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Mach number analysis on multi-stage perforated plates in high pressure reducing valve

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ABSTRACT

High pressure reducing valve (HPRV) is a key device for the pressure control of high temperature and pressure steam in industrial processes. Perforated plate is used as the throttling element to ensure the suitable pressure of steam and reduce aerodynamic noise inside HPRV and the linked pipelines. Mach number is the parameter to reflect the compressibility of steam flow. Higher Mach number may cause serious aerodynamic noise of steams flow, waste large amount of energy and do harm to the valves and pipelines. In this paper, Mach number on multi-stage perforated plates inside a novel HPRV and the linked pipelines is investigated. Mach number in reversible isentropic process is analyzed and the design method of multi-stage perforated plates in HPRV is proposed. Then, the RNG k–ε model combining with compressible gas is established, and the Mach number simulation of single perforated plate and multi-stage perforated plates is carried out in software Fluent 6.3. Meanwhile, Mach number inside HPRV is also presented, and the pressure ratio of perforated plate is also investigated. It can be found that under higher pressure ratio, the influence area of the last perforated plate becomes larger, and the energy loss in perforated plate is larger than the valve core. Furthermore, there exists a limited pressure ratio of every stage perforated plate, and it is better to keep the pressure ratio of every stage perforated plate larger than 0.5. This work presents the function of perforated plates in HPRV for throttling and reducing aerodynamic noises, and it can benefit the researchers who are dealing with multi-stage perforated plates design for valves and pipelines.

1. Introduction

High pressure reducing valve (HPRV) is widely used in pipelines as a key device for the pressure control of high pressure steam in industrial processes. Perforated plate is used as the throttling element to ensure the suitable pressure of steam. Suitable perforated plate cannot only reduce aerodynamic noise but also reduce energy consumption of the whole piping system.

Based on the enormous demands of pressure control in pipelines, many scientists have paid a lot of attentions to the pressure control technologies of valves in piping system. Beune et al. [1,2] carried out a research on a high pressure safety valve by numerical and experimental method and in their study the numerical and the experimental results on mass flow rates agree within 3% and on flow force 12% for gas flows. Casoli et al. [3] did a numerical prediction on a high pressure homogenizing valve and the research could be a starting point for further more complex effects. Chalet and Chesse [4] analyzed the unsteady flow of a throttle valve, while Dai and Li [5] and Freni et al. dealt with the pressure reducing valves for the optimal pressure regulation, and their model was demonstrated to be reliable in the implementation of pressure management areas in the network [6]. For another point, Galbally et al. [7] paid attention to the pressure oscillations of a safety relief valve and Hős et al. [8,9] analyzed the dynamic behavior of a pressure relief valves in the gas service. Li et al. [10] took a high-pressure electro-pneumatic servo valve as the research subject to investigate the steady gas flow force. Lisowski et al. [11,12] analyzed pressure and flow force of a hydraulic directional control valve, and for multi-section proportional directional control valves, they also pointed out that appropriate shaping of the spool geometry allowing usage of flow forces for pressure compensation. Meanwhile, Man et al. [13] dealt with a second-stage valve for the pressure difference feedback analysis, and they found that with adjusting the pressure difference feedback gain, the same square wave input could be freely controlled between 0% and 50%.

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Nomenclature

A	flow area (m^2)	P_o	outlet pressure (Pa)
A_n	circulation area of n stage perforated plate (m^2)	q_m	mass flow (kg/s)
c	local speed of sound (m/s)	R_{cr}	critical pressure ratio
c_0	stagnation speed of sound (m/s)	S	discharge coefficient
h	enthalpy (kJ/kg)	T	temperature (K)
Ma	Mach number	T_0	stagnation temperature (K)
n	number of perforated plate	u	flow velocity (m/s)
P	pressure (Pa)	v	specific volume (m^3/kg)
P_0	stagnation pressure (Pa)	γ	Specific heat capacity ratio
P_i	inlet pressure (Pa)	ρ	density (kg/m^3)
P_n	pressure after $n-1$ stage perforated plate ($n \geqslant 2$) (Pa)	ρ_0	stagnation density (kg/m^3)

Qian et al. [14,15] proposed a novel pilot-control globe valve with low driving energy consumption and analyze its flow and cavitation characteristics, and it could use a small pilot valve to control the main valve with a low energy consumption. Saha et al. [16,17] and Chattopadhyay et al. [18] developed a deep research work on the pressure regulating valve and also got some meaningful results. Shin [19] analyzed the transient flow from a pressure control valve, and Song et al. [20,21] analyzed a direct-operated safety relief valve and a high-pressure regulating valve respectively focusing on the flow dynamics. Trentini et al. [22] investigated a pneumatic proportional pressure valve for its structure parameter identification. Wang et al. [23] also paid attention to a throttle valve focusing on the erosion simulation with an error less than 10%. Furthermore, Wu et al. [24] developed a study on a pressure control valve with its low-pressure characteristics, and Xie et al. [25] also simulated a pressure relief valve with pop actions, while Zuo et al. [26] analyzed on a control valves in the natural gas pipelines for its pressure drop control.

As one of the most common components, perforated plate is easy to manufacture, and it is very useful for pressure regulation and noise control. In the recent years, there are also many scientists paying close attention to it. Andreassen et al. [27] observed the wave propagation in perforated plates, and the obtained results showed the predictive ability of considered numerical model. Meanwhile, Barros Filho et al. [28] analyzed the pressure drop of perforated plates under the effects of chamfer and pointed out that in the flat regions the chamfer angle was more important at the outlet. At the same time, Bayazit et al. [29] took the perforated plates for fluid management and research on its geometry, and Gullaud and Nicoud [30] took the perforated plates as combustors and observe its effects. For another concentration point, Guo et al. [31] simulated the gas flow though the perforated plates, and Laurens et al. [32] and Zhou et al. [33] paid attention to the acoustic wave reflection by a low-porosity perforated plate. Furthermore, Maynes et al. [34] and Malavasi et al. [35,36] analyzed the cavitation and pressure loss of the perforated plates and carried out a formula for its estimation. Putra and Ismail [37] and Qian et al. [38] investigated the transmission loss of the perforated plates, while Scarpato et al. [39,40] also used perforated plates in acoustic dampers and analysis its effects.

Mach number is the parameter to reflect the compressibility of steam flow. As is known to all, noise is mainly generated by the interaction of velocity pulsation, entropy and viscous force with unsteady and nonlinear flow disturbance. If the Mach number is too high, which means the flow velocity is much larger than the local speed of sound, and at this state, steams have a better compressibility and its flow will be much more unsteady and nonlinear. Thus, under a higher Mach number condition, steams may cause serious aerodynamic noise and do harm to the valves and pipelines. During this process, the mechanical energy of steams conversion into heat energy, and it also means a waste of large amount of energy. For Mach number study, there are also some researchers carrying out some interesting works. Donev et al. [41] analyzed the low Mach number fluctuating hydrodynamics for liquid mixtures. Léonard et al. [42] simulated a turbine blade under high subsonic outlet Mach number. Penel et al. [43] proposed the coupling strategies for compressible flow under Mach number. Varade et al. [44] paid attention to the velocity measurement through a tube under low Reynolds and low Mach number.

In the field of pressure control and noise analysis of valves and pipelines, our group have done some previous works on the optimization design of HPRV [45,46], noise analysis inside HPRV [47], and adopting perforated plates for valve contained pipelines for noise control [38]. In this paper, the Mach number (Ma) on the multi-stage perforated plates in the novel HPRV [45] is investigated. The Mach number in reversible isentropic process is analyzed firstly and the design method of multi-stage perforated plates in HPRV is proposed. Then, an RNG k–ε model combining with compressible gas is established to simulate the pressure and Mach number inside HPRV and pipelines, and Mach number under different pressure ratios in single perforated plate and multi-stage perforated plates are observed, respectively. Meanwhile, the analysis of Mach number under different valve openings inside HPRV is carried out. In addition, the pressure ratio analysis of every stage perforated plates is also presented. This work can be referred by the researchers who are dealing with multi-stage perforated plates design.

2. Numerical method

In this part, the relationship between the Mach number (Ma) and the cross-sectional area is established firstly. Then, the design method of multi-stage perforated plates for high pressure reducing valve (HPRV) is proposed. Furthermore, the computational model of HPRV along with different numbers of perforated plates is introduced.

2.1. Mach number

Speed of sound is the pressure wave propagation velocity in a continuum under weak perturbations. The ratio of the flow velocity and the local speed of sound is called Mach number (Ma), which is shown in Eq. (1).

$$Ma = \frac{u}{c} \tag{1}$$