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A combined numerical-experiment investigation on the failure of a pressure relief valve in coal liquefaction

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ABSTRACT

In a direct coal liquefaction unit, pressure relief valves locate on the pipeline between the atmospheric and vacuum towers. Failures of the valve components occur frequently owing to the harsh operation conditions. A combined numerical-experiment investigation on the failures of valves is conducted in this paper. The variation of relative erosion rates of WC–Co coating with impact angles, the function of relative particle velocity, and the distribution of particle diameters are obtained from the high-temperature erosion experiments. Furthermore, the erosion mechanism of WC–Co coating under large impact angles is clarified. In the numerical simulation, the evaporation–condensation, particle motion, erosion, and the modified RNG k-ε turbulence models are used to analyze the phase transition and particle erosion in the valves. Results showed that: due to the high pressure drop and convergent–divergent structure of angle valve, the coal-oil slurry flashes as it enters into the valves. The evaporation of liquid oil produces a large amount of vapor oil, and results in a rapid increase in flow velocity. High concentration solid particles, driven by the high-speed stream, tend to erode the inner surface of valves. Severe erosion can be found in the spool of angle valve, downstream bushings at the angle valve and ball valve. The calculation results agree well with actual failure morphologies, verifies the accuracy of the present prediction method.

1. Introduction

Solid particles (involve coal pulverized, residue, catalysts, and etc.) exist in the whole technical process of direct coal liquefaction [1]. Under high temperature and pressure drop conditions, these particles tend to be accelerated by high speed flow, and wear the inner surface of pipelines and valves. Pressure relief valves, locate on the pipeline between atmospheric and vacuum tower, are consisted of an angle valve, ball valve and connected pipes. In order to mitigate erosion and extend service life of valves, hard and wearable bushings are installed on the downstream from angle valve and ball valve. However, the failures of valves are still very serious, which lead to frequent non-planned shutdowns, and restrict the safety running of unit.

Many numerical simulations have been conducted to investigate the hydrodynamics characteristics of pressure relief valves. Song X.G et al. [2] analyzed the process of a compressible fluid flowing through a safety relieve valve by using computational fluid dynamics (CFD) and moving mesh techniques. Through a CFD analysis with fluid–structure interaction of a high pressure safety valve, A. Beune [3] observed pressure oscillations caused by interaction between cavitation flow and flow towards the valve closure. F. Bassi [4] used an implicit Discontinuous Galerkin (DG) solver to investigate the complicated flow phenomena in the air-water safety relief valves. A numerical and experimental investigation on relief valves is carried out by V. Dossena

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[5], to clarify the fluid dynamics and physical characteristics of different gases inside the valve bodies. If fluid contains certain solid particles, erosions of valve components probably occur. For engineering requirements, many researches have been made on the erosion wear of valves. Through the numerical analysis on the particle erosion of an oilfield control valve, Forder et al. [6] proposed that the valve structure can be optimized by reducing maximum flow velocity when pressure drop between valve inlet and outlet was under a certain level. Erosions of two valves with different geometries were analyzed via CFD by Wallace [7], and the simulation was verified by the corresponding erosion experiments. Wang et al. [8] predicted mass loss and wear distribution of a throttle valve via CFD, and an optimized method of mitigate erosion was proposed. Xu et al. [9] obtained the location and region of erosion in a float valve via numerical calculation, and present an optimal design to eliminate high-velocity region as well as reduce intensities of disturbance and vortex. However, the gas–liquid flow characteristics and erosion distribution in pressure relief valves of coal liquefaction have not been researched.

In this paper, failures of a pressure relief valve in direct coal liquefaction are investigated by a combined numerical-experimental approach. Properties of particles, surface coating, erosion rate variation under different impact conditions and erosion mechanism are clarified through high-temperature erosion experiments. Evaporation–condensation process of coal-oil slurry, fluid feature of gas–liquid flow and particle erosion of valve components are captured by numerical simulation. The numerical results agree well with actual failure morphologies, verifies the failure process predicted by the approach mentioned previously.

2. Failure description

2.1. Technical process

The schematic diagram of direct coal liquefaction unit is shown in Fig. 1. In this unit, a high pressure and temperature hydrogenation process is applied to convert the coal slurry stream to oil. Once the stream pressure has been letdown through a series of high pressure and medium pressure separators, it proceeds to an atmospheric tower. Then the coal-oil slurry from the bottom of atmospheric tower is pumped to a vacuum tower for further distillation. The pressure relief valves, highlighted by a red circle in Fig. 1, locate on the pipeline between the atmospheric and vacuum tower.

As shown in Fig. 2, the pressure relief valves involve an angle valve, a ball valve and associated valve bushings. The angle valve and ball valve are used to adjust the flow rate into vacuum tower and cut off the steam, respectively. There are two branching of pressure relief valves and the construction of each branching is the same. The design purpose is to allow operators to cut off either one of them without shutting down the unit, therefore the service life of unit can be extended.

The normal opening of angle valve is 30%, the valve inlet angle α is 60°, and transitional angle β is 5°. The ball valve operates in a full open state, its inlet and outlet diameter are DN 350 and DN 700, respectively. Wolfram Carbide (WC) with adhesives of Co is coated in the whole flow region via High Velocity Oxy-Fuel (HVOF) spraying. The thickness of WC–Co coating is approximately 2 mm. The stream of coal-oil slurry contains approximately 12–15 wt.% of pulverized coal particles. The operational

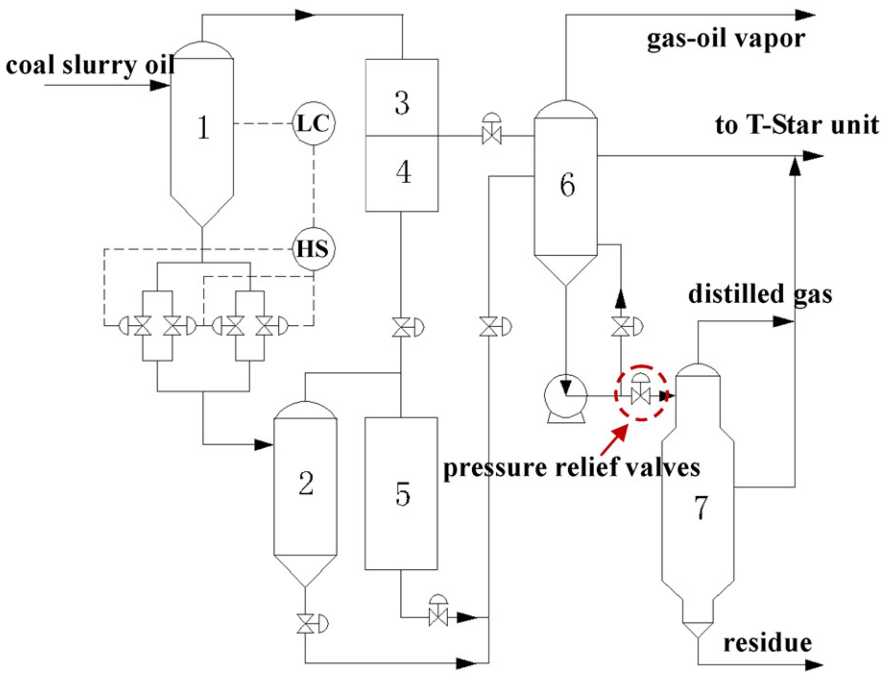

Fig. 1. The process of direct coal liquefaction: 1. high pressure separator; 2. medium pressure separator; 3. medium temperature and high pressure separator; 4. low temperature and high pressure separator; 5. high temperature and medium pressure separator; 6. atmospheric tower; and 7. vacuum tower.