Impact of Sudden Expansion Structure Length on Shock Wave Dynamics and Autoignition in High-Pressure Hydrogen Releases

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Abstract. This study investigates the effects of expansion structure length on shock wave behavior, specifically focusing on pressure dynamics, and subsequent autoignition in high-pressure hydrogen systems. Using configurations EPT1 and EPT2, along with a direct pipe (SP1) as a control, we analyze how different expansion lengths influence pressure profiles, shock wave attenuation, and ignition phenomena.

Keywords: High-pressure hydrogen; shock wave; sudden expansion.

1. Introduction

With the increasing application of hydrogen as a clean and efficient energy source [1], the safety concerns associated with its storage and transportation, especially the risk of autoignition and shock wave propagation following high-pressure release, have gained significant attention [2]. Xu [3] conducted numerical simulations to explore the effect of local contractions on spontaneous ignition during pressurized hydrogen release, finding that such internal geometries significantly promote ignition by generating high-temperature combustible mixtures and enhancing turbulent mixing from shock wave interactions. Although extensive studies have explored these phenomena [4,5], the specific impact of sudden expansion structure remains less understood. This research aims to fill this gap by examining how variations in expansion length affect shock wave and autoignition behaviors in high-pressure hydrogen release scenarios.

2. Methodology

2.1 Experimental Setup

2.1.1 Experimental device

Figure 1 shows the overall structure of the high-pressure hydrogen leak self-ignition platform. The entire experimental setup is divided by blast panels into high-pressure and low-pressure areas. Within these two areas, there are four subsystems: the gas supply system, high-pressure hydrogen storage system, pipeline exhaust system, and data acquisition system.

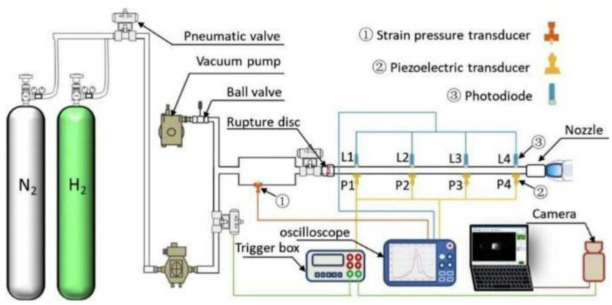

Fig. 1 Schematic diagram of experimental device

2.1.2 Experimental pipeline type

As shown in Figure 2, there are three types of experimental pipelines, each with a total length of 700mm(65+193.33+193.33+193.33+55). SP1 is a conventional straight pipeline with a diameter of 10mm, while EPT1 and EPT2 are expansion pipelines with different lengths of expansion sections (the diameter of the expansion sections is 15mm).

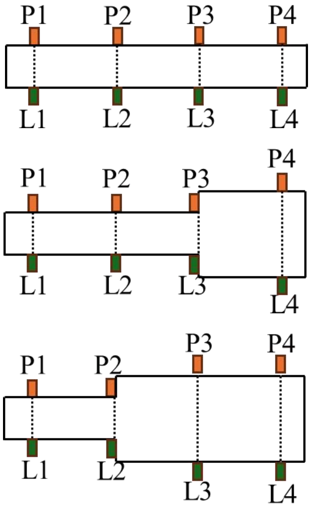

Fig. 2 Three types of sudden expansion pipes (SP1, EPT1, and EPT2)

2.2 Data collection methods

Pressure sensors and photoelectric sensors are symmetrically installed on these pipelines to record changes in pressure and photoelectric signals inside the pipes. The collected data are used to analyze changes in shockwave pressure within the pipes and self-ignition conditions.

3. Results and discussion

3.1 Shock wave propagation in sudden expansion pipe

Figure 3 presents a comparison of shock wave pressure curves for a straight pipe (SP1) and two types of suddenly expanded pipes under the same relief pressure. The graphs include readings from pressure sensors (P1, P2, P3, P4) positioned at different points along the pipe. This data allows us to analyze the pressure variation and its effect on shock wave propagation, comparing the differences between straight pipes and expanded pipes.

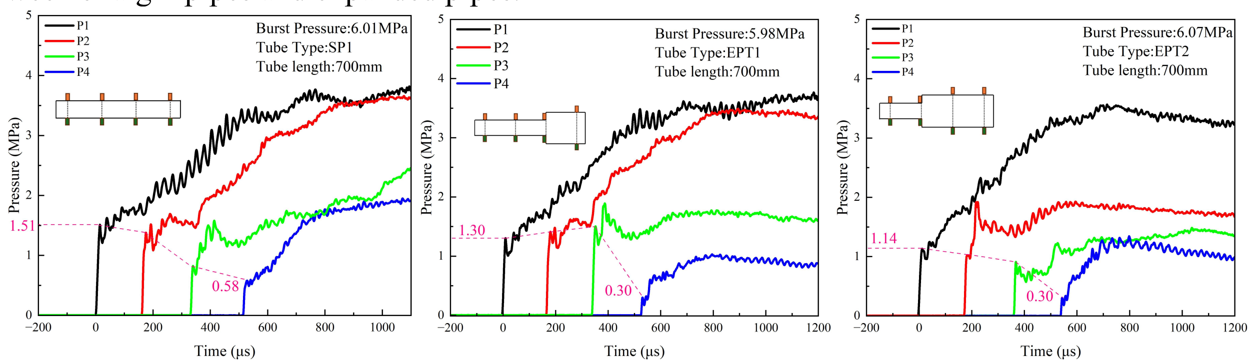

Fig. 3 Pressure and photoelectric diagrams of straight pipes and two suddenly expanded pipes under the same relief pressure

In the SP1 straight pipe, the P1 sensor shows a sharp rise in pressure, signaling the start of the shock wave. As the shock wave propagates downstream, P2 and P3 show a gradual increase in pressure without the decrease seen in expanded pipes. The pressure at P4 remains stable, indicating that at the end of the straight pipe, the shock wave has attenuated to a relatively low level. The EPT1 pipe also shows a sharp rise in pressure at P1, but then a significant drop in pressure at P2, indicating that the expansion structure causes attenuation of the shock wave. The pressure curves at P3 and P4 are smoother than in the SP1 straight pipe, suggesting that the shock wave propagates more slowly and with less pressure variation after passing through the expansion. The rise in pressure at P1 in the EPT2 is similar to EPT1, but the drop in pressure at P2 is even more pronounced, indicating that a larger expansion area can attenuate the shock wave more effectively. At P3 and P4, the pressure continues to rise slowly, and the speed of the shock wave is reduced in EPT2 compared to EPT1, possibly due to the interaction of the shock wave with the larger expansion structure. The pressure profile in the SP1 straight pipe shows a consistent decay of the shock wave starting from high pressure and gradually attenuating as it propagates, without significant pressure drop regions, indicating that gas dynamics within the straight pipe are simpler, with shock attenuation primarily due to viscous losses and the length of the pipe. In contrast, the shock wave pressure curves in EPT1 and EPT2 show a significant drop in the expansion region, indicating that the expansion structure significantly affects the gas flow and shock wave propagation, causing energy dissipation and a reduction in pressure. The shock wave attenuation in EPT2 is more pronounced than in EPT1, likely due to the larger expansion area providing more space for gas mixing, promoting energy dissipation, and reducing the strength of the shock wave propagating downstream.

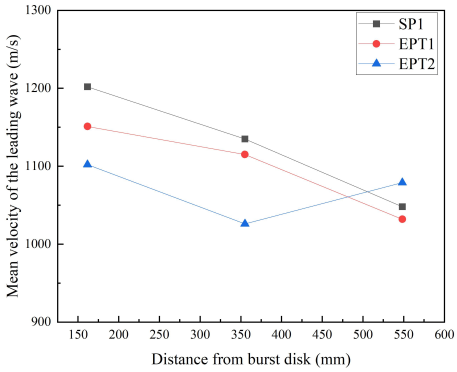

Fig. 4 Comparison of average shock wave velocities of different pipeline types

The graph compares the mean velocity of the leading wave as a function of distance from the burst disk for three types of pipelines: SP1 (straight pipe), EPT1, and EPT2, all under similar relief pressure. The data for the straight pipe indicates a relatively gradual decrease in the mean velocity of the leading wave as the distance from the burst disk increases. This behavior is typical for shock waves in straight pipes where the wave loses energy primarily due to friction and the expansion of the gas. The mean velocity in EPT1 starts higher than in EPT2 but decreases more significantly as it travels away from the burst disk. The initial higher velocity could be due to a less abrupt expansion compared to EPT2, allowing the shock wave to maintain its speed over a shorter distance. However, as the wave encounters the expansion and increased surface area, there's a more significant drop in velocity, likely due to the increased energy dissipation in the expansion zone. The velocity in EPT2 shows a more pronounced initial drop, suggesting that the impact of the expansion on the shock wave is more immediate and substantial than in EPT1. This is indicative of a larger expansion area or more abrupt change in geometry, causing a rapid decrease in kinetic energy of the shock wave. Notably, after the initial drop, the EPT2 curve flattens out and then slightly increases, possibly due to complex interactions such as reflections or secondary shock wave formations within the expanded area before resuming its decay.

Each pipe shows a unique deceleration pattern, with the expanded pipes (EPT1 and EPT2) showing a more significant decrease in wave speed compared to the straight pipe (SP1). This indicates that expansions have a considerable effect on the shock wave's energy and velocity.

The more significant decrease in mean velocity for the expanded pipes points to greater energy dissipation, which can be beneficial in reducing the risk of damage or autoignition due to shock waves in hydrogen pipelines. The steeper velocity drop in EPT1 and EPT2 suggests that the design of expanded structures should be carefully considered to manage shock wave speeds within safety limits for hydrogen transportation systems.

3.2 Spontaneous combustion in the pipe

The graphs show the photoelectric signals corresponding to autoignition events inside the pipelines SP1, EPT1, and EPT2 under similar burst pressures. These signals likely represent the light intensity over time, which can be associated with flame presence and development after the burst.

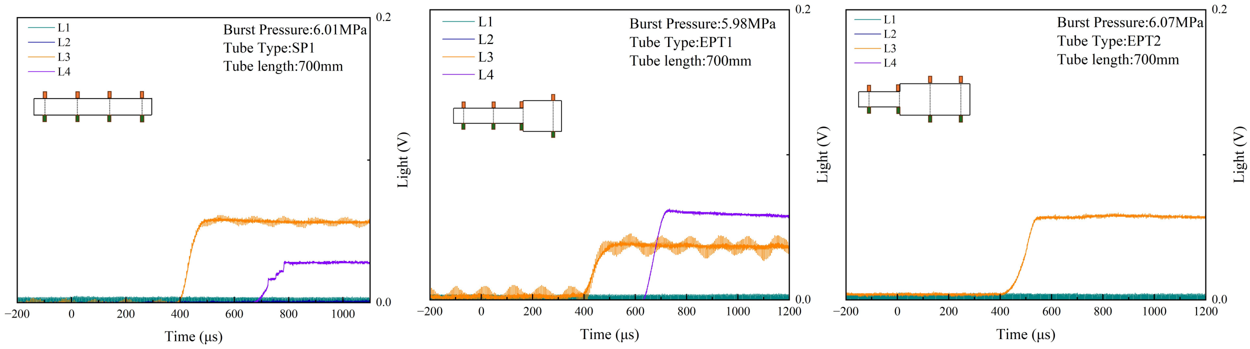

Fig. 5 Spontaneous combustion in different pipeline types

The SP1 graph displays a steady increase in light signal at sensor L1, indicating the presence of a flame that persists and stabilizes after initial ignition. Sensors L2, L3, and L4 show no significant change in the light signal, suggesting that the flame does not propagate far from the burst disk, possibly due to the straight pipe's geometry not favoring flame travel. The light signal in EPT1 at sensor L1 shows a quick spike, followed by a decline and then a stabilization at a higher level than SP1, which may indicate a more intense initial combustion or a reaction front moving past the sensor. L2 demonstrates fluctuation, which could be due to the turbulence within the expanded section affecting the flame stability and movement. L3 and L4 show a similar pattern to L1 but with delayed onset, which suggests the flame or combustion products are moving down the pipe, likely facilitated by the expansion. Comparing SP1 with EPT1 and EPT2, there is a clear trend where the expansions lead to a more intense initial reaction (higher light signal spikes), indicating that the expansions may contribute to more vigorous combustion events. The delay and fluctuation in signals in EPT1 and EPT2 suggest that expansions influence the combustion dynamics, potentially creating conditions that favor a stronger but more turbulent flame front, which could affect the stability and uniformity of the flame propagation. The decreased light intensity down the length of EPT2 might indicate that while the initial combustion is more intense due to the expansion, the energy of the combustion wave is more dispersed, leading to a less intense flame as it progresses down the pipeline.

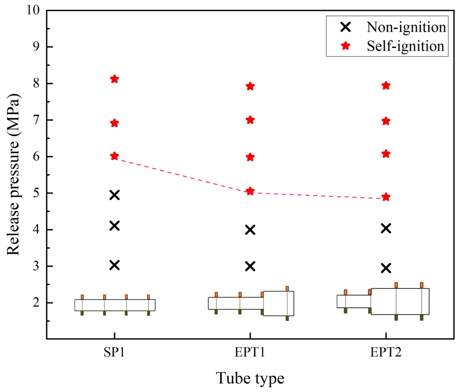

Fig. 6 Critical spontaneous combustion conditions of different pipeline types

The graph indicates that as the expansion size increases (from SP1 to EPT1 to EPT2), the pressure threshold for self-ignition increases. This trend may be due to the expansions' influence on mixing and cooling of the gas, which are critical factors in the ignition process. The self-ignition threshold appears to shift upwards with increased expansion, suggesting that pipeline designs that include expansions can be optimized to reduce the risk of self-ignition during high-pressure hydrogen release events. The presence of expansions in pipelines (EPT1 and EPT2) appears to raise the pressure threshold for self-ignition compared to a straight pipe (SP1), which has implications for the design and safety of hydrogen transport systems.

Understanding the relationship between pipeline geometry, specifically expansion features, and self-ignition thresholds is critical in designing safer hydrogen infrastructure to prevent accidents associated with unintended ignition.

4. Summary

Expanded pipes (EPT1 and EPT2) compared to the straight pipe (SP1) significantly slow down the shock wave speed and reduce pressure peaks, having a noticeable attenuating effect on shock wave propagation. The photoelectric signals suggest that the geometry of the pipe significantly affects the development and propagation of combustion, with expansions in EPT1 and EPT2 likely creating conditions that can enhance the initial combustion but also introduce complexities to the flame's stability and propagation. These findings may have significant implications for the design and safety assessment of high-pressure hydrogen systems, where controlling the behavior of autoignition is critical.

References

[1] Song Y, Zhang X, Xu S, Guo X, Wang L. International hydrogen energy policy summary and Chinese policy analysis: IEEE 4th conference on energy internet and energy system integration. Wuhan, China: IEEE; 2020 .

[2] Zhang Y, Zhang Y, Li Y, Shi X, Zhang Y. Heat effects and kinetics of coal spontaneous combustion at various oxygen contents. Energy 2021;234:121299 .

[3] Xu B, Wen J. The effect of tube internal geometry on the propensity to spontaneous ignition in pressurized hydrogen release. Int J Hydrogen Energy 2014;39(35):20503.

[4] Li P, Duan Q, Gong L, Jin K, Chen J, Sun J. Effects of obstacles inside the tube on the shock wave propagation and spontaneous ignition of high-pressure hydrogen. Fuel 2019;236:1586.

[5] Gong L, Duan Q, Sun Q, Jin K, Sun J. Effects of the geometry of downstream pipes with different angles on the shock ignition of high-pressure hydrogen during its sudden expansion. Int J Hydrogen Energy 2017;42(12):8382.