Effect of Metal Foam Mesh on Flame Propagation of Biomass-Derived Gas in a Half-Open Duct

Mengming Wang, Xiaoping Wen,* Sumei Zhang, Fahui Wang, Qifeng Zhu, Rongkun Pan, and Wentao Ji

ABSTRACT: The effect of metal foam mesh on flame propagation of biomass-derived gas in a half-open duct was studied. The explanations are based essentially on the experimental investigations of premixed biomass-derived gas explosions carried out in a rectangular half-open combustion chamber. The initial temperature $T_0$ and pressure $P_0$ were 300 K and 1.0 atm, respectively. The key parameters of explosive characteristics, such as flame propagation images and explosive overpressure, were analyzed by changing the porosity, the pore density of porous metal foams, and the gas components. The results show that the use of porous metal foam has a significant inhibitory effect on the gas explosion. Although the combustion structure of the flames is similar, the action of the porous metal foam during the experiment also shows the characteristics consistent with the obstacles. When the porosity of the porous foam is 97%, the flame can be stimulated to produce turbulence, and then the shock–flame interaction generated by the reflection of the lead shock wave can enhance the explosion propagation and promote the explosion escalation. However, with the increase of hole density, the existence of the porous metal foam by momentum loss and heat loss to curb the spread of the explosion not only hindered the flow of not flammable but also extracted energy from the expansion of the combustion products at the same time. This study also confirms that the biological hydrogen and methane component has a vital role in the flame, and a reasonable hydrogen and methane ratio can improve the flame burning to get more economic value.

1. INTRODUCTION

With the decrease of fossil energy and aggravating environmental pollution, it is particularly urgent to search for new renewable energy and improve the efficiency of energy combustion.1 Biomass energy is an ideal renewable energy with the following characteristics:2 (1) renewable; (2) low pollution (low sulfur content and nitrogen content of biomass, low $SO_2$ and $NO_x$ during combustion, and nearly zero net carbon dioxide emission when biomass is used as fuel, which can effectively lessen the greenhouse effect); (3) wide distribution. Areas lacking coal can make full use of biomass energy.

As research findings confirm, for biomass-derived gas with a low calorific value, according to the principle of controlling key parameters of combustion characteristics, different combinations such as $CH_4$, $H_2$, and $N_2$ should be selected according to specific characteristics of benchmark gas to achieve accurate gas distribution.3 Its interchangeability controls parameters. Variability of biomass-derived gas composition has an important influence on combustion and explosion characteristics, making it more difficult to prevent the syngas explosion.4 Therefore, post-graduate material gas explosion suppression is of great significance to reduce biomass-derived gas explosion accidents and promote the safe use of clean energy. The combustion of biomass-derived gas has been widely investigated in past decades, but experiments on biomass-derived gas/air flames in a half-open duct are quite limited. Knowing the explosion mechanism and flame propagation law of premixed gas is the key to taking explosion suppression measures in time to reduce the loss caused by the accident. The explosion suppression measures generally used in pipelines are physical and chemical. The metal foam mesh, as an explosion suppression device, has a double coupling effect, which can reduce the loss caused by accidents and has important practical significance.

Babkin et al.5 first revealed that at low subsonic propagation speeds, heat loss dominates the porous media, while at hypersonic propagation speeds, turbulence and compressibility are important. The mixing of these important phenomena leads to no obvious transformation of the transmission...
mechanism, which is characterized by a sudden change in transmission velocity. The subsequent experimental results of Gao et al.\textsuperscript{7} indicated the premixed combustion of methane/air mixtures in different alumina fillers. The flame stability limit, flame temperature distribution, flame temperature, pressure drop, and emission of carbon monoxide, hydrocarbons, and nitric oxide were analyzed. At the same flame velocity, the flame temperature of foam is significantly lower than that of filler beads and honeycomb due to its radiative heat transfer characteristics. The pressure drop of the reaction flow is higher than that of the corresponding cold flow due to the significant change of density. Sathe et al.\textsuperscript{8} investigated the premixed flame propagation process in porous media through experiments and numerical simulations and found that in a porous media burner, the flame can reside in the first half of the burner and the exit region. Ciccarelli et al.\textsuperscript{9} studied the quenching performance of foam ceramics and obtained that the quenching effect of the granular filler was better than that of the ceramic foam under the same conditions. The effects of the thermal effect, flame extension, and precursor wave diffusion on quenching performance were analyzed. Cui et al.\textsuperscript{10} revealed the dual suppression effect of a multilayer network structure on the methane/air mixture explosion in a spherical container connected to the pipe. The suppression effect of dual meshes is analyzed with different layers and meshes and compared with that of monolayer meshes. The results show that the effect of explosion suppression mainly depends on the number of layers and grids. When enough layers are used, the number of layers plays a positive role in suppressing the explosion, while the number of grids also has a significant effect on suppressing the explosion. Later, Yan et al.\textsuperscript{11} studied the flame velocity reduction caused by a premixed gas explosion and attenuation explosion overpressure. The results show that aluminum silicate wool is a kind of fibrous porous material with a high specific surface area. Ciccarelli\textsuperscript{12} found that explosion in porous media transmission channels and obstacles of explosion propagation have many similarities. On the one hand, the obstacles through the early shear-driven turbulence generation mechanism and then through the lead impact shock wave reflection flame interaction enhanced the explosion propagation. On the other hand, the presence of obstacles can be through the heat and momentum loss to suppress explosion propagation, already hindered the flow of not flammable, and can extract energy from the expansion of the combustion products. Teodorczyk and Lee\textsuperscript{13} performed systematic photographic investigations of detonation interactions with foams and wire meshes along acoustic absorbing walls, giving evidence that the use of appropriate, acoustically absorbing materials to line the channel walls can effectively attenuate a fully established detonation wave. At the same time, the porous ferric foam-nickel metal has a certain absorption capacity, which can strongly resist the shock wave, and the attenuation effect of the gas explosion shock wave is obvious, with attenuation rates between 12.9 and 73.8%. Wen et al.\textsuperscript{15,14} also supported this viewpoint. They studied the propagation, quenching, and overpressure characteristics of gas deflagration flame when it encounters porous media. The results show that the porous media have an inhibitory effect on the downstream overpressure. The more obstacles there are, the more obvious the multifield coupling effect is, and the less easily the flame is quenched in the porous media. The quenching failure mechanism is related to the flame propagation velocity and the increase of overpressure. The thickness of porous media also has a great influence on quenching and antidetonation performance. In other words, the higher the hole density or thickness of porous media is, the better the quenching performance will be, but the greater the pressure drop through the porous media will be.

Although many studies have qualitatively revealed the mechanism of foamed polymetallic foams inhibiting flame, more information is needed to establish a quantitative theory to explore the characteristics of biomass-derived gas combustion. Therefore, more premixed flame combustion data are needed to be obtained for full consideration. In addition, studies on flame propagation and pressure dynamics of biomass-derived gas explosion under different conditions are still lacking. To solve the problem of the safety of the combustion of angry matter gas, the flame characteristics of the graduate biomass-derived gas/air mixture under a wide range of mixture components are of vital importance.

We systematically studied the flame characteristics of biomass-derived gas/air mixtures by several tests in a transparent half-open rectangular duct. The structure and velocity of the biomass-derived gas explosion flame are obtained using a high-speed camera. At the same time, the pressure dynamic characteristics of the system are obtained through the pressure sensor. We change the combustion characteristics of biomass-derived gas/air mixtures that have been studied in detail. This work can provide much more knowledge about premixed flame dynamics and contribute to safe industrial designs.

2. RESULTS AND DISCUSSION

To understand the influence of different factors on the combustion characteristics of flame, Table 1 shows the experimental results.

2.1. Effect of Fuel Composition Variation on the Flame Quenching Mechanism.

| Porous Media Characteristics | Case | Fuel Mixture | Pore Density (PPI) | Pore Porosity (%) | Behavior | Overpressure Peak (mbar) |
|------------------------------|------|--------------|-------------------|-------------------|----------|------------------------|
| 1                            | F1   | Methane/air  | 20                | 85                | Quenched | 121.9                  |
| 2                            | F2   | Methane/air  | 20                | 85                | Quenched | 127.8                  |
| 3                            | F3   | Methane/air  | 20                | 85                | Quenched | 99.9                   |
| 4                            | F1   | Methane/air  | 20                | 87                | Not quenched | 115.3        |
| 5                            | F1   | Methane/air  | 20                | 90                | Not quenched | 102.8        |
| 6                            | F1   | Methane/air  | 10                | 85                | Not quenched | 138.6        |
| 7                            | F1   | Methane/air  | 30                | 85                | Quenched | 152.8                  |
| 8                            | F1   | Methane/air  | 30                | 85                | Quenched | 141.3                  |
structure, flame speed, and explosion pressure are the most important parameters that determine the severity of a gas explosion. In this stage study, our main goal is to understand the exact mechanism of premixed flame propagation of biomass-derived gas/air mixtures in a half-open duct when a deflagration occurs.

Figure 1 illustrates the high-speed photographs of premixed flame propagation for biomass-derived gas in the combustion channels with porous meshes. Figure 1a–d shows the flame propagation structures of premix deflagration of biomass with different hydrogen components over time. The measurements were obtained in the empty channel, where no porous media exist, to investigate the suppressing performance. We can find that the flame shape changes experience similar development both in the empty channel and in the channels with porous meshes from Figure 1.

Here, we take the flame propagation in the chamber as a representative example to illustrate the flame shape changes in Figure 1a. The typical flame structural evolution stage in a half-open duct is proposed by Clanet and Searby. The flame propagation in Figure 1a can be divided into five typical stages, drawn on the geometrical model: (1) hemispherical flame, it starts after ignition and the flame expands hemispherically in all directions, unaffected by the channel sidewalls; (2) finger-shaped flame, the flame front does not come into contact with the sidewalls, and its surface area expands with an exponential increase. Subsequently, the flame lateral sides move close to the channel sidewalls; (3) flat flame, the flame surface area decreases to a minimum value; (4) tulip flame, the flame front travels with a cusp going backward to the burnt gas after the inversion of the flame front, whereafter a tulip shape is formed; (5) deformed flame, at this stage, the tulip flame is deformed. The upper part of the flame travels faster than the lower part, forming a very long trip. In Figure 1b,c, after the upper end of the flame reached the surface of the porous media, the lower end of the flame still develops laterally but did not pass through the porous medium and eventually the flame was quenched. That is to say, the flame was quenched in the porous media.

From Figure 1, we can see that before the flame passes through the metal foam mesh, the tulip flame has been completely deformed, and the upper part of the flame first passes through the metal foam mesh, and the flame is absorbed and reflected inside the porous metal foam. The flame fluctuates after passing through the foamed metal mesh, increasing the instability of flame propagation. As for Figure 1b,c, we can clearly see that the flame has an obvious tulip shape when it reaches the porous metal foam. As it passes through the foamed metal mesh, due to the obstruction, small turbulence is formed in front of it, and the flame undulates more violently. Therefore, the overall time of flame propagation is shortened. The acceleration of the flame propagation behind the obstacle is caused by the turbulent
diffusion and the thermal diffusion of flame following the breakdown of the eddy and flame fronts.20

In ANSYS Chemkin-Pro, the GRI 3.0 one-dimensional freely propagating laminar flame model with the PREMIX module is used to calculate the laminar combustion velocity of the biomass gas mixture. Using the EQUIL program to obtain the adiabatic temperature of the biomass gas, the results are shown in Figure 2. We all know that adding methane to biomass-derived gas with a higher hydrogen volume fraction will reduce the laminar combustion rate of biomass-derived gas. As shown in Figure 1, the delay time of flame rises to decrease nonlinearly with the decrease of H2 fraction in the fuel mixture. For the decrease of H2 fraction cases, it is seen from Figure 2 that the adiabatic flame temperature slightly increases with increasing CO2 concentration in the fuel mixture20 and even higher than that of the H2 with 15% conditions. The increase in flame temperature, in principle, should have a positive effect on the flame burning velocity. However, it can be seen that the laminar flame velocity at H2 15% (23.11 cm/s) and 10% (19.42 cm/s) decreased, while the laminar flame velocity decreased to 17.73 cm/s when H2 concentration dropped to 5%. This indicates that the effect of H2 and CO2 concentration changes on the combustion characteristics of biosynthesis gas cannot be determined based on adiabatic flame temperature alone because the competition between the thermal effect and chemical effect contributes to this result.22,23 It is not difficult to find that the adiabatic flame temperature of the multicomponent fuel mixture does not seem to have a high-level combustion rate in principle. This observation is similar to that of Zhou et al. and Wu et al.22,23 Based on the rule that if the flame temperature is higher, the light wavelength is shorter, we can see that the flame color is blue or purple. As can be seen from Figure 1, the biomass-derived gas flame color is blue, and the combustion temperature of methane combustible gas is higher. When the hydrogen gas volume fraction is 15, 10, and 5%, the flame propagation times to reach the open end of the pipeline are 317, 204, and 269 ms, and the variations of the flame propagation time relative to the nonporous media (222 ms) are +95, −18, and +47 ms. This indicates that the existence of foamed metal has a certain inhibitory effect on the flame propagation velocity of biomass-derived gas premix gas laminar flow. As the hydrogen component decreases and the CH4 component increases, higher CO2 products are formed, making it easier to enhance flame instability. As a result, when the flame passes through the porous foam metal, the heat loss is too high, and the flame is quenched. According to the Williams quenching criterion:21 the rate of exothermic heat release from a chemical reaction in a region must be approximately equal to the rate of heat dissipation in that region due to equilibrium heat transfer. As the volume fraction of hydrogen gas decreases, the adiabatic temperature of the biomass mixture decreases, and as the biomass-derived gas passes through the porous medium, a large amount of heat is dissipated, the gas temperature decreases, the chemical reaction rate decreases, and the flame that meets the Williams quenching guidelines is extinguished. Based on Figure 3, compared with the 15%

Figure 2. t, Tad, and Sf of different hydrogen volume fractions.

condition, the 10% condition with similar explosion pressure peak pressure and time has a slightly higher leading effect, and mainly due to the limited effect of heat, the flame burns quickly and has a short residence time in the porous media, which quenches and fails. While for the H2 with 5% condition, the concentration of CH4 is too high, which makes the side effect of the chemical effect more obvious, thus reducing the explosion pressure and increasing the time of peak pressure.3 In these cases, the addition of methane increases the rate of combustion of methane or natural gas in the mixture, not the overall rate of combustion of biomass-derived gas. The addition of hydrogen to biomass-derived gas can improve the combustion characteristics of biomass-derived gas. However, in one respect, the increase of CH4 concentration will change the flame propagation speed22,23. The key to suppressing the continued development of the flame is the complete quenching of combustible gases in porous media.

Figure 3. Flame overpressure dynamics with different hydrogen volume fractions: φ = 0; φ = 15%; φ = 10%; φ = 5%.
metal foam mesh, and due to the disturbance obstructions, flame propagation speed increases rapidly and the overpressure rises directly to form the second peak pressure. The flame continued to propagate under four conditions with maximum overpressures of 141.3, 121.9, 127.8, and 99.9 mbar. When the flame propagates to the outlet of the pipeline, the gas in the pipeline rapidly decompressed and causes the explosion of pressure to drop rapidly. For the case of 10 and 5% volume of hydrogen, due to the good quenching to suppress the effect of the explosion, the downstream region of the porous medium reaction rate decreases and the pressure drop is faster, avoiding the generation of pressure oscillation. We can see that the pressure of the hydrogen component at 15% is lower than that at 10%. This is because as the hydrogen component in the mixed gas decreases, the methane component in the mixed gas increases, which makes the overall combustion speed of the mixed gas faster. The flame is affected by the porous foam metal during the propagation process, which leads to a faster pressure growth rate. Under the coupling effect of speed and obstacles, the pressure of 10% hydrogen concentration exceeds that of the 15% hydrogen concentration. In summary, combined with the previous analysis of the flame propagation structure in Figure 1 and the explosion overpressure in Figure 3, the hydrogen gas fraction has a great influence on the growth of overpressure and the development of the flame structure, which will affect the explosion suppression effect of porous foam metal.

2.2. Effect of Pore Density Variation on the Flame Quenching Mechanism. Figure 4 gives the pressure–time curves of the CO/H₂ mixture with CO₂/N₂ dilution at different pore densities. The porous medium has a high specific surface area, and its solid skeleton can quickly absorb the heat carried by the flame into the narrow channel, reducing its temperature rapidly until the flame is quenched. The explosion suppression capability and resistance coefficient of the porous medium are of great help in quenching explosive flames. When the pore density (the larger the pore density, the smaller the pore diameter) is large enough, the flame will be quenched. Figure 4 demonstrates that the deflagration flames are not quenched through the porous medium at hole densities of 10 and 20 PPI. However, the flame was quenched successfully when the density of the porous medium increased to 30 PPI. These experiments display that under the condition of the same porosity of porous media, the larger the pore density is, the smaller the pore diameter is, and the larger the specific surface area of the solid skeleton is, which increases the convective heat transfer coefficient between the gas-solid phases so that when the pore density is large enough, the flame can be quenched by the porous media.

In the early stage of the biomass-derived gas explosion, the pore density of the porous medium has little effect on the explosion overpressure. The transient change of the explosion overpressure is consistent. At about t = 100 ms, the overpressure reaches the peak pressure. The coupling effect caused the PVC film on the right end of the cavity to rupture. After this, the venting rate of the pipeline becomes larger, which causes the explosion overpressure to drop. The combustion pressure of the gas increases slowly and reaches the second peak, and it is due to the coupling effect of the deflagration flame and turbulence. The specific surface area of the flame will become larger, causing the combustible gas-burning rate to increase. The presence of porous foam reduces the explosive overpressure, indicating that the porous medium has good energy absorption and noise reduction effect, which can inhibit the pressure wave of biomass-derived gas from continuing to propagate.

It can be seen from Figure 4 that the maximum explosion pressure decreases with the pore density changed and the timing for reaching the maximum explosion pressure increases with the pore density changed. We can get that the maximal pressure in the empty duct is 140.4 mbar, while the counterparts are 138.6 mbar in the duct with 10 PPI metal foam meshes, 121.9 mbar with 20 PPI, and 152.8 mbar with 30 PPI.

In this part, in order to explore the accuracy of the experimental data and ensure the feasibility of the study, the repeatability of the experimental data is verified. Figure 5 shows the development of the flame front position under different hole densities. Error bars indicate the standard deviation of the flame front position recorded in repeated experiments. It is obvious that there is consistency, so the experimental data is more reliable.

We can see that from Figure 5, the flame was quenched when the hole density was 30 PPI. However, the large pore density results in high fluid resistance, making the upstream
overpressure too high. It can also be seen from the figure that increasing the pore density will lead to a big difference between the peak overpressure and the peak time. The peak value at 30 PPI is 99 ms, while the peak value at 20 PPI is 77 ms, and the peak value at 10 PPI is 48 ms. It is mainly due to the increase in the density of porous media and the increase of the gas flow resistance, so the peak value of overpressure will be higher. The higher flow resistance will reduce the flame propagation speed, which will delay the multiphase coupling process of flame and make the peak time come later.

As mentioned earlier, biomass-derived gas is composed of a variety of components, including a considerable part of diluents (N₂ and CO₂). In some practical applications, these dilution gases are deliberately introduced to the unburned mixtures to reduce the NOx emission. Therefore, we must investigate the explosion characteristics of biomass-derived gas/air mixtures with N₂/CO₂ dilution. Due to the dilution effect of N₂ and CO₂, the laminar combustion speed of the biomass-derived gas is low and prolongs the propagation time in the pipeline. A portion of the energy has been lost before passing through the metal foam mesh. Then the premixed flame encounters the porous media during the forward propagation process. By the reason of the interaction of the flame and the porous medium, the porous medium acts as an obstacle, which will accelerate the propagation of the flame and distort the flame structure. The generation of turbulence will lead to higher flame velocity and overpressure, which cause the operation of quenching in porous media to fail.

According to previous research, each experiment has a minimum overpressure value. If the overpressure is lowered during propagation, the flame will stop propagating forward and be extinguished. However, the overpressure enhancement caused by the presence of the metal foam mesh according to Figure 5 facilitates the flame to propagate in the porous medium and may cause the flame to escape from the porous medium flame arrester and cause quenching failure.

2.3. Effect of Porosity Variation on the Flame Quenching Mechanism. The gas is F1: CO (20%); H₂ (15%); CH₄ (0%); CO₂ (15%); N₂ (50%). The condition we changed in this set of experiments was the porosity of the metal foam mesh with pore densities, which is 20 PPI. The flame combustion structure is shown in Figure 6.

The foam metal mesh is studied under the conditions of a pore density of 20 PPI, porous metal foam porosities of 85, 87, and 90%, and flame propagation times of 317, 309, and 200 ms, respectively, and the flame overpressure dynamics were 121.9, 115.6, and 102.8 mbar, respectively, and the pressure and pressure peak value are almost the same change trend. You can see that the porosity of porous foam metal has an effect on the explosion overpressure peak and flame propagation at the same time. It can be seen that the size of porosity affects the decaying capacity of porous foams. With the same pore size, materials with greater porosity are crisscrossed by internal channels. The absorbed precursor shock wave and explosion shock wave will pass through the porous metal foam, forming turbulence to promote flame propagation.

Figure 6. Flame propagation images of metal foam mesh with different porosities: (a) 85%; (b) 87%; (c) 90%; (d) empty duct.
Under the conditions of 85, 87, and 90% porosity, the development morphology of the flame in each stage is similar, but the flame propagation speed is affected, and the flame shape evolution and quenching process are more complex. As can be seen from Figure 6, when the void ratio is 90%, the flame propagation time in the pipeline is 200 ms, which is shorter than that in the empty pipeline. When the flame reaches the porous foamed metal, the flame surface is affected by the entrainment of the flow field, the flame is stretched and curled, the frontal surface is folded, local turbulence occurs, the flame surface area increases, and the propagation speed becomes faster. This indicates that turbulence excitation greatly increases the combustion speed, resulting in higher turbulence intensity, and a positive feedback effect is formed between the deflagration flame and turbulence.\(^{30}\) The more intense the coupling effect of flame turbulence overpressure is, the failure of flame quenching will occur. Based on Babkin et al.’s study\(^6\) that flame propagation speed is related to deflagration overpressure, their results suggested that higher overpressure reduces the laminar combustion speed of deflagration flame. However, the increase of overpressure makes the flame propagation speed become faster, resulting in the flame staying time in the porous medium to further shorten, and the temperature cannot be reduced. As a result, the flame is easy to pass through the porous medium, resulting in the flame quenching failure.

In this case, the porous media play double roles. Figure 6 shows that when the porosity is 90%, the forward position of the flame suddenly inverts after the propagation of the porous foam metal, exceeding the empty duct, and further flow reduces the propagation time of the flame and increases the velocity. However, when the porosity is 85 or 87%, extinguish is more evident. From this phenomenon, the flow obstruction within the porous media can promote explosion escalation in the duct, and the porous foam metal strengthens explosion propagation through an early shear-driven turbulence production mechanism and then later by shock—flame interactions that occur from lead shock reflections.\(^{30}\) What is more, the presence of the porous metal foam can suppress explosion propagation through momentum and heat losses, which not only impede the unburned gas flow but also extract energy from the expanding combustion products.

As can be seen from Figure 7, with the increase of porosity, the upstream pressure value of the porous foam metal rises, and the time to reach the peak is slightly delayed. Compared with the maximum peak value of the empty pipe, the porous foamed metal has a good ability to attenuate the overpressure when the flame quenching fails. It can be seen that the size of porosity affects the depressurization capacity of porous metal foam. At the same pore density, the turbulence effect of the material with higher porosity is enhanced and some of the absorbed precursor and explosion shock waves may pass through the porous foam metal. The flame quenching fails, and the inhibition effect is weakened.

According to the flame pressure diagram, the flame quenching fails. At this point, the porous foam metal acts as an obstacle. When the flame passes through the porous foam metal, due to the enhanced turbulence, the flame propagation speed is accelerated and the pressure rises abruptly. Due to the unburned flammable gases in the pipe, the resulting large-scale vortex causes the periodic oscillation of the pressure curve due to the periodic recoil of air to fully burn.\(^{31}\)

It is known from previous studies that the change in flame shape is the result of pressure changes coupled with velocity. According to Figure 7, we get that the flame follows closely the propagation of the pressure wave, so the pressure wave causes the pressure field to change, which greatly affects the flame structure and propagation. When biomass-derived gas explosion flame spreads from left to right up to the metal foam mesh before, the emptier bubble on the path of metal foam mesh in the flame propagation and density is relatively large. Therefore, the compression effect of the foam metal mesh on the flame front makes the flame front wrinkle, curl, and stretch after passing through the foam metal. Due to the increase of the flame front surface area, the contact area with unburned gas increases, which makes the chemical reaction speed and heat release rate inside the flame larger. When the flame passes through the mesh, the flame front is wrinkled, curled, and stretched similarly to the pressure wave-front under the action of the long and foam metal mesh. The flame front is stretched to form a wave or jagged shape. As the surface area of the flame front grows, the contact surface with the unburned premixed gas rises; the chemical reaction tends to be intense, the heat release rate enhances, and the explosion intensity also increases. Meanwhile, the turbulence intensity inside the flame increases.

3. EXPERIMENTAL APPARATUS AND PROCEDURES

The experimental setup is schematically shown in Figure 8. The system consists of a combustion chamber, a gas distribution system, an ignition system, and a data acquisition system. A high-transparency rectangular plexiglass duct with an inner cross section of 100 mm $\times$ 100 mm is employed as the combustion chamber. The length of the duct is 1000 mm. The left of the duct is closed with stainless half-open steel plates, in which the end of the vent is closed by the PVC membrane.\(^{28}\) Moreover, it breaks up easily for safety’s sake. There is a porous foamed metal with a thickness of 50 mm, about 680 mm from the left end of the pipe. A biomass-derived gas/air mixture enters the pipe through the inlet of the steel plate on the left, and it can be discharged through a valve near the rear of the plexiglass pipe. The premixed gas flow rate is about 2.56 L/min for 10 min, and a total of 25.6 L of mixture gas is supplied, which is more than 4 times the volume of the tube, then the desired mixture is ready.\(^{32}\) This step is necessary to clean the pipes and ensure...
that the mixture in the test unit is homogeneous. The flow was then stopped, and the mixture in the tube ignites after 15 s of rest. The ignition source is an electronic ignition device triggered by a 6 V regulated DC power located in the center of the left steel plate. The mixture is ignited by a pair of spark electrodes with a 2 mm gap perpendicular to the duct axis. The spark electrodes are located on the left stainless-steel plate at the center of the cross section.32

For collecting the dynamic pressure details in the duct, the pressure is measured by an MD-HF piezoelectric gauge pressure transducer from Shanghai Mingkong Sensor Technology Co., Ltd. The pressure transducer with a measurement range of −1.5 to 1.5 bar locates the left stainless plate 20 mm away from the spark electrode. Besides, a Phantom M310 high-speed camera is used to record the flame shape. The data acquisition frequency of the pressure transducer and the photodiode sensor is 15 kHz. They were placed in the center of the sealed steel plate.

The photelectric sensor will automatically trigger the DAQ and high-speed camera software when ignite and then save the test data after completion of data acquisition. The initial temperature and pressure for the experiments were approximately 300 K and 1.0 atm, respectively, and the chemical stoichiometric ratio (Φ) was 1. To ensure the accuracy and reproducibility of the results, each experiment was repeated at least four to five times.

To prove the repeatability of the experiment, four sets of repeatability experiments were conducted under the same working conditions. It can be seen from Figure 9 that the pressure curves of the four groups of experiments have the same trend. When the flame spreads to about 50 ms, the four sets of data have reached the peak pressure, 141.3, 140.2, 139.8, and 142.4 mbar, and the error is within 1%. The trend after the change is also consistent. The pressure of the four trials is very consistent. From this, we can be sure that the experiment is repeatable.

The gas used in the experiment was the biomass-derived gas. The biomass-derived gas component fraction \( X_i \) is defined as eq 1. Premixed biomass-derived gas/air mixtures (the equivalence ratio is equal to 1) with different hydrogen fractions were studied experimentally. The gas composition is shown in Table 2.

\[
X_i = \frac{x_i}{x_{\text{CO}} + x_{\text{H}_2} + x_{\text{CH}_4} + x_{\text{CO}_2} + x_{\text{N}_2}} \times 100
\]

From the viewpoint of explosion safety, the mechanism of combustion is explored by comparing experiments based on the flame structure, flame speed, and pressure. Biomass gasification under certain thermodynamic conditions, with the existence of air (or oxygen) and water vapor, includes the biomass high polymer pyrolysis, oxidation, and reduction reforming reaction to finally give a combustible gas consisting of carbon monoxide, hydrogen, and low-molecular hydrocarbons. The main gases produced include CO, H\(_2\), CH\(_4\), and so...
the following gases are used for research. The specific gas component is shown in Table 2, and each gas is 99.999% pure.

The ferronickel foam meshes used in the experiment are porous materials that can resist high temperatures up to 1500 °C. The pore densities of the foam meshes are 10, 20, and 30 (note: PPI, pores per inch, means the number of pores per inch; the larger PPI, the smaller pore diameter), with porosities of 85, 87, and 90%, (note: porosity is defined as the ratio of pore volume to total volume in porous media), and density of 0.8 g/cm³, as shown in Table 3 and Figure 10.

Table 3. Metal Foam Mesh Porous Media Parameters

| porosity (%) | pore density (PPI) |
|--------------|--------------------|
| 85           | 10                 |
| 85           | 20                 |
| 85           | 30                 |
| 87           | 20                 |
| 90           | 20                 |

Figure 10. Ferronickel foam metals.

4. CONCLUSIONS

The biomass-derived gas explosion suppression experiments were conducted with metal foam mesh in a half-open obstructed chamber. Key parameters of explosive characteristics, such as flame propagation images and explosive overpressure, were analyzed by changing the porosity (85, 87, 90%), the pore density of porous metal foams (10, 20, 30 PPI), and the gas component. Then we get some main conclusions summarized as follows:

(1) The experimental results show that the multicomponent fuel mixture does not seem to have a high combustion rate in principle. With the increase of CH₄, a higher CO₂ product will be formed, which makes it easier to promote flame instability, resulting in a flame with a low hydrogen content that is more easily quenched.

(2) Compared with pure methane gas, biomass-derived gas with different gas components has a higher calorific value when the burning flame appears blue. The combustion efficiency of biomass-derived gas can be improved by changing the proportion of hydrogen and oxygen. Due to the excessive inert gas added to biomass, the buoyancy will lead to the stability of flame combustion, which is of guiding significance for future experimental research.

(3) We found that the porous media had a slowing effect on flame propagation but increased upstream overpressure. For porous media with a pore density of 30 PPI, the better its quenching and quenching performance, the more explosive airflow through the porous media when the pressure drop is also greater. Besides, the increased flow resistance also reduces the flame propagation speed, causing the flame turbulence coupling process to be delayed, making the overpressure peak moment come later.

(4) The porosity of porous media plays a dual role in flame propagation. When the porosity is 85 or 87%, the flame energy is weakened when passing through the porous medium, showing a significant inhibitory effect. When the porosity is 90%, the explosion propagation is enhanced by the turbulent flow generation mechanism driven by early shear, and the flow obstruction within the porous media can promote the explosion escalation in the pipeline. One of the main conclusions of this paper is that the action of metal foam mesh on flame propagation is dual. In the future, a new simulation model of flame stretching and deformation in a half-open pipe with a large aspect ratio will be established to explore the role of metal foam mesh in flame propagation.

■ AUTHOR INFORMATION

Corresponding Author
Xiaoping Wen — School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo 454003, PR China; Phone: +138-4952-6279; Email: wenxiaoping666@163.com

Authors
Mengming Wang — School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo 454003, PR China; orcid.org/0000-0002-1064-9220
Sumei Zhang — School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo 454003, PR China
Fahui Wang — School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo 454003, PR China
QiFeng Zhu — School of Mechanical and Power Engineering, Henan Polytechnic University, Jiaozuo 454003, PR China
Rongkun Pan — College of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, PR China
Wentao Ji — College of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454003, PR China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.0c03055

Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We would like to acknowledge the financial support of the National Key Research and Development Program of China (2018YFC0808103) and the National Natural Science Foundation of China (Nos. 51774115, 51904094).

■ REFERENCES

(1) Pio, G.; Ricca, A.; Palma, V.; Salzano, E. Experimental and numerical evaluation of low-temperature combustion of bio-syngas. Int. J. Hydrogen Energy 2020, 45, 1084–1095.
(2) Demirbas, A. Combustion characteristics of different biomass fuels. Prog. Energy Combust. Sci. 2004, 30, 219–230.
(3) Zhou, Q.; Cheung, C. S.; Leung, C. W.; Li, X.; Huang, Z. Explosion characteristics of bio-syngas at various fuel compositions and dilutions in a confined vessel. Fuel 2020, 259, 116254.
(4) Panigrahi, S.; Dalai, A. K.; Chaudhari, S. T.; Bakhshi, N. N. Synthesis gas production from steam gasification of biomass-derived oil. Energy Fuels 2003, 17, 637–642.
(5) Chaudhari, S. T.; Bej, S. K.; Bakhshi, N. N.; Dalai, A. K. Steam gasification of biomass-derived char for the production of carbon monoxide-rich synthesis gas. Energy Fuels 2001, 15, 736–742.
(6) Babkin, V. S.; Korzhavin, A. A.; Buneev, V. A. Propagation of premixed gaseous explosion flames in porous media. Combust. Flame 1991, 87, 182–190.
(7) Gao, H.; Qu, Z.; Feng, X.; Tao, W. Combustion of methane/air mixtures in a two-layer porous burner: A comparison of alumina foams, beads, and honeycombs. Exp. Therm. Fluid Sci. 2014, 52, 215–220.
(8) Sathe, S. B.; Kulkarni, M. R.; Peck, R. E.; Tong, T. W. An experimental and theoretical study of porous radiant burner performance. Symp. (Int.) Combust. [Proc.] 1991, 23, 1011–1018.
(9) Ciccarelli, G.; Fowler, C. J.; Bardon, M. Effect of obstacle size and spacing on the initial stage of flame acceleration in a rough tube. Shock Waves 2005, 14, 161–166.
(10) Zhang, K.; Wang, Z.; Yan, C.; Cui, Y.; Dou, Z.; Jiang, J. Effect of size on methane-air mixture explosions and explosion suppression in spherical vessels connected with pipes. J. Loss Prev. Process Ind. 2017, 49, 785–790.
(11) Yan, X. Q.; Yu, J. L. Effect of aluminum silicate wool on the flame speed and explosion overpressure in a pipeline. Combust. Explos. Shock Waves 2013, 49, 153–158.
(12) Teodorcezyk, A.; Lee, J. H. S. Detonation attenuation by foams and wire meshes lining the walls. Shock Waves. 1995, 4, 225–236.
(13) Wen, X.; Xie, M.; Yu, M.; Li, G.; Ji, W. Porous media quenching behaviors of gas deflagration in the presence of obstacles. Exp. Therm. Fluid Sci. 2013, 50, 37–44.
(14) Wen, X.; Yu, M.; Liu, Z.; Li, G.; Ji, W.; Xie, M. Effects of crosswise obstacle position on methane–air deflagration characteristics. J. Loss Prev. Process Ind. 2013, 26, 1333–1340.
(15) Chen, P.; Huang, F.; Sun, Y.; Chen, X. Effects of metal foam meshes on premixed methane-air flame propagation in the closed duct. J. Loss Prev. Process Ind. 2017, 47, 22–28.
(16) Clanet, C.; Searby, G. On the “tulip flame” phenomenon. Combust. Flame 1996, 105, 225–238.
(17) Guo, J.; Peng, W.; Zhang, S.; Lei, J.; Jing, J.; Xiao, R.; Tang, S. Comprehensive Comparison of the Combustion Behavior for Low-Temperature Combustion of n-Nonane. ACS Omega 2020, 5, 4924–4936.
(18) Yan, S.; Tang, G.; Zhou, C. Q.; Guo, X. Computational Fluid Dynamics Modeling of Combustion Characteristics of a CH4/O2 Combustor in a Copper Anode Furnace. ACS Omega 2019, 4, 12449–12458.
(19) Oh, K.-H.; Kim, H.; Kim, J.-B.; Lee, S.-E. A study on the obstacle-induced variation of the gas expansion characteristics. J. Loss Prev. Process Ind. 2001, 14, 597–602.
(20) Watanabe, H.; Marumo, T.; Okazaki. K. Effect of CO2 Reactivity on NOx Formation and Reduction Mechanisms in O2/CO2 Combustion. Energy Fuels 2012, 26, 938–951.
(21) Williams, F. A. Spray Combustion Theory. Combust. Flame 1959, 3, 215–228.
(22) Wu, C.; Chao, Y.; Cheng, T.; Chen, C.; Ho, C. Effects of CO addition on the characteristics of laminar premixed CH4/air opposed-jet flames. Combust. Flame 2009, 156, 362–373.
(23) Zhou, Q.; Cheung, C. S.; Leung, C. W.; Li, X.; Li, X.; Huang, Z. Effects of fuel composition and initial pressure on laminar flame speed of H2/CO/CH4 bio-syngas. Fuel 2019, 238, 149–158.
(24) Ibrahim, S. S.; Masri, A. R. The effects of obstructions on overpressure resulting from premixed flame deflagration. J. Loss Prev. Process Ind. 2001, 14, 213–221.
(25) Jahangirian, S.; Engeda, A.; Wichman, I. S. Thermal and Chemical Structure of Biogas Counterflow Diffusion Flames. Energy Fuels 2009, 23, 5312–5321.
(26) Yang, X.; Yu, M.; Zheng, K.; Wan, S.; Wang, L. An experimental investigation into the behavior of premixed flames of hydrogen/carbon monoxide/air mixtures in a half-open duct. Fuel 2019, 237, 619–629.
(27) Zhang, Y.; Shen, W.; Zhang, H.; Wu, Y.; Lu, J. Effects of inert dilution on the propagation and extinction of lean premixed syngas/air flames. Fuel 2015, 157, 115–121.
(28) Yu, M.; Yang, X.; Zheng, K.; Zheng, L.; Wen, X. Experimental study of premixed syngas/air flame deflagration in a closed duct. Int. J. Hydrogen Energy 2018, 43, 13676–13686.
(29) Ciccarelli, G. Explosion propagation in inert porous media. Philos. Trans. R. Soc., A 2012, 370, 647–667.
(30) Yu, M.; Zheng, K.; Zheng, L.; Chu, T.; Guo, P. Scale effects on premixed flame propagation of hydrogen/methane deflagration. Int. J. Hydrogen Energy 2015, 40, 13121–13133.
(31) Wen, X.; Wang, M.; Su, T.; Zhang, S.; Pan, R.; Ji, W. Suppression effects of ultrathin water mist on hydrogen/methane mixture explosion in an obstructed chamber. Int. J. Hydrogen Energy 2019, 44, 32332–32342.
(32) Lv, X.; Zheng, L.; Zhang, Y.; Yu, M.; Su, Y. Combined effects of obstacle position and equivalence ratio on overpressure of premixed hydrogen–air explosion. Int. J. Hydrogen Energy 2016, 41, 17740–17749.