effect of inlet flash ratio on velocity.

3 Prevention and control strategies of erosion damage in black water angle valve

3.1 Evaluation of erosion damage under variable working conditions

In order to analyze and evaluate the erosion caused by rigid particles in carbon steel valve body, the following equation for the erosion rate m is concluded as a function of the inlet angle α [14,15]:

$$m = \frac{cM}{p} f(a) v_s^n (n = 2.2 \sim 2.4) \tag{13}$$

where c is the particle fraction, M is the mass of the particle, v_s is the particle velocity and p is the elastic flow pressure between the particle and the target. When only considering the change of particle velocity, equation (13) shows that the volumetric erosion rate m of the carbon steel valve body of black water angle valve is positively correlated with the velocity of solid particles v_s powered by n, and $n = 2.2$ is picked for further calculation.

The inlet flash ratio x_1 has an effect on w_1, x_2, w_2; for a common working condition in Table 1, when different x_1 substitute into equations (7)–(12), the relationship between outlet flash ratio x_2 and the inlet flash ratio x_1, the inlet velocity w_1 (outlet velocity w_2) and the inlet flash ratio x_1 can be obtained respectively, as shown in Figures 5 and 6.

As shown in Figure 5, when the inlet flash ratio x_1 is 0%, the corresponding outlet flash ratio x_2 is 4.83 wt.%; when $x_1 > 0$, the outlet flash ratio x_2 follows the equation: $x_2 \approx x_1 + 4.83\%$. As shown in Figure 6, when the inlet flash ratio

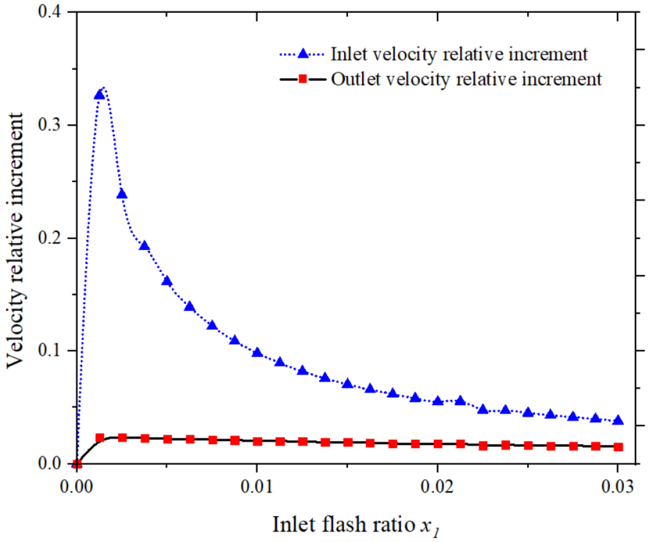

Fig. 7. The effect of inlet flash ratio on relative increment.

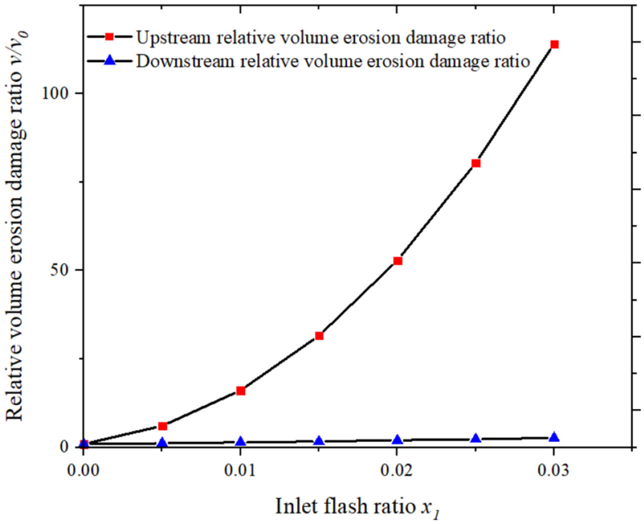

Fig. 8. The effect of inlet flash ratio on upstream and downstream relative volume erosion damage ratio.

of medium increases by every $\Delta x_1 = 0.5\%$, the inlet and outlet velocity w_1, w_2 will be increased by 1.24, 2.20 m/s respectively.

For further discussion and analyzing the connection between the inlet flash ratio x_1 and the inlet and outlet velocity of the black water angle valve, the relationship between the inlet flash ratio and the relative increment of the inlet and outlet velocity is graphed, as shown in Figure 7. Observing Figures 6 and 7, we can see that when $x_1 = 0.125$ wt.%, the inlet and outlet flow rates w_1 and w_2 of the angle valve are 1.30 and 23.39 m/s respectively, and their relative increments are 32.65% and 2.36% respectively. As x_1 continues to increase, the inlet and outlet flow rates increase linearly, but the relative increase in flow rate gradually slows.

According to the rigid particles erosion rate of the carbon steel valve body expressed in equation (13), comparing the upstream and downstream volume erosion damage ratios at $x_1 = 0$ and $x_1 > 0$, the correspondence effect of inlet flash ratio on upstream and downstream relative volume erosion damage ratio is obtained, as shown in Figure 8.

In Figure 8, the upstream relative volume erosion damage ratio of the angle valve at $x_1 = 3$ wt.% is 114 times as much as that at $x_1 = 0$. Obviously, the high-speed flash flow which formed by the flash evaporation of the liquid phase on upstream of the valve causes a significant damage to the upstream valve, especially in the vortex area near the throat of the valve body. While the downstream relative volume erosion damage ratio of the angle valve at $x_1 = 3$ wt.% is only 2.7 times as much as that at $x_1 = 0$, it can be expected that the increase of inlet flash ratio has a relative small effect on the erosion damage to the downstream valve.

3.2 Prevention and control strategies of erosion damage

According to the working conditions listed in Table 1, the gas phase fraction at the inlet of the black water angle valve is an important factor in the destruction of the valve body upstream of the angle valve. First, the inlet flash ratio should be inhibited as small as possible; at the same time, prevention strategies such as increasing the inlet diameter or enlarging the middle cavity of the valve body to reduce inlet impact velocity, hardening the upstream of the angle valve to resist the impact abrasion, and distributing the flow guide device to disperse the impact of the inlet fluid are also adopted. As the black water of the three-stage flash evaporation system is recycled, lack of the freshwater replenishment may cause the corrosive water leading to an erosion and corrosion coupling damage. Thus, it is suggested to replace the carbon steel valve body with stainless steel to improve the corrosion resistance of the low-pressure black water angle valve.

4 Conclusion

- For the internal flow characteristics of the three-stage flash evaporation system of coal gasification, CFD numerical simulations were used to obtain the distribution of gas phase fractions and flow velocities inside the black water angle valve under typical working conditions, and the numerical predictions confirm that the upstream area near the valve trim is a high-risk area for erosion, and the dissection results remain consistent with the predicted results.
- A characterization model of the erosion was developed, and the effect of the inlet flash ratio on the outlet flash ratio and the inlet/outlet velocity of black water angle valve was obtained. The outlet flash ratio, inlet and outlet velocity increase linearly with the increase of inlet flash ratio. When the inlet flash rate is 0.125 wt.%, the inlet flow rate and outlet flow rate are 1.3 and 23.39 m/s respectively, and their relative changes amount to 32.65% and 2.36% respectively. As the inlet flash ratio increases, velocity increases linearly, but the relative increment of velocity slows down;

- The upstream volume erosion ratio of the angle valve at $x_1 = 3\,\text{wt.\%}$ is 114 times as much as that at $x_1 = 0$. Meanwhile, the downstream volume erosion ratio of the angle valve at $x_1 = 3\,\text{wt.\%}$ is only 2.7 times as much as that at $x_1 = 0$, so the damage on upstream valve body caused by increasement of inlet flash ratio is more severe than the damage on downstream valve body.
- Inhibiting the inlet flash ratio as small as possible, increasing the valve inlet diameter, appropriately expanding the valve body cavity, hardening treatment of upstream angle valve, using deflector to disperse inlet fluid erosion, using stainless steel valve body and other strategies would reduce or avoid erosion damage to the upstream body of black water angle valve.

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