Influence of Different Bifurcation Angles on the Flame Propagation of Gas Explosions in Three-Way Bifurcated Pipes

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ABSTRACT: Exploring the flame propagation law in the process of gas explosion under different bifurcation angles is of great significance to the design of coal mine roadway and the prevention of gas explosion accidents. To study the variation of flame propagation law with bifurcation angle, an in-house experimental system based on a small scale three-way bifurcated pipe was developed to perform gas explosion experiments using mixtures of premixed methane-air with a methane concentration of 9.5%. Numerical simulations were conducted to study the propagation of the explosion flame. The results show that, (i) during the flame propagation process, the flame morphology evolves in the following manner: hemispherical, concave entrainment-deformation-flattening; (ii) in the case of gas explosion of three-way bifurcated pipes, there are significant differences in damage at different positions, and the damage at the pipe connection is the most serious. (iii) Although the parameters of the explosion flame in the bifurcated pipe exhibit similar trends across four different bifurcation angles, the values of the flame parameters obtained by the experiments and numerical simulations were not completely consistent. (iv) When the bifurcation angle is between the 45° and 75° bifurcation range, the area of the turbulent vortex formed by the air flow increases as the angle of the pipe widens. The research results analyze the propagation law of gas deflagration flame in the bifurcated pipeline, providing reference for the propagation mechanism of gas deflagration in underground bifurcated roadway and the formulation of prevention measures, which is conducive to preventing the propagation of gas explosion, reducing the intensity, and reducing the loss caused by gas explosion. However, large-scale tests are needed to determine the applicability of small-scale tests and calculations in this paper to full-scale mine conditions.

1. INTRODUCTION

Gas explosion accident is one of the most serious coal mine accidents, in which the main form of gas accident is gas deflagration. Under the influence of mining conditions, the bifurcation phenomenon of coal mine roadway is more common. In the case of gas explosion accident, the bifurcation of roadway junction is particularly damaged by explosion impact. Therefore, mastering the flame propagation law after gas explosion in roadway with different bifurcation angles is helpful to formulate effective explosion-proof and explosion suppression measures and avoid casualties caused by explosion.1−3

In recent years, domestic and foreign scholars have mainly analyzed the propagation characteristics of gas explosions in different types of pipes through experiments or numerical simulation methods. Jia et al.4 performed a gas explosion test within a pipe system to analyze the relationship between the shock wave overpressure coefficient and the bifurcation angle of the unidirectional bifurcation pipe, while Li5 tested seven types of angled pipes to explore the relationship between flame propagation speed and the amount of gas with different angles. The bend of the one-way bifurcated pipe has been found to produce a significant acceleration effect on the flame front propagation in empirical investigations by several research groups,6−8 and the effect of the vacuum chamber on the gas explosion flame propagation in the straight pipe was studied by Zhu.9 By analyzing the propagation of a hydrogen-methane-air premixed flame in a closed pipe, Zheng et al.10 obtained a “tulip” type flame pattern using the high-speed schlieren method. A large eddy simulation of the flame front was combined with the interaction between the pressure wave and the combustion wave to explain the cause of the tulip-type flame. Maremonti et al.11 used the Auto Reagas software package to numerically simulate the gas explosion in the pipe, revealing that changes in the cross-sectional area of the pipe cause disturbance to the combustible gas. In addition, Prodan,
Mitu, et al. deeply discussed the propagation law of methane explosion under different working conditions, and found that the initial pressure, geometry and inert gas had a significant impact on the characteristics of methane explosion. Although a lot of research has been carried out on gas explosions in straight pipes or one-way branching pipelines, the actual environment of underground mines is relatively complicated. At present, there are only a few studies on the characteristics of gas explosion flame propagation in two-way roadways.

Therefore, given the universality and diversity of bifurcated pipe ways in underground tunnels, an in-house gas explosion testing system consisting of a square multi-angle bidirectional bifurcated pipe was used in conjunction with the ANSYS Fluent 17.0 simulation software to investigate the flame propagation characteristics with varying bifurcation angles. Experimental data and simulation results were used to compare and analyze the influence of the bifurcation angle of the pipe on the flame propagation characteristics. This paper focuses on first comparing the experimental results with those of the numerical simulation followed by studying the influence of the bifurcation angle on the effect of the extent of the gas explosion. Therefore, the size of the model used in the numerical simulation is the same as that of the test bifurcation tube so as to ensure that the test and simulation data can be mutually verified. The results of the analyses have an important practical significance for the design of coal mine underground roadways and can aid in the design of effective blast suppression and explosion prevention measures to reduce the severity of gas explosion accidents.

2. EXPERIMENTAL SYSTEM DESIGN AND MODELING

As large-scale explosion experiments in straight pipes have been carried out and reported in the literature, this paper focuses on the influence of the bifurcation angle in branched pipes. Four two-way bifurcated pipe models with different bifurcation angles of 45, 60, 75, and 90° were designed to model the conditions of various underground coal mines and evaluated through numerical simulations. Further studies on

![Figure 1. (a–d) Three-way bifurcated pipe with four bifurcation angles.](https://doi.org/10.1021/acsomega.2c02016)
the flame propagation characteristics of gas explosions in straight tunnels will be carried out in the future.

2.1. Design of the Three-Way Bifurcated Pipe. Four three-way bifurcated pipes with different bifurcation angles of 45, 60, 75, and 90° are shown in Figure 1. The pipes are made of plexiglass, with inner dimensions of 80 mm × 80 mm. The three-way bifurcated pipes are composed of a horizontal section and a branch, where the angle between the left side of the horizontal section and the branch pipe is the bifurcation angle β, and the angle between the right side of the horizontal section and the branch pipe is γ.

2.2. Experimental System. Figure 2 illustrates the 90° bifurcated pipe gas explosion testing system, which consists of three 400 mm long straight pipes and a three-way bifurcated pipe with a 90° split angle connected through a square flange. The inflation pipe and the detonating needle are sealed and fixed to the port of the branched pipe, which is in a sealed state. The two straight pipe ports on the left and right sides are weakly sealed with plastic wrap. A data acquisition system was used to obtain data from the pressure sensors, thermocouples, ion probes, and photosensors. The testing system has a total of 10 sets of photoelectric sensors and four sets of temperature, velocity, and pressure measuring points, which are evenly distributed on the side of the pipe. The positions of the four groups of sensors at the positions numbered 2, 4, 6, and 9 are defined as the cross sections of the branch pipe, the branch, the left straight pipe, and the right straight pipe respectively.

2.3. Experimental Steps. First, the branch pipe and the ignition system were assembled, and the photoelectric sensors, ion probes, thermocouples, and pressure sensors were installed in the corresponding measuring points, as detailed in Figure 2. Next, the branched pipe was filled with a premixed gas mixture of 9.5% methane and air, and the methane concentration in the experimental pipe was monitored using a GJGX100(M) laser methane sensor. Once the concentration of methane after standing in the gas distribution tank for 30 min stabilized at 9.5%, the ports at both ends of the horizontal pipe and the intake port of the branch pipe were sealed. The storage recorder and all sensors were then set to the synchronous trigger state, and the SFK-300 detonator and house-made detonating pin were used to ignite and detonate the gas at the port of the branch pipe. A digital video camera was used to record the entire process of gas explosion in the bifurcated pipe, and a HIOKI 8826 storage recorder was used to collect and store the physical data of the explosion flame.

2.4. Empirical Tests and Data Collection.

(1) A K-type Teflon thermocouple with a wire diameter of 0.011 mm was used in the experiment, with an instantaneous temperature measurement range of 0–1300 °C and a response time of 0.2 s. A HIOKI 8937 temperature/voltage module was used to record the data. The two poles of the thermocouple were inserted into the temperature module, and the detected flame temperature signal was transmitted to the data acquisition device.

(2) A CY-YD-205 piezoelectric pressure sensor and corresponding YE853 charge amplifier were used to measure the gas deflagration pressure in the pipeline. The sensor is suitable for this measurement due to its high sensitivity, wide frequency response, and stable performance. The pressure sensitivity of the sensor is 100 pC/MPa in the pressure range of 0–30 MPa.

(3) The photoelectric testing device used in this experiment was a photodiode module with the model of Risym, which is sensitive to the ambient light intensity, and the working voltage is 8 V. The module can detect the brightness and light intensity of the surrounding environment and can react to the light source from a fixed direction. It has a good light-seeking capability and can adjust the sensitivity according to the ambient light intensity.

3. SIMULATION MODEL PARAMETER SETTINGS

3.1. Geometric Model and Meshing. The software package Ansys Fluent 17.0 was used to simulate the flame propagation of a gas explosion in branched pipes with bifurcation angles of 45, 60, 75, and 90°. To reduce the volume of calculations, the three-way bifurcated pipe was simplified into a two-dimensional plane model for the numerical simulation. The variations of shock wave pressure, flame propagation speed, and temperature in the pipe were the primary parameters of interest. During the numerical modeling process, the center of the branch port was set as the ignition point, the two ends of the straight pipe were set as pressure outlets, and the walls of the pipe were set as wall surfaces. The model used a tetrahedral mesh element, and an unstructured
mesh was used to divide the model mesh. Data sensing points were located along the centerlines of the branch pipe and the straight horizontal pipe. Taking a bifurcated pipe with a bifurcation angle of 60° as an example, the number of grids divided by the pipe model was 6594, with 7018 grid nodes. The average grid mass was 0.98476, and diagrams of the pipe model and meshing are shown in Figure 3.

3.2. Calculation Parameter Settings. The gas mixture was ignited at the branched port of the bidirectional branched pipe, and the whole reaction process was regarded as a thermal expansion process of an ideal gas under adiabatic conditions. The numerical simulation used a pressure-based solver, and the RNG k-epsilon model was adopted for turbulence. Compared with the standard k-epsilon, RNG theory utilizes an analytical method and specific calculation formula to consider the flow viscosity of low Reynolds number flows. Furthermore, additional terms are added to consider the average flow of turbulence dissipation. The accuracy and reliability can be effectively improved by considering the turbulence vortex. The finite volume method (FVM) was used to divide the calculation area into several small volume units. In each volume element, the discrete control equations were solved and calculated for the gas detonation process. In this model, the Arrhenius formula and eddy dissipation equation were simply combined, which not only combines the dynamic factors and turbulence factors but also avoids the early combustion problem of the ED model in premixed combustion. In the numerical simulation of gas detonation in the bifurcated pipeline, the parameter values specified in the initial value list of standard initialization were used to initialize the calculation domain. Using the standard SIMPLC algorithm as the solution method and a spark ignition energy of 10 J, the chemical reaction rate was calculated according to the eddy dissipation model. The gas explosion process was defined as an irreversible reaction. Monitoring points located along the centerlines of the branch and straight pipe at the same positions as the sensors in the physical experiment were used to monitor the variation of parameters such as surface temperature, shock wave pressure, and flame propagation speed of the explosion flame in the pipe.

4. RESULTS AND DISCUSSION

4.1. Flame Propagation Process. The gas explosion in an underground mine is a process that typically involves the reaction between a certain concentration of methane and oxygen in air to release a large amount of heat, resulting in a sudden increase in pressure and temperature to cause an explosion. The premixed methane-air gas in the pipe has a methane concentration within the explosion limit and generates a flame after being ignited. The flame of the explosion then rapidly expands to the surrounding areas to form a flame front with a certain thickness, called the combustion wavefront. Under the influences of the combustion explosion reaction and high temperature, the methane gas and combustion products in the pipe expand rapidly and form a precursor pressure wave at the front end of the flame front. This area of the methane-air premixed gas in front of the precursor pressure wave is the unburned area; the area between the precursor pressure wave and the combustion wavefront is the disturbance zone, and the area where the combustion wavefront has passed is the burned zone. The precursor pressure wave, combustion wave, unburned zone, disturbance zone, and burned zone constitute the propagation of the “two-wave three-zone” structure of deflagration. The flame propagation characteristics of a gas explosion in a bidirectional bifurcated pipe with a bifurcation angle of 60° obtained by numerical simulation at different stages are shown in Figure 4.

The analyses in Figure 4 show that, at the initial stage of ignition, the explosion flame expands from the ignition point to the periphery in a hemispherical shape. Then, due to the limited space of the branch pipe and the surface roughness of the walls, the shock wave reflects the diffracted waves, leading to increased gas turbulence and the generation of an obvious turbulent vortex and entrainment backflow during flame propagation. The explosion flame then propagates along the branch pipe to the bidirectional horizontal section of the pipe due to the positive feedback mechanism generated by the precursor shock wave and flame combustion. The angles between the branch pipe and the left and right sides of the straight pipe are different, so the turbulence of the gas differs according to the bifurcation angle. In addition, due to the sudden enlargement of the pipe area at the branching location, the flame will wrinkle and deform, and most of the shock waves flow into the right side of the straight pipe, which forms an obtuse angle with the branch pipe. Therefore, the flame intensity and speed of combustion in the right side of the straight pipe are greater than on the left. The flame propagates forward in a flat shape through both sides of the straight pipe.
and finally propagates from the outlets at the ends with an approximately planar waveform.

4.2. Effect of Bifurcation Angle on Flame Propagation Speed. The propagation speed of the flame refers to the moving speed of the front of the explosion flame in the pipe relative to the unburned region along the normal direction. The propagation velocity of the flame front directly affects the reaction intensity of the gas explosion and the generation of the shock wave. As the photoelectric sensor is photosensitive, the light signal generated by the flame can be converted into a voltage signal through the photoelectric sensor when the flame front sweeps over the photoelectric sensor. As such, the time taken by the flame front to pass a fixed distance can be calculated according to the triggering of the sensor’s output voltage signal. The areas between the 10 photoelectric sensors on the bifurcated pipe were defined as intervals $I_{1-2}, I_{2-3}, I_{3-4}, I_{4-5}, V_{5-6}, V_{6-7}, V_{7-8}, V_{8-9}, V_{9-10}$. The formula for calculating the average propagation velocity $u$ of the flame front in different sections of the pipe is

$$u = \frac{L}{d_t}$$

where $L$ is the distance between adjacent photosensors, which also represents the propagation distance of the explosion flame, and $d_t$ is the jump interval of the voltage signal corresponding to the triggering of the sensor’s output voltage signal.
to the adjacent photosensor, which also represents the time of explosion flame propagation.

In the numerical simulation process of the gas explosion in the bifurcated pipe, the monitoring points were used to monitor the gas disturbance velocity during flame propagation. The locations were set at the center of the pipe branch cross section, the center of the cross section of the branch, and the center of the cross sections of the left and right straight pipes. The coordinates of the monitoring points are as described above. As the chemical reaction at the core of the flame is the most intense, the gas perturbation velocity near the core is the highest. Therefore, the average propagation velocity of the flame front in the branch pipe, the branching of the pipe, the straight pipe on the left side, and the straight pipe on the right side can be calculated by measuring the time intervals at which the flame passes the sensors and using eq 1.

4.2.1. Experimental and Numerical Simulation Results.

The flame propagation processes within the bifurcated pipes exhibited similar characteristics across the four different bifurcation angles. Due to the significant amount of data obtained, only the experimental and numerical simulation results of the bifurcated pipe with a bifurcation angle of 60° are shown in Figure 5 below. When the photosensitive head of the photodiode module senses the environmental light source, it generates an electrical signal and transmits it to the connected data acquisition system. The variation of the photoelectric signal during the propagation of the flame in the pipe is shown in Figure 5a,b and shows the variation of the flame propagation velocity corresponding to the four areas of the pipe obtained by numerical simulation.

Figure 5 shows that the electrical signals and gas perturbation speeds at all monitoring locations begin to change on the arrival of the flame front, and the curves exhibit successive peaks as the flame spreads in the pipe. Owing to the combined influences of energy released by the chemical reaction, the pipe wall surface, and turbulent vortex at the branch, the electrical signal and gas disturbance speed accelerate to a maximum in a short time. Then, due to factors such as the friction of the pipe walls, heat loss, and the negative gauge pressure of the gas, the electrical signal and the gas disturbance speed are gradually attenuated. Moreover, when the flame propagates to the branch of the pipe, the photoelectric voltage generated by the combustion and the flame front velocity in the right straight pipe, which has an obtuse angle with the branch pipe, is larger than the left straight pipe. Moreover, due to the ignition energy and distance from the ignition point, the electrical signal and the propagation velocity at the cross section of the pipe branch are the first to reach a peak and exhibit the greatest magnitude. The measured photoelectric signal and the propagation velocity at the cross section of the pipe branch are the first to reach a peak and exhibit the greatest magnitude.

The results show that consistent trends between the curves of the gas disturbance velocity and the flame light signal variation were obtained empirically and numerically.
4.2.2. Discussion and Analysis of Results. To analyze the influence of the bifurcation angle on the flame front propagation velocity, the average propagation velocity of the flame front in different sections of the pipe was calculated using eq 1 based on the experimental data and the numerical simulation results. The pipe bifurcation angle is used as the independent variable to plot the curve of the flame front propagation velocity in different sections of the pipe, and the results are shown in Figures 6−8.

Figure 6 summarizes the average flame propagation velocity in different sections of the pipe obtained by experiments based on the bifurcation angle, and Figure 7 shows the results of the numerical simulation of the gas perturbation velocity at each cross section of the pipe based on the flame flow direction. It is evident from Figures 6 and 7 that the flames in the pipes with different bifurcation angles propagate from the branch pipe to the junction of the pipe and then flow to the left and right straight pipes. The overall trends of the variation of average flame velocity have high consistency. After the methane-air premixed gas is ignited, the flame expands from the point of ignition to the periphery. During the propagation of the flame from the branch port to the left and right straight pipe outlets, the average velocity of the flame front increases continuously, and the gas disturbance velocity in the core reaction zone continues to increase. When the flame propagates to the splitting port of the pipe, the area of the pipe cross section suddenly expands, and the branching point of the pipe can be regarded as a disturbance source that induces additional turbulence, which will cause the bending of the flame and the gas turbulence in the reaction zone to increase. Therefore, as the flame continues to accelerate in the pipe, the propagation speeds of the flame in the left and right straight sections of the pipe are significantly faster. At the same time, in the later stage of explosion, due to the consumption of combustible gas and the heat dissipation of the pipe wall, the flame propagation speed continues to decrease.17

The plots in Figure 8 show comparisons of the peak flame propagation speed. The results suggest that the flames are bent and wrinkled at the junction, and the surface area, turbulence, fuel consumption rate, heat and active material transport rate, and combustion reaction rate are all increased. When the bifurcation angle is changed from 45 to 75°, a greater degree of flame turbulence is observed with a faster flame propagation speed, causing the flame to pass out of the pipe within a shorter duration. Moreover, the average propagation velocities of the flame in the branch pipe, the left straight pipe, and the right straight pipe become higher with increasing bifurcation angle, and the flame propagation speed in the right straight pipe is higher than that of the left straight pipe. At a bifurcation angle of 90°, the propagation

![Figure 7](a, b) Numerical simulation results of gas perturbation velocity of the left and right straight pipe cross sections of the three-way bifurcated pipe.

![Figure 8](a, b) Comparison of the average flame propagation velocity of the three-way bifurcated pipe.
trajectory of the explosion flame in the branch pipe is straight, while the flame will be vertically reflected at the junction of the pipe, and the effect of turbulence is obvious. The reverse shock wave at the junction obstructs the propagation of the flame, which causes the rate of burning in the core reaction zone to be reduced. Thus, the average propagation velocity of the flame across the different sections of the pipe is the lowest in comparison to the other bifurcated pipes, and the flame takes the longest time to exit the pipe. Finally, the flame is evenly distributed to the left and right straight pipes through the splitting port. It should be noted that, as the photoelectric sensor is sensitive to light, the propagation time of the flame front over a certain distance is calculated according to the output voltage. This causes the results to be inevitably affected by the sensitivity of the photoelectric sensor, time delay, and other material characteristics, resulting in errors. At the same time, the results of the numerical simulation have a certain ideal state, which can be seen from Figure 8, where the experimental flame speed is much slower than the numerical simulation flame speed. Further efforts are needed to reduce the impact of this in subsequent work.

4.3. Effect of Bifurcation Angle on the Explosion Overpressure. 4.3.1. Results of Experiments and Numerical Simulations. According to the “two waves and three regions” mechanism, the flame front generated by the methane-air premixed gas in the pipe will flow into the area where no combustion occurs. Under the effects of the explosion reaction and high temperature, the gas produced will expand rapidly, forming a precursor pressure wave in front of the flame front, also known as the precursor shock wave. Figure 9a,b shows the experimental data and numerical simulation results of the shock wave explosion overpressure at four locations in a bidirectional bifurcated pipe with a bifurcation angle of 60°.

It can be seen from Figure 9 that, following the combustion of the premixed gas in the pipe, the explosion overpressure in the pipe rapidly rises to a peak value in a short time and then falls into a state of negative gauge pressure. Subsequently, the plastic wrap used to close the two ends of the straight pipe ruptures due to the high-pressure gas, and the methane gas in the pipe dissipates, causing the rate of combustion to slow down. The precursor shock wave generated by the flame then slowly returns to normal atmospheric pressure. The precursor shock wave signals in the cross sections of the branch pipe, the junction, and the left and right straight pipes were measured sequentially. The reflection of the pressure wave at the walls and the turbulence generated helps to promote the combustion process, and thus, the shock wave overpressure at the cross sections of the branch pipe and the junction is much larger than the shock wave overpressure of the left and right straight pipes. Figure 9b shows the curve of the explosion overpressure in the bifurcated pipe generated by the numerical simulation. It is evident that the explosion flame is affected by the reflection and deflection of the shock wave as well as the turbulence during the propagation process. The explosion overpressure of the numerical simulation oscillates and exhibits multiple peaks during the flame propagation process. Meanwhile, the explosion overpressure obtained empirically shown in Figure 9a is affected by the sensitivity of the pressure sensor. Although
the empirically obtained data of overpressure do not exhibit multiple peaks and fluctuations, the experimental and numerical simulation results do not differ significantly in terms of overall trend and magnitude.

4.3.2. Discussion and Analysis of Results. To analyze the relationship between the shock wave intensity and the bifurcation angle at the branching point of the pipe, the peak overpressures at the four locations of the bifurcated pipe with four different bifurcation angles were evaluated. Plots of the peak overpressure with varying bifurcation angles at various locations are shown in Figure 10. The shock wave attenuation coefficient $K$ is defined as the ratio of the peak pressure at the cross section of the branch pipe to the peak pressure of the cross section at the branching point. The shock wave splitting coefficient $M_1$ is defined as the ratio of the cross-sectional peak pressure of the left straight pipe to the cross-sectional peak pressure at the branching point. The shock wave splitting coefficient $M_2$ is defined as the ratio of the cross-sectional peak pressure of the right straight pipe to the cross-sectional peak pressure at the branching point. The shock wave attenuation coefficient $K$ and the splitting coefficient $M$ are calculated to analyze the variation of the explosion overpressure in the bifurcated pipes with different bifurcation angles. The shock wave attenuation coefficient $K$ and the splitting coefficient $M$ of each bifurcated pipe are shown in Table 1.

### Table 1. Attenuation Coefficient and Splitting Coefficient of the Explosion Overpressure in a Three-Way Bifurcated Pipe

| Bifurcation Angles | $K$    | $M_1$ | $M_2$ | $K$    | $M_1$ | $M_2$ |
|---------------------|--------|-------|-------|--------|-------|-------|
| 45°                 | 1.39   | 0.35  | 0.69  | 1.38   | 0.50  | 0.75  |
| 60°                 | 1.41   | 0.38  | 0.63  | 1.35   | 0.52  | 0.67  |
| 75°                 | 1.44   | 0.46  | 0.59  | 1.30   | 0.55  | 0.60  |
| 90°                 | 1.82   | 0.67  | 0.67  | 1.25   | 0.67  | 0.67  |

As shown in Figure 10, the CY-YD-205 piezoelectric pressure sensor used in this experiment is an electromechanical transducer that uses the piezoelectric effect of piezoelectric materials to convert the measured pressure into an electrical signal. There are some errors associated with the hysteresis and repeatability, resulting in a substantially lower empirical peak overpressure than the numerical simulation result. The results of the overpressure peak distribution reveal that the overpressure of the flame shock wave varies similarly across the various bifurcation angles. When the bifurcation angle changes from 45° to 75°, the peak value of explosion overpressure within the pipe increases with the bifurcation angle. The shock wave pressure of the flame front is greatest at a bifurcation angle of 75°, indicating that the combustion reaction in the pipe is the most severe at this angle, and the shock wave intensity is the largest. The shock wave produces two shunts and gas vortices at the branching point of the pipe, and the flame exhibits wrinkles and entrainment. The angle between the branch pipe and the straight pipe on the right side is obtuse, leading to a large shock wave and combustion surface area in the right side of the straight pipe. As a result, the peak overpressure in the straight pipe on the right side is higher than that in the left straight pipe. Furthermore, the internal disturbance of the pipe at the branching point will accelerate the deformation of the flame due to the vertical reflection of the shock wave and the unevenly distributed flow of the flame into the left and right sides of the straight pipe. Therefore, in the three-way bifurcated pipe with a split angle of 90°, the explosion overpressure value is significantly reduced, and the explosion overpressures generated by the flames in the left and right straight pipes are the same. The reason is that, when the shock wave passes through the tee pipe, there are diffraction and reflection between the shock wave and the pipe wall, and there is a turbulence effect in the local area, resulting in a certain difference in the peak overpressure at the left and right end faces of the pipe.

From the results in Table 1, the shock wave in the pipe continuously attenuates during flame propagation and diverts at the branching of the pipe. When the bifurcation angle varies from 45° to 75°, the shock wave overpressure attenuation coefficient $K$ at the branch of the pipe increases from 1.30 to 1.44, and the shock wave splitting coefficient $M_1$ increases from 0.35 to 0.67. In addition, the shock wave splitting coefficient $M_2$ decreases from 0.69 to 0.67 with increasing bifurcation angle. Affected by the disturbance of the bifurcation angle of the pipe and the sudden expansion of the orifice area, after the precursor shock wave generated by the explosion flame propagates along the branch of the pipe, most of it diverts to the right side of the straight pipe, which forms an obtuse angle with the branch pipe. In pipes with bifurcation angles of 45°, 60°, and 75°, as the angle between the left straight pipe and the branch pipe is smaller than the angle between the right straight pipe and the branch pipe, less shock wave propagates to the left straight pipe, and the peak overpressure and shock wave shunt coefficient of the left straight pipe are lower than in the right straight pipe. The shock wave splitting coefficients $M_1$ and $M_2$ of the three-way bifurcated pipe with a split angle of 90° are both 0.67, which indicates that, in the T-type branching pipe, the shock wave propagates evenly divided into the two sides at the junction.

During the combustion of methane-air premixed gas in the pipe, the wall surface of the pipe can be regarded as a flow barrier, and the bifurcation angle of the pipe can be regarded as a source of disturbance. The larger the bifurcation angle, the greater the turbulence generated by the flow field, and the longer the propagation distance of the explosion flame. Furthermore, the greater the attenuation of the shock wave, the smaller the shock wave intensity. It can be seen from the characteristics of the overpressure peak, shock wave attenuation coefficient, and the shock wave shunt coefficient shown in Figure 10 and Table 1 that the pipe bifurcation angle is an important factor affecting the shock wave attenuation and shunt generation. When the bifurcation angle increases from 45° to 75°, the gas turbulence at the branching point of the pipe, the surface area of the flame combustion, the combustion reaction rate, the flame propagation speed, the peak value of the explosion overpressure, and the shock wave shunt in the left straight pipe rise continuously, while the shock wave attenuation coefficient $K$ is gradually decreased. Due to the vertical reflection of the shock wave at the wall, the value of the explosion overpressure in the pipe with a bifurcation angle of 90° is significantly reduced, and the shunt coefficients of the shock wave in the left and right straight pipes are equal.

In the numerical simulation of a gas explosion in a three-way bifurcated pipe, factors such as pipe wall roughness, gas mass force, and weak seals at the outlets of the straight pipe were not considered. Therefore, the overpressure value, the attenuation coefficient $K$ and the shunt coefficient $M$ at the branch, and the cross sections of the left and right straight pipe obtained by the simulation are numerically different from the experimental.
The shock wave attenuation characteristics and trends of the shock wave overpressure of the flame precursor obtained empirically and by numerical simulation are both similar.

4.4. Effect of Bifurcation Angle on the Flame Front Temperature. 4.4.1. Results of Experiments and Numerical Simulations. Flame temperature is one of the indicating factors of the extent of damage in a coal mine roadway. The tiny thermocouple is a contact-type temperature measuring element. When the flame produced by premixed gas deflagration passes through the thermocouple, the temperature of the cross section at which the thermocouple is located is collected. In the gas explosion experiment of a three-way bifurcated pipe with a bifurcation angle of 60°, the temperature changes of the explosion flame at four locations of the pipe obtained by thermocouple and numerical simulation are shown in Figure 11a,b.

The temperature variations in Figure 11a show that the temperatures at the four locations of the bifurcated pipe rise consecutively shortly after the gas in the pipe is ignited. Subsequently, as the flame combustion weakens and the gas in the pipe mixes with air outside of the pipe, the temperature inside the pipe slowly drops to the ambient temperature. As the flame temperature is not much higher than 600 °C, a thermal hysteresis effect exists in the tiny thermocouple, which causes the maximum temperature measured to be significantly lower than the theoretical temperature of the gas deflagration flame. However, the trend of temperature change at each measuring point can reflect the change in the temperature field of the flame at a relative position. Figure 11b clearly shows the discrete jumps in the frontal temperature of the flame at the four locations within the pipe, which occur in accordance with the direction of flame propagation. The gas explosion is characterized by deflagrating characteristics. As the monitoring point of the branch pipe is only 300 mm away from the ignition source, the heat within the pipe continues to accumulate even after the flame in the branch pipe has burned completely. In addition, due to the reflected shock wave at the closed end of the branch pipe, the pressure and flame combustion increase, resulting in the highest peak temperature within the cross section of the branch pipe. The flame accelerates from the junction of the pipe to the left and right sides of the straight pipe. The plastic wrap at the ends of the straight pipe ruptures under the shock wave and gas expansion before the flame arrives, causing the gas in the pipe to escape. As a result, the flame in the pipe does not burn completely, and therefore, the temperatures at the cross sections of the left and right sides of the straight pipe are reduced. Since the angle between the straight pipe and the branch pipe on the right side is larger than the angle between the straight pipe and the branch pipe on the left side, the majority of the shock wave is shunted into the right straight pipe, leading to large amounts of gas turbulence and increases in the surface area of the flame combustion. The high intensity of flame combustion intensity causes the explosion flame temperature in the right straight pipe to be significantly higher than in the straight pipe on the left side. Finally, due to the unsteady heat exchange between the gas in the pipeline and the outside world, with the passage of time, the heat exchange temperature difference becomes smaller, resulting in the smaller heat flow density between the two, which makes the gas temperature curve in the container gradually flatten.

The experimental data shown in Figure 11 have lower values than the results of the numerical simulation. These differences may be explained by the following factors: first, the thermocouple used in the experiment has low sensitivity while the flame propagation speed is high, which can cause delays in temperature measurement; second, the closed ports at the left and right ends of the straight pipe rupture before the flame arrives; third, the walls of the pipe are assumed to be insulated and the premixed gas is taken as an ideal fluid in the numerical simulation process. In general, the trends of temperature variation in the bifurcated pipe obtained by numerical simulation and by experimentation are similar, suggesting that the data measured by the thermocouple to analyze the temperature variations of the flame front during propagation can be used as a reference.

4.4.2. Discussion and Analysis of Results. The numerical simulation of the temperature variations at various locations within the pipe stops with the end of the gas explosion reaction, and therefore, the temperature drop at the different locations within the pipe after the gas explosion reaction is not calculated. The walls of the pipe are assumed to be insulated, leading to the accumulation of heat in the pipe and the temperatures at the different locations of the pipe to eventually reach the same peak. Meanwhile, the thermocouple in the experiment can continuously monitor the temperature changes inside the pipe. As such, to analyze the influence of the bifurcation angle of the branched pipe on the flame temperature, the peak temperature measured by the
thermocouple at the various locations is plotted against the bifurcation angle, as shown in Figure 12.

Figure 12. Temperature peaks of different cross sections of bidirectional bifurcation pipes.

It can be seen from the changes in flame propagation speed and shock wave overpressure that, when the bifurcation angle is varied from 45 to 75°, the reflection and diffraction of the shock wave from the wall surface become more obvious, and the turbulence and flame temperature in the branch pipe also increase. With increasing bifurcation angle, the degree of flame turbulence at the junction also becomes larger, and much of the shock wave is shunted in the straight pipe on the left side, while both the flame burning rate and propagation speed increase. Furthermore, the peak temperature of the flame front at the junction and the left straight pipe both become larger. Conversely, the angle between the right straight pipe and the branch pipe reduces, leading to reductions in the flame burning rate and propagation speed as well as the flame front temperature and the shock wave shunted to the right straight pipe. At a bifurcation angle of 90°, the branch pipe is perpendicular to the straight pipe. Due to the influences of the vertical reflection of the shock wave at the perpendicular pipe wall and the turbulent flow of the flame at the junction of the pipe, the flame temperature of the branch pipe increases significantly. Moreover, following the rupture of the plastic wrap at the ends of the straight pipe by the high-pressure gas, the gas concentration and pressure in the pipe are reduced, and the energy is largely dissipated, leading to decreases in temperature at the junction of the pipe and the left and right sides of the straight pipe. In addition, the peak temperatures and propagation speed of the flames in the left and right straight pipe are similar, demonstrating the even split of the shock wave between the left and right sides of the straight pipe.

4.5. Effect of Bifurcation Angle on Ion Current Intensity and Reaction Rate of the Flame Front.

4.5.1. Results of Experiments and Numerical Simulations.

The organic combustible gas produces a certain concentration of ionic compounds during the combustion process, which gather and move together to generate minute ion currents. Combustion reactions with greater intensity have a higher chemical reaction rate and generate more ionic groups. Therefore, the chemical reaction rates and ion current intensity can be used to analyze the composition and propagation of the flame and the characteristics of the chemical reaction.

The ion current intensity detected by the ion probe and chemical reaction rate obtained by numerical simulation at different cross sections of the bifurcated pipe with a bifurcation angle of 60° are shown in Figure 13a and Figure 13b, respectively.

In the combustion process of an organic combustible gas, a certain concentration of ionic compounds is produced. The ionic compounds will gather together to move directionally to produce a tiny ionic current. The greater the intensity of the combustion reaction, the greater the number of ionic groups that will be produced, and the higher the chemical reaction rate and combustion intensity. Therefore, the chemical reaction rate and ion current intensity can be used to analyze the flame structure, propagation, and chemical reaction characteristics as well as to characterize the intensity of combustion. The results in Figure 13 indicate that the ion current signal and chemical reaction spike rapidly as the center of the flame approaches, in accordance with the direction of flame propagation. The methane-air premixed gas is unevenly distributed in the pipe, causing the flame shape to be deformed and exhibit evident turbulent characteristics. As such, the ionic current signal collected and the chemical reaction rate are slow and show obvious oscillations. The peak value of the ion current in the branch pipe is the highest due to the proximity to the point of ignition. The junction of the pipe asserts significant distortion of the flame front, causing the flame combustion area, turbulent flow energy, and reaction rate to increase. Therefore, the ion current and chemical reaction rate measured at the branching section are the largest in the cross

Figure 13. (a) Ion current signal and (b) chemical reaction rate of a three-way bifurcated pipe with a bifurcation angle of 60°.
sections of the branch pipe and the left and right straight pipes. In addition, factors such as seal rupture and pressure relief, weak gas concentration, and reduced flame surface area at the port weaken the combustion reaction in the left and right straight pipes. The energy and the ionic groups generated by the chemical reaction are subsequently reduced. Therefore, the ionic current and chemical reaction intensity in the left and right straight pipes are lower than in the junction and branch of the pipe.

4.5.2. Discussion and Analysis of Results. To study the correlation between the flame combustion reaction intensity and the pipe bifurcation angle, the ion current and peak

Figure 14. Peak current variation of (a) ionic current and (b) reaction rate in the gas explosion of the three-way bifurcated pipe.

Figure 15. Vector illustration of CH4 gas at different bifurcation angles in 25 ms.
reaction rate at the four cross sections of the pipe were plotted against the bifurcation angle in Figure 14. When the flame produced by a gas detonation burns, charged ions are generated. The probe can detect the ion current generated by the movement of charged ions, causing a current signal to be detected when the flame passes through the probe measuring point.

Figure 14 shows that, in a three-way bifurcated pipe with bifurcation angles of 45, 60, and 75°, the rate of reaction increases in the core reaction zone with increasing bifurcation angle, and more ionic groups are generated, leading to a stronger ion current. The angle of bifurcation and the wall of the pipe can induce a vortex within the flame, and as the angles between the branch pipe and the left and right straight pipes are different, the shock wave, flame deformation, reaction rate, and the intensities of the flame combustion reaction and ion current differ between the left and right sides of the straight pipe.

Meanwhile, in the t-way bifurcated pipe with a bifurcation angle of 90°, the branch pipe is perpendicular to the straight pipe, and the shock wave will reflect vertically the reflection at the wall of the junction and split evenly to both sides of the straight pipe. At this instance, the energy of the shock wave suddenly reduces and the flame propagates uniformly to both sides. Therefore, the rate and intensity of the combustion reaction and the ion current intensity of the flame are similar in the left and right straight pipes.

4.6. Effect of Unburned Gas Flow on the Flame Propagation. 4.6.1. Gas Flow Simulation Results. Figures 15 and 16 show vector diagrams of CH₄ gas flow with different bifurcation angles at 25 and 50 ms, respectively. The turbulent area formed by the flow of unburned gas is observed to be sensitive to the change of the bifurcation angle. The number and size of turbulent vortices can be seen in the figure, which is related to the angle of bifurcation. About 25 ms after ignition, the flame surface reached the middle of the pipe, and the unburned gas flowing at the branch quickly formed a turbulent vortex. Only two obvious turbulent vortices are formed at the 45° pipe branch and at the pipe splits of the 60 and 75° bifurcated pipe. Three vortices are formed at the fork.

In the 45−75° bifurcation range, the area of the turbulent vortex increases as the bifurcation angle of the pipeline widens. Although three turbulent vortices are formed at the bifurcation of the 90° pipeline, the area is the smallest. The turbulent vortex causes the burning of the flame to intensify, which enhances the turbulence. This mutual excitation effect causes
the gas flow to accelerate. Due to the different angles of the bifurcated pipes, the diversion of gas differs, which affects the size of the vortex and in turn leads to reactions of varying intensity in the left and right straight pipes.

4.6.2. Discussion and Analysis of Results. The results of the numerical simulation show that different bifurcation angles cause different distortions to the gas flow in front of the flame, which affects the turbulent eddies. The turbulence intensifies the chemical reaction, forming a positive feedback effect with the combustion reaction on the flame surface. A greater bifurcation angle results in a larger turbulent vortex area formed in the region before the pipe bifurcation, leading to a faster flame surface reaction speed. In addition, due to the influence of experimental conditions, the unburned gas data cannot be collected in the experiment, and the corresponding research will be carried out in the later stage.

5. CONCLUSIONS

(1) The propagation process of the explosion flame in a three-way bifurcated pipe is characterized by the following stages: hemispherical expansion, concave entrainment, deformation at the junction, flat tensile, and plane waveform. The flame front temperature and shock wave overpressure at the junction of the pipe are the largest, resulting in the most serious damage at the pipeline bifurcation.

The experimental data and numerical simulation results indicate that, when the area of the pipe at the branching point suddenly expands, the surface area of the flame increases, the wrinkles of the flame are deformed, the shock wave is split, the degree of turbulence is deepened, and the burning rate of the flame core reaction zone is accelerated. Therefore, the flame front temperature, flame propagation speed, shock wave overpressure, ion current intensity, and chemical reaction rate are the highest at the branching point of the pipe. This suggests that, in the event of a gas explosion accident, the coal mine roadway is the most seriously damaged. Therefore, it is necessary to investigate the design of the roadway to increase safety, and future research will focus on how to effectively attenuate the damage of the branched roadways and develop gas explosion suppression methods in coal mine underground roadways.

(2) The trends in the variation of flame properties were similar across the bifurcated pipes with different bifurcation angles, and the sets of results obtained by experiments and numerical simulations were in good agreement. The unburned gas flow is affected by the bifurcation angle and forms turbulent vortices at different positions, which affects the flame propagation.

In the three-way bifurcated pipe, the flame front temperature and propagation speed, shock wave overpressure, ion current intensity, and chemical reaction rate all typically increase rapidly to a peak value and then slowly decrease. Moreover, when the bifurcation angle is increased from 45 to 75°, the flame front temperature, flame propagation speed, shock wave overpressure, ion current intensity, and chemical reaction rate all increase accordingly. The peak values of the various parameters of the flame are larger in the right straight pipe than the left straight pipe due to the larger angle formed with the branch pipe. In addition, in the bifurcated pipe with a bifurcation angle of 90°, the vertical reflection of the explosion shock wave at the junction wall is greatly attenuated, resulting in reductions in the severity of the combustion reaction and the peaks of the various flame parameters. Since the branch pipe is perpendicular to the straight pipe, the flame propagates uniformly to the left and right sides, and the flame combustion reaction rate, reaction intensity, and the intensity of the ion current generated by combustion are basically the same in both sides of the straight pipe.

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Notes
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