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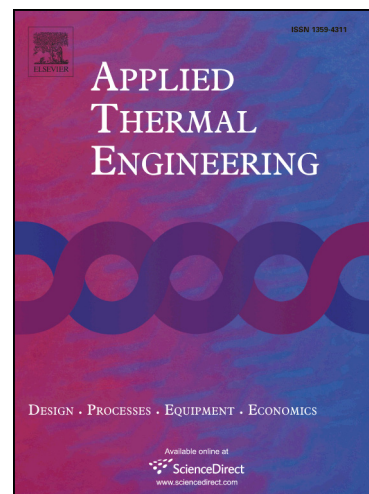
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Experimental Study on the Influence of Wall Heat Effect on Gas Explosion and Its Propagation

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**Abstract:** In order to understand the mechanism and the influence degree of wall heat effect on gas explosion and its propagation, the influence of wall heat effect on gas explosion and its propagation is theoretically analyzed mainly from perspectives of the heat transportation and reaction process. Results show that the influence of wall heat loss on gas explosion strength is significant. In addition, the influences of wall heat effect on explosion wave and flame propagation velocity in the gas explosion process are experimentally investigated in the adiabatic condition and heat conduction. It is found that the wall heat effect can affect gas explosion strength, flame propagation velocity, peak overpressure and the peak flame propagation velocity, and their influence degree becomes more significant with the increase of the adiabatic degree. Therefore, it can be seen that the wall heat effect has an important influence on the gas explosion and its propagation. The influence of wall adiabatic condition on gas explosion with a higher combustion level is greater than the influence on gas explosion with low combustion levels.

**Keywords:** Wall heat effect; Gas explosion; Heat transportation; Propagation velocity; Explosion wave pressure

## 1 Introduction

Gas explosion is a very complex physical-chemical reaction occurring in the gas-air mixture within a very transient time. As the behaviors of heat- mass transportation between unburned mixture and burned mixture are very complex, plus gas explosion happens in the limited space with

the high temperature and high pressure, thus the changes of gaseous parameters are great, which brings a lot of difficulties to understand and study the gas explosion process. In general, in order to facilitate research or reach experimental goal, so some seemingly unimportant factors are artificially ignored, for example, the wall heat loss, etc.

In the gas explosion experiment, the energy supporting flame movement forward continuously is from chemical reaction caused by the violent heat-mass exchange between the unburned mixture and flame front, which is important for the initial gas combustion. If the heat loss consumes the released energy of some chemical reactions, the flame propagation velocity will be reduced and even the flame will be extinguished<sup>[1]</sup>. Gas explosion products have a high temperature, therefore, there is an inevitably considerable temperature difference between the products and experiment pipes. In this situation, part of the released heat in gas explosion process will be lost by means of heat conduction, convection and radiation, which will reduce heat transportation to the unburned mixture, affect the flame propagation velocity and weaken the explosion strength<sup>[2]</sup>. Yunfei Yan et al. carried out the numerical study on influence of wall parameters on catalytic combustion characteristics of CH<sub>4</sub>/air in a heat recirculation micro-combustor, their results show that with the decrease in thermal conductivity of wall materials, the temperature of the reaction region increases and hot spots becomes more obvious<sup>[3]</sup>. The effect of thermal radiation on the dynamics of a thermal explosion of a flammable gas mixture was studied, it was pointed out that the effects of thermal radiation can be significant, especially at high temperatures, and cannot be ignored in the analysis of this phenomenon<sup>[4]</sup>. The material thermal characteristics also have influence on explosion parameters<sup>[5]</sup>. However, for safety reasons, the steel pipes with thickness wall withstanding a higher pressure have been frequently used in gas explosion experiments<sup>[6-8]</sup>, but the good heat conductivity and high heat capacity of steel pipes make heat losses more obvious,

and produce deviations. For example, the long-pipe experiments were employed in these experiments<sup>[9-13]</sup>, the region behind the reflected shock wave can be considered isothermal prior to the main chemical reaction, but significant heat transfer to the walls of the shock tube brings observable deviations from the isothermal assumption. Actually, the heat conductivity of the underground roadway wall is poor<sup>[14]</sup>, and the influence of wall heat loss on gas explosion is different from the influence in steel pipes. It can be obtained that there are still some differences between the laboratory experiment and the actual mine situation, To better apply the existing research outcomes to the actual mine's safety work, the influence degree of wall heat effect on gas explosion must be deeply studied, so the influence of wall heat effect on gas explosion and its parameters is studied in this paper. The study outcomes have an important practical significance for the gas explosion prevention during underground mining, safe and rational utilization of natural gas and other industrial energy.

## **2 Theoretical analysis on the influence of wall heat effect on gas explosion**

It is obtained that thermal conductivity and convection on the surface of solid wall have an apparent influence on combustion in related literatures<sup>[15,16]</sup>. From the viewpoint of heat transportation, the pipe geometry size, pipe material and pipe wall structure commonly determine the heat losses caused by radiating propagation from hot products with high temperature to pipe wall. The wall heat effect was specially put forward in literatures<sup>[17,18]</sup>, the concept of wall heat effect was formed and discussed in other disciplines, such as heat transfer. In the field of gas explosion, although it has been put forward, but so far, a detailed study and monographs about this issue have not yet seen. Normally, in order to facilitate the study and highlight the specific purpose of the experiment, the problems are often simplified as follows: the reaction region of unburned gas and the flame front is very thin, the contact surface between the pipe wall and reaction region is

very small, plus the flame velocity is very fast. Therefore, it is considered that the heat transfer loss from hot products with high temperature to wall surface is very little in process of gas explosion, the influence of heat transfer loss on the flame propagation characteristics also is little, so as to ignore the influence of wall heat effects on gas explosion. With the further research, this view is not correct. The flame thickness in gas explosion is far more than the thickness of micron order of magnitude in the classical kinetic theory, so the radiating heat is large. In the initial stage of gas explosion, the flame wave is still in the low velocity stage, the heat- mass transportations between wave front and the unburned mixture are not severe, but the wall heat effect of pipe will inevitably affect the next flame acceleration <sup>[19]</sup>. In the transient process of continuous acceleration and eventual detonation formation, due to the increase in the internal turbulence and violent heat release of reaction, the heat exchange between the reactants and the pipe wall is bound to increase.

Gas explosion is a chemical reaction process with high temperature and high pressure. Hence experimental pipe of gas explosion should be the steel pipe with a good heat conductivity and high heat storage capacity, so that the heat loss caused by wall is bound to weaken the explosion strength and flame propagation velocity. On the contrary, the improvement of the wall's adiabatic condition can significantly accelerate gas explosion. Gas explosion energy is from the released heat of chemical reaction of gases, the energy loss is transferred to wall by method of convection, conduction and radiation, when the gases with high temperature and high pressure contact with the wall surface in process of fast flow. Because the shock wave does work to gas in front of wave, so there will be an upward jump change in the internal energy, enthalpy and kinetic energy of gas behind the shock wave, which is shown in Fig.1. The shock wave does not have energy, but it creates condition for the chemical reaction. At the same time, the energy released from the chemical reaction continuously supports the shock wave propagation. According to the propagation structure

of detonation state, the energy conservation equation could be expressed as follows.

$$q + e_1 + \frac{p_1}{\rho_1} + \frac{1}{2}(D_f - u_1)^2 = e_2 + \frac{p_2}{\rho_2} + \frac{1}{2}(D_f - u_2)^2 \quad (1)$$

To facilitate the study on explosion energy conversion, the equation is rewritten as:

$$q + h_1 + \frac{1}{2}(D_f - u_1)^2 = h_2 + \frac{1}{2}(D_f - u_2)^2 \quad (2)$$

Where,  $e$  is the internal energy;  $p$  is the pressure;  $u$  is the particle velocity;  $C$  is the velocity of sound;  $T$  is the temperature;  $\gamma$  is the adiabatic index;  $\rho$  is the gas density; subscript 0, 1 and 2 denote 0 zone, 1<sup>th</sup> zone and 2<sup>th</sup> zone, respectively: 0 zone is the initial state of combustible gas mixture; 1<sup>th</sup> zone is the state behind shock wave front; 2<sup>th</sup> zone is the state behind detonation wave front (flame front).

From the above formulas, it could be obtained that the reaction of combustible mixture per unit mass releases energy  $q$ . Part of the energy  $q$  supports the propagation of shock wave; another part of it is transformed into the internal energy and enthalpy of combustion products. At the same time, the volume of the combustion products is rapidly expanded, and the unit mass volume ( $\text{m}^3/\text{kg}$ ) is about 5 -15 times of volume of the unburned gases <sup>[20]</sup>. Combustion products do work by the expansion, the fundamental energy is transformed into pressure energy and kinetic energy. Because gas explosion experiments are done in the pipes and the gas explosion is completed instantly, the relative temperature rise of pipe wall is not large. Theoretically, there is a significant temperature difference between the high temperature combustion products and pipe wall. Meanwhile, there is also a great temperature difference between the burned products and the unburned gases. So the hot burned products transfer a part of the energy to the wall by method of convection and radiation; the hot burned products transfer the energy to the unburned gas by method of conduction, diffusion, etc.

Based on above analysis, more detailed combustion energy equation of the combustible

mixture of per unit mass can be got <sup>[21]</sup>.

$$q = q_1 + q_2 + W + F_K + L \quad (3)$$

Where,  $q_1$ ,  $q_2$  is the heat of combustion products radiating to the unburned gas and pipe, respectively, KJ/Kg;  $W$  is the increased energy of shock wave, KJ/Kg;  $F_K$  is the increase in kinetic energy of combustion products, KJ/Kg;  $L$  is the energy loss, KJ/Kg.

The above formula adequately reflects the combustion energy distribution of gas in the unit mass, i.e. under the condition of certain combustion energy, if the amount of radiating heat increases, the energy supporting shock wave propagation forward will reduce, the propagation velocity and overpressure of the shock wave will consequently be weakened. On the other hand, if the radiating heat reduces, the energy supporting shock wave propagation forward will increase, thus the propagation velocity and overpressure of the shock wave will increase, and the chemical reaction rate will increase, the explosion strength will be greatly enhanced. Therefore, the wall heat effect will reduce the explosion strength and temperature. The reduction of gas explosion strength and the temperature will reduce the collision probability among the particles further, and finally result in the reduction of reaction rate. From the viewpoint of heat -mass transportation, the wall heat effects can cause heat loss, reduce turbulence, reduce the flame combustion rate, reduce flame propagation velocity, transfer more energy and reduce energy of explosion wave, so the wall heat effect can reduce the gas explosion and its propagation.

Through the theoretical analysis, the wall heat effect will cause the wall heat loss, the wall heat loss will reduce the explosion energy of positive feedback of gas explosion propagation process, so it can weaken the explosion strength and propagation velocity, which are also tested and verified in following experiments.

### **3 Experimental study on influence of wall heat effect on gas explosion and its propagation**

### 3.1 Experimental system

The experimental system of the influence of the wall heat effect on gas explosion and its propagation is shown in Fig. 2. This system consists of eight parts, namely, gas explosion experiment pipe (chamber), vacuum instrumentation, gas explosion ignition device, pumping system, gas distribution system, gas explosion pressure measurement system, the flame propagation velocity measurement system, dynamic value acquisition and the analysis system. The experiment equipment instruction and other test equipments can be referred in literature [8].

### 3.2 Experimental scheme

The pipes used in the gas explosion experiments are 4m or 21m in length, the internal dimension is 80mm×80mm. The adiabatic materials used in the experiments are asbestos cloth with good adiabatic properties of 0.8mm in thickness. In order to study the differences in the pipes with adiabatic material and non-adiabatic material, and obtain the influence of wall heat effect on gas explosion, the adiabatic materials are affixed on the internal surface of pipes by high temperature glue. The internal layer of insulation is treated to be smooth, so the surface roughness is little and neglected. In order to investigate the influence degree of wall heat effect on different stages of gas explosion, in pipes of 4m in length, three experiments are carried out in pipes with inner non-adiabatic material, adiabatic material with 2m and 4m in length, respectively. In pipes of 21m in length, the experiments are implemented with the adiabatic material of 2m in length in the ignition side. Based on experimental results, the wall heat effect on gas explosion in pipe with different lengths is analysed, and then gas explosion (flame, explosion wave) propagation laws in different conditions are also analyzed. The flame sensors and pressure sensors are installed at measurement points to measure the flame propagation velocity and explosion wave overpressure.

The detailed experiment conditions are shown in Table 1. The experiments with same condition are repeated 5 times, the data of each measuring point in all tables are the arithmetic mean value of 5 experiments. The physical parameters measured in experiments are flame propagation velocity and explosion wave overpressure.



### 3.3 Experimental results and discussion

#### 3.3.1 Influence of wall heat effect on explosion wave overpressure and flame propagation velocity

The experimental results of the influence of wall heat effect on explosion wave overpressure are listed in Table.2 and Fig.3, the Fig.3 is corresponding to the data in Table 2. The experimental results of the influence of wall heat effect on flame propagation velocity are listed in Table.3 and Fig.4, the Fig.4 is corresponding to the data in Table 3.

According to above data and curves, the adiabatic layer affixed on inner wall of the pipe has an important influence on flame velocity and pressure of gas explosion. The flame peak velocity in smooth pipe is 103.33m/s (when  $L/D=40$ ), while the flame peak velocity in pipe with the inner adiabatic layer of 2m in length is 197.71m/s (when  $L/D=34$ ). The flame peak velocity in pipe with the inner adiabatic layer of 4m in length is 266.21m/s (when  $L/D=34$ ), which is 2.56 times of the velocity in the smooth pipe. The flame propagation time is 0.01675s in smooth pipe, 0.01471s in pipe with inner adiabatic layer of 2m in length and 0.01382s in pipe with inner adiabatic layer of 4m in length, respectively. The peak overpressure is  $0.25375 \times 10^5$ Pa in smooth pipe,  $0.320483 \times 10^5$ Pa in pipe with inner adiabatic layer of 2m in length and  $0.3563 \times 10^5$ Pa in pipe with inner adiabatic layer of 4m in length, respectively. The results show that the adiabatic layer affixed on inner wall has a great influence on flame propagation velocity, overpressure and the whole process of gas explosion. It can also be seen that the adiabatic layer affixed on inner wall has a great influence on gas explosion, and the effect degree increases with improvement of the adiabatic degree. So the influence of dissipated heat on flame acceleration propagation and explosion strength is very large.

As shown in the theoretical analysis, in the process of gas explosion, the flame thickness is in the meter order of magnitude, not the millimetre order of magnitude from the results of static flame

experiments. It can be seen that the contact area between the flame and the pipe wall is at least 1000 times larger than that of the previous understanding, and the wall heat loss greatly increases. Especially in the peak stage of gas explosion, the turbulence degree of gas is very large and the explosion temperature is very high, in this case, the heat and mass exchange between flame front and unburned gas is large, plus the temperature difference between reaction area and pipe wall is very large. As we know, the wall heat loss mainly depends on the temperature difference, therefore, the influence of wall adiabatic condition on gas explosion with a higher combustion level is greater than the influence on gas explosion with low combustion levels.

### 3.3.2 Influence of wall heat effects on the gas explosion in long pipe

The influence law of the adiabatic condition on gas explosion in the 4m-length pipe is already obtained. To be able to better reflect the gas explosion in the coal mine, it is necessary to study the influence of wall heat effect on gas explosion in long pipe. Gas explosion data measured in pipe of 21 m in length are list in Table 4 and Table 5. Fig.5 and Fig.6 are corresponding to the data in Table 4 and Table 5, respectively.

In Fig. 5, in the flame measuring point (when  $L/D=52$ ), the flame propagation velocity in pipe with adiabatic layer increases rapidly. In contrast, the flame propagation velocity in smooth pipe increases slowly. In the flame measuring point (when  $L/D=134$ ), the flame propagation velocity peak in pipe with adiabatic layer is 367.4m/s, in the flame measuring point (when  $L/D=165$ ), the velocity difference valve in pipe with adiabatic layer and smooth pipe is 170.5m/s.

For experiments in long pipe, there is shock wave signal generated in the gas explosion, compared with the short pipe of 4m in length, the explosion wave overpressure can better illustrate the influence of wall heat effect on gas explosion in condition of long pipe. In Fig. 6, the explosion wave curve in short pipe increases with distance ( $L/D$ ). The explosion wave curve in long pipe is

parabolic, which shows that the adiabatic layer of 2m in length affixed in front of pipe of 21m in length can reduce the energy loss caused by wall heat effect, can increase the flame combustion, and then reach a peak. Meanwhile, the overpressure value increases. But in the subsequent propagation process, the pipe without adiabatic layer generates heat loss, compared with the peak state, the explosion wave strength takes on the downtrend trend, so the explosion wave shows generally parabolic curve. From above analysis, it could be concluded that the influence of the adiabatic conditions on gas explosion process in long pipe is obvious.

Finally, it can be obtained that the influence of wall heat effects on the gas explosion propagation not only can correct the previous result, but also can offer the experiment basis for the development of better barrier equipment. Moreover, the essential component of petroleum and natural gas is hydrocarbon, there are many similarities between the reaction mechanism (flame propagation mechanism) of hydrocarbon fuel-air mixture explosion and gas explosion. Due to the simplicity of  $\text{CH}_4$ , the explosion mechanism of other complex hydrocarbon fuels are often studied based on the  $\text{CH}_4$ , thus the research on  $\text{CH}_4$  explosion factors has an important practical significance for the safe and rational utility of the oil and natural gas.

#### **4 Conclusions**

The influences of wall heat effect on gas explosion are experimentally in this studied, and following conclusions could be obtained:

- (1) The influence of the adiabatic layer affixed on the inner pipe wall on the gas explosion process is very obvious, the flame velocity and overpressure value increases more than those in non-adiabatic pipes, and the flame propagation time in pipe with adiabatic layer significantly reduces, the influence degree increases with improvement of adiabatic degree.
- (2) The influence of wall adiabatic condition on gas explosion with a higher combustion level is

greater than the influence on gas explosion with low combustion levels.

(3) The wall heat effect could reduce the strength and temperature of gas explosion. However, the reduction of the strength and temperature will reduce the probability of collisions between the particles, which will result in the decrease in reaction rate. From the viewpoint of heat- mass transportation, the wall heat effect could cause heat loss, reduce turbulence, reduce the flame combustion rate, reduce flame propagation velocity, transfer more energy and reduce the energy of explosion wave. Therefore, the wall heat effect could reduce the gas explosion and its propagation.

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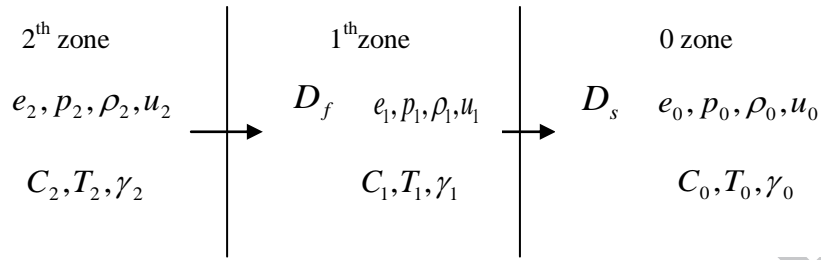
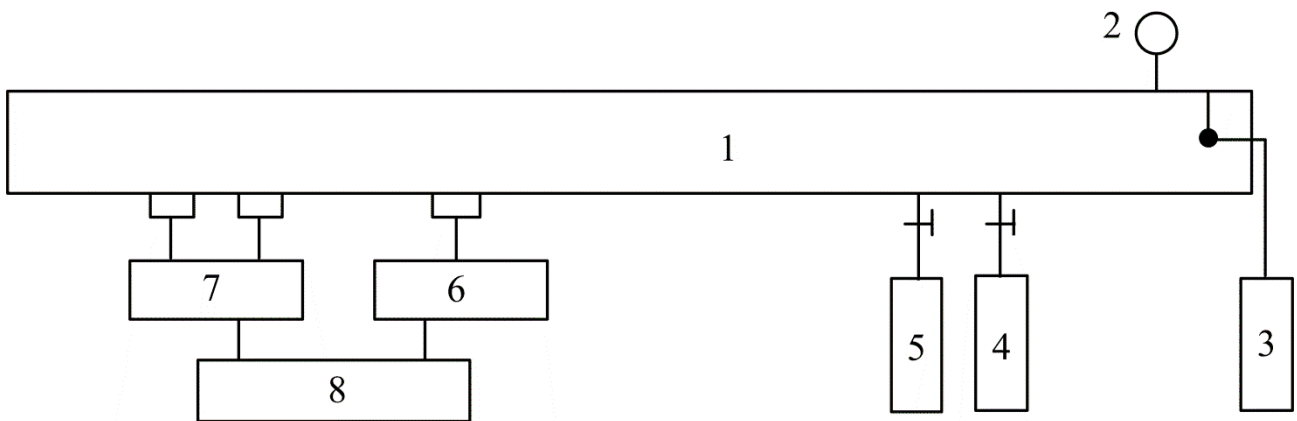


Fig.1. Gas state distribution of combustion zone during gas explosion



1-gas explosion experiment pipe (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

Fig.2. Schematic figure of experiment system of gas explosion

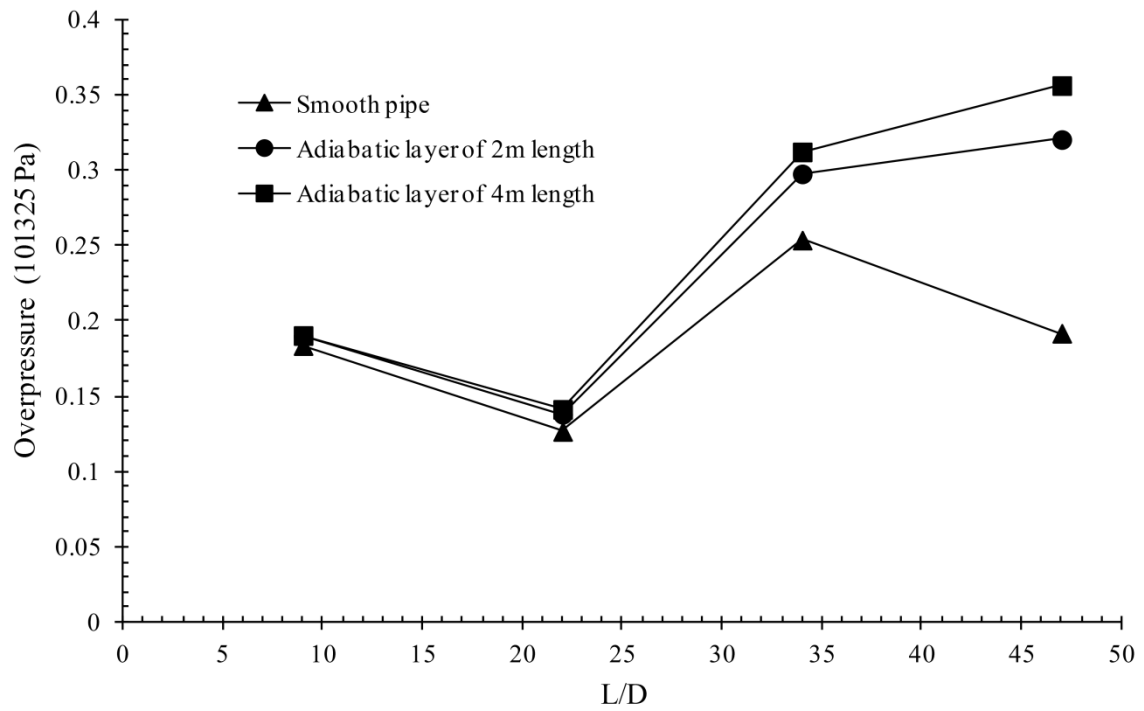


Fig.3. Overpressures in pipe of 4m in length

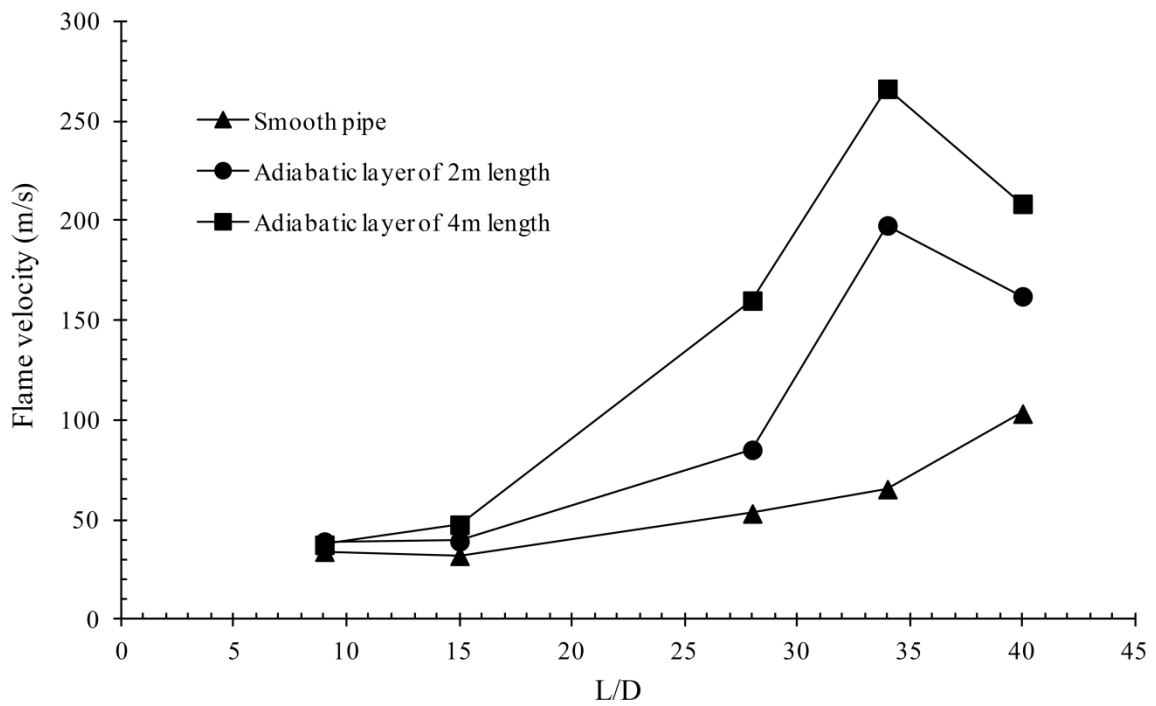


Fig.4. Flame velocities in pipe of 4m in length



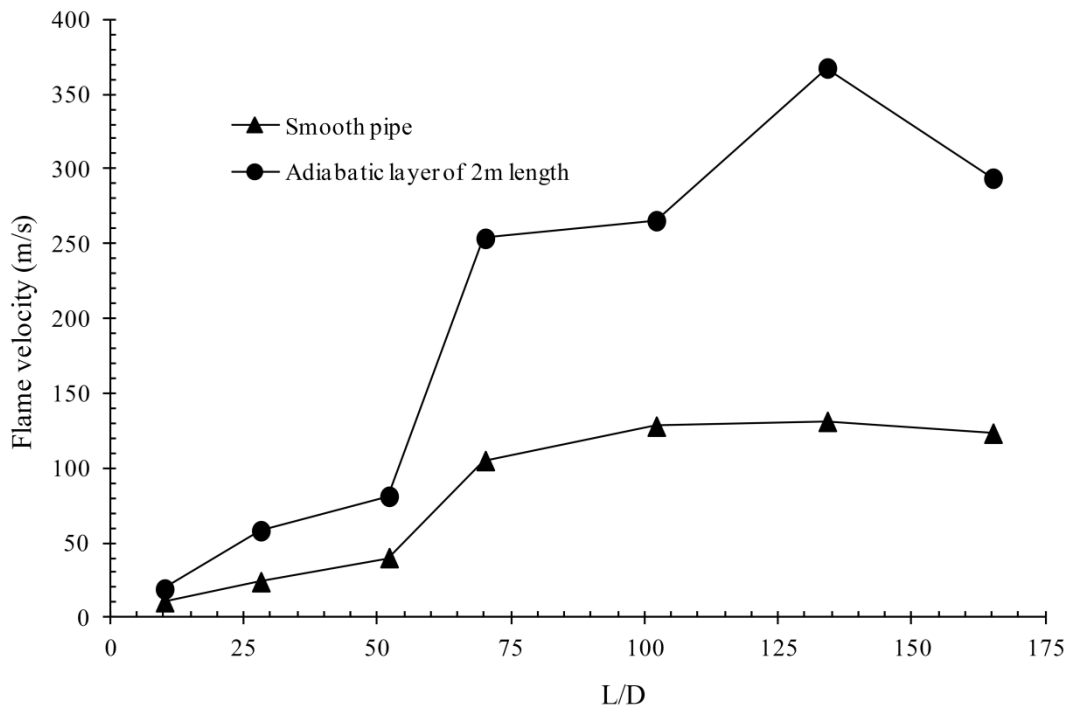


Fig.5.The flame propagation velocity in pipe of 21m in length

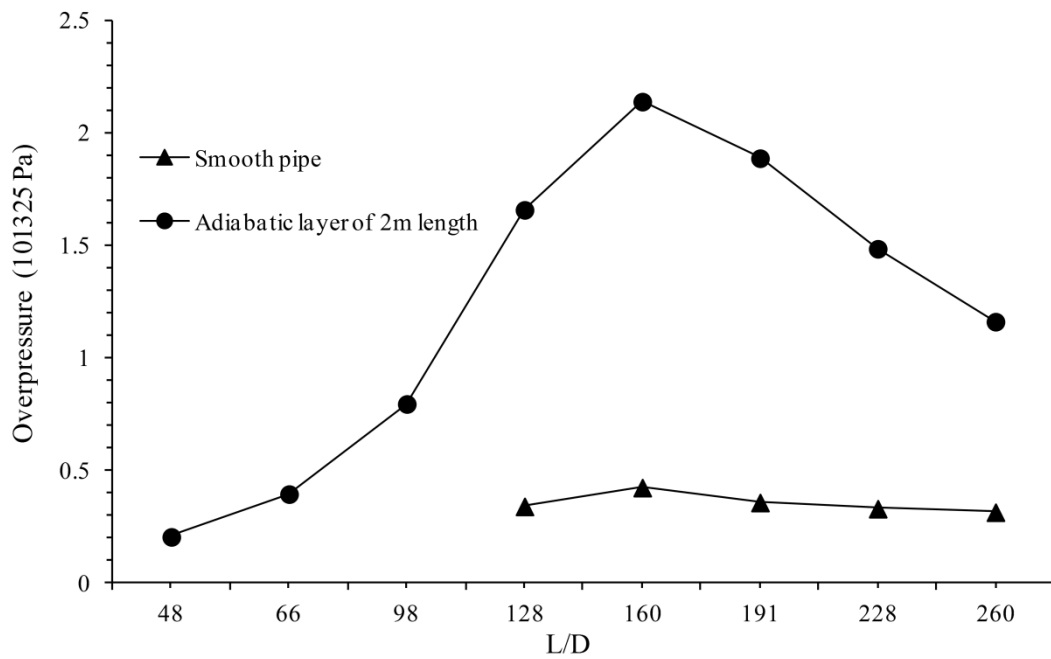


Fig.6.The overpressures in pipe of 21m in length.

Table.1. Detail list of experimental condition

Short pipe of 4m in length	Smooth pipe	End is open
	Adiabatic layer of 2m in length	End is open
	Adiabatic layer of 4m in length	End is open
Pipe of 21m in length	Smooth pipe	End is open
	Adiabatic layer of 2m in length	End is open

Table.2. The explosion wave overpressure in pipe of 4m in length and with inner adiabatic material  
(unit:  $1.01 \times 10^5 \text{Pa}$ )

measuring point No	P1	P2	P3	P4
L/D	9	22	34	47
smooth pipe	0.183767	0.1268	0.25375	0.191921
adiabatic layer of 2m length	0.190022	0.138183	0.2977	0.320483
adiabatic layer of 4m length	0.190451	0.14145	0.312275	0.356311

Table.3. The flame propagation velocity and process time in pipe of 4m in length and with inner adiabatic material (unit: m/s)

Measuring point No	F1	F2	F3	F4	F5	process time (s)
L/D	9	15	28	34	40	
Smooth pipe	34.08	32.04	53.27	65.45	103.33	0.08507
Adiabatic layer of 2m in length	39.17	39.30	85.19	197.71	162.16	0.04041
Adiabatic layer of 4m in length	37.57	47.62	160.01	266.21	208.54	0.03234

Table.4.The flame propagation velocity in pipe of 21m in length and with inner adiabatic material

(unit: m/s)

Measuring point No	F1	F2	F3	F4	F5	F6	F7
L/D	10	28	52	70	102	134	165
Smooth pipe	10.5	23.9	40.0	104.9	127.9	131.1	123.2
Adiabatic layer of 2m in length	19.0	58.0	81.0	253.5	265.3	367.4	293.7

Table.5.The overpressure in pipe of 21m in length and with inner adiabatic material (unit:

 $1.01 \times 10^5 \text{Pa}$ )

Measuring point No	P1	P2	P3	P4	P5	P5	P6	P8
L/D	48	66	98	128	160	191	228	260
Smooth pipe	Overpressure			0.3423	0.4257	0.3594	0.3320	0.3164
Adiabatic layer of 2m in length	Overpressure	0.2070	0.3969	0.7969	1.6583	2.1387	1.8876	1.4856
	Velocity(m/s)			352.92	540.15	683.23	642.73	606.62

Note: the dash means no corresponding measured data.