Effect of Abrupt Changes in the Cross-Sectional Area of a Pipe on Flame Propagation Characteristics of CH₄/Air Mixtures

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ABSTRACT: To study the flame propagation characteristics of methane/air premixed gas in the pipeline with a sudden change of the pipe cross-sectional area, six kinds of customized pipes are used to study the methane/air premixed gas with a concentration of 9.5%. The results show that when the initial smooth flame front encounters an abrupt change in the cross-sectional area, the flame front becomes disordered and a turbulent flame is formed. A greater change in the cross-sectional area results in more severe flame turbulence. Compared with larger cross-section pipes set at the ignition end and downstream end, when the large cross-sectional area pipe is set in the middle of the pipe, the flame propagation process receives the secondary mutation induction effect of the abrupt cross section and the turbulence effect is stronger. The maximum propagation velocity and pressure are observed in configuration with the larger pipe in the middle of the pipe network. Moreover, when the cross-sectional area of this larger pipe increases, the flame is more substantially influenced by longitudinal expansion, the maximum propagation velocity and maximum overpressure increase accordingly, and the pressure oscillations are more obvious.

1. INTRODUCTION

Since the beginning of this century, the demand for fossil fuels has greatly increased with the sustained development of the global economy. Due to high consumption of fossil fuels and the increasingly serious air pollution, the development of clean and renewable energy has become a primary task for the advancement of countries all over the world. In China, many families use natural gas as the main household fuel. Because of the advantages of low carbon emissions, high thermal efficiency, and low cost, natural gas is also used as a clean energy for automobile fuel. The main component of natural gas is methane, which may form an explosive mixture with air during production, transportation, or use. When exposed to a fire source, natural gas explodes and spreads along the pipe network, causing serious damage and possibly causing casualties. Therefore, from the viewpoints of safety and prevention of natural gas explosion accidents, it is of great significance to study the propagation of flame in complex pipe networks.

To date, many experts and scholars have conducted extensive research on the explosion propagation characteristics of premixed methane/air in pipes and during other industrial processes. Cui et al. measured the explosion characteristics of methane/air mixtures at different initial temperatures and pressures and obtained two empirical correlation formulas when the equivalence ratio was 1.0, which can be used to calculate the combustion duration and flame development duration based on the experimental settings. Yao et al. performed an experimental study on the effects of initial concentration and ignition position on pressure accumulation and flame behavior. The results showed that the ignition position substantially affects the Taylor instability of the flame front caused by the Helmholtz vibration. Wang et al. found that the closer the methane/air mixture concentration is to the stoichiometric concentration, the greater the flame velocity. All these studies have shown that any gas mixture with a methane concentration in the combustible range is likely to explode when exposed to an ignition source, and explosions in air containing a methane concentration of 9.5% are the most destructive. Explosion venting is commonly used to prevent or minimize the damage sustained by pipes during an internal gas explosion. An experimental study on the influence of the ignition position on venting is carried out by Chao et al. and Cao et al. Sezer et al. and Kuznetsov et al. found that the concentration of the mixture has an important influence on the venting effect. In...
addition, the venting area and venting position have more important influences on the effectiveness of venting measures. For high-concentration combustible gases, an excessive venting area may cause external gas reflux to trigger a secondary explosion. When the lateral explosion vent is placed at a certain position from the ignition source, the pressure relief effect is closer to ideal. According to experimental studies on explosions in methane/air mixtures carried out under the stoichiometric ratio, the existence of obstacles can accelerate flame propagation. For most combustion channels, there is an optimal blockage ratio that leads to maximum flame acceleration. The number and shape of obstacles also have substantial impacts on flame propagation in a channel, an increase in the number of obstacles affects the flame propagation speed in the pipeline, and the flame propagation speed is proportional to the number of obstacles. Continuous flame acceleration leads to the transition from deflagration to detonation. Yu et al. reported that triangular hollow square obstacles cause the highest flame turbulence intensity, flame propagation velocity, and explosion overpressure, while circular hollow square obstacles produce the lowest values by using experiments and numerical simulations. In addition, the explosion characteristics of premixed gases are also different in explosion vessels with different geometric shapes. These geometric structures include bifurcations, bends, and connected containers. Changes in the structure of the explosion vessel will reflect the pressure wave and disturb the airflow to form a turbulent flame, and the formation of a turbulent flame will increase flame propagation velocity and explosion overpressure.

Previous studies have been carried out on the propagation characteristics of methane/hydrogen/air premixed flames in pipes with various cross sections, focusing on the analysis of the influence of the variable cross-section position and the mixing ratio of the premixed gas on flame propagation. Few studies have been carried out in the existing literature on the effects of the position and size of variable cross-section pipes on the flame propagation characteristics of methane/air premixed gases. Therefore, this paper mainly studies the influences of the position and magnitude of sudden changes in the cross-sectional area of pipes on the explosion process of methane/air premixed gas and analyzes the corresponding rules of flame propagation and overpressure variation, which are accomplished by performing experiments on a custom-built experimental platform containing a semiconfined pipe.

2. EXPERIMENTAL SETUP AND MIXTURE COMPOSITION

The experimental system shown in Figure 1 is mainly composed of transparent plexiglass pipes, an ignition system, a gas distribution system, an image acquisition system, a pressure and optical signal acquisition system, and a synchronization control system. The transparent plexiglass pipes used in the experiment are composed of three 500 mm long pipes with cross-sectional dimensions of $70 \times 70 \text{ mm}^2$ (S), $100 \times 100 \text{ mm}^2$ (M), and $140 \times 140 \text{ mm}^2$ (L), respectively. These pipes are tested in total of six different configurations (M–S–S, S–M–S, S–S–M, L–S–S, S–L–S, and S–S–L), as shown in Table 1. The left side of the pipe is the ignition end, which is enclosed by a plexiglass plate, and the right side is the bursting end, which is fully opened and covered with a polyvinyl chloride (PVC) film. This membrane (the PVC film) is used to keep the methane/air premixed gas in the pipe, the rupture pressure of the PVC film is about 15 mbar, and the effect of the PVC film on flame propagation is negligible. Premixed gas of 9.5% of methane/air is obtained by using two mass flowmeters, and the mixture is introduced through the air inlet at the left end of the pipe, while the exhaust is carried out at the upper right end of the pipe. The experiment ensures that five times the pipe volume of the mixed gas flows through the

![Figure 1. Schematic diagram of the experimental system.](https://doi.org/10.1021/acsomega.1c01350)

| configuration | dimensions |
|---------------|------------|
| M–S–S         | 100 mm × 100 mm × 500 mm – 70 mm × 70 mm × 500 mm |
| S–M–S         | 70 mm × 70 mm × 500 mm – 100 mm × 100 mm × 500 mm |
| S–S–M         | 70 mm × 70 mm × 500 mm – 100 mm × 100 mm × 500 mm |
| L–S–S         | 140 mm × 140 mm × 500 mm – 70 mm × 70 mm × 500 mm |
| S–L–S         | 70 mm × 70 mm × 500 mm – 140 mm × 140 mm × 500 mm |
| S–S–L         | 70 mm × 70 mm × 500 mm – 140 mm × 140 mm × 500 mm |
pipeline, so that the original air in the pipe can be exhausted. In the experiment, the ignition device consists of two domestic ignition electrodes with distances of 6 and 0.3 mm, which are installed in the center of the pole plate and triggered by a 6 V DC power supply. The initial ignition energy is 100 mJ. A USB-1208 data acquisition card is used to record the signal data from a pressure sensor and photodiode sensor at a rate of 15 kHz. Two pressure sensors (Shanghai MIND Ltd.) are installed on the left closed end of the pipe and the right semiclosed end of the pipe, respectively. The photodiode sensor is located on the outside of the explosion pipe, pointing toward the ignition source. The photoelectric sensor is used to capture the ignition time and ensures the synchronization of the pressure signal, high-speed camera, and ignition. The image of the premixed flame is captured by a high-speed camera at a shooting speed of 2000 fps to capture the flame structure and its front position, and the exposure time of the high-speed camera is 500 μs. Each working condition is tested at least three times to ensure the accuracy and reproducibility of the experiment.

Figure 2. Evolution of the flame front in six different pipe configurations with abrupt changes in the cross-sectional area. (a) Comparison of configuration M–S–S and L–S–S; (b) comparison of configuration S–M–S and S–L–S; and (c) comparison of configuration S–S–M and S–S–L.
3. RESULTS AND DISCUSSION

3.1. Effect of the Pipe Structure on the Flame Structure and Flame Front Position.

Figure 2 shows the propagation evolution of methane/air premixed flames in six different pipe configurations. The relationship between the position of the flame front in the six pipe configurations over time is shown in Figure 3. In this paper, the influence of the pipe structure on the flame is studied from two aspects: the dimensions and the position of a single expanded pipe in the pipe network. The flame propagation in the two configurations with the expanded pipe occurred at the ignition end of the pipe network (Figure 2a), wherein the flame transforms from a hemispherical flame to a finger-shaped flame within the first pipe. In these configurations, the flame propagates from the expanded pipe into a smaller pipe at a distance of 500 mm from where the pipe network begins. The sudden reduction in the cross-sectional area of the pipe blocks the flow of the premixed gas and the propagation of the flame on the wall, causing this compressed flame to jet into the smaller pipe. The figure shows that the flame takes 50 ms to propagate through M in the M−S−S configuration, whereas the flame takes 55.5 ms to propagate through L in the L−S−S configuration. This variation in flame propagation time is caused by different aspect ratios of M and L. Figure 3a shows that before reaching a distance of 500 mm from the ignition end of the pipe network, the flame front position curve has a high slope in the M−S−S configuration, indicating that the flame propagation speed is higher in M than in L. However, at a distance of 500 mm on the right side of the pipe, the blockage ratio of the L−S−S configuration is higher than that of the M−S−S configuration. Accordingly, there is a stronger reflection of pressure waves in the L−S−S configuration, indicating that this configuration has a greater influence on flame propagation and results in more severe flame turbulence than the M−S−S configuration. Therefore, the
slope of the position–time curve of the flame front beyond a 500 mm pipe length is higher in the L–S–S configuration than in the M–S–S configuration.

Figure 2b shows the flame propagation in the two configurations with the expanded pipe located in the middle of the pipe network (i.e., S–M–S and S–L–S). Similar to the previous configurations, in these configurations, the flame also transforms from a hemispherical flame to a finger-shaped flame in the first pipe. Moreover, in these configurations, the flame propagates from a smaller pipe into the expanded pipe at a distance of 500 mm from where the pipe network begins. This sudden increase in the cross-sectional area of the pipe and the accompanying disturbance of sparse waves at the upper and lower walls form a local turbulent vortex, which accelerates the gas near the upper and lower walls, leading to the production of folds and distortions in the flame front and an increase in the degree of flame turbulence. At a pipe length of 1000 mm from the ignition end, the propagating flame is blocked to some extent by the transition from the expanded pipe to the smaller pipe, thereby strengthening the degree of the flame turbulence. In the S–L–S configuration, a greater amount of turbulence is generated during flame propagation and the flame propagation time is shorter. As shown in Figure 3b, the slope of the flame propagation curve in the S–L–S configuration is higher than that in the S–M–S configuration at a distance of 500 mm from the ignition end. This difference in slope exists because the S–L–S configuration has a larger abrupt change in the cross-sectional area and a stronger flame turbulence created by the gas near the upper and lower walls.
pipe structure than the S–M–S configuration, which leads to a faster flame combustion speed.

Figure 2c shows that the flame propagation in the two configurations with the expanded pipe is located at the downstream end of the pipe network (i.e., S–S–M and S–S–L). The flame propagation process is very similar to previous research results. In the first two pipes, the flame exhibits typical characteristic changes, which can be clearly divided into four stages: spherical, finger-shaped, flame skirt touching the sidewall, and “tulip” flames. In the S–S–M and S–S–L configurations, the positions of the typical tulip flames are observed at 627 and 617 mm, respectively, and the corresponding times are 63 and 54 ms. These results show that setting the expanded pipe downstream in the pipe network has little effect on the formation position of the tulip flame and that the formation of the tulip flame is caused only by hydrodynamic instability, which is controlled by the aspect ratio of the pipe. A larger cross-sectional area of the pipe at the downstream end of the network results in less time required for the flame to spread to the same position in the first two pipes. When the flame spreads to a pipe length of 100 mm from the ignition end, a sudden increase in the cross-sectional area of the pipe will further disturb the flame front. The larger this sudden expansion is, the higher the turbulence degree of the flame front. The abrupt change in the cross-sectional area in the S–S–M and S–S–L configurations occurs at a pipe length of 100 mm from the ignition end. At the initial stage of flame propagation, the slope of the flame front curve in the S–S–L configuration gradually increases, which also shows that when the expanded pipe located at the downstream end of the network is larger, the flame propagation speed increases faster in the first two pipes of the network.

3.2. Effect of the Pipe Structure on Flame Propagation Velocity. A comparison of the relationship between the flame propagation velocity and the flame front position in the configurations where the expanded pipe is located in the same position in the pipe network is illustrated in Figure 4. The flame front velocity in the pipe is calculated based on the flame front position with respect to time. Figure 4a shows that the overall flame propagation speed is very slow at the initial stage of flame propagation, and the flame propagation speed in the M–S–S configuration is higher than that in the L–S–S configuration at the same location. As the flame propagation approaches a pipe length of 500 mm, the flame propagation velocity in L–S–S gradually increases, and then, the flame propagation velocity curve changes obviously in both configurations upon reaching a pipe length of 500 mm from the ignition end. In the subsequent 1000 mm of the pipe length in the network, the flame propagation speed in the L–S–S configuration is higher than that in the M–S–S configuration at the same position. As shown in Figure 4b, the difference in the flame propagation velocity in the first 500 mm pipe length in the network is very small, and the flame propagation velocity in the S–L–S configuration is slightly higher than that in the S–M–S configuration. At pipe lengths between 500 and 770 mm from the ignition end, the flame propagation speed in the S–M–S configuration is greater than that in the S–L–S configuration because the flame expands longitudinally when entering the expanded pipe, which reduces the flame propagation acceleration. A larger cross-sectional area of the expanded pipe results in a more pronounced influence of this longitudinal expansion. Beyond a pipe length of 770 mm from the ignition end, the flame propagation speed in the S–L–S configuration is greater than that in the S–M–S configuration at the same location. The figure shows that the first sudden change in the cross-sectional area has a substantial influence on the flame propagation velocity curve, whereas the second sudden change in the cross-sectional area has little influence on the flame propagation velocity curve. However, the premixed flame in these two configurations is subjected to two sudden changes in the cross-sectional area, which increases the turbulence intensity and the flame propagation speed. In Figure 4c, the flame propagation velocity curves in the S–S–M and S–S–L configurations are similar, and the values are low. Within the first 1000 mm pipe length in the network, the propagation speed in the S–S–L configuration is slightly higher than that in the S–S–M configuration at the same location. When the cross-
sectional area suddenly expands at a pipe length of 1000 mm from the ignition end, the flame propagation velocity changes and increases rapidly, and the flame propagation acceleration in the S–S–L configuration is greater than that in the S–S–M configuration.

Figure 5 presents a diagram comparing the variation in the flame propagation velocity with respect to the flame front position in the configurations with the same expanded pipe (M or L) at different positions in the pipe network. Figure 5 shows that when the expanded pipe is located at the ignition end of the network, the flame propagation speed curve will first change abruptly due to the flame blocking effect in which the smaller pipe accelerates flame propagation. At pipe lengths between 430 and 900 mm from the ignition end, the flame propagation speed in the M–S–S configuration is higher than that in the S–M–S and S–S–M configurations at the same position, whereas after 900 mm, the S–M–S configuration has the highest flame propagation speed and the S–S–M configuration has the lowest flame propagation speed. At pipe lengths between 430 and 1020 mm from the ignition end, the flame propagation speed in the L–S–S configuration is higher than that in the S–L–S and S–S–L configurations at the same location, whereas after a pipe length of 1020 mm from the ignition end, the S–L–S configuration has the highest flame propagation speed.

3.3. Effect of the Pipe Structure on Overpressure. Figures 6 and 7 compare the relationship of overpressure with respect to time in the different pipe configurations. Cooper et al.32 and Ibrahim and Masri33 discussed the mechanism of typical overpressure in exhaust explosions. There are two overpressure peaks in the pressure curve; the first peak is the “venting” pressure $P_v$ and the second peak is called the “overpressure” peak. After ignition, the overpressure increases

![Figure 6](https://pubs.acs.org/doi/10.1021/acsomega.1c01350)
Figure 7. Relationship of overpressure with respect to time when the same expanded pipe (M or L) is located at different positions in the pipe network. (a) Comparison of configurations M−S−S, S−M−S, and S−S−M and (b) comparison of configurations L−S−S, S−L−S, and S−S−L.

due to the combustion of the combustible gas in the pipe. Once the overpressure exceeds the failure pressure of the PVC film, the film ruptures and the unburned gas in the pipe begins to escape from the downstream end. This process includes the increase and decrease of overpressure. The first peak of overpressure formed is called the “venting” pressure \(P_v\). The “overpressure” peak is the maximum overpressure achieved by combustion and gas expansion in the pipe. There is a small peak in the early stage in all six configurations shown in Figure 6 because after ignition, combustion gas is generated in the pipe and the overpressure begins to increase. Once the overpressure exceeds the failure pressure of the PVC film, the film breaks and the unburned gas begins to escape from the exhaust outlet. This process leads to a decrease in overpressure, thus forming the first peak in the overpressure curve. In this case, although the unburned gas is released due to the PVC film failure, the emission rate of the unburned gas is always lower than the volumetric rate of combustion gas generation. The net volume ratio is always positive over time, resulting in a continuous increase in pressure, followed by a larger peak pressure. Figure 6 shows that the overpressure of pure methane over time in the configurations with the expanded pipe is located at the same position in the pipe network. As shown in Figure 6a,b, when the expanded pipe is located at the ignition end or the middle of the pipe network, the maximum pressure produced in the L−S−S and S−L−S configurations will be greater than that produced in the M−S−S and S−M−S configurations. However, when the expanded pipe is located at the downstream end of the pipe network, as shown in Figure 6c, the maximum pressure in the S−S−L configuration will be lower than that in the S−S−M configuration.

Figure 7 shows a diagram comparing the overpressure of pure methane over time in configurations with the same expanded pipe (M or L) at different positions in the pipe network. As shown in Figure 7, the pressure is the highest when the expanded pipe is located in the middle of the network, followed by that when the expanded pipe is at the ignition end, and finally by that when the expanded pipe is at the downstream end. The main reason that the pressure is low in the configuration with the expanded pipe at the downstream end of the network can be explained. On the one hand, when the expanded pipe is located at the downstream end of the pipe network, the flame propagation time will be longer; on the other hand, the combustible gas escapes quickly because the cross-sectional area of the downstream end is larger, which leads to the fact that the combustible gas will essentially completely react when the flame propagates through the expanded pipe. The pressure and velocity still increase due to the abrupt change in the cross-sectional area of the pipe, but the maximum overpressure is much lower than that of the expanded pipe at the ignition end and the middle of the network.

4. CONCLUSIONS

In the present work, six configurations having different locations and sizes of the variable cross sections have been examined in order to obtain abrupt changes in the cross-sectional area of a pipe on the flame propagation process of CH\(_4\)/air mixtures. The flame front propagation and overpressure dynamics of premixed gas in the pipe during the process of flame propagation are found to be different for the position and size of the variable cross section as follows:

1. When the expanded pipe is located at the ignition end or in the middle of the pipe network, the flame front will no longer be smooth due to the change of the blockage ratio at a pipe length of 500 mm from the ignition end, and the rapid transition of the flame from laminar flow to turbulence leads to the rapid increase of the flame velocity. When the expanded pipe is located at the downstream end of the pipe network, the change in the flame structure in the early stage will not be affected, and the flame undergoes four stages, forming a special tulip flame structure.

2. In the configurations with the expanded pipe located at the same position in the pipe network, the flame propagation velocity curves exhibit a similar trend. When the expanded pipe is located in the middle of the pipe network, the flame is subjected to a sudden change in the cross-sectional area twice, which increases the flame...
turbulence and accelerates the flame propagation. When the flame enters the expanded pipe, the flame propagation speed will decrease due to the influence of longitudinal expansion. A larger cross-sectional area of the expanded pipe results in a more substantial effect of this longitudinal expansion. Cross-overs occur in the velocity curves of these configurations.

(3) When the expanded pipe is located at the ignition end or in the middle of the pipe network, the pressure increases as the cross-sectional area increases. When the expanded pipe is located at the downstream end of the pipe network, the pressure caused by the smaller change in the cross-sectional area is greater. By comparing the relationship between overpressure and time in the configurations with the expanded pipe located at different positions, it can be found that when the expanded pipe is located in the middle of the pipe network, the overpressure is greater and the pressure oscillations are more obvious than those when the pipe is at the ignition end or at the downstream end of the pipe network.

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Notes

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