

Article

Research on the Impact of Crimped-Ribbon Flame Arrester Structure Parameter on the Flow Resistance and Pressure Drop

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Abstract: In response to the requirement that the flow pressure drop test must be conducted before the explosion resistance performance test of flame arrester, this experiment investigated the impact of structural parameter on the pressure drop of hydrogen crimped-ribbon flame arrester based on a testing system for flow pressure drop. Meanwhile, a predictive model for the pressure drop of flame arresters under multi-factor influences was established using a response surface methodology, and the impact levels of each factor were identified. This model could provide theoretical support for the pressure drop performance analysis of flame arresters under different structural parameters and flow rates. The result indicates that the pressure drop histories showed an increasing trend under different structural parameters as the gas flow rate was gradually enlarged. The influences of expansion chamber angle and structure on pressure drop was not significant. However, the pressure drop displayed a gradually increasing trend as the porosity decreased and the element thickness improved, and the change in porosity had a greater impact on the pressure drop in contrast to the element thickness.

Keywords: crimped-ribbon flame arrester; structural parameter; expansion chamber; flow resistance; response surface analysis

1. Introduction

Hydrogen has attracted widespread attention from countries around the world due to its high calorific value and clean and pollution-free characteristics [1,2]. The safety production and transportation issues are becoming particularly important with the increasing development of hydrogen energy industry. Hydrogen has the characteristics of high diffusion, low ignition energy, and wide explosion limit, making it highly prone to causing explosion accidents [3,4]. In recent years, hydrogen explosion accidents have occurred frequently worldwide, causing significant casualties and property damage, seriously threatening the developments of hydrogen energy industry and urban public safety. Flame arresters, especially the crimped-ribbon flame arrester, have been widely used in the petrochemical industry as the key components for flame retardancy and explosion protection [5,6]. It can effectively stop the spread of flames over a large area in the pipeline network and cause catastrophic accidents. Therefore, ensuring effective flame prevention and intrinsic safety was the crucial for improving the safety of the hydrogen energy industry [7,8].



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Currently, scholars mostly focused on the explosion resistance performance of flame arresters and confirmed that the explosion resistance effect of crimped-ribbon flame arrester was superior to other structural forms [9,10]. Meanwhile, researchers had also paid more attention to the influence of structural parameter on the explosion resistance effect, and proposed that initial conditions and expansion chamber structure were key factors affecting the explosion resistance performance of flame arrester [11,12]. In engineering practice, flame arresters were usually installed in the middle and ends of pipelines and vessels, which could effectively prevent the spread of flames and reduce accident losses in the occurrence of an explosion event [13]. However, flame arresters could ensure the regular transport of gases and liquids under normal operating conditions and had a lower pressure difference on both sides of the equipment to reduce the pressure loss inside the gas transmission pipelines in the absence of an explosion. According to the “Petroleum Gas Pipeline Flame Arrester” (GB/T 13347-2010), it was also necessary to conduct a flow pressure drop test before conducting the flame arrester explosion resistance performance test. Nevertheless, prior studies on hydrogen crimped-ribbon flame arresters predominantly focus on explosion suppression performance, with insufficient systematic analysis of pressure drop characteristics. Most relevant works only adopt single-factor tests to characterize pressure loss, lacking quantitative evaluation of multi-parameter interactions and comparative analysis of factor significance via Response Surface Methodology. Moreover, few multi-factor pressure drop predictive models have been developed to support the structural optimization of hydrogen pipeline flame arresters. To address these research gaps, this work establishes a dedicated pressure drop test system to reveal structural parameter effects and construct a reliable prediction model. Therefore, this article mainly investigated the impact of different structural parameter on the flow pressure drop characteristics of crimped-ribbon flame arrester based on the experimental system of flow pressure resistance drop, and their influence regular was analyzed.

2. Experiment Apparatus

2.1. Pressure Drop Experimental System and Scheme

According to standards such as GB/T 13347-2010 and ISO 16852, a pressure drop experimental system for hydrogen crimped-ribbon flame arrester was designed and built independently, as shown in Figure 1 [14,15]. The experimental system included the flame arrester device, the experimental pipeline, the fan system, the data acquisition system, and related auxiliary equipment.

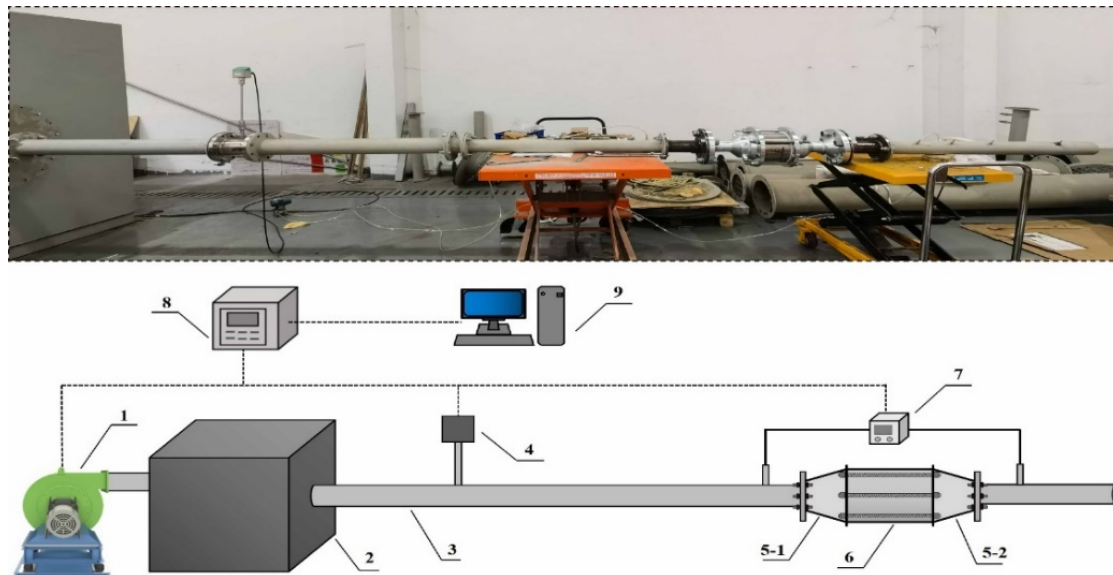


Figure 1. Pressure drop testing system for hydrogen crimped-ribbon flame arrester. 1—Industrial fan; 2—Gas storage chamber; 3—Test pipeline; 4—Flow monitor; 5—Expansion cavity; 6—Flame-retardant unit; 7—Differential pressure monitor; 8—Synchronization controller; 9—Program and collection system.

2.1.1. Flame-Retardant System

The crimped-ribbon flame arrester in the experiment consisted of a flame arrester unit and an expansion chamber [16,17]. The overall material was made of 304 stainless steel. Three porosity rates ($\alpha = 0.35, 0.5$ and 0.65), four-element thicknesses ($H = 60$ mm, 80 mm, 100 mm and 120 mm), three expansion chamber angles ($\theta = 30^\circ, 45^\circ$ and 60°), and three expansion chamber structures (the conventional, the baffle and the extension structures) were

selected, as shown in Figure 2. Meanwhile, the precise control of the internal ventilation volume inside the pipeline was achieved and real-time pressure drop data was obtained based on the data acquisition and control system and the fan system. Besides, the impacts of various influencing factors on the pressure drops before and after the flame arrester under different ventilation rates were clarified, and provide the theoretical basis for the selection and optimization design of flame arrester.

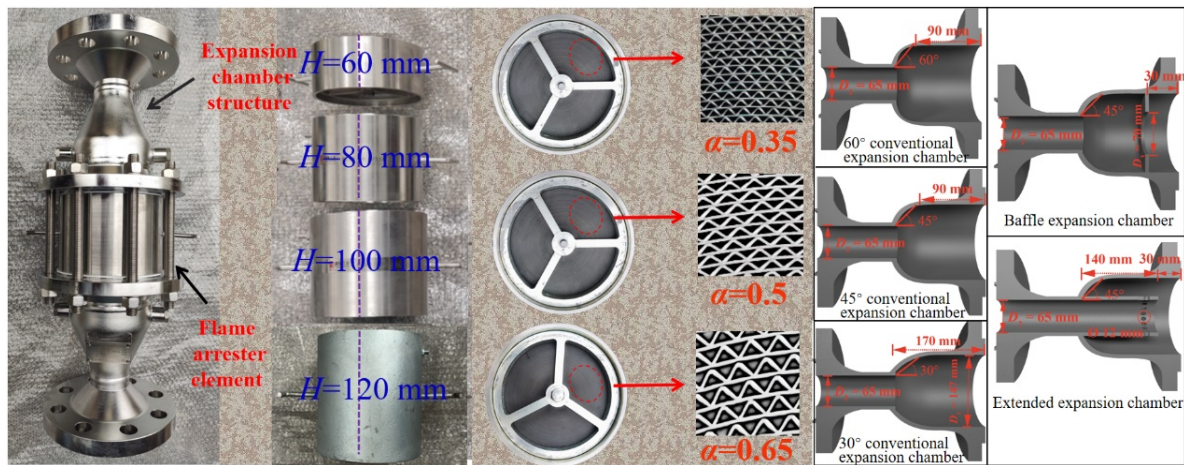


Figure 2. Physical image of crimped-ribbon flame arrester and expansion chamber.

2.1.2. Experimental Pipeline and Fan System

Figure 3 displays the pressure drop testing pipeline and the fan system. The main material of the pipeline was 20 carbon steel, designed to withstand a pressure of 6 MPa, with a single length of 1 m, and the threaded holes reserved at corresponding positions. The 8-09-NO7.1A-ST1 industrial fan with an air volume of 2000 m³/h and a speed of 2574 r/min manufactured by Inso (Guangzhou) Ventilation Technology Co., Ltd. (Guangzhou, China) was adopted during the experiment. The volume of the gas storage chamber was 8 m³, the main material was Q235 carbon steel, and the design pressure was 0.05 MPa. The German CS plug-in flow monitor (VA500) was installed on a pipeline 1000 mm away from the fan outlet, with a range of 0–185 m/s, a maximum working pressure of 50 bar, and an accuracy of $\pm 0.3\%$ FS. This flow monitor adopted the modular design to integrated display the flow rate. Besides, the flow monitor was connected to the fan through ethernet to achieve collaborative control and real-time display through a synchronous controller.



Figure 3. Experimental pipeline and fan system. ((a)-Test pipeline, (b)-Industrial fan, (c)-Gas storage chamber, (d)-Flow monitor).

2.1.3. Data Acquisition and Control System

The pressure drop data was collected through the data collection, the controller, and the differential pressure monitor. A BLD-type differential pressure monitor was deployed in the experiment, featuring a measurement range

of $-6\sim 6$ kPa, acquisition accuracy of 0.1% FS, response time less than 90 ms, and temperature drift below 0.03% FS/10 K. According to relevant testing specifications, the differential pressure monitoring devices were respectively installed on pipelines 130 mm and 65 mm away from the front and rear ends of the flame arrester to measure the pressure drop of flame arrester. Based on ethernet data transmission and control technology, the start-up and air volume output of industrial fan were controlled, and the precise regulation of ventilation volume in the pipeline was achieved. Besides, the real-time pressure difference data could be collected by the differential pressure monitor under different ventilation levels, thereby obtaining pressure drop data before and after the flame arrester under different structural parameters.

2.1.4. Experimental Scheme Design

To study the interaction and influence degree of various influencing factors, the response surface methodology (RSM) was used to investigate the impact of multi-factor interaction on the pressure drop based on the result of single factor influence. A multi-factor analysis scheme for structural parameter was designed using a central composite experimental design (CCD), with the response parameter being the pressure drop (ΔP) of flame arrester. The three variables (pipeline flow rate Q , flame-retardant unit porosity α and element thickness H) were selected for CCD response surface design according to single-factor test screening criteria: all three parameters impose remarkable independent impacts on pressure drop and exhibit prominent interaction effects, which dominate the variation of pressure loss. By contrast, expansion chamber angle and structural form exert insignificant effects on pressure drop, with the pressure drop difference induced by different expansion chamber configurations less than 7%. Given their weak sensitivity to pressure loss and to avoid excessive redundant experimental groups, expansion chamber parameters were not incorporated into the multi-factor pressure drop prediction model. The design parameters were the flow rate (Q) inside the pipeline, the porosity (α), and the element thickness (H). The specific scheme was shown in Table 1. The impacts of various factors on the pressure drop were analyzed through experimental results, and the influence of multi-factor interaction was also clarified. A multi-factor pressure drop prediction model was established to provide the technical support for analyzing the pressure drop performance of flame arresters under different structural parameters and flow rates. To ensure the reproducibility and accuracy of the experimental data, each experiment was repeated 5 times.

Table 1. Experimental scheme of flame arrester pressure drop based on response surface method.

No.	$Q/(\text{m}^3/\text{h})$	α	H/mm	No.	$Q/(\text{m}^3/\text{h})$	α	H/mm
1	50	0.5	80	11	70	0.65	100
2	50	0.5	120	12	70	0.35	100
3	70	0.65	60	13	30	0.5	80
4	50	0.5	80	14	30	0.65	100
5	30	0.35	60	15	90	0.5	80
6	50	0.65	80	16	50	0.5	80
7	30	0.35	100	17	50	0.35	80
8	30	0.65	60	18	50	0.5	60
9	50	0.5	80	19	70	0.35	60
10	50	0.5	80	20	50	0.5	80

3. Results and Discussions

3.1. Influence of Structural Parameter on Pressure Drop

3.1.1. Impact of Expansion Chamber Angle

Figure 4 shows the variation histories of pressure drop with gas flow rate at different expansion chamber angles under four element thicknesses ($H = 60, 80, 100$, and 120 mm). As shown in the Figure, the pressure drops at both sides showed a continuous increasing trend with the improving fan flow rate, while the pressure drop value did not change significantly with the change of expansion chamber angle. As the element thickness was 80 mm and 120 mm, there was a slight increase in the trend of variation. As the expansion chamber angle enlarged, the chamber volume was also increased. After entering the chamber, the gas formed a large vortex, and the unevenness of the velocity distribution inside the chamber continued to enhance, further leading to an increase in the flow resistance and a decrease in the axial velocity of the gas, which in turn increased the pressure drop on both sides of flame arrester. However, it was also found that the chamber angle had a small effect on the pressure drops on both sides of the flame arrester under different flame-retardant units, indicating that the change in the chamber angle had a relatively small impact on the pressure drop.

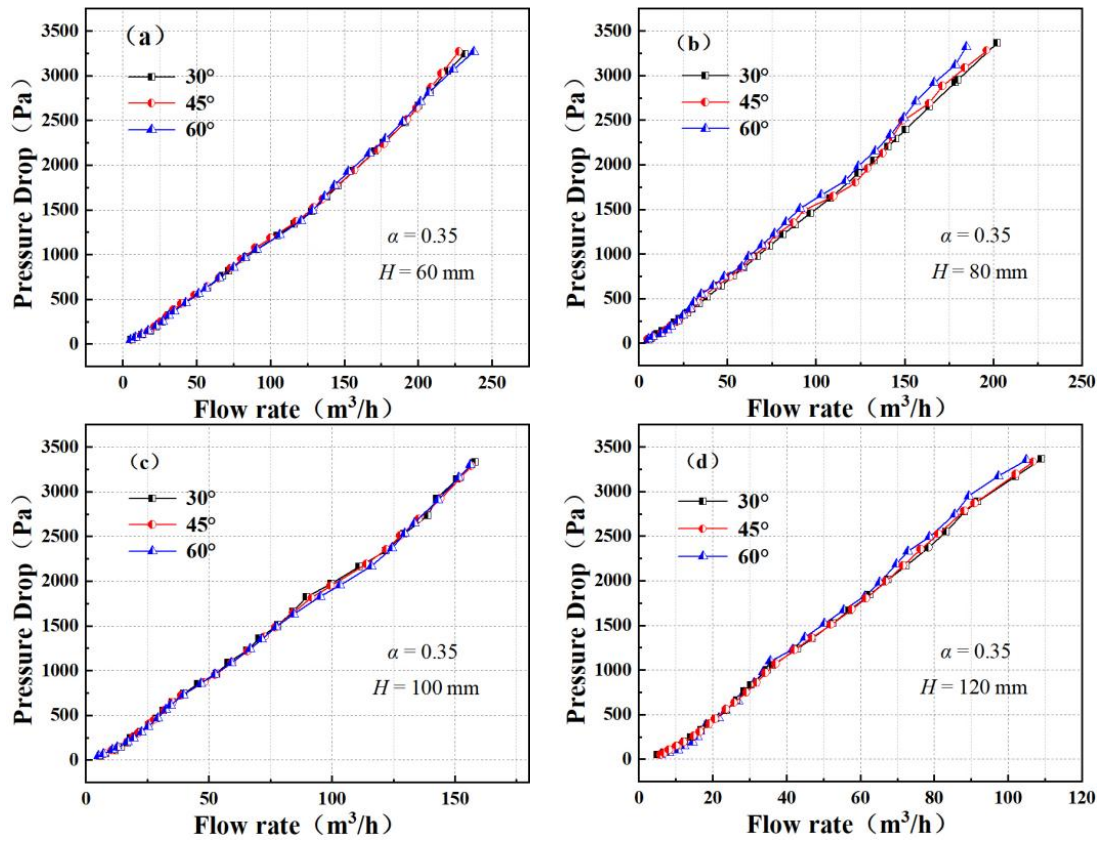
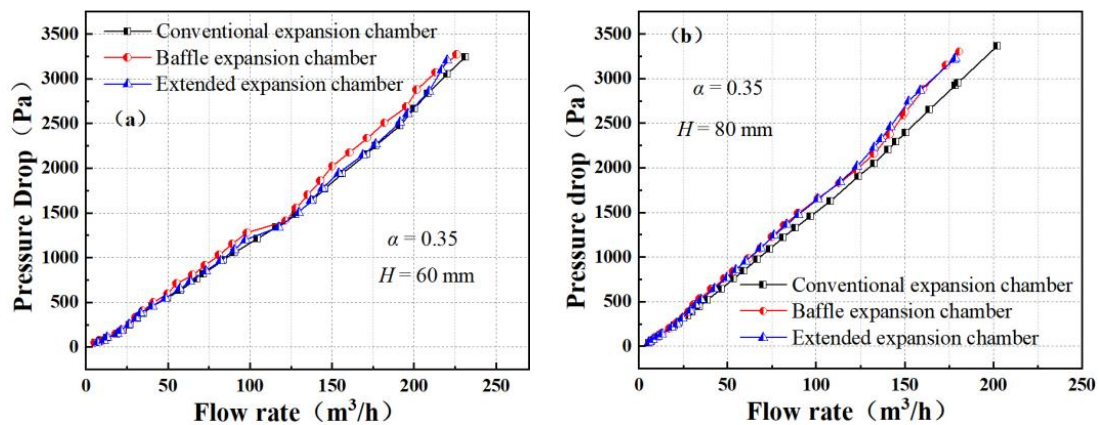


Figure 4. Variation of pressure drop with flow rate under different expansion chamber angles ($\alpha = 0.35$, $\theta = 30^\circ/45^\circ/60^\circ$, the conventional expansion chamber).

3.1.2. Impact of Expansion Structure

Figure 5 shows the variation histories of pressure drop with gas flow rate under different expansion chamber structures. In contrast to the conventional expansion chamber structure, the change in the structure of expansion chamber slightly increased the pressure drop of gas flow through the flame arrester under the baffle and extension type expansion chambers. Especially the increase of pressure drop was obviously under 60 mm and 80 mm flame-retardant unit. The increase in the structure would enhance the fluid vortex entering the expansion chamber, resulting in an uneven distribution of gas velocity and a decrease in axial velocity. And the change in the expansion chamber structure also enhanced the collision effect between gas and the internal structure, thus resulting in an enhancement of airflow attenuation and flow resistance. Besides, it is clear that the baffle type had a greater impact on pressure drop than the extension type by pressure drops histories under the action of two types of chambers. However, the pressure drop difference of each flame arrester was relatively small and within 7% under the action of different expansion chamber structures, and its impact on the pressure drop was not significant.



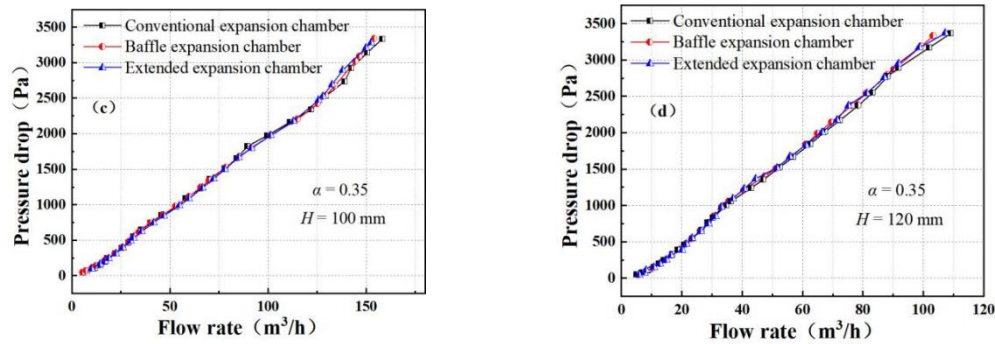


Figure 5. Variation of pressure drop with flow rate under different expansion chamber structures ($\alpha = 0.35$, $\theta = 30^\circ$).

3.1.3. Impact of Porosity

Figure 6 presents the pressure drop variation against gas flow rate at different porosities. For all tested porosities, the pressure drop across the flame arrester increases gradually with rising pipeline flow velocity. As the gas flow rate in the pipeline was low, the difference in pressure drop histories for different porosities under various operating conditions was relatively small. Especially for the pressure drop histories with porosity of 0.35 and 0.5. However, the difference between the pressure drop histories under different porosities was gradually increased as the gas flow rate continued to improve. In contrast to the pressure drop histories of various operating conditions, it is clear that the decrease in porosity resulted in a gradual increase in the pressure drop under each operating condition. Especially, the pressure drop history was suddenly raised under various operating conditions as the porosity was reduced from 0.65 to 0.5. When the gas flow entered the flame-retardant unit from the expansion chamber, its propagation velocity was greatly decreased due to the blocking effect. After entering the flame-retardant element it was divided into a large number of small gas flows by narrow channels, further resulting in significant increase of flow resistance. As the porosity reduced, the number of narrow channels per unit area was enlarged and the specific surface area was also accordingly improved. The gas flow was further divided into smaller the flow fluid, resulting in the greater velocity attenuation and the flow resistance. As the flow rate enlarged, the flow resistance would be also greatly improved.

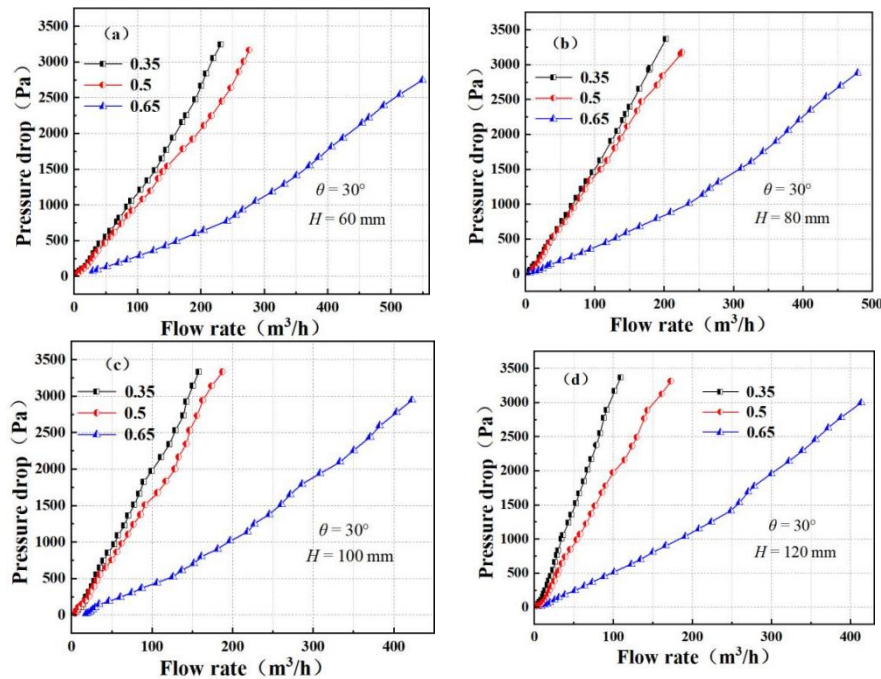


Figure 6. Variation of pressure drop with flow rate at different porosities ($\theta = 30^\circ$, the conventional expansion chamber).

3.1.4. Impact of Element Thickness

Figure 7 displays the variation histories of pressure drop with gas flow rate under different element thicknesses. It was observed that the pressure drop of flame arrester under different element thicknesses was

slightly low as the gas flow rate was small inside the pipeline. As the element thickness was improved from 60 mm to 120 mm, the pressure drop was gradually enlarged under various operating conditions. Due to the blocking effect of flame-retardant unit, the velocity attenuation was greatly improved after gas entered the narrow channel. Besides, the inertial collision and compression between the airflow and the channel wall were enhanced due to the improvement of gas flow resistance. As the flame-retardant element thickness increased, its resistance effect was further enhanced, and appeared the greater velocity attenuation. Meanwhile, the increase in element thickness would also increase the flow time of gas inside the narrow channel, further enhancing the attenuation effect of flame arrester, thus resulting in a gradual increase in the pressure drop. In addition, it is clear that the difference in pressure drop history of each element thickness was gradually increased with the decrease of porosity. Especially the difference in pressure drop history of each element thickness was most significant as the porosity was 0.35 according to the pressure drop histories under different porosities.

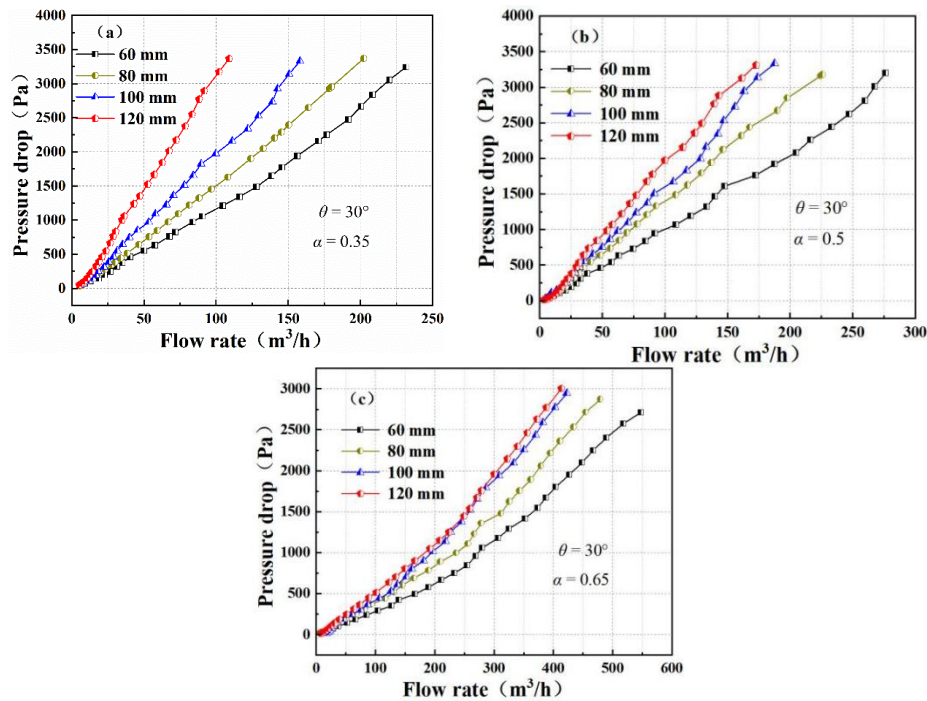


Figure 7. Variation of pressure drop with flow rate for different flame-retardant element thicknesses ($\theta = 30^\circ$, the conventional expansion chamber).

Based on the above analysis, it was concluded that changes in structural parameters had a significant impact on the pressure drop of flame arrester. Under normal operating conditions, flame arresters must have a lower pressure difference to achieve gas and liquid transport. According to the Selection, inspection, and acceptance standards for flame arresters in petrochemical petroleum and gas pipeline (SH/T 3413-2019), the pressure drops of flame arresters under normal operating conditions should not exceed 10 kPa. And the above structural parameters all met the corresponding specification requirements.

3.2. Multi-factor Influence and Prediction Model

Based on the effect of structural parameter on the flame arrester pressure drop, it is clear that changes in porosity and thickness could greatly affect the pressure drop. And the pressure drop was gradually increased as the gas flow rate increased inside the pipeline. In order to further analyze the impact of various influencing factors on the flow pressure drop, the response surface methodology was used to study the influences of multiple factor interactions on the pressure drop, and a multiple factor prediction model was established to provide theoretical basis for the selection and optimization design of flame arrester structure. In response surface research, CCD experimental design was adopted, with the response parameter being the pressure drop of the flame arrester (ΔP), and the design parameters being the flow rate inside the pipeline (Q), porosity (α), and element thickness (H). The pressure drop prediction model of flame arrester under multiple factors was as follows:

$$\Delta P = -2894.106 + 25.198 * Q + 6225.683 * \alpha + 29.247 * H - 69.175 * Q\alpha + 0.307 * QH - 67.766 * \alpha H$$

$$R^2 = 0.951$$
(1)

To verify the effectiveness of prediction model for flame arrester and determine the impact of influencing factor and their interactions on pressure drop, ANOVA was used to analyze the errors of model and the influence degree of each factor. The results of the variance analysis were shown in Table 2. The ANOVA results reveal that the p-value for the prediction model is below 0.0001, demonstrating high statistical significance of the model. The mismatch term of the model also displayed an insignificant state. And R^2 value of the model was greater than 0.90, indicating that the pressure drop prediction model had the good reliability.

Table 2. ANOVA for the RSM prediction model of ΔP under different influencing factors.

Variance Source	Sum of Squares	Degrees of Freedom	Mean Square	F	P	Significance
Model	4.18×10^6	6	6.96×10^5	42.67	<0.0001	Significant
Q	1.20×10^6	1	1.20×10^6	73.73	<0.0001	
α	1.59×10^6	1	1.59×10^6	97.14	<0.0001	
H	6.00×10^6	1	6.00×10^5	36.73	<0.0001	
$Q\alpha$	3.45×10^5	1	3.45×10^5	21.11	0.0005	
QH	1.21×10^5	1	1.21×10^5	7.43	0.0173	
αH	3.31×10^5	1	3.31×10^5	20.26	0.0006	
Residual	2.12×10^5	13	16,320.38			
Lack of Fit	2.12×10^5	8	26,478.45	392.38	<0.0001	Not significant
Pure error	337.41	5	67.48			
Total	4.39×10^6	19				

To further validate the model accuracy, a comparative analysis was conducted between the predicted values of the pressure drop model and the experimental values, as shown in Figure 8. It was observed that the predicted values of the pressure drop model were in good consistency with the experimental values. The above analysis indicates that the pressure-drop prediction model for flame arresters under different flow rates, porosities, and element thicknesses had good accuracy and reliability [18]. This model could provide the theoretical basis and technical support for the development and selection of flame arresters under different structural parameters and flow rates. Besides, the influences of porosity and element thickness on the pressure drop were also analyzed based on the variance results of the model. Comparison of the p-values for porosity and element thickness reveals that both structural parameters yield p-values below 0.0001, demonstrating their significant influence on pressure drop [19]. In order to further clarify the influence strengths of porosity and element thickness, the F-values of two factors were compared. And the larger F-value reflected the stronger impact on the pressure drop. By comparing F values of porosity and element thickness, it indicates that porosity had a greater impact on the pressure drop in contrast to the thickness. Although the p-value for the interaction term between porosity and element thickness was below 0.05, these two factors exerted a significant effect on pressure drop. The effect of their interaction on the pressure drop was shown in Figure 9. As the porosity decreased and the element thickness enlarged, the pressure drop value showed a gradually increasing trend. Through the upward trend and contour lines of the pressure drop surface, it is clear that the change in porosity had a stronger impact on the pressure drop than the element thickness.

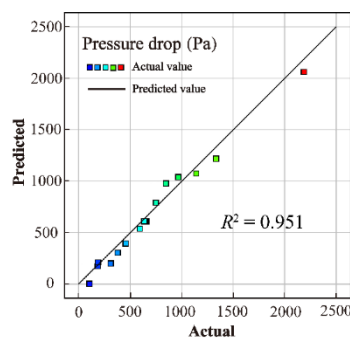


Figure 8. Predicted versus actual values plot for ΔP using prediction model under different influencing factors.

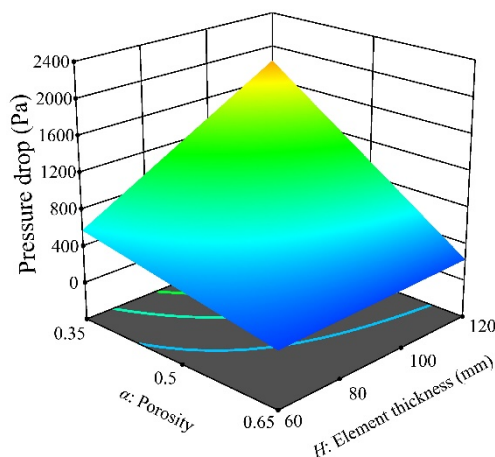


Figure 9. Response surface plot for interaction influence of different influencing factors on pressure drop.

4. Conclusions

This paper carried out experimental research on the pressure drop variation law of hydrogen crimped-ribbon flame arresters. An independent pressure drop test system was built to test pressure drop characteristics under various working conditions, and response surface methodology (RSM) was adopted to quantify the influence degree of each structural parameter. The main conclusions are listed as follows:

- (1) The self-designed test system can realize accurate pressure drop measurement for flame arresters. The pressure drop is affected by both the flame-retardant unit and expansion chamber. The angle and structural type of the expansion chamber barely influence pressure drop, while the porosity and thickness of the flame-retardant unit impose obvious effects; pressure drop rises continuously with increasing ventilation flow rate.
- (2) A multi-factor pressure drop prediction model of flame arresters is established via RSM, which clarifies the influence weight of each factor and accurately predicts structural parameter-induced pressure drop changes. To guarantee stable and efficient medium transportation in hydrogen industrial production, designers should comprehensively optimize flame-retardant units and expansion chambers, and this model can serve as a quick auxiliary tool for preliminary structural design evaluation.

Author Contributions

C.L.: Investigation, Writing—reviewing and editing. X.C.: Writing—original draft preparation; Funding and Investigation. W.F.: Investigation. S.S.: Funding and Investigation. D.L.: Funding and Investigation. Z.D.: Funding and Investigation.

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Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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