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Investigation on failure process and structural optimization of a high pressure letdown valve

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A B S T R A C T

High pressure letdown valve in direct coal liquefaction is used to adjust the flow rate of coal–oil slurry that enters into the downstream separator. Severe erosion–cavitation wear is found on the valve spool, seriously affecting the safety and reliability of unit. The majority of this paper investigates the failure process of valve spool and proposes a corresponding structural optimization via computational fluid dynamics (CFD) methodology. Three geometries of different failure states are selected as the computational domains in the numerical simulation. The Schneer–Sauer model, particle rebound-velocity model and erosion model are employed to calculate the cavitation phenomenon and erosion rates distribution. Experiments of flow rates and cavitation on valve model under different pressure drops are conducted to validate the accuracy of numerical approach. Results showed that the damage development of valve spool aggravates the erosion–cavitation wear. The maximum erosion rates are located on the top of spool head in all the three states. The erosion rates on spool arc surface are two orders of magnitude higher than that on parabolic surface. The decrease in radius of spool head reduces the intensities of erosion–cavitation wear. The numerical results are in agreement with actual failure morphologies of valve spool in different states.

1. Introduction

High pressure letdown valve is used for controlling the flow rate of coal–oil slurry that enters into the high temperature and intermediate pressure (HTIP) separator in direct coal liquefaction. In most cases, the inlet and outlet pressures of valve are 18.7 MPa and 2.9 MPa, respectively. Under such large pressure differential, the cavitation occurs easily when the stream flows into the valve. In addition, pulverized coal particles of high concentration are contained in the slurry. During the transportation of vapor–liquid–solid flow, the erosion–cavitation wear usually occurs on the valve spool, resulting in many unplanned shutdowns and accidents [1–2]. Therefore, analysis on the failure process and optimized structural design of valve spool are urgently needed.

The erosion wear or cavitation erosion on the valves has been investigated by many researchers, e.g. Liu [3], M. Stosiak [4], and P·Forsberg [5] et al. On the basis of failure mechanism, many optimizations also have been made to improve the performance or prolong the service life of valves which operate in the harsh working conditions. For the purpose of maximizing the electromagnetic force, an analytical optimization of submersible solenoid valves was conducted by Baoping Cai, et al. In addition, the

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proposed analytical approach was verified by the numerical calculation [6]. Numerical studies were conducted by Forder A et al. to investigate the erosion wear in the oilfield control valve, and an optimization by reducing the maximum flow rate at a fixed valve opening was proposed [7]. A structural optimization of stop valve based on the simulation of erosion wear was suggested by Mazur Z et al., and the results showed that the optimized geometry can reduce the maximum erosion rate by 50% [8]. Moreover, in order to enhance the hardness of metal surface, thermally sprayed WC-Co coating is widely used for providing high hardness, wear and corrosion resistance [9]. The erosion wear behavior of HVOF sprayed WC-Co/NiCrFeSiB coatings was investigated by M.R.Ramesh et al. The results showed that the coating can express the erosion behavior as the ductile or brittle material at different impact angles [10]. The corrosion behavior of a nickel WC cermet is compared with 316L stainless steel in four different water–glycol hydraulic fluids by Lei Zheng via electro-chemical experiments. And the effects of seawater ingress and temperature on the corrosion rates and mechanism are also discussed [11]. In this special case, the cavitation and particle erosion on the valve spool should be taken into account together. And the influence of valve's failure process on the erosion–cavitation wear is still not clarified.

In this paper, the influence of failure process on the cavitation erosion and erosion wear of valve spool is discussed via numerical simulation. The transition form liquid to vapor phase is calculated by using cavitation model and the erosion rate distribution is obtained by adopting particle erosion model. A cavitation flow test rig is developed to validate the numerical modeling. The failure process of valve spool is analyzed, and the optimization method of reducing the radius of spool head is proposed. The results are beneficial for further analyzing the failure mechanism of valve spool and extending the valve's service life.

2. Description of failure process

2.1. Different damage states

For the severe erosion–cavitation wear during the sustained operation of high pressure letdown valve, the shape of valve spool changes with its running time. It means that the flow structure inside the valve is also changed. At a fixed valve opening, damages

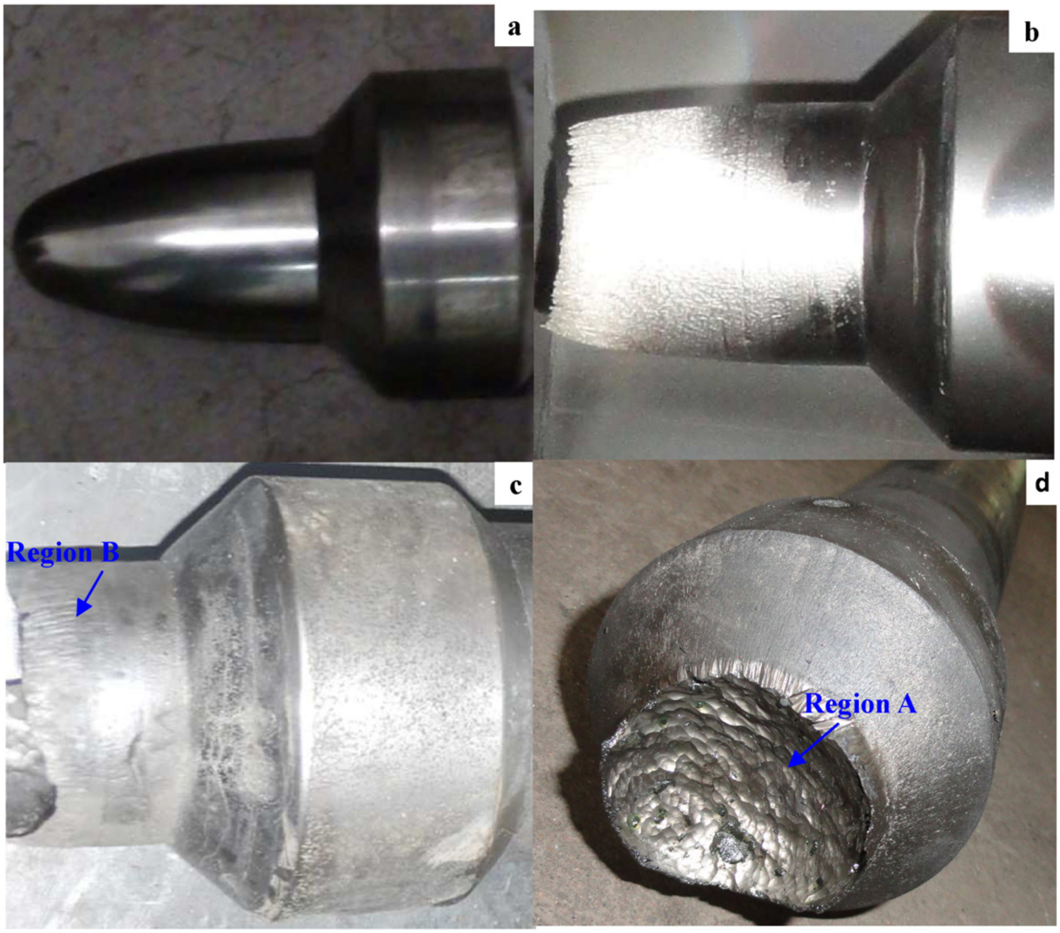

Fig. 1. Photographs of valve spools: (a) initial state with 60% valve opening; (b) minor damage state with 40% valve opening; (c) serious damage state with 20% valve opening; (d) appearance of damaged surface.