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Numerical analysis of flow and temperature characteristics in a high multi-stage pressure reducing valve for hydrogen refueling station

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ABSTRACT

Hydrogen refueling station is one of the most important parts for the hydrogen energy utilization. In this paper, a novel high multi-stage pressure reducing valve (HMSPRV) is proposed, which can be used for hydrogen stable decompression in hydrogen refueling station. In HMSPRV, the inner and outer porous shrouded valve core is used to replace piston valve core to achieve the first-stage throttling, and the porous orifice plate is chosen as the second-stage throttling component. Meanwhile, in order to verify the applicability of HMSPRV, the flow characteristics of two fluids are studied. Firstly, the choked flow, flow and temperature characteristics of superheated steam under different valve openings are carried out. Secondly, the flow characteristic of hydrogen is also conducted to validate the application of HMSPRV in hydrogen refueling station. The results show that, for superheated steam flow, with the increasing of valve openings, the maximum gradient of fluid pressure moves from the fitting surface where inner and outer porous shrouded to the orifice plate. The regulation of its amount is decreasing first and then increasing. With the increasing of valve openings, the maximum velocity, turbulent dissipation rate and pressure loss are all increasing gradually, while the temperature does not change significantly. For hydrogen flow, both the pressure changing process and velocity changing process are similar to superheated steam. It can be concluded that HMSPRV has good flow and temperature characteristics in complex conditions, and it does not prone to choked flow. Throttling effect of the multi-stage pressure reducing way is obvious. This work can benefit the further research work on hydrogen stable decompression in hydrogen refueling station.

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Introduction

Nowadays, pressure reducing valves are widely used in process industry to control fluid pressure. Their performances have a great effect on the security and stability of the entire system. For the purpose of much more widely using of hydrogen energy, especially in the hydrogen energy automobile, the research on hydrogen refueling station has attracted many scientists to deal with its safety, stability and efficiency technologies. During the process of injecting hydrogen, its pressure and velocity change a lot. Thus, the pressure reducing valve can play an important role for the hydrogen stable decompression.

However, with the construction of worldwide energy conservation projects, a series of problems are arising with the traditional pressure reducing valves, such as large transmission loss, high energy consumption and low efficiency, which are mainly resulted from the single-stage pressure reducing way. On the other hand, traditional pressure reducing valves cannot meet the requirements of pressure adjustment under complex conditions such as high parameters, high flow velocities and large pressure ratios. Therefore, it is necessary to develop a novel valve with multi-stage pressure reducing way and low driving energy consumption to deal with the complex conditions mentioned above. In our previous work, we proposed a novel high pressure reducing valve (HPRV) with an orifice plate, focusing on the mechanisms of pressure reduction and energy conversion [1]. Meanwhile, the relationship between the orifice plate structure and the aerodynamic noise was studied [2], and the characteristics of flow-induced noise in this HPRV were also researched, and some guidance for noise control, such as transmission loss analysis of thick perforated plates for valve contained pipelines, was provided [3,4].

Up to now, there have been lots of literature dealing with the energy consumption of different types of valves. Qian et al. [5,6] proposed a novel kind valve named pilot-control globe valve with simple structures and low driving energy, and the numerical method was employed to numerically simulate its dynamic characteristics. Alessandro et al. [7] equipped the new-generation of solenoid injectors with pressure-balanced pilot valve for energy saving and dynamic response improvement. Nay et al. [8] analyzed the flow forces and energy loss characteristics in a flapper-nozzle pilot valve with different null clearances, and showed that energy consumption increases with the increasing of inlet pressure and null clearance.

At the same time, flow characteristics of valves were also studied by many researchers in order to reflect the internal working situation directly. An et al. [9] simulated the 3-D incompressible turbulent flow in valve, and analyzed the pressure loss, flow coefficient and its cavitation. Beune et al. [10] simulated the emissions as well as start-up characteristics of a high pressure safety valve by CFX software, and the results of numerical simulation were verified by comparison with experimental results. A pressure reducing valve with a constant pressure ratio was developed by Luo et al. [11], and its pressure and leakage characteristics were theoretically analyzed by simulation. Ulanicki et al. [12] presented why pressure relief valves tended to oscillate at low flow. Lisowski et al. [13] focused on the reduction of flow resistance in a hydraulic system. Samad et al. [14] studied the dynamic behavior of control valve in the response to self-excited fluid flow. Binod et al. [15] investigated the dynamic modeling of flow process inside a pressure regulating and shut-off valve by using a Computational Fluid Dynamic approach.

As is a novel valve, we have paid lots of attention to HPRV, mainly targeted at its structural characteristics and noise characteristics. However, there are virtually no literature about the multi-stage flow and temperature characteristics of HPRV in theory and through numerical simulation for further applications. In this paper, the novel HMSPRV is proposed, and its mathematical model is established. Then, the internal flow fields of superheated steam and hydrogen in the valve under different valve openings are analyzed. This study can provide technological support for energy saving and achieve multi-stage flow in pressure reducing valves, and it can also benefit the further research work on hydrogen stable decompression in hydrogen refueling station.

Working principle

Fig. 1(a) is the structure of HMSPRV, and its structure improvements are carried out on the basis of HPRV [1]. The innovative optimizations mainly include that, the inner and outer porous shrouded valve core is used to replace piston valve core to achieve the first-stage throttling, and porous orifice plate is chosen as the second-stage throttling component. Both the new valve core and the sleeve have the same holes with the same size. When they are relatively rotated, the coincidence degree of the holes can be modified correspondingly. Thus, the flow and pressure situation in the valve can be adjusted according to the requirement. Moreover, the number of plates can be adjusted randomly to achieve a multi-stage pressure reducing way.

The main advantage of HMSPRV is that it can reduce energy consumption effectively. The valve reduces energy consumption mainly through three points. The first point is chamfering of orifice holes. The specific operation is to carry out chamfering on those original orifice holes, which is showed in Fig. 1(b). It will make fluid velocity increase gradually when passing through the orifice holes. The second point is the optimization of the number of orifice plates. The specific operation is to increase two orifice plates on the basis of the original structure. The energy consumption of the new multi-stage pressure reducing structure is significantly less than the original structure. The third point is changing valve core. As is mentioned above, the new valve core is made by inner and outer porous shrouded to replace the traditional piston valve core. The new valve core can achieve the regulation of outlet pressure by adjusting the degree of overlap between valve core holes and sleeve holes.

HMSPRV contains three pressure reducing channels. The first channel is the inflow of fluid from the valve inlet, and then it will flow through the valve core holes and sleeve holes. The second channel is that fluid flows into the valve chamber, and then it will flow through those orifice plates in valve chamber successively. The third channel is that fluid flows