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Experimental Study on Gas Explosion Propagation in Porous Metal Materials

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Abstract: Serious damage and large losses often result from gas explosions in coal mining. However, porous metal materials can suppress a gas explosion and its propagation. Therefore, a gas explosion and its propagation suppression characteristics of porous metal materials are analyzed theoretically. According to the propagation characteristics of a gas explosion in duct, a gas-explosion experiment system with porous metal material (steel wire mesh) is constructed in this paper, and the propagations of explosion wave and flame in porous metal materials are experimentally studied. The study results show that the flame propagation velocity and overpressure of explosion wave are related to the length and layer number of porous metal materials. When the gas explosion propagates a certain distance in porous metal materials, the flame and explosion wave begin to be attenuated. The longer the length of porous metal material is, the better the attenuation effect is. At the same time, the more layer numbers, the better the attenuation effect is. In this experiment, the maximum decreases of explosion wave overpressure and flame propagation velocity are 84% and 91%, respectively. The attenuation of the explosion wave overpressure and the flame propagation velocity has synchronism and correspondence during gas explosion propagation in porous metal materials. The experimental results show the porous metal material has a good suppression effect on gas explosion propagation. The study results can provide an experimental basis for the development of gas explosion propagation suppression technology and devices, and have a great practical significance for the prevention and control of a gas explosion disaster.

Keywords: gas explosion; porous metal material; explosion wave; flame propagation velocity; attenuation

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1. Introduction

Gas explosion disasters are a major problem affecting coal mine safety production, so many scholars have carried out a lot of research on the prevention and control of gas explosions [1–3] and the corresponding research results were obtained [4–7]. The prevention and control of gas explosions is mainly reflected in two aspects: how to attenuate the explosion wave and extinguish the flame [8]. In 1815, Davy invented the Davy lamp (called firedamp or mine damp). Davy discovered that a flame enclosed inside mesh with certain fineness cannot ignite firedamp. The mesh screen acts as a flame arrestor; air can pass through the mesh freely enough to support combustion, but the holes can prevent a flame from propagating through them and ignite any gas outside the mesh [9]. Vasil'ev experimentally studied the near limit detonation of the porous tube wall. The concept of an inelastic collision between the shear wave and tube wall was introduced, and the reflection coefficient was used to explain this phenomenon [10]. Teodoreczyk et al. found that the porous materials can obviously attenuate the explosion wave intensity and the porous material installed on the tube wall can effectively suppress the detonation wave [11]. Fedorov et al. studied the effects of porous materials on explosion waves, and found that porous materials can substantially attenuate explosion waves [12]. Mehrjoo et al.

used the attenuation of the transverse wave on a porous wall to describe the influence of instability on the diffraction failure mechanism of a detonation wave [13]. Mazaheri et al. carried out the experiment and numerical simulation on porous material suppressing a gas explosion, and measured the influence of diffusion-turbulence mixing and transverse wave on the detonation suppression in the porous wall channel [14]. They found that the transverse wave's propagation velocity in the porous section can be decreased. Zhang et al. theoretically studied the explosion mechanism of different gases, discussed the applicability of existing explosion suppression measures, and analyzed the feasibility of applying porous materials in coal mine roadways [15]. They found that porous material is a very promising material; if it is used together with the water bag, the explosion can be reduced to the minimum. Nie et al. experimentally studied the porous material Al_2O_3. By using foam ceramic, the maximum pressure of a gas explosion can be attenuated by about 50%; the flame propagation velocity can be attenuated from 50 m/s in a smooth tube to 2.2 m/s in porous material [16]. Chen et al. measured the flame dynamics of stoichiometric methane/air mixtures under smooth duct and porous materials [17]. The results show that the maximum pressure rising rate is linear with the porous density. The metal foam with larger pore density has a great influence on the formation of a tulip-type flame. Foam metal mesh can reduce overpressure by 33.3–46.6%. Porous material is an effective fire-retardant material, which are commonly used for explosion suppression of fuel containers [18]. Ji found that porous materials can quench the explosion flame with low velocity and attenuate some explosion waves [19]. Wen et al. experimentally studied the quenching mechanism of gas deflagration in porous materials [20]. The results showed that the porous plate with a smaller pore diameter has better quenching performance. Wang et al. installed some porous materials on the inner wall of the experimental duct, and found that the porous materials have the effect of reducing pressure [21]. Bivol et al. performed the experimental study on the attenuation intensity of detonation wave in air by sound absorption surface [22]. Results showed that the attenuation of a detonation wave depends on the volume fraction of hydrogen in a gas mixture. The study also showed that increasing the thickness of porous materials can further reduce the detonation wave [23]. Sun and Zhao experimentally studied the effects of stainless steel wire mesh, foam ceramic, metal wire mesh and the foam ceramic combination on the gas explosion propagation [24]. The results showed that the combination of wire mesh and foam ceramic with certain parameters can restrain the energy propagation of the explosion wave and reduce the intensity of gas explosion. Yu et al. carried out an experimental study on a gas explosion and its propagation in multilayer screen mesh. The relationship between the geometric parameters of multilayer wire mesh and critical quenching rate (and critical quenching overpressure) was obtained [25]. Wang et al. experimentally studied the relationship between wire mesh and flame propagation [26]. The experimental formula between the parameters of wire mesh and the critical velocity of flame extinguishment was also obtained, which further verified the effect of wire mesh on the explosion. Duan experimentally studied the effect of porous materials on the explosion characteristics of premixed gas, the results showed that porous materials with different porosities can either promote or suppress the flame and overpressure [27]. Han et al. numerically simulated the flame extinguishment and explosion wave attenuation by porous metal material, and obtained the quenching effect of porous metal material on a gas explosion [28]. Cui et al. found that the explosion suppression effect primarily depends on both the number of layers and number of meshes [29]. Jin et al. found that flame quenches in the cases of adding wire mesh of 60, 80, and 100 meshes with 45 and 50 layers, while for the wire mesh of 40 meshes, 50 layers cannot even quench the flame [30]. Jia et al. used FLUENT software to simulate the propagation of gas explosion in porous metal materials [31]. The simulation results showed that the flame propagation velocity and the overpressure of explosion wave are related to the length and layer numbers of porous metal materials. Wei et al. experimentally studied the attenuation effect of porous materials with different parameters on flame temperature of a gas explosion in a duct. The results showed that the wire mesh has a good effect on attenuating the flame temperature of a gas explosion. The maximum attenuation rate of a flame temperature of a gas explosion in wire mesh is 8.7–26.9%. They also found that the thickness, pore size and relative density of porous materials are important factors affecting the attenuation effect of the flame temperature [32]. Peng et al. performed the numerical simulation on gas explosion propagation in a confined space [33]. The relationship of the length-velocity and length-overpressure was obtained when the thickness of porous media was constant.

From the above analyses, it can be concluded that porous metal material has a suppression effect on a gas explosion and its propagation, but the influence laws of the parameters of porous metal material on the explosion suppression effect need to be studied further; in particular, the suppression effect of multi-layer porous metal materials installed in the duct along the axial direction. In view of the shortcomings of the existing research, according to the characteristics of gas explosion propagation, an experimental system of porous metal materials is constructed to suppress a gas explosion, and the suppression effect of porous metal materials with different layers on gas explosion propagation is experimentally studied. Study results cannot only further explain the essence of gas explosion and its propagation, but also reduce the intensity of gas explosion accidents. In addition, it will also play a positive role in enriching and perfecting the theory of a gas explosion. The outcomes can also be extended to other industries such as explosion suppression, explosion proof, explosion extinguishment and other safety fields, so it has a high academic value and wide application prospects.

2. Attenuation Theory of Gas Explosion by Porous Metal Material

At present, the gas explosion mechanism includes thermal explosion theory and chain reaction theory [30,32]. According to the thermal explosion theory, when the heat accumulates to a certain extent, the temperature rises, resulting in combustion and explosion. According to the chain reaction theory, the self-ignition condition of gas is that the number of branches of the chain reaction exceeds the number of interruptions. At this time, even if the temperature of the mixture remains unchanged, it can still lead to self-ignition. Therefore, there are two theories to explain that porous metal materials can quench a flame [7,12,34,35]. One is the thermal theory, and the other is the chain reaction theory. The thermal theory is based on the thermal transfer theory. Based on the thermal theory, as long as the flame temperature is reduced below its quenching temperature, the flame propagation can be prevented. When the flame enters the small pores of the porous metal material, it will be subdivided into several smaller flames. Thus, the flame temperature can rapidly drop below its quenching temperature and combustion is stopped, which restrains the flame propagation. The chain reaction theory is based on the theory of the vessel wall effect. The chain reaction generally includes the following four steps: chain initiation, chain propagation branching chain reaction, chain termination. In the four steps of chain reaction, chain initiation must be excited by external energy; once the chain starts, the next steps are very easy to carry out. When the flame enters the pores of the porous metal material, the collision probability between the free radicals and porous metal material increases, the number of free radicals destroyed by the collision with the porous metal material increases, so the number of free radicals participating in the reaction decreases. When the thickness and length of the porous metal material reach a certain degree, the collision between free radicals and the porous metal material is dominant, the number of free radicals decreases sharply, the reaction cannot continue and the flame quenches, which prevents the propagation and spread of the flame, thus it can attenuate the propagation of the gas explosion.

On the other hand, the propagation of explosion waves in porous materials produces reflection, diffraction and other effects, so that the explosion waves cancel each other out and wave attenuation is caused [11,12]. When the explosion waves enter the porous metal material, a part of the explosion waves and gases enter the inner layer, and the other parts are reflected by the surface of the porous metal material. Once the explosion waves enter the pores, they will make an oscillating reflection, and enter the inner layer and interact with the surface of the porous metal material in the middle layer. Therefore, the porous metal material significantly changes the boundary conditions of promoting the propagation of the gas explosion wave. As a large amount of gases with high temperature and high pressure enter the pores, the heat is absorbed, and part of the explosion waves entering the pores are absorbed; namely, porous metal materials play a role in reducing energy and wave attenuation for the gas explosion propagation. Therefore, when an explosion wave propagates in porous metal materials, its attenuation is inevitable. The collision between an explosion wave and porous metal material produces various forms of waves, which includes reflected wave and transmitted wave. When the transmitted wave enters the deeper layer and finally reaches the duct wall, the reflected wave is also generated at the end, which results in the multiple reflection process. Because multiple reflections are generated in the porous metal material during the propagation of a gas explosion, the intensity of the reflected wave is determined by the gas velocity behind the explosion wave; however, the gas velocity is determined by the gas on the solid surface and whether the gas enters the porous metal material, so the porous metal material needs a certain time to attenuate an explosion wave, which results in the incident explosion wave pressure generated in the porous metal material after the reflection from the surface of the porous metal material does not increase suddenly, but keeps increasing continuously. Moreover, in the process of the pressure drop, it is not a sudden drop, but a continuous drop. Because of the repeated movement of the explosion wave, the explosion wave propagation in the porous metal material has a delay.

At the same time, in the process of gas explosion propagation in the duct, due to the large temperature difference between the high temperature combustion products and the duct wall, part of the heat in the explosion heat release is absorbed by porous metal materials, which correspondingly reduces the heat transferring to the unreacted gas mixture by means of heat conduction, diffusion and radiation, and thus affects the flame combustion velocity and weakens the gas explosion intensity. Therefore, the attenuation effect of porous metal materials on a gas explosion is mainly reflected in three aspects: energy reduction, explosion wave attenuation and chain interruption.

3. Materials and Methods

3.1. Experimental System

The experimental system of porous metal material suppressing a gas explosion and its propagation is shown in Figure 1. The experimental equipment in this study consists of nine parts: gas-explosion experiment duct, vacuum instrumentation, gas-explosion ignition system, pumping system, gas-valve system, gas-explosion-pressure measurement system, flame-propagation-velocity measurement system, dynamic value- acquisition and analysis system, porous metal material. As a mature experiment system, it is similar to the reference [2,6]; only the porous metal materials are designed and installed on the inner wall of a duct to construct the porous metal material suppression system in this experiment.

The original experimental duct is a straight duct with a diameter of 80 mm and length of 5 m; in order to install porous metal material in the duct, a circular duct with a diameter of 300 mm is added in the middle of the duct, and both ends are connected by a variable diameter duct, which is shown in Figure 2. The length of the duct with a diameter of 80 mm is 4.5 m in the ignition section, length of the circular duct with a diameter of 300 mm is 3 m and length of the duct with the diameter of 80 mm is 0.5 m in the end section. A spiral accelerating ring is installed at the ignition section. According to the experimental requirements, the porous metal materials with different layers are installed in the duct with a diameter of 300 mm, as shown in Figure 2. Eight pairs of flame transducers are arranged at each point of the duct to measure the flame propagation velocity of a gas explosion under different working conditions; when the experiment is over, the flame transducers are removed and 6 pressure transducers are installed to measure the overpressure value of the explosion wave under different working conditions.

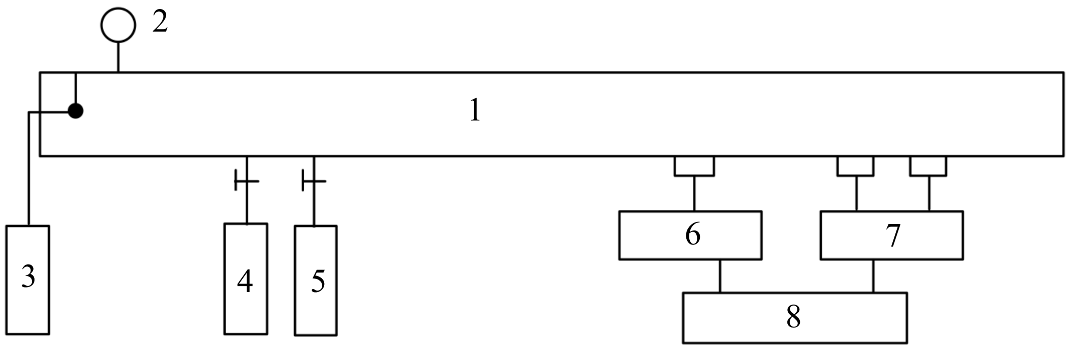

Figure 1. Diagram of experimental system of gas explosion. Note: 1. Gas-explosion experiment duct (chamber), 2. Vacuum instrumentation, 3. Gas-explosion ignition device, 4. Pumping system, 5. Gas-distribution system, 6. Gas-explosion pressure measurement system, 7. Flame-propagation velocity measurement system, 8. Dynamic value-acquisition and analysis system.

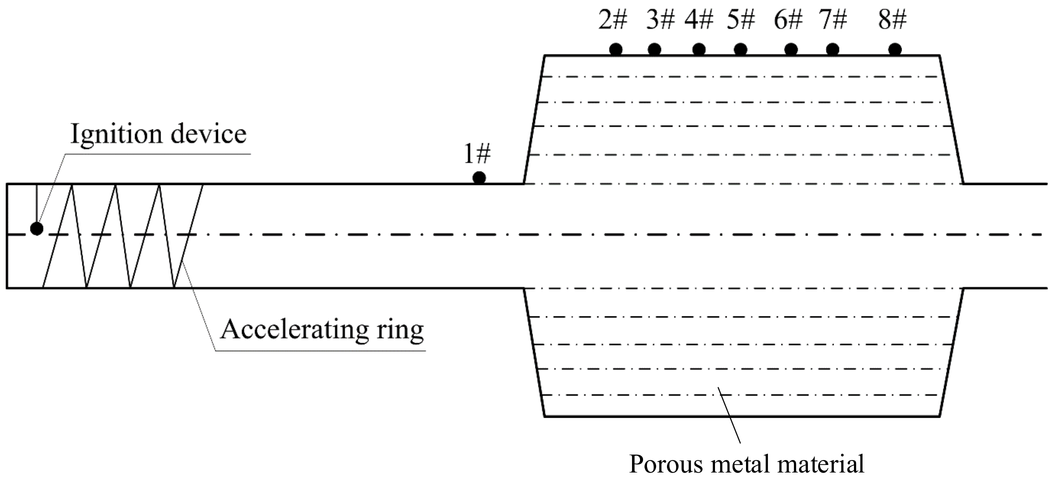

Figure 2. Schematic diagram of measuring points of flame transducers. Note: 1–8, Serial number of transducer and their point.

3.2. Experimental Scheme

(1) Selection of porous materials

Based on the research results of the propagation characteristics of a gas explosion in duct [2,6], the experimental studies on gas explosion propagation in porous materials are carried out. Taking into account the characteristics of a gas explosion, such as high strength, instantaneous high temperature, intense vibration and other characteristics; in addition, porous materials with good thermal conductivity and seismic resistance are required; therefore, steel wire mesh (porous metal mesh, for convenience, later referred to as porous metal materials) is chosen as porous metal material to perform a suppression experiment on gas explosion propagation.

(2) Experimental parameters

According to the analysis result of the mass settlement effect [26], the interlayer spacing is 30–50 mm. The diameter of the duct before changing diameter is 80 mm, and the diameter of the section with porous metal materials is 300 mm. Taking into account the specific experimental conditions and convenient operation, porous metal material with different composite layers (1–5 composite layers) is designed in duct with a diameter of 300 mm; each composite layer (shorted for layer in the following text) can be disassembled and tested separately; the diameters of each layer are 110 mm, 160 mm, 200 mm, 240 mm and 270 mm, respectively. According to the porosity analysis results shown in reference [26], along the radial direction, porosity should be from large to small. Therefore, the porosity of each layer of the porous metal material is 6, 10, 15, 20 and 40 meshes, respectively. The length of porous metal material is 3 m. Taking into account the operability, repeatability and effectiveness of the experiment, the gas explosion propagation is suppressed only in the section after 4.5 m, namely, when the gas explosion develops to a considerable explosion intensity, it begins to be suppressed. As the main component of mine gas is CH_4, CH_4 is elected as an explosion gas in this paper to perform the experimental study. The concentration of experimental gas (CH_4) is 10% in this experiment, which is prepared by the valve system and is evenly distributed. The initial temperature T_0 is 25 °C and the initial pressure P_0 is 1 atm. There is only a heat source of a gas explosion in the roadway.

(3) Experimental steps

First, the duct is cleaned. Second, the duct is vacuumed by vacuum instrumentation and then filled with gas of 10% CH_4. Third, the end closure cover is opened. Fourth, the gas-explosion ignition device is activated. Fifth, the explosion formation, dynamic value-acquisition and analysis system automatically obtain data through sensors.

4. Result Analyses and Discussion

The experiment of gas explosion propagation suppressed by porous metal materials with different layers is carried out, and the propagation law of a gas explosion (flame and explosion wave) in different layers and smooth ducts is compared. The statistical values of measured results of flame propagation velocity of the gas explosion in duct with porous metal materials of 5 layers, 4 layers, 3 layers, 2 layers and 1 layer are shown in Table 1. The statistical values of measured results of explosion wave overpressure in duct with porous metal materials of 5 layers, 4 layers, 3 layers, 2 layers and 1 layer are shown in Table 2. The values of each experimental point in Tables 1 and 2 are the arithmetic mean of many experimental data.

Table 1. Flame propagation velocity in porous metal materials (m/s).

Serial Number		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Measuring point position (m)		4.3	5.2	5.4	5.6	5.8	6.1	6.3	7.2
Layer number	0	297.5	485.4	521.7	560.4	605.8	674.5	725.7	893.6
	1	296.1	485.3	485.6	489.3	495.7	512.3	535.9	554.2
	2	296.1	483.3	471.2	452.6	415.2	386.3	371.8	300.5
	3	296.1	483.3	463.6	392.6	361.2	275.9	239.1	70.5
	4	296.1	480.3	451.1	385.9	352.9	266.2	234.8	61.8
	5	295.8	479.1	449.6	383.1	351.7	264.2	230.9	49.1

Table 2. Explosion wave overpressure in porous metal materials (atm).

Serial Number		**1**	**2**	**3**	**4**	**5**	**6**
Measuring point position (m)		4.3	5.2	5.4	5.6	6.1	7.2
Layer number	0	0.86	1.84	2.08	2.36	3.05	4.76
	1	0.87	1.84	1.97	2.09	2.41	3.09
	2	0.87	1.81	1.82	1.75	1.36	0.92
	3	0.87	1.79	1.69	1.55	1.26	0.43
	4	0.87	1.77	1.62	1.49	1.08	0.35
	5	0.87	1.71	1.52	1.36	0.98	0.28

4.1. Influence of Porous Metal Materials on Flame Propagation Velocity

The influence of porous metal material on flame propagation velocity is shown in Table 1 and Figure 3. The curve of the flame propagation velocity of a gas explosion at different measuring points in Figure 3 is obtained according to data in Table 1. From Table 1 or Figure 3, it can be seen that the suppression effect of flame propagation of the gas explosion in duct is affected by the layer number and length of the porous metal material. There is a minimum attenuation distance for porous metal materials. The flame propagation velocity can be effectively reduced only when it exceeds the minimum attenuation distance. The minimum attenuation distance is about 5–6 times of the duct diameter. Moreover, the minimum attenuation distance increases with the decrease of the layer number. The layer number not only affects the minimum attenuation distance, at the same time, it also has a great influence on the decreasing range of flame propagation velocity. The more the layers, the larger the reduction is, and even the quenching phenomenon of the flame happens. When the layer number of porous metal material is 1, 2, 3, 4, 5, respectively, the decreasing range of flame propagation velocity is about 14%, 38%, 86%, 88% and 91%, respectively. In the same experimental condition, there is the least layer number. In this experiment, only when the layer number is greater than or equal to 3, can the flame be effectively suppressed.

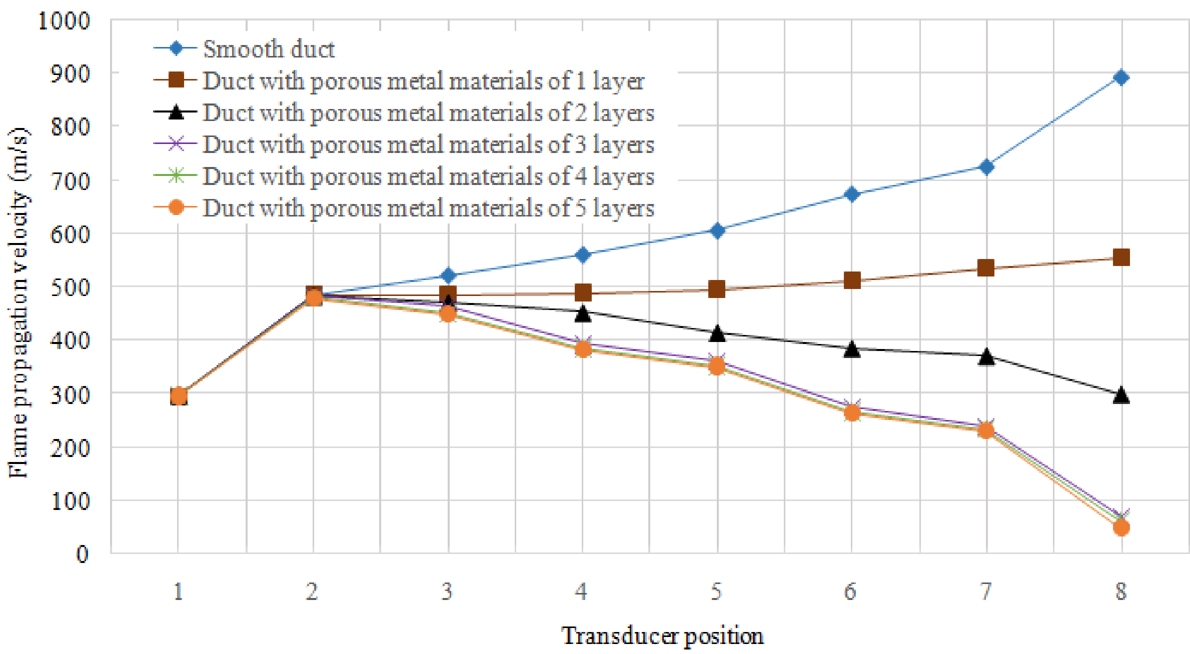

Figure 3. Flame propagation velocity in porous metal materials with different layers.

There are two main reasons of reducing flame propagation velocity by installing porous metal materials in duct. One is that the porous metal material occupies a part of the spaces in duct and reduces the flow space. With the increase of the layer number of porous metal materials, the flow resistance of gas increases. As a result, the flowing flame is blocked at the porous metal materials, and then the flame propagation velocity slows down. In addition, the attenuation effect of porous metal material on the flame is also the main cause leading to the decrease of flame propagation velocity.

From Figure 3, it can be seen that the suppression effect of the layer number of porous metal materials on flame propagation velocity is same as the suppression effect of the length on flame propagation velocity; there is a minimum attenuation length and a minimum layer number.

4.2. Influence of Porous Metal Material on Overpressure of Explosion Wave

The influence of porous metal material on the overpressure of an explosion wave is shown in Table 2 and Figure 4. The overpressure curve of a gas explosion at different measuring points in Figure 4 is obtained according to data in Table 2.

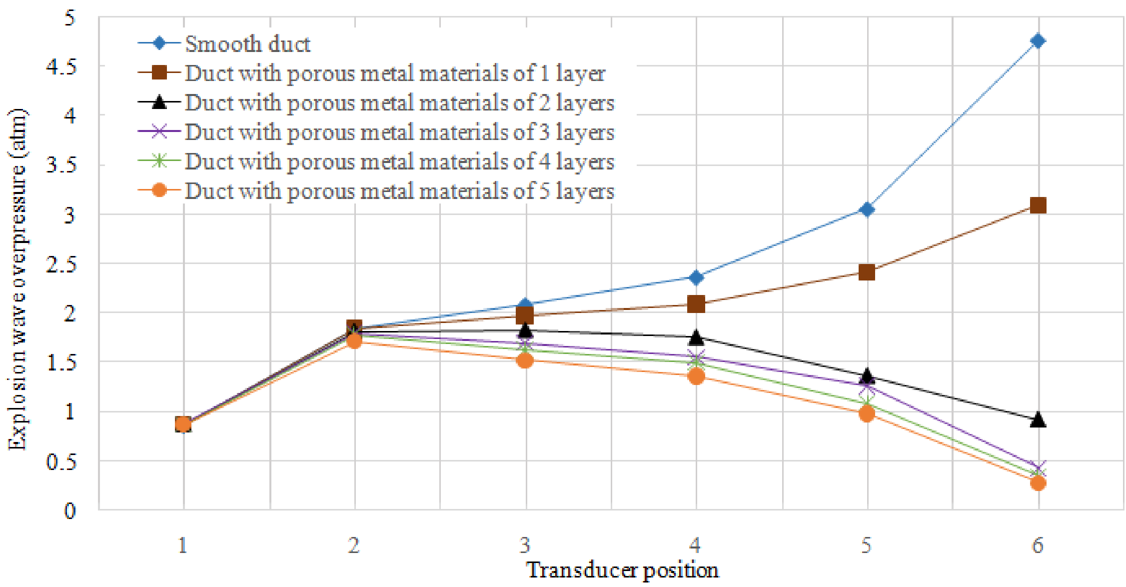

Figure 4. Explosion wave overpressure in porous metal materials with different layers.

From Table 2 or Figure 4, it can be seen that the suppression effect of gas explosion overpressure in duct is affected by the layer number and length of porous metal materials. There is a minimum attenuation distance for porous metal materials. The overpressure can be effectively reduced only when it exceeds the minimum attenuation distance. The minimum attenuation distance is about 5–6 times of the duct diameter. Moreover, the minimum attenuation distance increases with the decrease of the layer number. The layer number not only affects the minimum attenuation distance, at the same time, it also has a great influence on the decreasing range of overpressure. The more the layers are, the larger the reduction is. When the layer of porous metal materials is 2, 3, 4 and 5, respectively, the decreasing range of overpressure value is about 50%, 72%, 80% and 84%, respectively. In the same experimental condition, there is a least layer number. In this experiment, only when the layer number is greater than or equal to 3, can the overpressure be effectively suppressed. It should be noted that due to the flow attenuation, the overpressure decrease depends on the thickness of the porous metal materials; namely, the layer number and interlayer spacing of the porous metal materials. The relationship between the layer number and overpressure decrease is shown in Figure 5, but from the experimental results, the overpressure decrease is not linearly related to the layer number. The overpressure decreases quickly when the layer number is larger than a certain value. The overpressure decreases slightly when the layer number is less than a certain value. It can be seen from Figure 5 that with the increase of the length, the ability to suppress the overpressure of explosion waves is also increasing, which shows that the length of porous metal materials has a great effect on the suppression of the gas explosion overpressure.

It can be seen from Figure 4 that when the gas explosion propagates in porous metal materials, the explosion wave overpressure in each measuring point does not increase suddenly, but keeps increasing continuously. In the process of overpressure decrease, it does not decrease suddenly, but keeps decreasing continuously. In a word, when the gas explosion propagates in porous metal materials, the peak value of the explosion wave will be greatly reduced. It can be seen from Figure 5 that when the porous metal materials is installed in duct, the propagation time of the explosion wave in each measuring point increases; namely, the residence time in duct is increased. With the increase of layer number, the residence time increases. Therefore, the installation of porous metal materials in duct delays the propagation of the explosion wave and reduces the propagation velocity of the explosion wave.

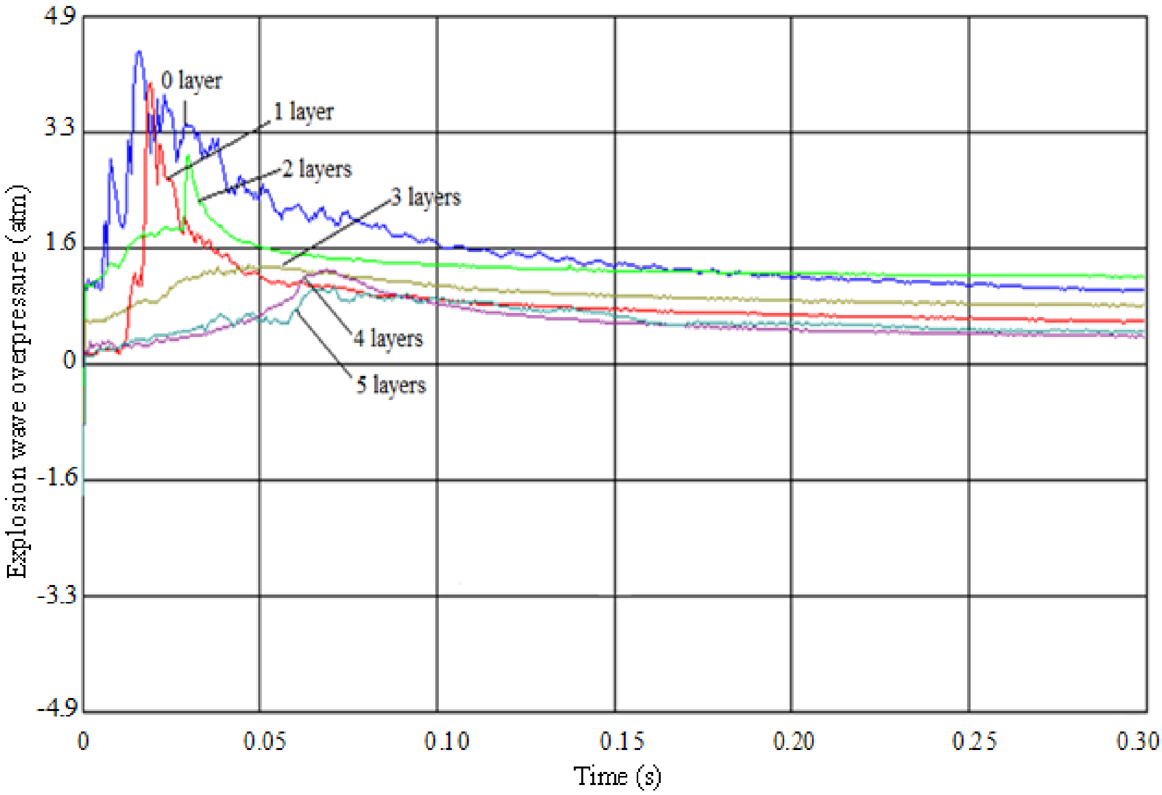

Figure 5. Explosion wave overpressure in porous metal materials with different layers at one point.

From the experimental results of the flame propagation velocity and explosion wave overpressure, it can be seen that the variation trend of gas explosion overpressure in duct with porous metal materials is synchronous with the variation trend of flame propagation velocity namely, the flame propagation velocity and overpressure decrease or rise at the same time; in addition, there is a minimum attenuation length and a minimum layer number.

5. Conclusions

In order to obtain the attenuation effect of porous metal materials on gas explosion propagation, the attenuation of porous metal materials with different layers on explosion wave overpressure and flame propagation velocity of a gas explosion is experimentally studied. Finally, the main conclusions are obtained as follows:

(1) The explosion wave overpressure and flame propagation velocity decrease with the increase of the layer number. The higher the layer number, the greater the attenuation of explosion wave overpressure and flame propagation velocity is. In this experiment, only when the layer number is greater than or equal to 3, can the overpressure be effectively attenuated.

(2) There is a minimum attenuation length of porous metal materials; only when the length is greater than 5 times the diameter can it obtain the suppression effect. Under the same layer number, with the increase of the length of porous metal material, the explosion wave and flame propagation velocity in porous metal material decrease continuously.

(3) When the gas explosion propagates in the porous metal material, the peak value of the explosion wave will be greatly reduced. The peak value of the explosion wave can be attenuated from 4.76 atm in a smooth duct to 0.28 atm in a porous metal material of 5 layers. The explosion wave overpressure does not increase suddenly, but keeps increasing

continuously, and in the process of overpressure drop, it does not drop suddenly, but keeps decreasing continuously, and has a time delay.

(4) Porous metal materials can delay the ignition, thus reduce the propagation velocity of a flame. The flame propagation velocity can be attenuated from 893.6 m/s in a smooth duct to 49.2 m/s in porous metal material of 5 layers.

(5) During the gas explosion propagation in porous metal materials, the increase or attenuation of the explosion wave overpressure and flame propagation velocity has synchronism and correspondence.

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