Experimental Setup for Assessing the Energetic Materials Deflagration Propagation under High Temperature and High Pressure Conditions

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Abstract: The technology of "explosion in fractures" is one of new synthetic engineering methods used in low permeability reservoirs. The most important problem arose from the technology is to assess the deflagration propagation capability of milky explosives in rock fractures. In order to investigate detailed this problem in the laboratory, an experimental setup was designed and developed in which different conditions can be simulated. The experimental setup mainly includes two parts. One is the experimental part and the other is the measurement part. In the experimental setup, the narrow slots with different width can be simulated; meanwhile, different initial pressures and initial temperatures can be loaded on the explosives inside the narrow slots. The initial pressure range is from 0-60 MPa, and the initial temperatures range is from room temperature to 100 ℃. The temperature and the velocity of deflagration wave can be measured; meanwhile the corresponding pressure in the narrow slot is also measured. In the end, some typical measurement results are briefly presented and discussed.
Keywords: mechanics of explosion; low permeability reservoirs; explosion in fractures; milky explosives; deflagration propagation; experimental setup

1 Introduction

Oil, as the most important energy and chemical resource, is consumed increasingly every year in China. In 2004 China became the second largest country in the word. At the same year China's oil import amount exceeded 100 million tons, and had been growing approximately 10% per year in the last five years, which led to the situation that China's oil demand must heavily depend on foreign oil resources. In order to reduce such dependence, China had to strengthen her mining intensity of domestic oil resources. However, with the oil reserves which can be easily mined becoming gradually less, the proportion of oil reserves stored in low permeability reservoirs (commonly refers its permeability coefficient betweens 0.1×10^{-3} and 50×10^{-3} μm^2; sometimes refers lower permeability coefficient) increased dramatically in recent years. At present, nearly half of newly founded oil reserves belong to low permeability reservoirs. Therefore, how to develop an effective mining technology for low permeability reservoirs became an important problem the state oil administrative department faced.

The technology of "explosion in fractures" is one of new synthetic engineering methods used in low permeability reservoirs, which was firstly put forward by Ding et al. in the middle of 1990s. The main idea of this technology is as follows: firstly formed two long narrow rock slots with about 5 mm thickness by using the hydraulic fracturing method, and pumped the milky explosives into these narrow slots; then triggered the explosive by an appropriate method. When the explosives deflagrated around the narrow slots, the deflagration pressure would act on the walls of the slots. As a result, many smaller fractures perpendicular to the former slots would be generated, which can greatly improve the permeability of oil-bearing formation and benefit the China's domestic oil output[1].

Since the "explosion in fractures" method is a synthetic one, many problems from different disciplines should be considered. Among them, the biggest one was to assess the deflagration capability of milky explosives in narrow rock slots. In order to investigate detailed on this problem in the laboratory, we designed and developed an experimental setup in our laboratory.

The purpose of this paper was to introduce this experimental setup mainly concerning its main components and corresponding structures. In particular, we had a detailed explanation on the structure mechanisms of these devices. In the end, some typical experimental results were also briefly presented.

2 Experimental Setup

2.1 Overall Description

As shown in Fig. 1, the main body of the experimental setup has a cylinder shape. It is 2.5 m in length and 20 cm in diameter. Considering the fact that there would have many repeated experiments under high pressure conditions, we chose the chromium steel which having high strength and enough toughness as the experimental setup's material.

The experimental setup can be roughly divided into two parts. One is experiment part and the other is measurement part. The experiment part mainly consists of ignition device, narrow slot section, Vacuum extractor, initial pressure loading system, initial temperature loading system, pressure adjustment device and pressure release device. The measurement part mainly consists of pressure measurement system, deflagration velocity and temperature measurement system.

On the middle line of the upper semi-circular surface of the experimental setup, twenty-one holes were drilled. Eighteen of them are through holes and the others are blind holes. The through holes are used to install different kinds of gauges and to connect different devices like the vacuum extractor, while the blind holes severe for temperature monitoring and controlling as well as for connecting lifting devices.

2.2 Narrow Slot Section

The narrow slot section, located in the location of the longitudinal section of the interior cylinder (Fig. 2), is the key component of the experimental setup where energetic explosives deflagrate. The slot is 2.1 m in length, 5 mm in width and 25 mm in depth. The width of the slot can be adjusted. The whole volume is about 290 mL. On the left of the slot, there exists a through hole whose diameter is 10 mm. Through the hole, a large amount of hot gas generated by the ignition device can burst into the slot, so the explosives inside the left bottom of the slot will be ignited. On the right bottom of the slot is a flat convex which can guarantee the top surface of the slot strictly face with the measurement holes.

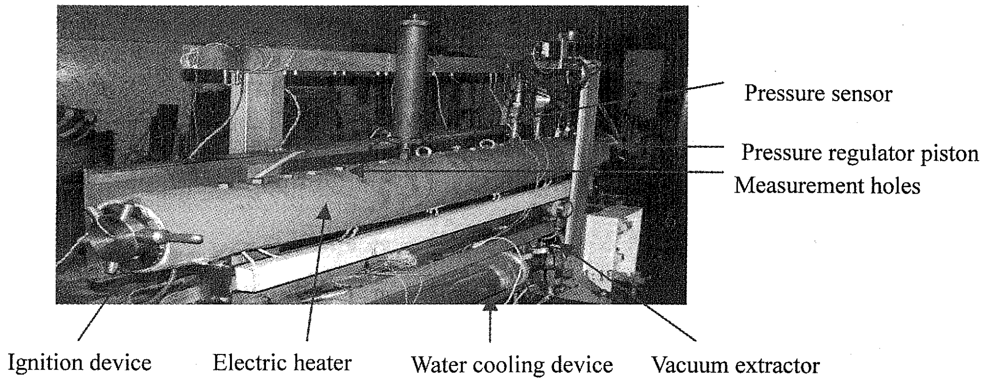


Fig. 1 Experimental setup built for studying the deflagration propagation of explosives

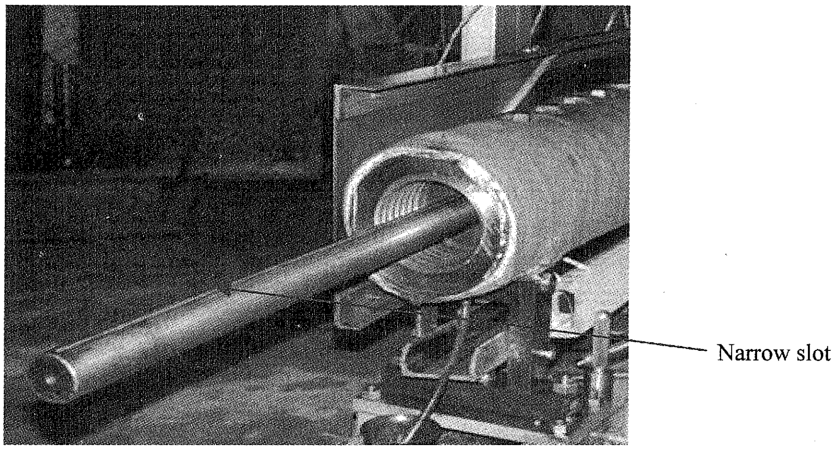
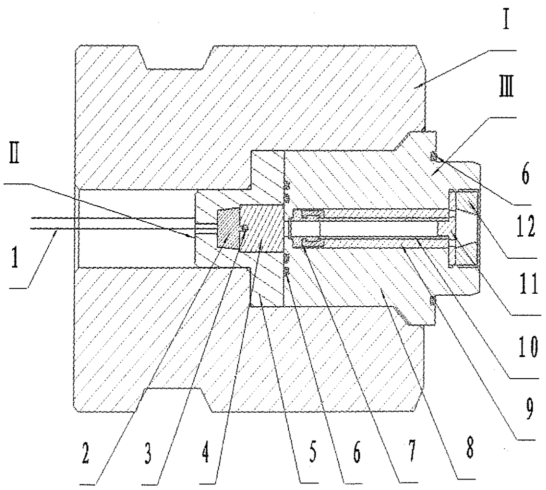


Fig. 2 Narrow slot section for explosives deflagration

2.3 Ignition Device

The function of the ignition device is to ignite the explosives inside the slot. As shown in Fig. 3, the ignition device consists of joining bolt, electric igniter and thermal igniter. The function of the electric igniter is to generate plenty of hot gas by using exterior electrical energy at atmospheric pressure, while the function of the thermal igniter is to generate an adequate amount of hot substances (most of them is hot gas) at relatively high pressures. The function of the joining bolt (part III of the ignition device, see in Fig.3) is tightly connecting the ignition device with the experimental setup.



Ⅰ: Joining bolt
Ⅱ: Electric igniter
Ⅲ: Thermal igniter
1. Conducting wire
2. Brass base
3. Fusehead
4. Electric igniter chamber
5. Electric igniter wall
6. O-ring
7. Positioning screw
8. Thermal igniter wall
9. Thermal igniter chamber

Fig. 3 Schematic of ignition device

Generally speaking, the function of ignition device is to ignite the main explosive charge by using exterior energy such as electrical energy, mechanical energy et al. Different from those ignition device which commonly worked at atmospheric pressure[2,3], the ignition device introduced here need work at two different pressures. The electric igniter works at atmospheric pressure, but the thermal igniter works at relatively high pressures. Commonly, the electric igniter chamber is filled with the black powder because of its good flame sensitivity. However, this behavior can be greatly affected under high pressure condition for the black powder being strongly stressed and thus leads to ignition process unreliable. Here a kind of thermal igniter is added to the device in order to deal with this problem.

The fusehead is the key component of the electric igniter. When given a certain amount of electric energy through conducting wires, the fusehead can be triggered. Then the black powder inside the chamber is fired. Subsequently, the jet flames rip into the interior of the aluminum pipe located in the middle of the thermal igniter through the interior hole of the positioning screw. During this process, the aluminum pipe is heated gradually and thus ignites the thermal-sensitive explosives surrounding the pipe which is in high pressure initially. Finally through the firing hole, the hot substances generated by thermal igniter can fire the explosive inside the slot.

2.4 Initial Pressure Loading System

The function of the initial pressure loading system is to load the explosives inside the slot at high pressure initially. As schematically shown in Fig. 4, the initial pressure loading system mainly consists of vacuum extractor, pressure gage, refueling unit and pressure regulator piston.

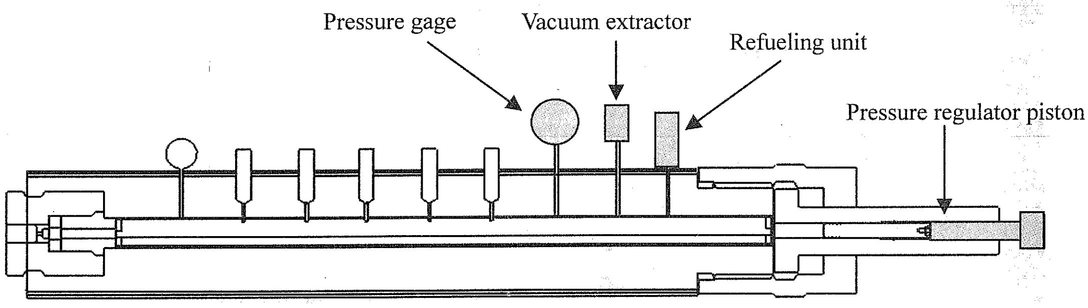


Fig. 4 Schematic of initial pressure loading system

When beginning to have an experiment, we can extract the air using the vacuum extractor since the slot is an enclosure space at atmospheric pressure. Consequently, the pressure in the slot becomes gradually lower than the atmospheric pressure and finally nearly tends to zero. At this stage, turn off the vacuum extractor and open the refueling unit so that the oil can enter the slot through the effect of gravity. By compressing the oil inside the slot through the piston, we can load the explosive under the appropriate pressure condition which can be monitored by the pressure gage.

2.5 Initial Temperature Loading System

The function of the initial temperature loading system is to let the explosives inside the slot under a high initial temperature condition. The system mainly includes electric heater, thermal barrier coatings, temperature sensors and temperature controller. The power of the electric heater is about 6 kW. In order to increase the heater's efficiency, thermal barrier coatings are used. The temperature controller is used to adjust and control the temperature of the explosives inside the slot.

2.6 Pressure Adjustment Device

Sometimes during an experiment process the pressure in the slot may exceed 300 MPa, which can greatly affect the performance of the experimental setup and thus reduce the service life. Considering this problem, a kind of pressure adjustment device is designed. The device (see in Fig. 5) mainly consists of gas reservoir, flow control valve, circular brass sheet and joining bolt. The maximum adjustment pressure is controlled by the thickness of the brass sheet. The gas leaking velocity mainly relies on the flow control valve. The volume of the gas reservoir can be adjusted from zero to 80 ml so that different final pressure of the slot can be effectively controlled.

2.7 Pressure Releasing Device

After an experiment, the residual pressure of the slot is about 200 MPa. If we do not take some effective measures, the mixture of oil and gas will eject from the slot when we open the experimental setup. This can greatly destroy the laboratory's environment and sometimes may injure the operators. In order to overcome this problem, a kind of unit named pressure releasing device is designed. The pressure releasing device (see in Fig. 6) mainly consists of oil reservoir, spherical valve, umbrella-shaped baffle plate, oil-filter strainer, gas escape hole and joining bolt. Through the joining bolt the device connects with the experimental setup. When we open the spherical valve slightly, the oil and generated gas at high pressure will eject into the oil reservoir. When resisted by the umbrella-shaped baffle plate, the direction of the mixture is reversed and ejects into oil-filter strainer. Finally the oil leaves in the oil reservoir because of its higher density and the resistance from the oil-filter, and only the gas can eject from the gas escape hole.

2.8 Pressure Measurement System

The pressure measurement system mainly includes pressure sensors, strain amplifier, synchronizer, A/D converter, computer and water cooling device. The pressure sensor is the key component of this measurement system and here we choose the strain type pressure sensor for its smaller electric resistance and good capability of anti-jamming. The response frequency of the pressure sensor is 1 kHz. Since the experiment time duration is relatively short and the A/D converter does not has enough capability of recording data, the synchronizer is used to guarantee the completeness of the experiment data. In some experiments, the electric heater is used to give the explosives insides the slot an initial temperature. Because of the existence of the heat conduction, the pressure sensor does not work normally in this condition. Thus the water cooling device (see in Fig. 7a and Fig. 7b) is designed. The pressure sensor is always at room temperature so that the influence caused by higher experimental temperature can be eliminated.

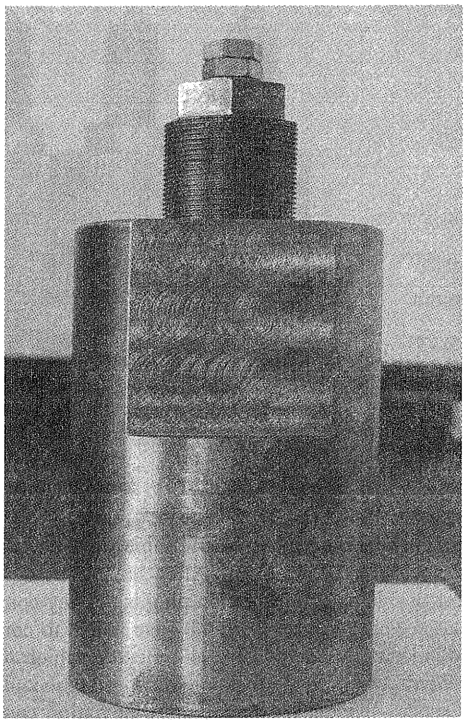


Fig. 5 Pressure adjustment device

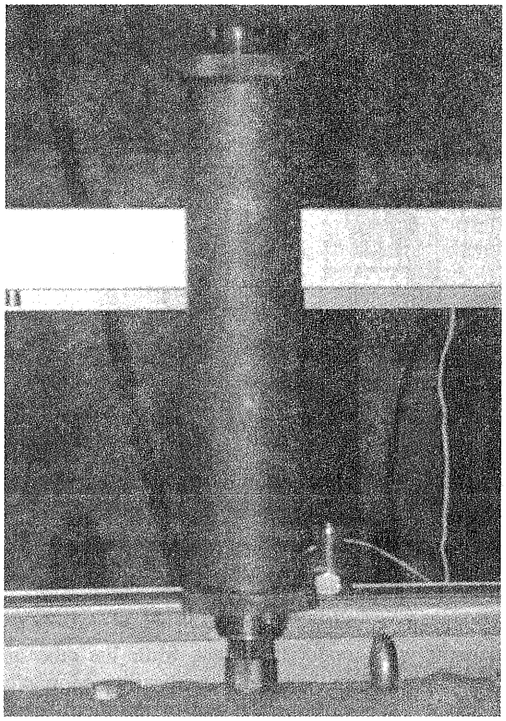


Fig. 6 Pressure releasing device

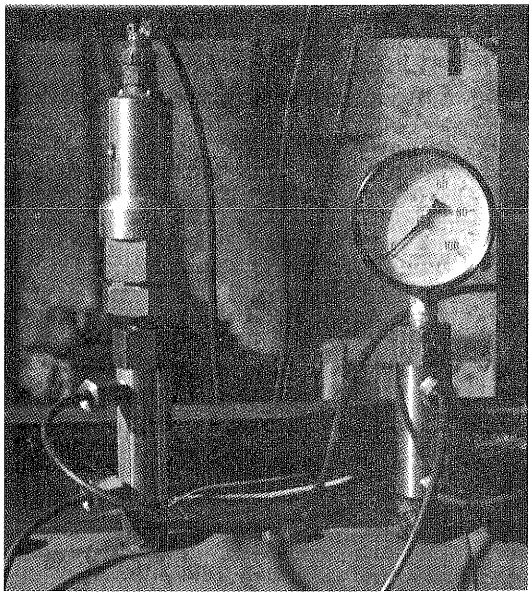


Fig. 7a Pressure sensor and gage under water cooling

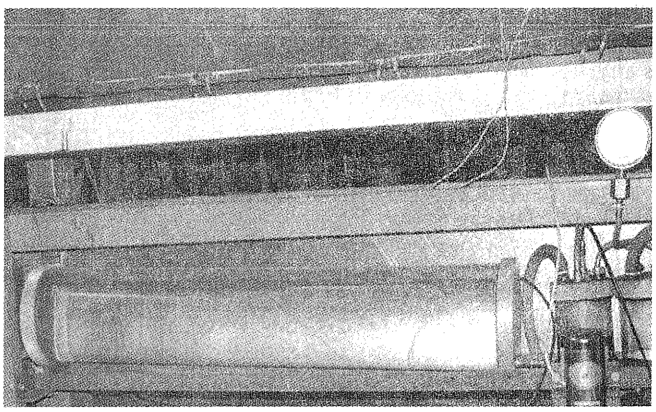
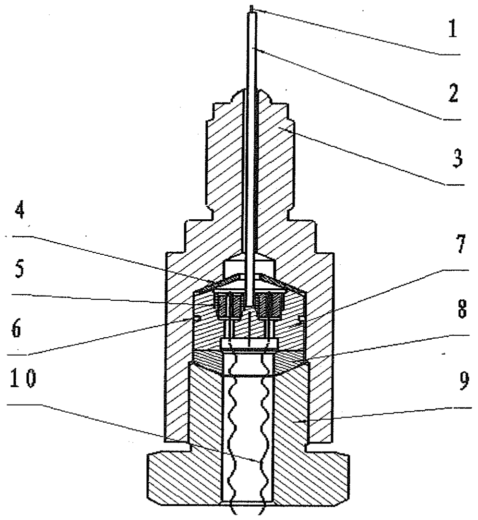


Fig. 7b Water circulation system

2.9 Velocity and Temperature Measurement System

The temperature and velocity of the deflagration wave are two important parameters in studying the explosives deflagration process. We all know that the explosive deflagration is an intense chemical reaction characterized by releasing a lot of heat and emitting light. If we put some sensors which are sensitive to heat or light into the explosives equidistantly, the reaction arrival times at different locations can be received. Thus we can receive the time interval during which the deflagration wave has traveled this distance. Then the average deflagration velocity over every space interval can be calculated.

Here we use the thermocouple as the thermal sensitive element to design velocity and temperature sensor. Therefore, we can not only acquire the temperature curves but also get the velocity value through analyzing and calculating this curve. The sensor's configuration is schematically shown in Fig. 8a. The true sensor used in our experiments is shown in Fig. 8b.



1. Thermocouple
2. Supporting pole
3. Joining bolt
4. Copper seal
5. Insulation plug
6. O-ring
7. Fixed bearing
8. Arc-shaped gasket
9. Compression nut
10. Conducting wire

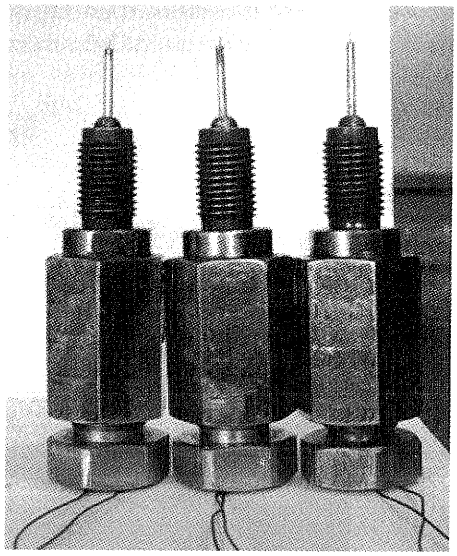


Fig. 8a Schematic of the configuration of the temperature sensor **Fig. 8b Temperature sensors used in experiments**

When designing this sensor, we must firstly consider the seal capability of the sensor, at the same time we must ensure the voltage signal transfer from the thermocouple successfully. This is not an easy problem. After having many attempts, the configuration described in fig.8a is used which can successfully settle this problem. The insulation plug is the key component of the sensor. It has a composite structure. The core of these plugs is a conductor which can serve as the base points to connect the each poles of thermocouple with conducting wires, while the other part around the conductor core is dielectric which can effectively separate the conductor core from the metal fixed bearing. Moreover, we should consider the dynamic response time and measurement deviation of the senor. Supposing the hot end of the thermocouple is sphere-shaped, the temperature deviation can be estimated by $\Delta T < \beta R^2 / 6\alpha$ [4], and the dynamic response time can be estimated by $t_{cr} < R^2 / 6\alpha$, where R is the radius of the sphere, α is the thermal diffusion coefficient and β is the temperature changing rate. In our experiments, we choose the K-type thermocouple with R=0.1 mm.

3 Experimental Measurement Results

The relationship between the temperature inside the slot and the heating time is shown in Fig. 9. If the slot being heated through the temperature loading system, its temperature will reach about 50 ℃ after 30 minutes. And if higher initial temperature is needed, more time should be used.

In order to examine the stability of the ignition device, we have conducted five times experiments in this experimental setup. In each experiment, the slot was filled with oil but not energetic explosives, so only the gas generated by the ignition device can make the pressure inside the experimental setup rise. The quantities of powders and the surrounding temperature are shown in Table 1. Fig.10 is a typical pressure curve of the ignition process. The average pressure over these five experiments is 91.1 MPa, and the maximum deviation is less than 5%.

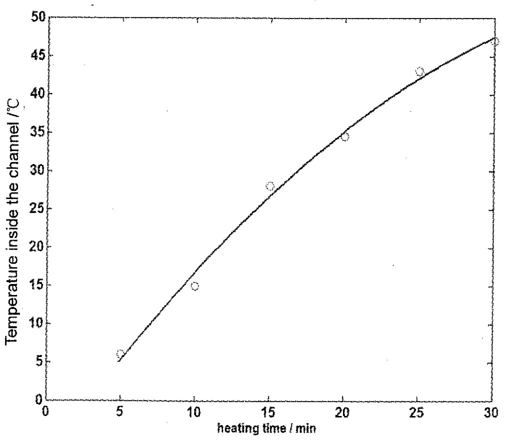


Fig. 9 Temperature inside the slot versus heating time

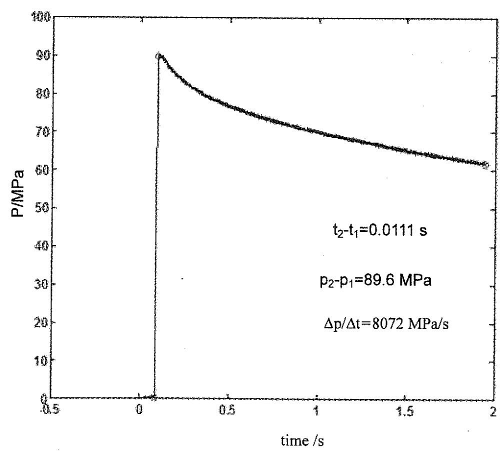


Fig. 10 Typical pressure curve of the ignition process

The function of the pressure adjustment device is let the pressure of the experimental setup beneath a scheduled level which can be controlled by the thickness of the brass sheet inside of it. Fig.11 is a typical pressure adjustment curve. From that we can see the maximum adjustment pressure is 232.8 MPa, under this condition the thickness of the used brass sheet is 0.85 mm. the final pressure is beneath 250 MPa, which can effectively protect the experimental setup.

Table 1 Surrounding temperature and the quantities of powders used in ignition experiment

number	Black powder mass/g	Thermal sensitive explosive mass/g	Initial temperature/℃	Initial pressure/MPa
t1	3.0	12.0	8.3	1.0
t2	3.0	12.0	9.0	1.2
t3	3.0	12.0	8.9	1.0
t4	3.0	12.0	9.6	1.1
t5	3.0	12.0	9.3	1.0

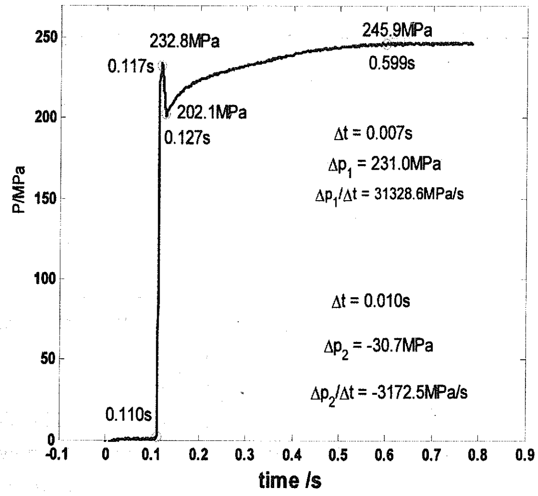


Fig. 11 Typical pressure adjustment curve

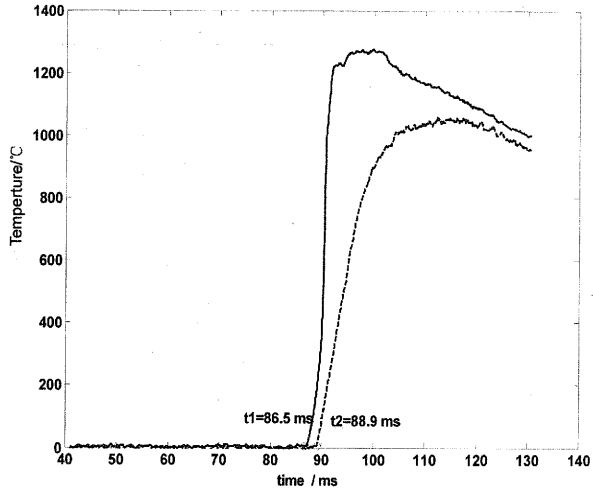


Fig. 12 Typical temperature curve of explosives deflagration

Fig.12 is a typical temperature curve of explosives deflagration in the slot. The maximum temperature is 1276 ℃. The distance of these two sensors is 10 cm and the deflagration reaching time interval is 2.4 ms, thus the average deflagration velocity over this distance is about 42 m/s.

4 Summary

In this paper, an experimental setup was introduced. At the experimental setup, we can have careful studies on the deflagration propagation capability of many kinds of energetic explosives under high temperature and high pressure conditions. The main measurement quantities are the temperature and the velocity of deflagration wave as well as the corresponding pressure in the narrow slot. At present, the experimental setup, as a basic laboratory tool, mainly serves for settling the basic problem arose from the technology of "explosion in fractures". We believe that the suitable explosives can be selected by using the experimental setup.

Acknowledgements

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