Propagation characteristics of the overpressure waves and flame fronts of methane explosions in complex pipeline networks

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ABSTRACT

The propagation characteristics of the overpressure waves and flame fronts of methane explosions in complex pipe networks under realistic conditions were studied. A custom-designed experimental platform was used, the propagation characteristics of overpressure wave and flame wave in complex pipe network were characterized by overpressure attenuation coefficient and flame mutation coefficient. The results showed that the overpressure wave propagation characteristics in complex pipe networks were more complicated and disordered than those in straight or simple branched pipes. The overpressure wave attenuation and superposition occurred many times in the propagation process, the explosion shock wave attenuation in the beveled branch pipe was faster. When the flame wave passed through all the branch tubes, the flame wave velocity increased significantly. When the flame wave passed through the same tube at different times, the flame wave mutation coefficient was different, the change of flame wave temperature had a certain lag compared with the change of flame velocity, resulting in the peak of flame wave temperature and flame wave velocity appearing in different branch tubes. The experimentally obtained data were fit to functional relationships using nonlinear multiple regression analysis, and good agreement between the functional relationships and the data was obtained.

1. Introduction

Methane explosions in natural gas pipeline networks are significant safety threats (Prodan et al. 2016; Mitu et al. 2017, 2018; Wang et al. 2020; Su et al. 2021). Accordingly, the behaviors of the overpressure waves and flame fronts associated
with methane explosions have been the subject of intense research interest involving experimental and computational studies (Razus et al. 2017; Luo et al. 2020; Mitu et al. 2020; Wang et al. 2020; Xing et al. 2020; Zhang et al. 2020).

In terms of experimental studies, Wingerden et al. (1990) implemented methane explosion tests first in 1990 using a custom-designed experimental pipeline, and the experimental platform was employed to explore the characteristics of the overpressure waves and flame fronts associated with methane explosions under different conditions. Ibrahim and Masri (2001) studied the interactions between the overpressure waves associated with methane explosions and pipeline obstacles and thereby ascertained the effects of the obstacle size and pipeline blockage rate on the overpressures of overpressure waves within pipelines. Blanchard et al. (2010) observed that bends in pipelines can indeed increase the shockwave overpressures and the flame front velocities associated with methane explosions. Thomas et al. (2010) observed that the travel of overpressure waves arising from methane explosions through heavily bent areas of a pipeline can cause turbulent acceleration and sudden changes in the combustion rate. Jia and Wang (2021) explored the propagation of methane explosions in pipelines by monitoring the temperature and pressure in test pipes with circular, square, rectangular, and trapezoidal cross sections during methane explosion events. The results demonstrated that the maximum pressure observed in all the test pipes was about 0.6 MPa. Additionally, the flame front propagation velocity and the flame front temperature were the lowest in the test pipe with a trapezoidal cross section, and this test pipe also required the greatest length of time to reach the maximum pressure. In contrast, the highest temperature was observed for the test pipe with the square cross section. Niu et al. (2019) investigated the characteristics of methane explosions in a pipeline system consisting of parallel and transverse branches. The results indicated that the transverse branch formed a region of increasing overpressure due to the superposition of pressure waves. Moreover, the maximum overpressure in the parallel branches of the system exhibited a gradually decreasing trend, and the flame front velocity initially increased and then decreased. Xie et al. (2019) studied the flame front propagation characteristics of methane explosions under different closure conditions and in a branched tube using a custom-developed transparent T-tube system and an experimental pipeline with an arbitrary bending angle. Yang et al. (2019) employed a simple experimental pipeline system composed of a long, predominantly straight test pipe having a single bend with a varying bending angle and investigated the characteristics of the overpressure wave and flame front induced by methane explosion events before and after the bend point. The results indicated that the attenuation rate of the peak shockwave overpressure increased with increasing pipe bending angle. In addition, the flame front propagation velocity increased gradually as the flame front approached the bend point and then decreased just prior to the bend point, while the flame front velocity suddenly increased just after passing the bend point. The observed sudden change in the flame front velocity at the bend point was analyzed based on the ratio $\frac{V_a}{V_b}$ of the flame front velocity $V_a$ just prior to the bend point and the flame front velocity $V_b$ just after the bend point. The value of $\lambda$ was observed to increase with increasing bending angle. Zhu et al. (2011) determined that the peak flame front velocities and the peak
overpressures of the overpressure waves at the two ends of a transverse pipe were similar in the initial phase of a methane explosion. However, the superposition of the flame fronts and overpressure waves in the transverse pipe resulted in an instantaneous change in pressure. Zhao et al. (2018) explored the propagation of overpressure waves due to methane explosions in different types of simple pipeline networks composed of two test pipes in different configurations, including ‘T’, ‘X’ and ‘L’ configurations. The results demonstrated that the rate of pressure increase in the simple networks decreased in the order of T-type, X-type, and L-type. In addition, the overpressure wave overpressure attenuation rate and overpressure wave velocity decreased in the order of L-type, T-type, and X-type.

In terms of numerical simulation research, Huld et al. and Dunn-rankin et al. (1996, 2000) found that obstacles had unstable disturbance effects on the overpressures of shockwaves and the flame front velocities associated with methane explosions in straight pipelines, and the existence of an accelerating effect near obstacles was verified. Zhu et al. (2015) investigated the explosion flow fields of five straight test pipes with different diameters and one bent test pipe. The results demonstrated that the overpressure wave and flame front exhibited different acceleration characteristics in the straight and bent pipes, where the acceleration effect in an elbow pipe was significantly greater than that in a straight pipe. Liu et al. (2018) used the Harten–Lax–van Leer contact solution algorithm to numerically simulate the methane explosion process in a straight pipe and studied the superposition effect of the reverse overpressure wave. The results indicated that the pressure would increase suddenly when the overpressure wave was superimposed in the reverse direction. Meng et al. (2019) studied the influence of obstacles in ventilation pipe networks on the characteristics of the shockwave overpressure due to methane explosion events. The results demonstrated that obstacles affect the propagation path of the overpressure wave in the initial explosion and the location of the superimposed area. This alters the accumulation of non-combusted methane in the pipeline network and thereby affects the shockwave overpressure obtained in the secondary methane explosion.

Most previous research on methane explosions was limited to long straight pipelines, and the few studies that considered multiple pipeline networks were limited to simple parallel pipelines (Zhu et al. 2011; Ye and Lin 2012) or single-branched pipeline configurations (Lin et al. 2016; Zhu et al. 2016, 2017; Chen and Wu 2017; Jing et al. 2017). As a result, research focused on the attenuation characteristics of overpressure waves and the characteristics of sudden changes in the flame front velocity arising from methane explosion events in complex pipe networks is particularly rare. Moreover, simple pipeline networks do not closely match the actual conditions prevailing when a methane explosion disaster occurs. Therefore, the explosion hazard effect cannot be investigated and analyzed in depth. In this study, we analyzed the behaviors of the overpressure wave and flame front in a complex pipeline network from multiple perspectives, including the overpressure attenuation coefficient, the flame front propagation velocity, and the sudden changes in the flame front velocity at network pipe bends and branches in each of the test pipes of the network. We then applied the experimentally obtained data to obtain functional relationships between the overpressure attenuation of shockwaves and the sudden changes in the
flame front velocity, and the results of multiple regression fitting to the experimental data met the requirements of high fitting accuracy. Accordingly, the present work provides a basis for analyzing the characteristics of methane explosions within complex pipeline networks with generalized structural parameters and a more comprehensive theoretical basis for the prevention and treatment of methane explosion disaster and the development of emergency rescue after the disaster.

2. Experimental system and data repeatability analysis

The experimental platform employed for testing is illustrated in Figure 1. The system was mainly composed of a pipeline network, a dynamic data acquisition system, and an ignition system. The pipeline network was composed primarily of structural steel pipes, where the volume of the explosion chamber was 0.5 m³, the inner diameter of each pipe was 360 mm, and the pressure capacity of the pipes was at least 20 MPa. The two outlets of the pipeline network were closed with flanges and equipped with explosion venting polytetrafluoroethylene films.

As shown in Figure 1, each pipe included 14-mm-diameter holes to insert pressure sensors, temperature sensors, and flame sensors simultaneously (the locations of the holes are shown in Figure 1). The various components were connected with the pipes using internal threads. The accuracy of the experiments was maximized by increasing the airtightness of the pipeline network through the installation of a silicone gasket at the connection between each component and its corresponding pipe. The experimental platform (as showed in Figure 2) employed the complex pipe network and a dynamic data acquisition system that was manufactured by Chengdu Keda Shengying Technology Co., Ltd. The system mainly included pressure sensors model QSY8124, transient high-temperature sensors model NANMAC, light-induction high-precision flame sensors model CKG100, a high-speed dynamic data acquisition device, a personal computer with appropriate software, and the associated electrical connections. The response time of pressure sensor, temperature sensor and flame sensor are 10μs, 10 ms and 1 ms respectively, and the accuracy of the data acquisition device is...
0.2%FS, and the continuous acquisition frequency is 10KHz/CH. The ignition system mainly included a DX-GDH high-energy igniter, high-energy sparkplugs, high-voltage-resistant and high-temperature-resistant cables, power supply cables, and external trigger devices. The ignition control box was connected with an external trigger wire. The sparkplugs were placed at the front end of the explosion chamber, the ignition voltage was about 2200 V, and the one-time energy storage was 30 J. Each branch and sensor interface in the pipeline network was numbered, as illustrated in Figure 3. The position of the explosion chamber was set to O point. The coordinates of all monitoring points are shown in Table 1. The pressure and temperature sensors were installed on each branch of the pipeline network to collect data associated with the overpressure wave and the flame front temperatures during the experiments. As for the flame velocity, the installation of two flame sensors in each of the branch pipes of the network enabled the use of a conventional method for measuring the propagation velocity of the flame front, where the times at which a flame front arrived at each flame sensor in a branch pipe were recorded, and the average velocity of propagation was
calculated as the ratio of the known distance between the two flame sensors to the difference in the times of flame front arrival.

The experimental gas is distributed according to Dalton’s law of partial pressure. A vacuum pump is used to inject the prepared methane-air gas into the explosion chamber. Use a circulation pump to circulate the gas for 20 minutes, ensuring that the methane and air mix well. At the end of each experiment, the Air compressor was used for 30 minutes for high pressure ventilation to vent the residual gas from the explosion. Before the experiment started, the explosion chamber was filled with a preconfigured methane test gas with a volume fraction of 9.5% and an equivalence ratio of 1. The explosion chamber was separated from the experimental pipe, which contained air, by a polytetrafluoroethylene film.

The reproducibility of the methane explosion experiments was first evaluated by performing three tests at the same standard charge level with 9.5% methane gas (by volume). Pressure, flame temperature, and flame front position data were acquired at monitoring point 1 of branch 1. A comparison of the pressure data obtained for the three tests is presented in Figure 4(a).

The results indicate that the measured peak pressure values had a relative standard deviation of less than 1%. Moreover, the pressure trends observed throughout the three methane explosion events were nearly identical. The same test method was
Figure 4. Experimental data repeatability analysis.

(a) Overpressures obtained at monitoring point 1 for the three tests

(b) Flame temperature peak at the five network branches for the three tests

(c) Flame front propagation velocity at the five network branches for the three tests
applied to verify the reproducibility of the explosion overpressure in the other branch pipes (all other monitors), and the results indicated that the measured peak overpressure had a relative standard deviation of less than 1% for all other branch pipes.

The peak flame front temperature and velocity values are presented in Figure 4(b) and (c), respectively. The results indicated that the relative standard deviation was less than 1.5% for both peak flame front temperature and velocity values. The high reproducibility of the experiments verified the accuracy of the obtained experimental data.

3 Results and discussions

3.1. Overpressure wave characteristics

The overpressure variations at the two monitoring points in branch pipe 1 are presented in Figure 5 as a function of time. The results in Figure 5 can be summarized as follows.

1. The complexity of the pipeline network induced multiple points of superposition and attenuation of the overpressure waves in the network during overpressure wave propagation, resulting in multiple overpressure extrema over the entire explosion event (this is particularly evident compared with the overpressure variation curve at monitoring point 1 during the repeatability check). The maximum overpressure values observed at the two monitoring points appeared within about 0.1 s after the initiation of the explosion. The overpressures at the two monitoring points then gradually attenuated over time. Accordingly, high overpressures were concentrated mainly in the early phase of the explosion event, while the overpressures in the later phase of the explosion were affected mainly by the propagation of the overpressure waves from the other pipes of the pipeline network, which resulted in a reversed flow or reflux.
The overpressure at monitoring point 1 arising from the initial explosion event increased exponentially to a maximum of 0.466 MPa and then began to decrease. An inflection point in the overpressure appeared at 0.48 s in the form of a briefly sustained increase in the overpressure. This was mainly due to the concerted reflux of the overpressure waves derived from branch pipes 4 and 5, which were connected to branch pipe 1 (Zhang et al. 2015). An extremely high overpressure maximum appeared in branch pipe 1. While the overpressure waves derived from other pipes in the network caused multiple fluctuations in the overpressure of branch pipe 1 within 1 s of the explosion, their values were small, and the pressure attained a steady state.

The general overpressure trends observed at monitoring point 2 were similar to those observed at monitoring point 1. However, the maximum overpressure of 0.415 MPa observed at monitoring point 2 was significantly less than that at monitoring point 1. This indicated that the overpressure in the complex pipeline network attenuated considerably because monitoring point 2 was farther from the source of the explosion than monitoring point 1. We also note from Figure 2 that part of the overpressure wave propagating in branch pipe 1 entered branch pipe 4. Meanwhile, the overpressure observed at monitoring point 2 was lower than that at monitoring point 1 in the middle and late stages of the explosion, and the fluctuations of the overpressure were less as well. This was because monitoring point 2 was located relatively further back from the source of the explosion, and therefore, the overpressure waves generated from other branches of the pipeline network had relatively smaller impacts than that at monitoring point 1.

The overpressure changes observed at the two monitoring points in branch pipe 2 are presented in Figure 6 as functions of time. The results in Figure 6 can be summarized as follows.
1. The number of points of the superposition and attenuation in branch pipe 2 associated with an overpressure wave arising in the network during overpressure wave propagation is significantly greater than that observed in branch pipe 1, which resulted in a greater number of overpressure extrema during the overall explosion event. The time difference between the two monitoring points reaching the peak overpressure was reduced to 0.075 s. This was mainly due to the relative positions of branch pipes 1 and 2 in the pipeline network. The overpressure observed at monitoring point 3 exhibited greater fluctuations prior to reaching its maximum value than that observed in branch 1, although the fluctuations decreased afterward. In addition, we note that the overpressure at monitoring point 4 exhibited greater fluctuations after reaching its maximum value than before.

2. Multiple points of superposition and attenuation of the overpressure wave arising in the network during overpressure wave propagation produced small amplitude oscillations in the overpressure at monitoring point 3 in the early phase of the explosion event (Wang et al. 2020). The overpressure reached a maximum of 0.385 MPa after about 0.61 s and then decreased gradually. An inflection point in the overpressure appeared at about 0.73 s in the form of a briefly sustained increase in the overpressure at monitoring point 3 due to the superposition of the overpressure wave propagating from branch pipe 1 through the bent pipe. The overpressure at monitoring point 3 reached another maximum at 0.87 s, followed by an overall decreasing trend afterward, that then it decreased rapidly at 1.03 s until the end of the explosion event.

3. The overpressure at monitoring point 4 exhibited greater fluctuations than that observed at monitoring point 3 over the course of the explosive event. These fluctuations were relatively minor in the first 0.4 s, but the overpressure increased rapidly afterward and reached a maximum value of 0.356 MPa at 0.685 s after
multiple fluctuations. We also note that the rate of decrease in the overpressure at monitoring point 4 increased as the explosion event proceeded.

The overpressure variations observed at the two monitoring points in branch pipe 3 are presented in Figure 7 as functions of time. The results in Figure 7 can be summarized as follows.

1. The number of points of superposition and attenuation in branch pipe 3 arising in the network during overpressure wave propagation was not significantly greater than that observed in branch pipe 2. While the data for branch pipe 3 exhibited no evident increase in the number of overpressure extrema over the entire explosion event relative to that observed in branch pipe 2, the periodicity of the fluctuations in branch pipe 3 increased slightly. However, the overpressure in branch pipe 3 was more prominently affected by the overpressure wave arising in the other pipes in the pipeline network than those in branch pipes 1 and 2 because branch pipe 3 was connected to a greater number of pipes in the network. As a result, the time difference between the two monitoring points in branch 3 to reach the peak of overpressure increased to 0.293 s, which was greater than the time difference observed in branch 2.

2. The overpressure at monitoring point 5 exhibited two distinct peaks. The first peak occurred at about 0.52 s. This peak arose due to the acceleration effect of the initial overpressure wave that propagated in the positive direction and passed through the bent pipeline twice. The second peak occurred at about 0.803 s with a maximum overpressure of 0.393 MPa. The main cause of this peak was that the overpressure increased due to the superposition of the overpressure wave in other pipes of the network during the attenuation process of the initial overpressure wave propagating in the positive direction. Finally, the overpressure wave continued to decay, and the overpressure began to decrease rapidly toward the end of the explosion event.

3. The overpressure at monitoring point 6 was affected by the overpressure waves in the other pipes of the pipeline network less than the overpressure at monitoring point 5. As a result, the overpressure quickly reached a maximum value of 0.412 MPa with the passage of the initial overpressure wave propagating in the positive direction. Here, the overpressure reached a maximum value in as little as 0.492 s, because monitoring point 6 was located close to the explosion source. The overpressure decreased to its lowest value over the entire explosion event after 0.924 s due to the venting effect of the relief port. After this, only minor fluctuations were observed in the overpressure due to the superposition of the overpressure wave arising in the other pipes of the network.

The overpressure variations observed at the two monitoring points in branch pipe 4 are presented in Figure 8 as functions of time. The results in Figure 8 can be summarized as follows.

1. In general, the maximum overpressure was observed at monitoring point 8 about 0.6 s earlier than that observed at monitoring point 7. The maximum
overpressure at monitoring point 8 arose from the initial overpressure wave propagating in the positive direction, whereas the maximum overpressure at monitoring point 7 arose from the superposition of multiple overpressure waves arising in the other pipes of the pipeline network.

2. Monitoring point 8 was located close to monitoring point 1. Therefore, the overpressure wave monitored by monitoring point 8 accelerated through the bent pipeline at the beginning of the explosion event, and the measured overpressure increased. A maximum overpressure of 0.406 MPa was observed at 0.393 s. The effect of the overpressure wave attenuation on the overpressure gradually exceeded the superposition effect of multiple overpressure waves arising in the other pipes of the pipeline network, and the overpressure at monitoring point 8 subsequently exhibited a continuously downward trend.

3. The first overpressure peak at monitoring point 7 appeared at about 0.426 s due to the effect of the initial overpressure wave propagating in the positive direction. This was followed by three prominent overpressure peaks that formed due to the superposition of multiple overpressure waves arising in the other pipes of the pipeline network. This process resulted in a maximum overpressure of 0.372 MPa at 0.993 s. This overpressure peak was somewhat different from that observed at monitoring point 8 because the explosion event entered its middle and late stages.

The overpressure variations observed at the two monitoring points in branch pipe 5 are presented in Figure 9 as functions of time. The results in Figure 9 can be summarized as follows.

1. The overpressure trends observed in branch pipe 5 were similar to those observed in branch pipe 2. Both monitoring points in branch pipe 5 recorded a maximum overpressure due to the effect of the initial overpressure wave
propagating in the positive direction. The difference of 0.091 s between the times when the maximum overpressures were recorded by the two monitoring points in branch pipe 5 was slightly greater than that in branch pipe 2. In terms of overall trends, the fluctuations in the overpressure observed at monitoring point 9 were greater than those observed at monitoring point 10. In addition, the overpressure decreased faster at monitoring point 10 than at monitoring point 9, and the fluctuations in the overpressure at monitoring point 10 were also smaller because monitoring point 10 was closer to the vent port.

2. Monitoring point 9 was relatively close to monitoring point 1. Therefore, the overpressure wave from the initial phase of the explosion event accelerated through the right-angle pipe, and the overpressure increased rapidly to a maximum value of 0.399 MPa at 0.36 s. This was followed by a gradually increasing attenuation of the overpressure wave. During this stage, the overpressure measured at monitoring point 9 fluctuated over a period of 0.27 s under the simultaneous effects of overpressure wave attenuation and the superposition of overpressure waves arising from other pipes in the network. Finally, the overpressure at monitoring point 9 decreased further as the explosion event proceeded.

3. A maximum overpressure of 0.365 MPa was measured at monitoring point 10 at 0.492 s, and the overpressure subsequently decreased. We can also attribute the fluctuations observed in the overpressure at 0.65 s to the effect of overpressure wave superposition. However, the effect of overpressure wave attenuation dominated at 1.18 s, resulting in a rapidly decreasing overpressure at monitoring point 10. The overpressure wave continued to attenuate in the final phase of the explosion event, and this formed a flame vortex cluster at the exit of the enclosure. The flame front propagation velocity gradually exceeded the overpressure wave propagation velocity, and the compressed gas began to expand, which generated a negative pressure in the overpressure wave under the combined effects of the flame front and the enclosure surface.
The above discussion clearly demonstrates that the results obtained for the complex pipeline network differ significantly from the basic increasing and decreasing trends in the overpressure observed in straight pipes (Blanchard et al. 2010; Zhang et al. 2015; Jia and Wang 2021) or simple branched pipes (Ye and Lin 2012; Zhu et al. 2011; Niu et al. 2019) due to the initial propagation of the overpressure wave in the positive direction followed by overpressure wave attenuation. The forward propagation of the overpressure wave and overpressure wave attenuation in all the interconnected pipes of the network were superimposed to produce complexly varying overpressures throughout the network over the entire explosion event. Therefore, we theoretically analyzed the behaviors of the overpressure waves in the complex pipeline network from multiple perspectives, including the overpressure attenuation coefficient in each branch pipe.

The overpressure attenuation coefficients obtained for the various branches of the complex pipeline network were based on the results of two experiments conducted under equivalent conditions, where the overpressure values of the overpressure wave arising from methane explosions were recorded at all the monitoring points of the branch pipes in the experimental network. Finally, the arithmetic mean of each measurement pair was calculated as the final experimental value to determine the maximum overpressure value $OP_{\text{max}}$ of the overpressure wave in each branch pipe of the pipeline network. The experimental data were analyzed to determine the relationships between the overpressure attenuation coefficients and the branching degrees and bend angles adopted in the complex pipeline network. In addition, relationships were also evaluated between the overpressure attenuation coefficients and the overpressures observed before and after overpressure wave attenuation.

The different overpressure attenuation coefficients calculated for the network were classified based on the types of pipes that appeared in the experimental pipeline network, as illustrated in Figure 10(a)–(c). Accordingly, we make the following definitions.

The attenuation coefficient of the overpressure wave in a straight pipe is denoted as $K_1$, which is defined as $K_1 = OP_{\text{max}}(A)/OP_{\text{max}}(B)$, where $OP_{\text{max}}(A)$ and $OP_{\text{max}}(B)$ are the values of $OP_{\text{max}}$ obtained at monitoring points A and B, respectively (Figure 10(a)).

The attenuation coefficient of the overpressure wave in the branch pipe is denoted as $K_2$, which is defined as $K_2 = OP_{\text{max}}(A)/OP_{\text{max}}(C)$, where $OP_{\text{max}}(C)$ is the value of

![Figure 10. Pipe bend types in the experimental pipeline network.](image-url)
The overpressure attenuation coefficient obtained at monitoring point C (Figure 10(b)). The attenuation coefficient of the overpressure wave in a bent section of the network is denoted as $K_3$, which is defined as $K_3 = \frac{OP_{\text{max}}(A)}{OP_{\text{max}}(B)}$ (Figure 10(c)). The shunt coefficient of the overpressure wave in the branch pipe is denoted as $M$, which is defined as $M = \frac{OP_{\text{max}}(C)}{OP_{\text{max}}(B)}$.

The overpressure attenuation coefficients obtained from the experimental results are listed in Table 2. The results listed in Table 2 indicate that $M$ was less than 1 in many cases. However, the value $M$ in the branched pipes should all be greater than 1 (Zhu et al. 2011; Ye and Lin 2012; Lin et al. 2016). This indicated that the complexity of the overpressure wave propagation in the complex pipeline network structure could cause the value of $M$ in the branch pipe to differ from those obtained in long straight pipes and simple branched pipes. Unlike the results in previous reports (Lin et al. 2016; Niu et al. 2019; Wang et al. 2020), a greater pressure loss was observed in the present study when the explosion overpressure wave passed through the diagonal pipe than when it passed through other pipes.

The overpressure attenuation behavior of the overpressure wave arising from the methane explosion events in the complex pipeline network was further explored by an assumption based on dimensional analysis to obtain the following functional relationship between the overpressure attenuation coefficient $K_{\text{attn}}$ (Gao et al. 2020), the pressure change $\Delta P$ before and after the overpressure wave attenuation, and the pipe bending angle $\alpha$ (Tan 2005):

$$K_{\text{attn}} = L \cdot \Delta P^M \cdot \alpha^N,$$

where $L$, $M$, and $N$ are coefficients to be obtained by fitting to experimentally derived data. Taking the natural logarithm of both sides of Equation (1) yields the following:

$$\ln K_{\text{attn}} = \ln L + M \ln (\Delta P) + N \ln \alpha.$$

Table 2. Overpressure attenuation coefficient at each monitoring point.

| Overpressure attenuation coefficient | Data   |
|-------------------------------------|--------|
| $K_1$                               | 1.118  |
|                                     | 1.082  |
|                                     | 1.059  |
|                                     | 1.095  |
| $K_2$                               | 1.023  |
|                                     | 1.069  |
|                                     | 1.086  |
|                                     | 1.016  |
|                                     | 1.077  |
| $K_3$                               | 1.079  |
| $M$                                 | 0.979  |
|                                     | 1.158  |
|                                     | 0.949  |
|                                     | 1.077  |
|                                     | 0.857  |

The application of a multiple regression fit to the experimental data according to Equation (2) yielded the coefficients $L = 1.1853$, $M = 0.016$, and $N = 0.2117$ with a
coefficient of determination value of $R^2 = 0.966$, which meets the accuracy requirements for the fitting operation. Applying these values to Equation (1) yields the following:

$$K_{\text{attn}} = 1.1853 \cdot \Delta p^{0.016} \cdot \alpha^{0.2117}. \quad (3)$$

In a long straight pipe, the overpressure attenuation coefficient $K_{\text{attn}}$ is a significant parameter for quantifying the time-variable characteristics of the explosive overpressure wave (Wingerden et al. 1990; Zhang et al. 2015; Jia and Wang 2021). When the explosion overpressure is propagated in the pipeline with a bending or bifurcation structure, the attenuation of the explosive overpressure wave can be quantified by $K_{\text{attn}}$ (Zhu et al. 2015; 2017; Zhao et al. 2018). It has been shown in the literature (Zhu et al. 2015; Zhao et al. 2018; Qiu et al. 2021) that the attenuation of the explosion overpressure wave satisfies Equation (3). This showed that the conclusions obtained in this paper can be generalized to describe the attenuation of explosion overpressure waves in complex pipe networks.

### 3.2. Flame front characteristics

We next analyzed various aspects of the behaviors of a flame front in a complex pipeline network, including the flame front propagation velocity, the peak temperature of the flame front, and the sudden change in the flame front velocity in each branch pipe, from a theoretical basis.

#### 3.2.1. Flame front velocity and sudden change coefficient

The flame front propagation velocity is an important parameter for characterizing the behaviors of flame fronts arising from methane explosions in pipeline networks. Values for the flame front propagation velocity also enable a detailed evaluation of the sudden changes in the flame front velocity in terms of the front velocity $V_a$ (m/s) just prior to a branch point and the front velocity $V_b$ (m/s) just after the branch point for all branches of the network. This is defined as the flame front velocity sudden change coefficient $\lambda$, which is defined as follows:

$$\lambda = \frac{V_a}{V_b}. \quad (4)$$

The obtained value of $\lambda$ can then be used to determine the acceleration or attenuation characteristics of the flame front after it passes a branched or bent pipe.

The flame front propagation velocities of the various branches of the complex pipeline network were based on the results of two experiments conducted under equivalent conditions, and the arithmetic mean of the two experimental measurements was calculated to determine the value of $v_{\text{peak}}$ in each branch pipe. The calculated results are listed in Table 3.

We then calculated the values of $\lambda$ obtained for the pipeline network over the entire explosion event. The flame front propagation velocity was observed to vary substantially over the course of the explosion event, which resulted in ten distinct
values of $\lambda$. This indicated that the complex pipeline network provided multiple and multi-directional pathways for flame front propagation. Table 4 presents the calculated values of $\lambda$ in sequence.

The results listed in Tables 3 and 4 can be summarized as follows.

1. Flame front propagation through the bent and branched pipes in the network could significantly increase the flame front velocity.
2. The passage of a flame front through a given branched or bent pipe at different times resulted in different increases in the flame front velocity. The acceleration characteristics of the flame front velocities were also affected by the pipe bending angle $\alpha$.
3. The obtained values of $\lambda$ differed when the flame front passed through the same pipes at different times.

The behavior of a flame front arising from a methane explosion event in a complex pipeline network was further explored by assuming the following functional relationship between $\lambda$ and $\alpha$ (Tan 2005; Qiu and Liu 2019):

$$\lambda = k \cdot \alpha^a,$$

where $k$ is a coefficient of proportionality, and $a$ is a power-law coefficient that can be obtained by fitting to the experimentally derived data. Taking the natural logarithm on both sides of Equation (5) yields the following:

$$\ln \lambda = \ln k + a \ln \alpha.$$  \hspace{1cm} (6)

The application of multiple regression fits to the experimental data in Table 4 according to Equation (6) yielded the coefficients $k = 0.9132$ and $a = 0.2733$ with an $R^2$ value of 0.954, which met the fitting accuracy requirements. Applying these values to Equation (5) yields the following:

$$\lambda = 0.9132 \cdot \alpha^{0.2733}.$$  \hspace{1cm} (7)

The flame sudden change coefficient is the main parameter for characterizing the flame front variation characteristics. Since the propagation characteristics of a flame front in a complex pipe network have not been clearly documented in the literature (Qiu and Liu 2019), the sudden change characteristics of the flame front in a complex pipe network can be inferred according to Equation 7, which provides a theoretical

| Branch | Peak front velocity (m/s) |
|--------|---------------------------|
| 1      | 372.5                     |
| 2      | 408.6                     |
| 3      | 420.3                     |
| 4      | 398.5                     |
| 5      | 381.6                     |
reference for further research on the propagation of flame fronts in complex pipe networks.

3.2.2. Flame front temperature

The peak temperature of the flame front in each branch pipe of the complex pipeline network is presented in Figure 11. The results can be summarized as follows.

1. The peak temperature ($T_{\text{peak}}$) values of the flame front of the branch pipes decreased in the order of $T_{\text{peak}}$ (branch pipe 1) > $T_{\text{peak}}$ (branch pipe 4) > $T_{\text{peak}}$ (branch pipe 5) > $T_{\text{peak}}$ (branch pipe 3) > $T_{\text{peak}}$ (branch pipe 2). The peak velocities $v_{\text{peak}}$ of the flame front of the branch pipes decreased in the order of $v_{\text{peak}}$ (branch pipe 3) > $v_{\text{peak}}$ (branch pipe 2) > $v_{\text{peak}}$ (branch pipe 4) > $v_{\text{peak}}$ (branch pipe 5) > $v_{\text{peak}}$ (branch pipe 1).

2. A comparison of the peak temperatures and peak velocities of the flame front in the branch pipes discussed in (1) revealed that the branch pipe with the highest $T_{\text{peak}}$ value may not necessarily have the highest $v_{\text{peak}}$ value. This is because variations in the flame front temperatures in the branch pipes lagged behind those

### Table 4. Flame front velocity sudden change coefficient of each propagation pathway.

| Coefficient | Data |
|-------------|------|
| $k_1$       | 1.355|
| $k_2$       | 1.583|
| $k_3$       | 1.602|
| $k_4$       | 1.614|
| $k_5$       | 1.557|
| $k_6$       | 1.383|
| $k_7$       | 1.296|
| $k_8$       | 1.203|
| $k_9$       | 1.117|
| $k_{10}$    | 1.039|

**Figure 11.** Peak flame front temperature of each branch pipe.
of the flame front velocities in time. In addition, the monodirectional distribution of the pipes in the experimental pipeline network generated complicated propagation pathways for the flame front and thereby accentuated the effects of the time lag.

4. Conclusions

The present work addressed the failure of past studies to accurately reflect the conditions prevalent under actual methane explosion events by experimentally evaluating the propagation characteristics of overpressure waves and flame fronts associated with methane explosions in complex pipeline networks. The obtained results and analyses provided the following main conclusions.

1. The evolution process of gas explosion overpressure in complex pipe networks was more complicated and disorderly than that in the long straight pipe and simple branch pipe. The forward propagation of the overpressure wave and the reverse propagation of the overpressure wave in all interconnected pipes of complex pipe network were superimposed together so that the pressure attenuation degree in the bevel branch pipe was larger than that in other branch pipes.

2. When the flame wave passed through all the branch tubes, the flame wave velocity increased significantly. When the flame wave passed through the same tube at different times, the flame wave mutation coefficient was different, the change of flame wave temperature had a certain lag compared with the change of flame velocity, resulting in the peak of flame wave temperature and flame wave velocity appearing in different branch tubes.

3. Multiple regression fitting to the experimental data led to the following functional relationship between the overpressure attenuation coefficient, the pressure change before and after the overpressure wave attenuation, and the pipe bending angle $\alpha$: $K_{\text{attn}} = 1.1853 \cdot \Delta P^{0.016} \cdot \alpha^{0.2117}$. The following functional relationship between the flame front velocity sudden change coefficient and the pipe bending angle $\alpha$: $\lambda = 0.9132 \cdot \alpha^{0.2733}$.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Data availability statement

The data and materials that support the results or analyses presented in our study are freely available.

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