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Study on hydrogen decompression performance of an orifice plate structure with parallel Tesla-type channels

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ABSTRACT

Hydrogen fuel cell vehicles (HFCVs) replacing internal combustion engine vehicles are a viable option to achieve net-zero carbon emission in transportation. Higher hydrogen storage pressure is necessary for increased recharge mileage, necessitating a hydrogen decompression mechanism. A unique pressure-lowering construction (Tesla-type orifice structure) is proposed in this study, in which Tesla-type channels are paralleled and incorporated into a standard orifice plate structure. A complete parametric analysis is used to optimize the Tesla-type orifice construction further. Compared to a standard orifice plate, at low inlet mass flow rates, the Tesla-type secondary orifice construction gives higher pressure drop performance. The presented study may provide a feasible technical structure for achieving high-efficiency hydrogen decompression in HFCVs.

Keywords: computational fluid dynamics, Hydrogen Fuel Cell Vehicle, high-pressure hydrogen decompression

1. INTRODUCTION

Nowadays, the transportation industry contributes approximately 26% of greenhouse gas emissions worldwide. Replacing fossil fuels with hydrogen is widely seen as a feasible method to achieve net-zero carbon emissions. The application of hydrogen fuel cell vehicles (HFCVs) is receiving increasing attention. In order to enhance the recharge mileage of HFCVs, the storage tank pressure is continually increased while the fuel cell's optimal operating pressure is relatively low, putting increasing demands on the pressure decompression system's performance. In recent years, an increasing amount of research on high-pressure gas depressurization processes has been carried out. Jin et al. [1] proposed a novel high-level multistage pressure-reducing valve (HMSPRV) used for stable hydrogen depressurization in hydrogen refueling stations. The results showed that the HMSPRV could regulate the temperature and pressure characteristics and is less prone to block flow. Hou et al. [2] conducted a parametric investigation of the throttling portion of an HMSPRV to optimize valve performance. The bigger the hydrogen kinetic energy, the stronger is the turbulent vortex, greater is the energy consumption. The above-mentioned pressure-reducing valve comprises rotating parts such as a multistage multiport sleeve and spool, which has a complex construction that causes turbulence in the flow field, a lot of noise, and a difficult valve manufacturing process. Because it causes a high-pressure drop when flowing in the opposite direction, the Tesla valve attracts growing attention to overcome these drawbacks. Gamboa et al. [3] optimized the valve shape using 2D CFD simulation combined with an optimization procedure for Tesla valves. Zhang et al. [4] proposed a 3D parametric model of the Tesla valve and optimized its geometric relationships.

In this study, a three-dimensional (3D) CFD model incorporated with the Peng–Robinson (PR) real gas EOS was developed to investigate the pressure reduction effect of a novel Tesla-type orifice structure. The simulations were run on ANSYS-Fluent, a commercial CFD package. The results of the simulation were compared to experimental data. According to the results, the model was able to accurately reproduce the true flow

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conditions of high-pressure hydrogen in a structurally complex depressurized system. The conventional perforated plate structure is replaced with a flow channel, having the Tesla valve structure (Tesla-type orifice structure) constituting a Tesla orifice plate pressure-reducing valve consisting of multiple Tesla valves connected in parallel to achieve higher pressure reduction performance. In addition, the design of the Tesla valve is optimized to enhance the backflow impact characteristics of the Tesla valve flow channel. And a two-stage Tesla-type orifice plate structure consisting of two Tesla in series is introduced. Then, the influences of structural parameters on the flow feature are studied to obtain a superior hydrogen decompression structure.

2. NUMERICAL CALCULATION

2.1 Model validation

As the experimental data of hydrogen flowing in the Tesla-type channel are few, and many scholars have studied the Tesla-type channel, the experimental data of water from Liu et al. [5] are used for flow model validation. The experimental and simulated magnitude of pressure drop at different inlet flow rates are given in Fig. 2. The simulated and measured data follow the same pattern. With an increase in incoming flow, the pressure drop increases even more. Because of the experimental uncertainty and grid precision, the model slightly over-predicted the pressure decrease. However, the largest relative error between simulated and observed values is only 4.48%, indicating that the simulation and experimental results agree well. The CFD model established can correctly simulate the real situation of fluid flow.

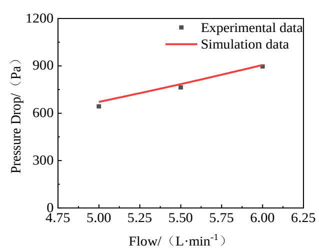


Fig.1.Comparison of pressure drop between experimental and CFD values

2.2 Computational domain and boundary conditions

Fig. 2 show the basic structure of the conventional orifice plate valve. The central area is a 200 mm diameter circular channel with an inlet section length of 50 mm, an outlet section length of 450 mm, and an orifice plate thickness of 25 mm. The Tesla-type channel has a great pressure reduction effect, and the pressure drop performance may be further optimized when the Tesla-type channel is embedded in the conventional orifice plate structure. The Tesla-type channel replaces the straight orifice flow channel in the traditional plate of orifice structure through improvement. The specific structure is shown in Fig. 3, and the Tesla structure uses a 5 mm diameter circular channel for better coupling with the main channel. The parameters for Tesla-type channel are specific as: inlet length L1 = 5 mm, outlet length L2 = 5 mm, side straight channel length L = 10 mm, side-channel and main channel angle α = 45 °, bending channel and main channel angle β = 130 °, the radius of the curve in the circular section R = 2.5 mm. It is feasible to structure 1/2 of the Tesla-type orifice structure as a computational domain due to symmetrical geometry.

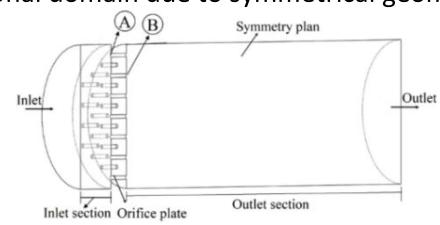


Fig.2. Sketch of the fluid domain of conventional orifice plate structure

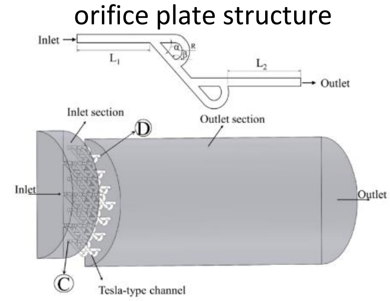


Fig.3. Sketch of fluid domain of Tesla-type orifice structure

However, the Tesla-type orifice structure may be further optimized to achieve a better pressure drop performance by improving the Tesla-type channel. Fig. 4 show the optimized Tesla-type orifice structure flow path. The performance of the Tesla-type orifice structure in terms of pressure drop is investigated. Orifice construction similar to Tesla's The fluid in the bent channel has an obstruction effect on the fluid in the straight channel, lowering pressure. To enhance the obstruction effect, introduce a novel construction in the bent channel and the straight channel connection place. The new structure has a parameter, line L3; therefore, the angle β of the bent channel becomes larger, increasing the return flow impact effect of the bent channel. The other structural parameters of the improved Tesla-type orifice structure are the same as before, with the line L3 = 8.6 mm.

In addition to the improved Tesla-type channels, this section introduces another set of parallel Tesla-type channels to the Tesla-type orifice structure for the Tesla-type secondary orifice structure. This structure uses a modified Tesla-type orifice structure flow channel. The lengths of the inlet section, the primary outlet section, and the secondary outlet section are 50 mm, 100 mm, and 200 mm, respectively. The mainstreams channel is also a circular channel with a diameter of 200 mm, and 1/2 of the proposed structure is defined as computational domain as shown in Fig. 5.

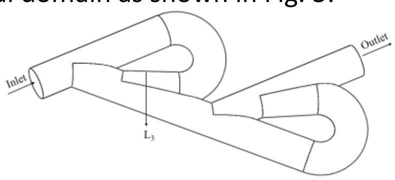


Fig.4. Improved Tesla-type channel

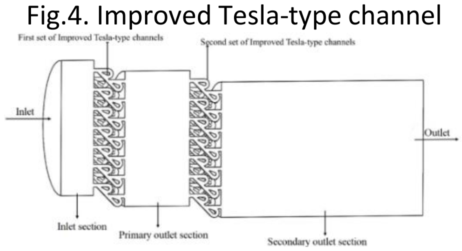


Fig.5.Tesla-type secondary orifice structure calculation fluid domain

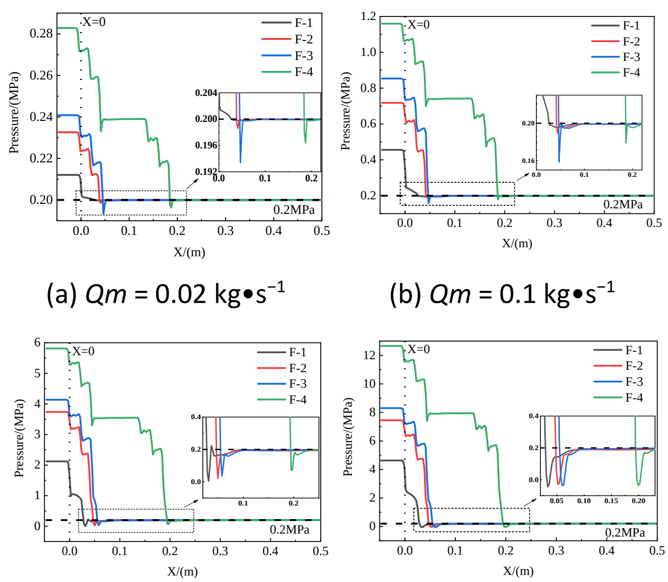
The boundary conditions for conventional orifice plate structure, Tesla-type orifice structure and Tesla-type secondary orifice structure are similar, which are defined as follows (see Fig. 2): (a) Inlet: mass flowrates inlet (Qm), and temperature is set to constant temperature (300 K) (b) Outlet: Pressure outlet (0.2MPa). (c) Symmetry plan: Symmetry impermeable boundary conditions with zero gradients of all variables. (d) Adiabatic wall boundary conditions specify other boundary surfaces.

2.3 Results

Figs. 6 displays the pressure on the centerline of the symmetry plan of the four structures. Among them, F-1, F-2, F-3, F-4 represent a conventional orifice plate structure, a Tesla-type orifice structure, an improved Tesla-type orifice structure, and a Tesla-type secondary orifice structure, respectively. The figure can well reflect the change in hydrogen pressure in the flow due to the difference in the structure. F-4 has the biggest pressure drop. In Figs. 6, the mass inlet flow in the X direction, perpendicular to the inlet surface and at X = 0, is where the inlet section is connected to the plate orifice in Figs. 2. It is visually reflected from the figure that the conventional orifice plate structure has only a single area of pressure drop; therefore, the pressure-reducing performance is insufficient. The hydrogen starts to decrease in pressure before entering the channel from the inlet section for all structures. The pressure in the channel decreases in steps, and when Qm = 0.02 kg•s^{-1}, the pressure drop slows down as the conventional orifice plate structure flows into the outlet section. As Qm increases to 0.1 kg•s^{-1}, this process slowing down the pressure drop turns from gentle to steep. This results in the pressure gradient does not show a step-change distribution as the hydrogen flows out of the plate orifice. When the Qm increases to 0.5 kg•s^{-1}, the hydrogen in the conventional orifice plate structure appears to flow at supersonic velocity and is located not far from the orifice outlet position. It is because of the sudden increase in flow cross-sectional area at the orifice exit position into the outlet section that an expansion wave is formed. The hydrogen velocity will increase instantaneously after the expansion wave, and the pressure drops abruptly, resulting in the pressure drop to 0.2 MPa and then back up in Figs. 6(c) and (d). Comparing the change of pressure distribution of the Tesla-type orifice structure and the improved Tesla-type orifice structure, the first pressure step is formed when hydrogen flows into the channel from the inlet section. In contrast, the two subsequent pressure step drops are created by the flow channel characteristics of the Tesla-type orifice structure. It can be found that after increasing the Tesla-type orifice structure parameter linear section L3, it does increase the effect of the Tesla-type orifice structure bending channel obstructing the flow so that the hydrogen gas obtains a more excellent pressure drop performance.

Though observing the pressure distribution along centerline of the Tesla-type secondary orifice structure, it is found that the size of the pressure drop gradient of the two groups of Tesla-type orifice structure at Qm = 0.02 kg•s^{-1} is not much different, which makes the hydrogen pressure energy and kinetic energy conversion approximately the same, forming a distribution of the maximum Mach number at the outlet of the flow channel of each group of Tesla-type orifice structure. And as Qm increases, it is evident that the pressure drop generated in the flow channel of the second group of Tesla-type orifice structure is more significant, which causes more conversion of hydrogen pressure energy to kinetic energy in the flow channel of the second group of Tesla-type orifice structure, resulting in faster flowrates and a more significant Mach number, creating a situation where the maximum Mach number occurs in the second group of Tesla-type orifice structure when the Qm increases to 0.1 kg•s^{-1}. It can also be seen from the figure that the F-1, F-2, F-3 also form a pressure drop followed by a curve change back up at the final orifice outlet for Qm = 0.02 and 0.1 kg•s−1, which is different from the pressure back up that forms at the flow into the outlet section for Qm = 0.5 and Qm = 1 kg•s^{-1}. When Qm = 0.5 and Qm = 1 kg•s^{-1}, low-pressure sectors are formed by the hydrogen flowing out of the orifice and the pressure dropping after the expansion wave. The pressure recovery curve is smoother, and the X is located further back.

In contrast, when Qm = 0.02 and 0.1 kg•s^{-1}, the variation of the pressure recovery curve formed is due to the hydrogen decompression characteristics in the Tesla valve flow channel. The faster flow of hydrogen via the curved channel impacts the straight channel hydrogen, obstructing flow and forming vortices. It uses the energy from hydrogen flow to produce a low-pressure zone at the intersection's back. At this moment, there is a pressure rebound, the curve's bottom is sharper, and the X is further forward.



(a) *Qm* = 0.02 kg•s^{-1} (b) *Qm* = 0.1 kg•s^{-1}

(c) *Qm* = 0.5 kg•s^{-1} (d) *Qm* = 1 kg•s^{-1}

Fig.6.Pressure distribution on the centerline of the symmetry plan of the four structures at different mass flowrates

3. CONCLUSIONS

In this paper, a novel Tesla-type orifice structure is proposed for high-pressure hydrogen decompression by replacing the straight channel in a conventional orifice plate structure with a circular Tesla valve flow channel. Furthermore, the Tesla-type channel is enhanced by inserting a new linear section L3, dubbed an upgraded Tesla-type orifice structure, which enhances the impact of reflux. The Tesla-type secondary orifice structure adds another set of parallel Tesla-type channels to the Tesla-type orifice plate construction. The Tesla-type secondary orifice structure is analyzed for flow field comparison. The variation of pressure during hydrogen flow in the four structures are studied through CFD numerical simulation. The following conclusions are specifically drawn.

The Tesla-type orifice structure introducing the parametric linear section L3- improved Tesla-type orifice structure has further improved the pressure drop performance over the Tesla-type orifice structure. As the inlet mass flow rates increase, the rate of relative pressure loss reduces. When the hydrogen gas in the structure is in a supersonic flow state, the rate of relative pressure drop increases to a minimum. The relative pressure drop rise rate will be raised once more by raising the inlet mass flow rates. At low inlet mass flow rates, the Tesla-type secondary orifice construction gives higher pressure drop performance.

ACKNOWLEDGEMENT

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