

Experimental Study of the Influence of H₂/CO on the CH₄ Explosion Pressure and Thermal Behaviors

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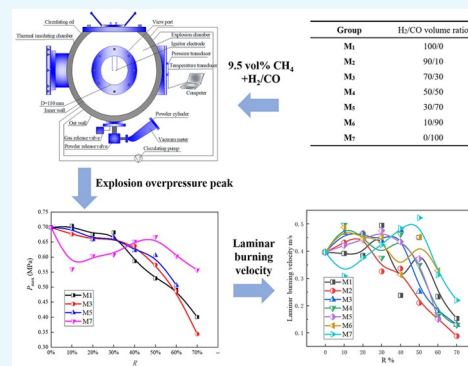
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ABSTRACT: In a spontaneous coal combustion environment and in the coal chemical process, multiple gases, such as CH₄, H₂, and CO, coexist, and explosion accidents are prone to occur. The causes of these disasters and the explosion characteristics are key to formulating preventive measures. To explore the effect of H₂/CO on the explosion pressure and thermal behavior of methane–air, CH₄ with initial volume fractions of 7, 9.5, and 12%, which correspond to three states of oxygen enrichment, equivalence ratio, and oxygen depletion, was selected. Moreover, a mixed fuel system is composed of H₂/CO with different volume ratios. A 20 L spherical gas explosion experimental system was used to test the peak explosion overpressure P_{max} , the maximum explosion overpressure rise rate $(dP/dt)_{max}$, and the corresponding time parameters of the H₂/CO–CH₄ mixed system. Combined with the thermodynamic calculation model, laminar burning velocity S_L , explosion heat loss q_{trav} and other parameters were obtained. The results show that due to the existence of the damping effect, CO has the dual characteristic of promoting or weakening methane explosions. Compared with CO, the effect of H₂ on the methane explosion is more significant, and the improvement or weakening of the laminar combustion rate of the reaction system by CO “lags” behind that of H₂. The heat loss in the process of a gas explosion is affected by factors such as the heat release rate, the propagation speed of the combustion wave, and the heat dissipation effect of the container wall. When H₂/CO increases the laminar burning velocity of the mixed system, the heat loss decreases accordingly. This study also found that the laminar burning velocity model of the mixed gas based on the ideal spherical flame propagation theory is not fully applicable to the H₂/CO/CH₄ mixed system in a spherical closed space, and the calculation results have large errors when the mixed system is close to the upper limit of the explosion.



1. INTRODUCTION

The prevention and mitigation of gas explosions have always been important topics in the field of process safety.^{1,2} For the mining industry, the gas explosion induced by spontaneous coal combustion has caused a series of accidents and resulted in heavy property losses.^{3–7} During this process, the main components that are generated from the oxidation of coal are H₂, CO, and CH₄.^{8–10} Since the multicomponent combustible gas explosion involves more complicated physical and chemical mechanisms, investigating the explosion behavior is particularly important for the development of the corresponding mitigation and control technology.¹¹

Explosion behaviors of methane–air mixtures, within the effect of other gases, have been reported in previous research.^{12–16} The fundamental parameters of the flammability limit,^{17,18} explosion pressure,^{19–21} and flame propagation behavior^{22–24} have been investigated in past decades. The lower flammability limits of methane in air decrease with the mixture of C₂H₆, C₂H₄, CO, and H₂, which results in an increase in the combustion hazard.¹⁰ When blending with CO, both the upper flammability limit and the lower flammability limit of methane will decrease, and H₂ could considerably widen the

flammable range of methane.²⁵ The experimental and numerical investigation results show that for fuel-lean mixtures, the addition of CO could promote the intensity of methane explosion, otherwise the explosion intensity decreases.²⁶ The elevated temperature will increase the peak explosion pressure rise rate and flame propagation speed of CO/CH₄/air mixtures. For the CO-involved syngas mixtures, the increase in the CO volume ratio greatly increases the explosion heat loss.²⁷ For the blended mixture of CH₄–H₂, an expanding volume fraction ratio of H₂ increases the maximum explosion pressure, K_G value, and pressure rise rate but shortens the explosion duration time. Additionally, blended H₂ dramatically increases the flame propagation speed of methane while weakening the flame stability. The results show that the increased initial pressure or

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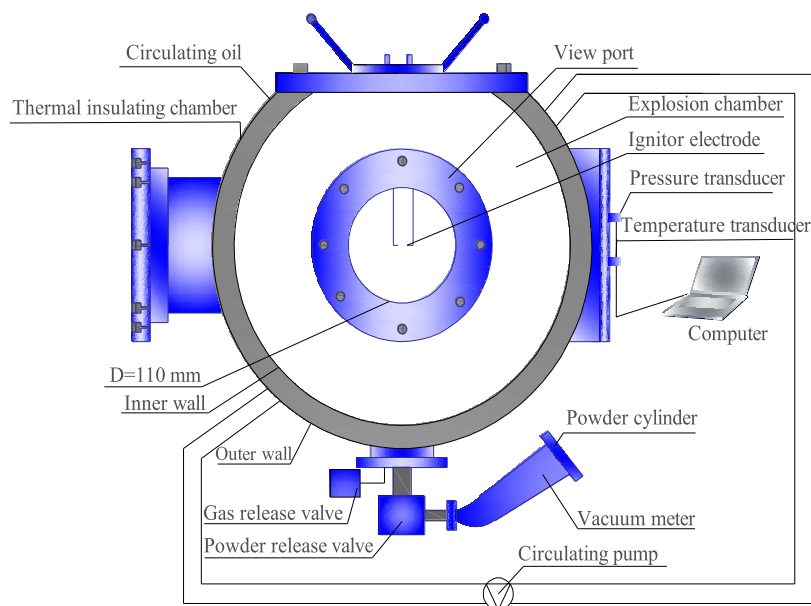


Figure 1. 20 L multifunctional spherical gas/dust explosion experimental system.

turbulence level greatly enhances the flame propagation instability for oxygen-lean $\text{CH}_4\text{-H}_2$ mixtures.²⁸

In the present research, a 20 L spherical gas explosion experimental system was used to test the peak explosion overpressure, the maximum pressure rise rate, and the corresponding time parameters of $\text{H}_2\text{-CO-CH}_4$ mixtures. Moreover, the corresponding laminar burning velocity and explosion heat loss were obtained by calculation. These results could contribute to the assessment of explosions induced by spontaneous coal combustion. Furthermore, the explosion pressure parameter, as well as the combustion heat loss data, will help to develop an explosion mitigation method.

2. EXPERIMENTAL SECTION

2.1. Experimental Equipment. The experimental equipment used in this study is a 20 L multifunctional spherical gas/dust explosion experimental system, which conforms to the specifications of GB/T 16426-1996 “Method for Determination of Maximum Explosion Pressure and Maximum Explosion Rising Rate of Dust Clouds” and ISO/IEC 80079-20-2-2016 Explosive atmospheres. Part 20-2 Material characteristics. In addition, this experiment has strong comparability with relevant studies. The setup of the experimental system is shown in Figure 1. The measurement and control and data acquisition units are composed of a pressure sensor, a 16-channel high-speed data acquisition card, and a measurement and control host. These components can effectively collect the dynamic pressure in the explosion process container. The acquisition rate was 5 kHz, and the recording time was 0–2000 ms.

Three repeatability tests were performed on the methane–air mixture with volume fractions of 7, 9.5, and 12%, and the results are shown in Figure 2. Among the three volume fractions of methane–air explosion overpressure P_{\max} and explosion overpressure rise rate $(dP/dt)_{\max}$, the largest error is the group with 12% methane–air, and the absolute errors are 0.03453 MPa and 1.34358 MPa/s, respectively. These results prove that the experimental system has good repeatability and reliable test results.

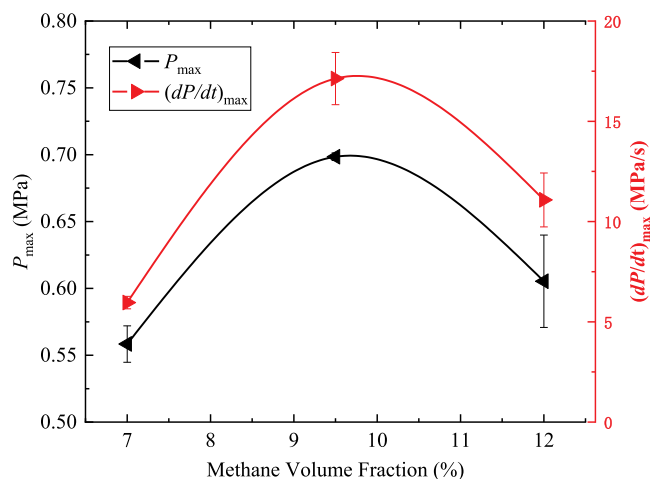


Figure 2. Reliability of the experimental setup.

2.2. Experimental Method. The experiments of this study were conducted at ambient temperature and pressure. The ambient temperature was 20 °C, the initial pressure was 0.1 MPa, and the ignition energy was 10 J. At the beginning of the experiment, the inside of the pipeline was turned into a vacuum with the use of a vacuum pump, and the gas mixture was prepared according to Dalton’s partial pressure ratio principle. The gas mixture was left to stand for 300 s after completion to ensure its uniformity. The initial volume fractions of CH_4 were selected as 7, 9.5, and 12%, which correspond to three states of oxygen enrichment, equivalence ratio, and oxygen depletion. A total of seven kinds of H_2/CO mixed gases were prepared from groups M1–M7, and the volume ratio of the two gases was changed from 100:0 to 0:100, as shown in Table 1.

In this experiment, R is the volume ratio of H_2/CO to the total fuel, and the definition is depicted in formula 1.

$$R = \frac{V_{\text{H}_2/\text{CO}}}{V_{\text{CH}_4} + V_{\text{H}_2/\text{CO}}} \quad (1)$$

Table 1. Volume Ratio of the Hydrogen–Carbon Monoxide Mixtures

group	H ₂ /CO volume ratio
M ₁	100/0
M ₂	90/10
M ₃	70/30
M ₄	50/50
M ₅	30/70
M ₆	10/90
M ₇	0/100

where $V_{\text{H}_2/\text{CO}}$ and V_{CH_4} are the volume fractions of H₂/CO gas and CH₄, respectively. During the experiment, the R -value of each group of H₂/CO increased by increments of 10% from a starting ratio of 0% until the mixed system did not explode.

3. RESULTS AND DISCUSSION

3.1. Explosion Pressure Parameters. Gas deflagration index (K_G) is an important parameter for measuring the explosive intensity of flammable gases and is an important guide for formulating protective measures and designing devices for the corresponding explosive hazards. This parameter's calculation method is depicted in formula 2. Using formula 2 and the maximum explosion rate of the mixed system, the explosion index distribution of the mixed system under each working condition can be calculated as formula 2.

$$K_G = (dP/dt)_{\max} \cdot V^{1/3} \quad (2)$$

where $(dP/dt)_{\max}$ is the maximum pressure increase rate of the mixed gas explosion, MPa/s, and V is the volume of the explosion container, m³. Notably, as K_G is obtained based on the product of the maximum pressure boost rate parameter and the volume constant of each group of mixed systems, the trends and amplitudes of both are consistent. Therefore, the following subsection will focus on the analysis of the maximum pressure boost rate parameters.

As shown in Figure 3, in the lean methane system, the addition of hydrogen (group M1) promoted the explosion of 7% methane. The peak explosive overpressure of the mixed system increases with further addition, and the time required to reach the peak pressure decreases. After adding carbon monoxide (group M7), with the increase in the addition amount, the explosion of 7% methane showed a trend of initial inhibition and then promotion, which is consistent with previous experiments by Deng et al.²⁹ that CO has a certain damping effect on methane–air explosion. However, the difference is that when CO reaches a certain amount of addition, its damping effect does not appear, but its promoting effect is more significant.

Figure 4 shows the effect of each ratio of H₂/CO on the explosion pressure parameters of 7% methane. Overall, all groups of H₂/CO, except M7 (pure carbon monoxide), showed a significant contribution to the 7% methane explosion overpressure peak and maximum ramp rate, and the R -value reached the maximum extent at approximately 60% and then appeared to be substantially weakened with an increasing R -value. As mentioned above, the addition of the M7 group has obvious stage effects on the explosion of 7% methane. When the R -value is lower than 30%, the pressure parameter of the system initially decreases and then rises slightly. Therefore, within this range of addition, the influence of CO is mainly the damping effect; when the R -value increases to 50–80%, the promoting

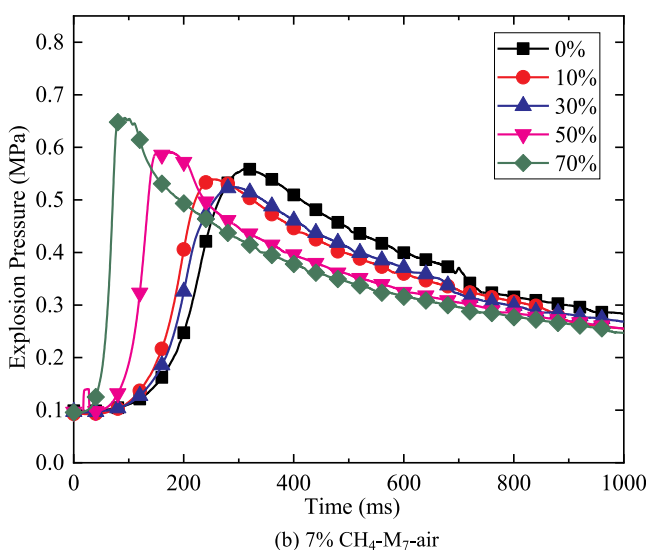
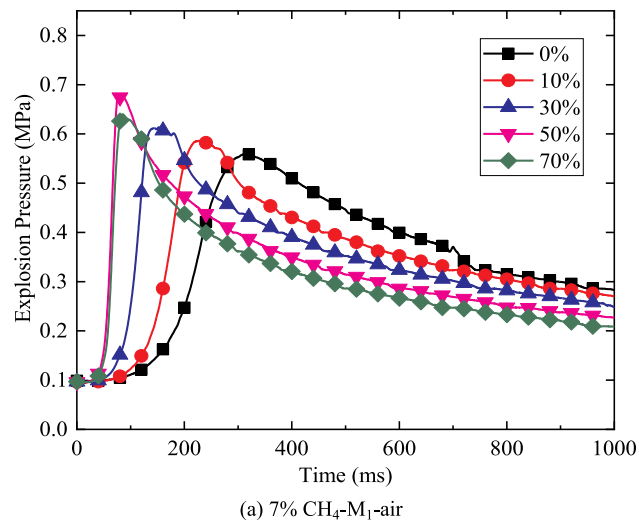
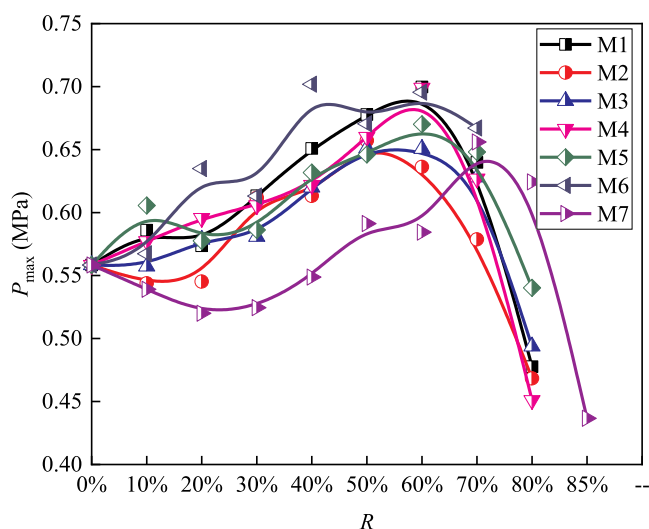


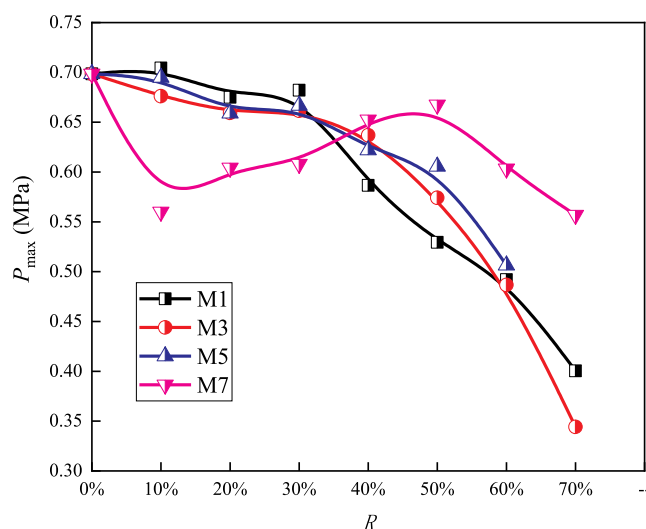
Figure 3. Explosion pressure–time curves of the 7% CH₄–M₁/M₇–air mixtures.

effect begins to gradually appear, and the pressure parameter increases to the maximum value. When the R -value of the M7 group is 85%, and the corresponding CO volume fraction reaches 39%, the system still has the ability to explode, while other groups of H₂/CO with the same R -value have made the mixed system no longer explode. The damping effect of CO on the explosion reaction of CH₄ makes the fuel system still within the explosion limit when the R -value of the M7 group is 85%.

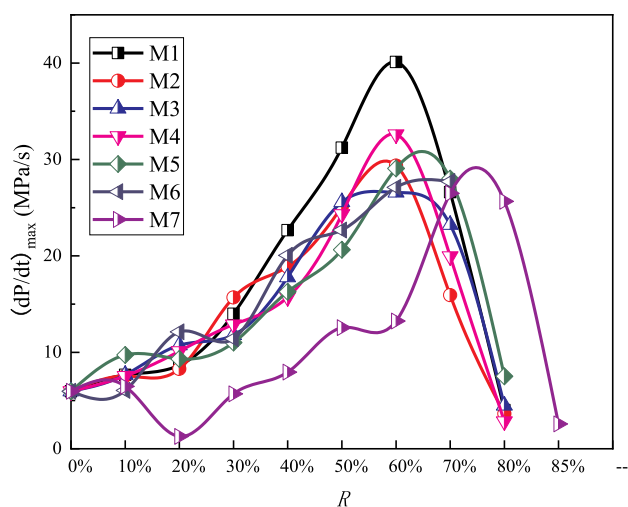
Figure 5 shows the change results of H₂/CO that affect the explosion pressure parameters of 9.5% methane. The M5 and M6 groups of H₂/CO at 70% R -value rendered the mixed system inexplorable; thus, their test data are not listed. Overall, the explosion overpressure peak of the mixed system weakened to different degrees with the addition of H₂/CO. With the increase in the R -value, the maximum pressure increase rate fluctuates, which is different from the change trend of the explosion overpressure peak. In addition, after CO addition, the macroscopic explosion characteristics of 9.5% methane also showed a stage characteristic of initial damping and then promoting. The reason for the change in the above characteristic parameters is that H₂/CO aggravates the degree of oxygen depletion in the mixed system. Conversely, the heat of



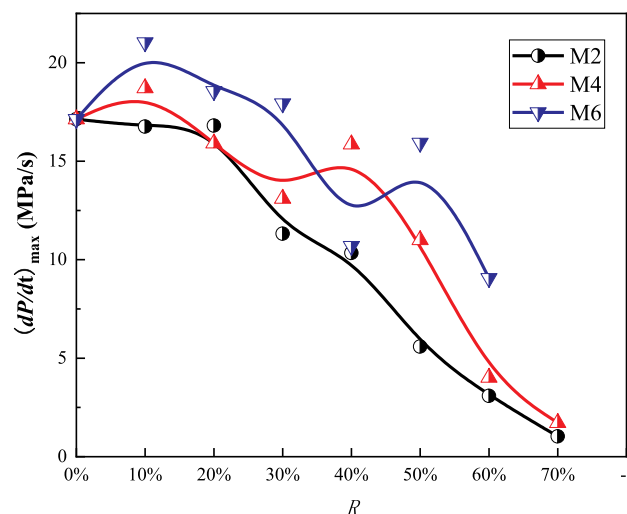
(a) explosion overpressure peak



(a) explosion overpressure peak



(b) maximum ramp rate



(b) maximum ramp rate

Figure 4. Explosion pressure parameters of 7% $\text{CH}_4\text{-H}_2/\text{CO}$ -air mixtures.

Figure 5. Explosion pressure parameters of the 9.5% $\text{CH}_4\text{-H}_2/\text{CO}$ -air mixtures.

combustion of both hydrogen and carbon monoxide is lower than that of methane, and the fuel in the mixed system does not burn sufficiently and does not release enough heat, which weakens the explosion overpressure peak of the system.

Figure 6 shows the change results of the explosion pressure parameters of the 12% $\text{CH}_4\text{-H}_2/\text{CO}$ -air mixtures. Since the initial reaction system is already in an oxygen-depleted state, the addition of any more flammable gas to the system will theoretically increase the degree of oxygen depletion of the system, thus reducing its explosion pressure parameters. The current experimental results show that the explosion overpressure peak and the maximum rate of pressure rise of the mixed system after the addition of H_2/CO in groups M1–M6 are in accordance with the above rule.

However, another trend can be found in the change of the explosion overpressure peak of the mixed system after the addition of CO. When the R -value is less than 30%, CO increases the explosion pressure parameter of the mixed system, and then the explosion pressure parameter of the system begins to decrease with the increase of the CO addition amount.

Comparing the M1 group with the M7 group, at the same R -value, the addition of hydrogen reduces the explosive overpressure peak of the mixing system much more than that of CO. For example, when the R -value is 60%, the hydrogen reduces the explosion overpressure peak of the mixed system from 0.605 to 0.162 MPa, which is a reduction of 73%. However, the same amount of CO only reduces the explosion overpressure peak by approximately 34%. Overall, for the same R -value of H_2/CO components in the experimental range, the higher the proportion of H_2 , the greater the reduction in the peak explosion overpressure of the system. In other words, the H_2/CO component with a higher proportion of H_2 has a greater effect on promoting or weakening the methane explosion.

3.2. Laminar Burning Velocity. Laminar burning velocity, as a basic parameter in the combustion and explosion reaction system, represents the important physical and chemical characteristic information in the reaction process. Additionally, this parameter can also reflect the development and change process of flame propagation, flashback, annihilation, and other phenomena. The assessment of disaster effects has important

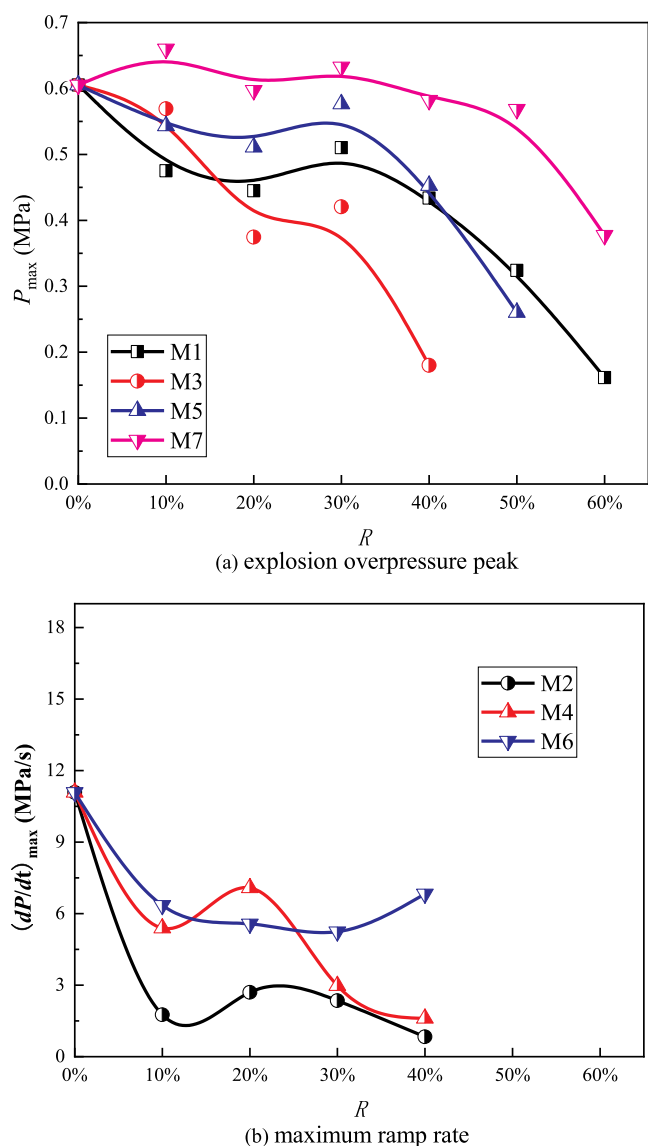


Figure 6. Explosion pressure parameters of 12% CH₄-H₂/CO-air mixtures.

reference significance. In this paper, the theoretical calculation model of the premixed gas laminar burning velocity based on spherical flame propagation is developed by Dahoe et al.^{30,31}

$$S_L = \frac{1}{P_{\max} - P_0} \cdot \frac{1}{3} \left(\frac{4\pi}{3V} \right)^{-1/3} \cdot \left(\frac{P_0}{P} \right)^{1/\gamma} \cdot \left[1 - \left(\frac{P_0}{P} \right)^{1/\gamma} \cdot \left(\frac{P_{\max} - P}{P_{\max} - P_0} \right) \right]^{-2/3} \cdot \frac{dP}{dt} \quad (3)$$

where S_L is the laminar burning velocity of the premixed gas, m/s; P_{\max} is the peak overpressure during the explosion, MPa; V is the volume of the reaction vessel, m³; γ is the adiabatic coefficient of the premixed gas; P_0 and P are the initial pressure and actual pressure in the experimental container, MPa, respectively; and dP/dt is the overpressure rise rate during the explosion, MPa/s. Thus, the laminar burning velocity of the combustible system can be obtained from the pressure-time data in the experimental vessel.

In the current experiment, using this model to calculate the CH₄-air system, the laminar burning velocity of the 9.5% methane-air mixtures is 0.3964 m/s, which is similar to Mitu's calculation of 0.40 m/s.³²

Figure 7 shows the laminar burning velocity distribution of the 7% CH₄-H₂/CO-air mixed system calculated based on

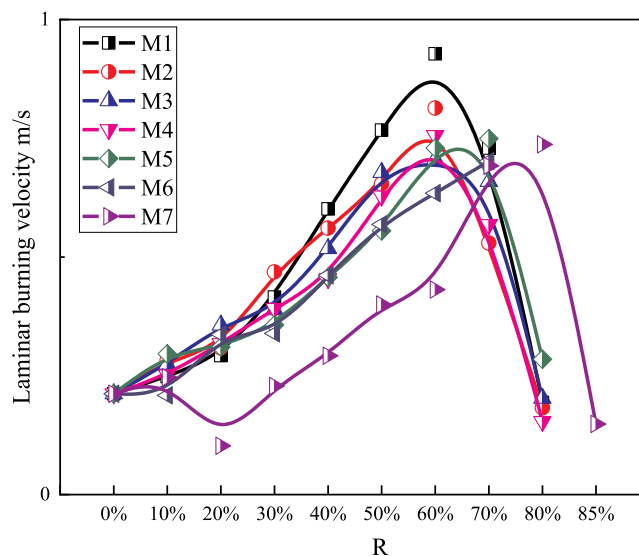


Figure 7. S_L values of 7% CH₄-H₂/CO-air mixtures.

Dahoe's model. The addition of H₂/CO components changes the laminar burning velocity of the system to different extents and changes the reaction process. The addition of hydrogen first accelerated the reaction process and increased the heat release rate, and then with the intensified oxygen depletion of the system, the reaction rate weakened, and the laminar burning velocity decreased. Due to the reactivity, CO has a "hysteresis effect" on the laminar combustion rate of the reaction system compared to hydrogen. That is, the H₂/CO component with carbon monoxide accounting for more than 50% can make the laminar burning velocity of the system reach its peak when the R -value is 70–80%. When the R -value is less than 30%, carbon monoxide weakens the laminar burning velocity of the mixed system, thus causing it to exhibit damping characteristics in macroscopic pressure parameters.

Figure 8 shows the distribution of the calculated laminar burning velocity of the mixed system after H₂/CO acts on 9.5% methane. Overall, with the addition of H₂/CO components, the laminar burning velocity of the multigroup mixed system first increased and then gradually decreased, which indicate that the reaction process was accelerated. However, the explosion pressure parameters did not show the corresponding change trend due to the aggravation of oxygen deficiency in the system. Carbon monoxide with an R -value of less than 30% weakens the laminar burning velocity of the system and then increases the characteristic parameter of the system to a peak value when the R -value is 50%, which leads to a consistent change trend in the explosion pressure parameters of the system. Notably, there are several large deviations in the laminar burning velocity values obtained based on Dahoe's model, and these deviations are inconsistent with the overall variation law. Thus, these deviations are not considered in the analysis, such as in the 9.5% methane- R (30%) M1 group and 9.5% methane- R (40%) M3 group. The laminar burning velocities under some

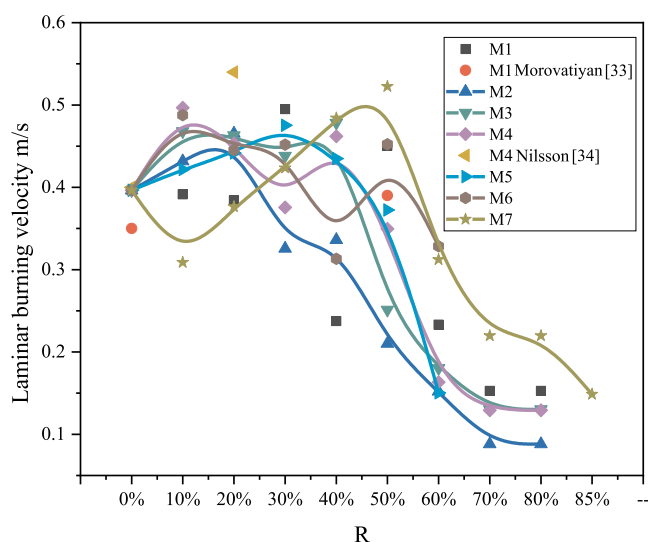


Figure 8. S_L values of the 9.5% $\text{CH}_4\text{-H}_2/\text{CO}$ -air mixtures.

conditions in Figure 8 have also been obtained in previous studies,^{33,34} and the calculation results in this paper are close to those in previous studies.

When the initial volume fraction of methane is 12%, the influence of the distribution of the addition of H_2/CO components on the laminar burning velocity is shown in Figure 9. When the proportion of hydrogen is more than 10%, the

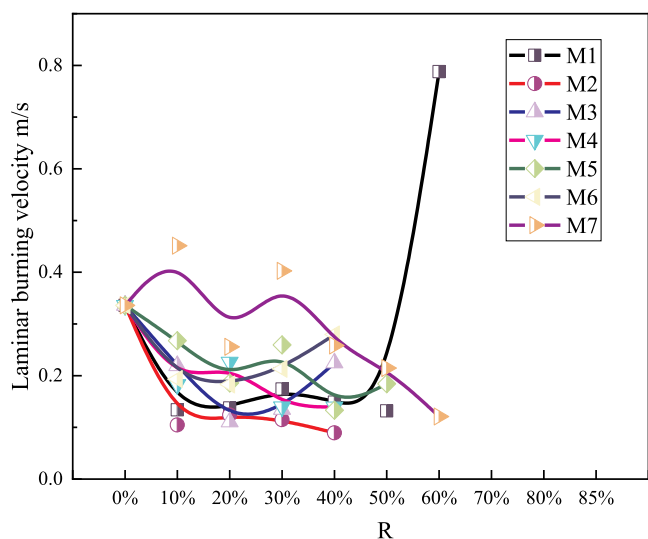


Figure 9. S_L values of 12% $\text{CH}_4\text{-H}_2/\text{CO}$ -air mixtures.

laminar burning velocity of the mixed system decreases with increasing addition of hydrogen. When the R -value is 60%, hydrogen greatly increases the laminar burning velocity of the system to 0.7879 m/s, which is obviously inconsistent with common knowledge. The reason is that the current calculation model of laminar burning velocity is based on center ignition—a spherical flame propagation process that expands around, and the flame radius increases uniformly with the ignition source as the center. The experimental results show that for the initial volume fraction of 12% methane, when the H_2/CO component reaches a certain amount, the development of the explosive flame behavior of the mixed system changes and is no longer uniform from the center of the ignition source to the

surrounding area in an ideal state. Instead, this component becomes an overall vertical upward floating characteristic while spreading to the surrounding unburned area from the ignition point. In this process, the mixed reaction system is greatly affected by the buoyancy effect caused by the density difference between the burned area and the unburned area, and the change in its morphological characteristics makes the theoretical calculation model of the laminar burning velocity no longer applicable, thus producing a larger error. According to the experimental test results, when the R -value is greater than 30%, the explosion flames of each group of mixed systems have different degrees of floating phenomenon. Therefore, for the data listed in Figure 9, the reliability of the laminar burning velocity value is reduced if the R -value is greater than 30%.

3.3. Explosion Heat Loss. During the whole process from the ignition of the flammable gas to the end of the explosion, part of the energy of the mixed gas increases the pressure and temperature of the system through the explosion reaction. Since the whole system is not a “closed system”, there must be heat exchange between the mixed gas and the reaction vessel in this process, so the actual explosion overpressure, explosion temperature, and other characteristic parameters of the mixed gas are all smaller than the corresponding values in the ideal state. This part of the heat that is consumed due to external reasons such as the heat exchange on the wall of the container is also called the heat loss during the explosion process.³⁵ Quantitative research and analysis can deepen the understanding of the explosion process and can provide a theoretical basis for the development of appropriate protective measures.^{36–38} Since the explosion reaction is an extremely fast process, we only consider the surface heat loss in the process of calculating the explosion heat loss, while ignoring the volumetric radiative heat loss, which is also ignored in most previous studies.^{28,39}

$$\begin{aligned} Q_{\text{tra}} &= Q_{\text{rel}} - Q_{\text{acc}} = mC_{e,v}(T_{\text{max,ad}} - T_{\text{max,real}}) \\ &= \frac{V}{\gamma_e - 1}(P_{\text{max,ad}} - P_{\text{max,real}}) \end{aligned} \quad (4)$$

Then, the heat loss per unit area in the closed container (referred to as the explosion heat loss) during the explosion process is

$$q_{\text{tra}} = \frac{V}{S} \cdot \frac{1}{\gamma_e - 1} \cdot (P_{\text{max,ad}} - P_{\text{max,real}}) \quad (5)$$

where Q_{rel} is the total energy released by the explosion of the mixed gas, J; Q_{acc} is the energy acting on the explosion overpressure and explosion temperature, J; Q_{tra} is the energy loss caused by the heat exchange between the mixed system and the container, J; m is the amount of mixed gas; $C_{e,v}$ is the average heat capacity of the burned gas; $T_{\text{max,ad}}$ is the theoretical adiabatic combustion temperature, K; $T_{\text{max,real}}$ is the actual peak combustion temperature, K; $P_{\text{max,ad}}$ is the theoretical adiabatic combustion overpressure peak, kPa; $P_{\text{max,real}}$ is the actual explosion overpressure peak value, kPa; γ_e is the adiabatic index of the burned gas (C_p/C_v); V is the volume of the airtight container, m^3 ; S is the inner surface area of the airtight container, m^2 ; and q_{tra} is the internal heat loss per unit area of the airtight container during the explosion process, J/m^2 .

According to the above mathematical model, three volume fractions of methane–air explosion heat loss are calculated, in which the peak adiabatic combustion temperature T_{max} and of the mixed gas and the adiabatic index of the combusted mixed

gas are calculated using the chemical thermodynamic program GASEQ.⁴⁰ The detonation heat losses of 7, 9.5, and 12% methane are 4.23, 4.10, and 5.97 J/m², respectively. According to this result, for the unit methane, the explosion heat loss is the smallest when the theoretical equivalent volume fraction is around, and the explosion heat loss is the largest near the lower explosion limit and the upper explosion limit. This characteristic can be attributed to the fact that the methane–air explosion is the most violent near the equivalent concentration, the methane is nearly completely burned, the combustion wave propagates the fastest, the heat release rate of the system is the largest, and the contact time between the flame and the container wall is the shortest. Thus, the system is made larger. Part of the energy release acts directly on the increase in the temperature and pressure, with minimal heat loss. In contrast, when methane is near the explosion limit, the combustion wave velocity decreases due to the reduction in its combustion heat release rate. Thus, the contact time between the flame and the inner wall of the container greatly increases, which directly aggravates the explosion heat loss.

The effect of adding H₂/CO on the explosion heat loss of 7% methane is shown in Figure 10. The effect of each group of H₂/

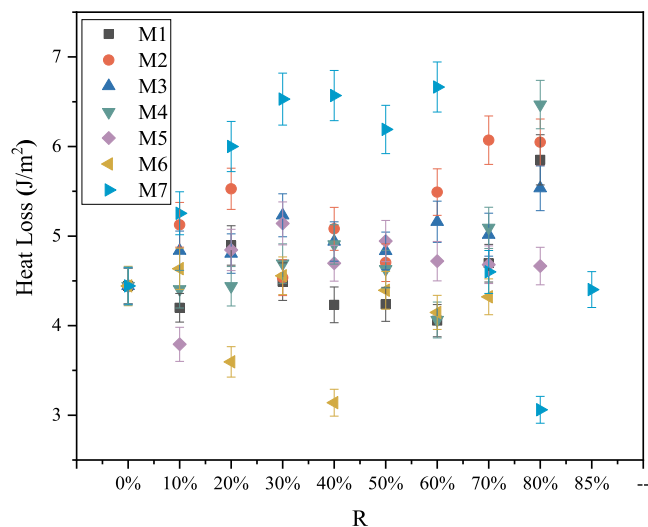
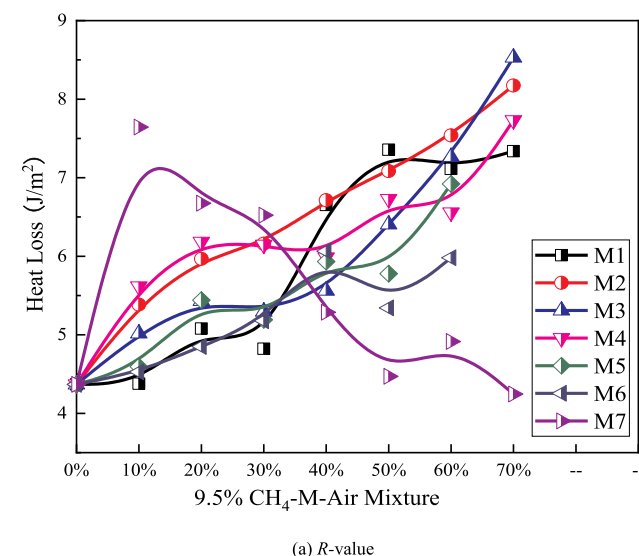


Figure 10. Heat loss values in the explosion of 7% CH₄-H₂/CO-air mixtures.

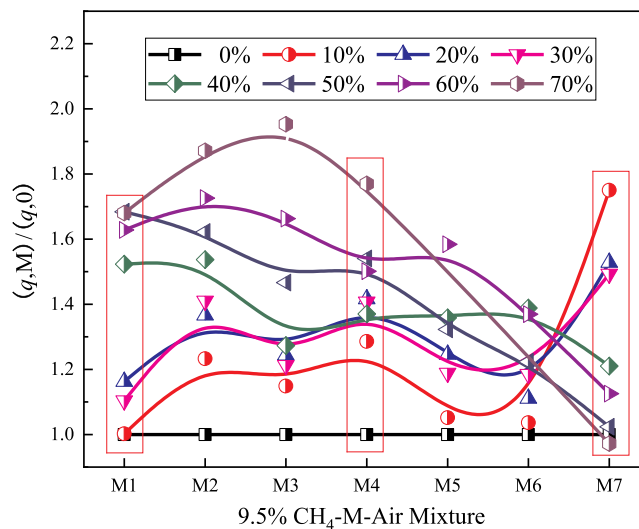
CO gases on the explosion heat loss of the mixed system shows a great difference with the change in the addition amount. For example, the addition of hydrogen initially reduces the explosion heat loss of the mixed system and reaches a minimum value of 3.79 J/m² when the *R*-value is approximately 60%. Then, the explosion heat loss increases with an increasing *R*-value. Since the addition of hydrogen increases the fuel–air ratio of the mixed system, the mixed system gradually changes from an oxygen-rich state to an equivalent state. When the *R*-value is 60%, this system is closest to the theoretical equivalent concentration, so the explosion heat loss is the smallest. Then, when H₂ continues to be added, the system becomes oxygen-depleted and approaches the upper limit of explosion and the heat loss of explosion increases to 5.64 J/m². The addition of carbon monoxide showed the opposite effect to that of hydrogen. As the *R*-value increases from 0 to 60%, the explosion heat loss of the mixed system gradually increased to a maximum of 6.32 J/m². Thus, the heat loss decreased nonlinearly to 6.32 J/

m². Afterward, the explosion heat loss decreased to the minimum value of 2.85 J/m² and then greatly increased. This phenomenon can be attributed to the dual effect of CO on oxygen-enriched methane mentioned above, which starts with damping and then promoting. For the H₂/CO of the M2–M6 groups, when the *R*-value is less than 60%, the explosion heat loss of each mixed system fluctuates in a wave-like manner, with a size distribution of 4.2–5.3 J/m²; when the *R*-value is greater than 60%, the explosion heat loss of the mixed system increases. This phenomenon can be attributed to the combined effect of the total energy of the mixed component system, the combustion wave velocity, and the combustion heat release rate after the addition of H₂/CO.

The effect of H₂/CO on the explosion heat loss of 9.5% methane is shown in Figure 11. The addition of H₂/CO in groups M1–M6 makes the explosion heat loss of the mixed system show a monotonically increasing trend. The addition of carbon monoxide causes the explosion heat loss of the mixed system to initially increase and then decrease and reaches the



(a) *R*-value



(b) H₂/CO

Figure 11. Heat loss values in the explosion of 9.5% CH₄-H₂/CO-air mixtures.

maximum value of 7.6 J/m^2 when the R -value is 10%; then, the explosive heat loss of the mixed system decreases monotonically with an increasing R -value. Consistent with the abovementioned reasons, the addition of H_2/CO in groups M1–M6 increases the contact time between the explosion flame and the inner wall of the container and reduces the release rate of the explosion heat of the mixed system. As a result, the explosion heat loss increases. The data were normalized to facilitate quantitative analysis and comparison of its effect. With the same R -value, the influence of H_2/CO in each group on the explosion heat loss of the 9.5% methane explosion is shown in Figure 11b. When the addition amount is less than 30%, H_2 has the weakest improvement effect on the explosion heat loss of the mixing system, and the increase degree is only within 1.2 times. The intensification effect of CO is the most significant, which increases the explosive heat loss of the system by more than 1.5 times. However, the increasing effect of the H_2/CO binary mixture is between these two values, increasing by 1–1.4 times. When the R -value is greater than 30%, the proportion of CO in H_2/CO gas is higher and the promotion effect of CO on the explosive heat loss of the mixed system is weaker.

For 12% methane, the effect of adding H_2/CO on the explosion heat loss of the mixed system is shown in Figure 12.

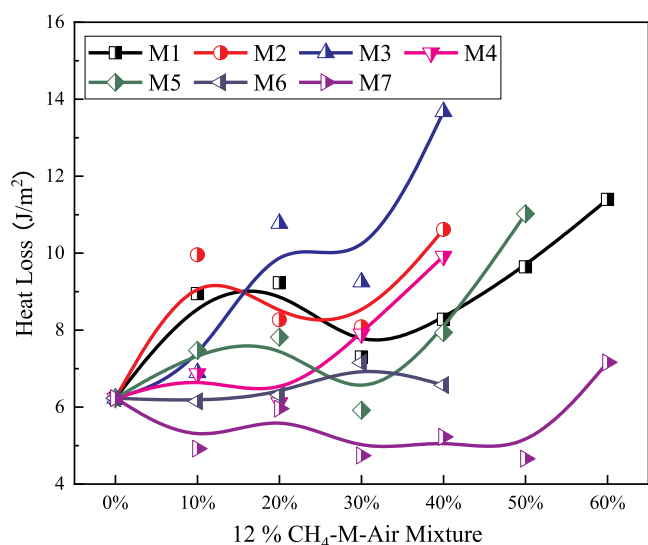


Figure 12. Heat loss values in the explosion of 12% CH_4 – H_2/CO –air mixtures.

Similar to the effect on methane–air in the equivalent state, the explosion heat loss of the mixed system after the addition of hydrogen/carbon monoxide in groups M1–M5 (CO volume ratio 0–70%) increases gradually with an increasing R -value, and the overall trend is increasing. The addition of H_2/CO (CO volume accounted for 90%) in the M6 group had a weak effect on the explosion heat loss of the mixed system, and its value fluctuated within a small range, which was within 1.2 times the initial value of 5.97 J/m^2 . However, with the increase in the R -value, carbon monoxide causes the explosion heat loss of the mixed system to first decrease and then increase. When the R -value is less than 50%, the explosion heat loss of the system decreases with an increasing R -value and then increases as the R -value continues to increase. When the R -value is within 40%, the higher the proportion of H_2 , the greater the explosion heat loss of the mixed system. Additionally, the higher the proportion of CO, the smaller the explosion heat loss of the mixed system.

4. CONCLUSIONS

- (1) The effect of hydrogen/carbon monoxide on the explosion characteristic parameters of the groups with 9.5 and 12% methane has the same trend as that of 7%, which is mainly reflected in the fact that the addition effect changes the laminar burning velocity of the system, which in turn leads to changes in the macroscopic explosion pressure characteristics.
- (2) Due to the reactivity, compared with hydrogen, carbon monoxide has a “hysteresis effect” on the increase/decrease in the laminar burning velocity of the reaction system. Specifically, the laminar burning velocity of the system reaches its peak only when the R -value is 70–80% for H_2/CO components with a CO ratio greater than 50%; however, the laminar burning velocity reaches its peak at a smaller R -value for the component with more hydrogen.
- (3) With the increase in the R -value, carbon monoxide has the dual effect of initially damping and then promoting methane explosion. The critical R -value of damping to promote methane explosion is approximately 50% for 7% methane and 40% for 9.5% methane. When the R -value is constant, the higher the ratio of the hydrogen to carbon monoxide, the greater the promoting or weakening effect on methane explosion.
- (4) The amount of explosion heat loss in the combustible mixture gas mainly depends on the comprehensive effect of its combustion degree, heat release rate, propagation speed of the combustion wave, and heat dissipation effect of the container wall. When the laminar burning velocity of the H_2/CO system is increased, the explosion heat loss decreases accordingly. The explosion heat loss of the mixed system is minimal when it is close to the theoretical equivalent volume fraction. In addition, when the R -value is less than 40%, the higher the proportion of H_2 , the higher the explosion heat loss of the mixed system. Additionally, the higher the proportion of CO, the lower the explosion heat loss of the mixed system.
- (5) Based on the ideal spherical flame propagation theory, the laminar combustion velocity model of the mixed gas has limitations in the scope of application. In the present experiment, the calculation results will have a large error when the mixed system is close to the upper explosive limit of the mixed system. This paper has not been able to elucidate the chemical kinetic behavior of the $\text{H}_2/\text{CO}/\text{CH}_4$ mixture explosion reaction, but it is a very important topic. The chemical kinetic behavior of ternary gas mixture is a very complex process but it is worth further exploration.

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Notes

The authors declare no competing financial interest.

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