"2014 ISSST", 2014 International Symposium on Safety Science and Technology

Static experimental study on flame retardant and explosion suppression performances of fire resistant diesel fuel

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Abstract

To assess the flame retardant and explosion suppression performances of fire resistant diesel fuel, static experiments with ordinary diesel fuel (Diesel fuel 1, D1 for short) and fire resistant diesel fuel (Diesel fuel 2, D2 for short) detonated by explosives were performed in this study. The explosion process and surface temperature of the fireballs were recorded using a high-speed camera and an infrared thermal imager. Meanwhile, the overpressures of the explosion shock waves of the two diesels were also recorded using pressure sensors embedded in the ground. The experimental results show that the diesel fuels are dispersed and ignited to produce explosion fireball when explosive is detonated in fuel tank. At the same time, part of diesel fuel produces pool fire on the ground. The pool fire of D1 lasts about 3000 ms, while D2 lasting only about 700 ms. The maximum temperature and the duration of high temperature of D1 explosion fireball are 1558.8℃ and 1392 ms respectively, which are 1.11 and 1.29 times those of D2. In the position of 2 m far from the vertical projection point of the explosion center, the overpressure of the explosion shock wave of D1 is 53.30 kPa, while that of D2 is 31.60 kPa. Moreover, the overpressures of D1 are also higher in the other location of the pressure area. Therefore, it is proved that the explosive power of D2 is significantly lower than that of D1, and the flame retardant and explosion suppression performances of D2 is better than those of D1.
Keywords: fire resistant diesel fuel; explosion suppression; explosion fireball; explosion shock wave; overpressure;

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1. Introduction

Diesel fuel is widely used to power heavy vehicles, construction or weaponry machinery. Fire or explosion could be caused by accidents or artillery attacks on a fuel tank. Therefore, an important approach to improve the survival rate of onboard personnel and vehicles is the development of fire resistant diesel fuel, which is flame retardant and explosion suppressive.

It has been thirty or forty years since the study on fire resistant diesel fuel is carried out in the United States[1,2] and Russia[3] that several mature products have been developed. While not until recently research in this field has just begun in China. Moreover, correct evaluation of the flame retardant and explosion suppression performance is the key to the development of fire resistant diesel fuel, which is conducive to promoting the increase of research techniques of fire resistant diesel fuel.

A large number of experiments were carried out by the two leading countries in order to test the flame retardant and explosion suppression effects of fire resistant diesel fuel. However, these experiments were mainly combustion experiments or ballistic test. For example[4], during an Army research program in the mid-1980s, fire resistant diesel fuel that self extinguished when ignited by an explosive projectile was developed. The experimental results showed that an untreated fuel burned out of control in less than one second, while the fireball and the pool fire of fire resistant diesel fuel were suppressed. Lack of the experimental data of static experiments with a stationary fuel tank detonated by explosives justifies the necessity of static experiments in order to validate the combustion and explosion characteristics of fire resistant diesel fuel.

For obtaining the surface temperatures of explosion fireballs and the overpressures of the explosion shock waves of ordinary diesel fuel (Diesel fuel 1, D1 for short) and fire resistant diesel fuel (Diesel fuel 2, D2 for short) under the action of static energy, static experiments were performed in this study. According to the experimental data, a comparative analysis was carried out to assess the explosive characteristics and the flame retardant effect, serving the purpose of further improving the technology of fire resistant diesel fuel.

2. Experimental details

2.1. Experimental devices

- Detonation energy: composed of a fuse and the main explosive. A #8 industrial electric detonator serves as the fuse and 50 g of Hexal-3 high explosive with an explosive energy of 283.8 kJ serves as the main explosive.
- Fuel tank: a cylindrical fuel tank made of #20 steel with a volume of 50 L, which is Φ360 mm×500 mm in size and 2 mm in wall thickness.
- Fuel tank holder: steel, 800 mm in height.
- High-speed camera: APX model, Fastcam nltima (Japan). Its maximum frame rate is 12000 frame/s and the largest resolution is 1024×1024 pixels.
- Infrared thermal imager: 7200V model, MikronScan (the United States). It uses 320×240 microbolometer UFPA detector to receive the released energy.
- Pressure sensor system: an in-house system integrates with the piezoelectric pressure sensors of PCB Company's 113A21 series, 481A16 multi-channel of PCB Company, AC powered sensor signal conditioner, four channel data acquisition card of Chengdu micro measuring Co. Ltd, and connecting lines.

2.2. Experimental samples

- Diesel fuel 1 (D1): ordinary diesel fuel, which is the -10 military diesel fuel.
- Diesel fuel 2 (D2): fire resistant diesel fuel, the -10 military diesel fuel adds with 0.5 wt% polymer explosion suppressor and trace amount of antioxidant.
  The basic physical and chemical properties of the experimental samples are shown in Table 1.

Table 1. The basic physical and chemical properties of the experimental samples.

Experimental samples	Flash point(℃)	Density(g·mL^{-1})	Kinematic viscosity (20℃)(mm^2·s^{-1})
D1	84	0.794	3.93
D2	89	0.823	22.08

2.3. Experimental method

The closed fuel tank with 30 L experimental samples was placed vertically on a holder. The high-speed camera and the infrared thermal imager were arranged respectively in the positions of 25 m far from the vertical projection point of the explosion center. Four pressure sensors were set up at 2 m, 3 m, 4 m and 5 m respectively from the projection point. They were installed in the steel bases which were Φ220 mm×130 mm. The sensitive surfaces of the sensors leveled with the surfaces of the steel bases and the ground. The layout of the test site is shown in Fig. 1. The explosive is fixed in the vapor region inside the fuel tank (literature [5] had confirmed by experiments that detonating the vapor of diesel fuel would result in greater consequences than that of the liquid phase). While experiment samples were detonated, the high-speed camera, infrared thermal imager and pressure test system recorded the explosion process, the surface temperature of the explosion fireball and the overpressure of the explosion shock waves to the ground. The frame rate of the high-speed camera was 1000 frame/s and the infrared thermal imager sampled about every 33 ms.
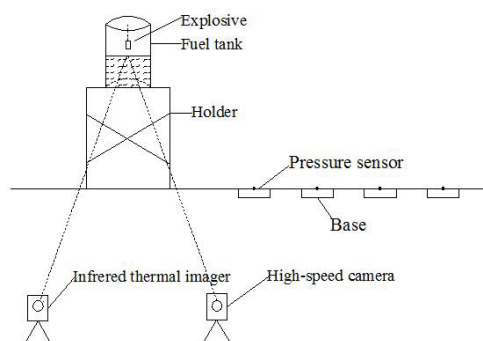

Fig. 1. The layout of the test site.

3. Results and discussion

3.1. Analysis of explosion process

Massive amounts of energy were released when the explosive was detonated. Explosion shock waves rendered the fuel tanks to deformation, rupture and decomposition. Part of the diesel fuel rapidly boiled, vaporized and ignited by the heat, forming a glowing and fuel-rich "explosive cloud"[6] (including detonation intermediates and some explosive components), which were manifested in the high-temperature fireballs. At the same time, diesel fuel ejected outward in the form of high-speed jets from the fuel tank being ruptured by the explosive products' expansion. Tens of milliseconds later, diesel droplets began peeling, smashing and volatilizing by shock waves and aerodynamic drag, then mixed with a lot of air and burn to maintain the fireball extension. At about 300 ms, with the increase of the contact area of air and diesel droplets, the air resistance increased, while the jet velocity and the fireball extension also rapidly decayed. The fireball temperature gradually decreased until the aerosols dispersed.

Fig. 2 shows a few typical photographs of two diesels at different explosion stages. At 0 ms, fireball forms with explosive detonation; at 50 ms, fireball is dazzling and bright. Because the strength of fuel tank cap is not enough, the explosive cloud jets upward at high speed under high pressure; at 200 ms, fireball diameter is very close to the

height, and fireball darkens gradually but still bright; at 400 ms, fireball burning significantly weakens while fireball surface in dark red. Experimental photographs show that part of D1 disperses on the ground forming a pool fire, which lasts about 3000 ms, while D2 lasting only about 700 ms, as shown in Fig. 2 at 1000 ms.
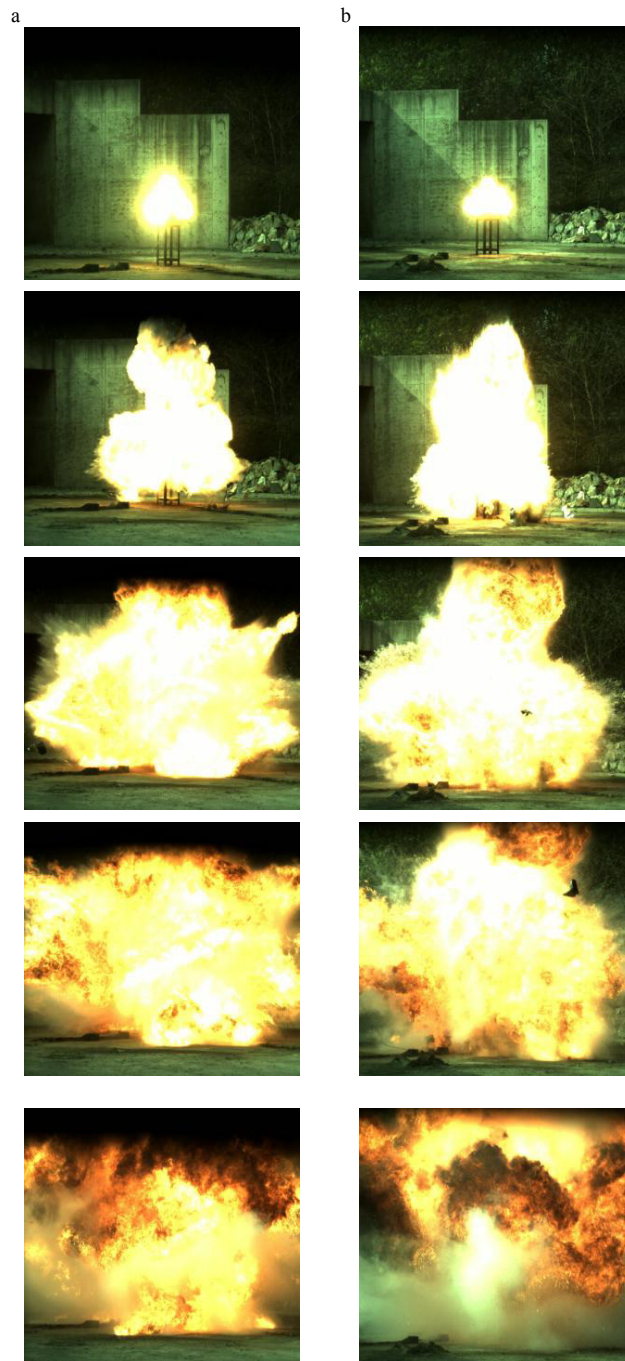

Fig. 2. (a) the experimental photographs of D1; (b) the experimental photographs of D2.

3.2. Surface temperature of fireball

The infrared thermal imaging system recorded the development of the surface temperatures of the fireballs. The change curves of the maximum temperature, the minimum temperature and the average surface temperature were obtained from the selected image area using the "MikroSpec" software. Surface temperatures of the two diesels are shown in Table 2, "t" is the duration of each temperature range. "T_m" is the maximum surface temperature of the fireballs. "T_n" is the minimum. "T_a" is average temperature of fireball when it reaches the maximum surface temperature. The change curves of the maximum surface temperature for the fireballs with time are shown in Fig. 3.

Table 2. Surface temperatures of fireballs.

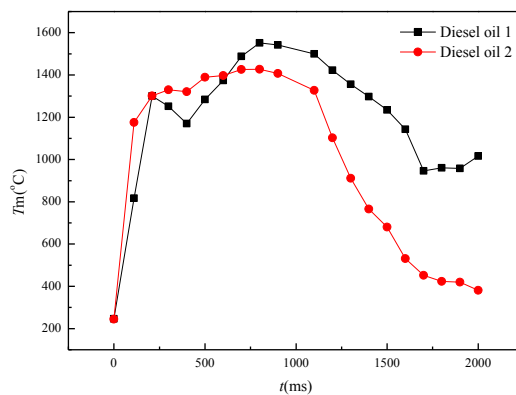| Experimental samples	t(ms)			T_m(℃)	T_n(℃)	T_a(℃)
	1000-1250 ℃	1250-1500 ℃	≥1500 ℃			
D1	340	792	260	1558.8	692.0	1222.3
D2	140	942	0	1435.0	658.2	1106.9

Fig. 3. The change curves of the maximum surface temperature for fireballs with time.

As shown in Table 2, the maximum temperature, the minimum temperature and the average surface temperature of D1 fireball are higher than those of D2. In terms of high temperature duration, the duration of the maximum surface temperature of D2 fireball above 1000 ℃ lasts for just 1082 ms, less than that of D1 fireball, which is 1392 ms. In general, surface temperature of D1 fireball is obviously higher, due to the higher viscosity of D2. The tension of the molecular chain of D2 causes tensile stress in high-speed dispersion, which resists the deformation of molecules[7,8], so D2 produces greater droplets in the process of dispersion[9]. Those big droplets did not adequately mix with air, and the intensity of combustion and explosion were decreased.

Fig. 3 shows that the maximum surface temperatures of fireballs of the two diesels vary with time within 2000 ms. The maximum surface temperature of D2 fireball is relatively stable in the high temperature range, while it begins to decline rapidly at about 1200 ms. The surface temperature of D1 fireball decreases slightly after it rises rapidly early in the fireball development, then increases rapidly to the maximum 1558.8 ℃. It is possibly that D1 has not been dispersed evenly under the influence of explosive products. As time goes on, the oil droplets burned more fully and fireball temperature continued to rise again.

The descending rate of surface temperature of D1 fireball is significantly less than that of D2. The surface temperature stopped falling at around 1700 ms and maintained at about 1000 ℃, indicating that pool fire of D1 maintained high temperature of the temperature field at this time. This indicates that the ability of sustainable burning of D1 is stronger, while D2 is easily self-extinguishing and the duration of pool fire is shorter.

3.3. Analysis of overpressure

High temperature fireball generated by the explosion of explosive source forms continuous pressure pulses (shock waves) in the surrounding medium in the process of expansion. Overpressure is that the pressure exceeds the ambient atmospheric pressure, which is generated when shock wave front propagates some point in the space.

The original waveforms of the explosion shock waves of D1 and D2 recorded by the pressure sensors at different locations are shown in Fig. 4.
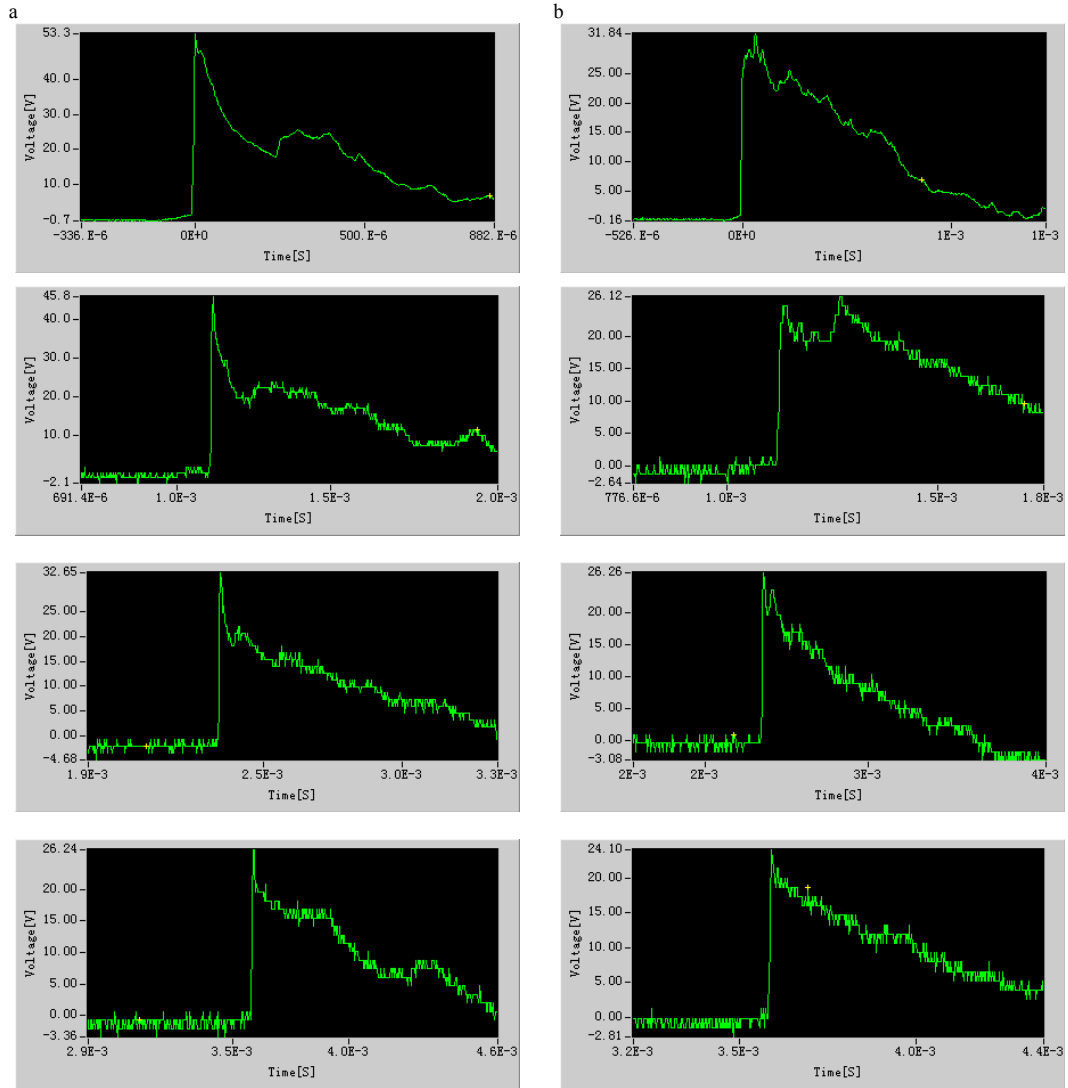

Fig. 4. (a) the original waveform of D1 at 2 m, 3 m, 4 m and 5 m; (b) the original waveform of D2 at 2 m, 3 m, 4 m and 5 m.

It is seen from Fig. 4, regardless of D1 or D2, the farther it is away from the explosion center, the more miscellaneous peaks of their overpressure curves are. It is indicated that the shock wave flow field is more complex because the speeds of fuel tank explosion fragments are higher than shock waves velocity in pressure area and these fragments pass through the air at supersonic speeds, forming ballistic shock waves, which are manifested overlap on

pressure curves varying with time in the many small pressure disturbances[10]. At the same time, because the fuel tank was on the holder, the shock waves with the axis of the fuel tank had an angle and the larger the angle was in pressure area, the greater impact of the overpressure measurement was.

The curve of the overpressure at 3 m in Figure 4(b) presents a bimodal structure, indicating that a secondary reaction that more violent than the first reaction is produced in the cloud. It is actually the process which oil droplets are breaking-up and being atomized between the first and the second peak[11]. The droplets of D2 are bigger under the action of explosion shock waves. A larger velocity variation is caused between the air flow and the droplets after the frontier shock waves pass through droplets, which make the air flow around the surface of the droplets to peel the oil droplets, thus the tiny fog droplets would produce in the tails of oil droplets. Moreover, they vaporize and burn rapidly to induce the explosion. Therefore, the reaction mechanism of the droplets of D2 contains the process of droplet deformation – breaking-up – partial explosion[12], which is different than that of D1. Due to the low viscosity, D1 would generate mist droplets and gasify rapidly. The deflagration reactivity would occur during the process of dispersion.

Voltage values of original waveform graphs can be converted to overpressure values by included data analysis software system. Overpressure values are shown in Fig. 5.
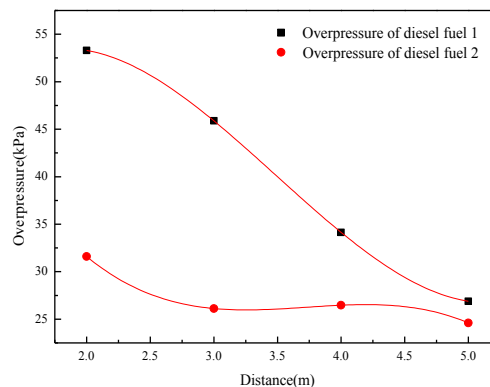

Fig. 5. Overpressures measured by sensors of different position.

Fig. 5 illustrates that all the overpressures of D1 are higher than those of D2 in the same position away from the explosion center, for example, the explosion shock wave overpressure of D1 is 53.30 kPa at 2 m, while that of D2 is 31.60 kPa. Due to the lower viscosity, easier to become fine mist droplets in the process of dispersion, bigger surface area, the explosive power value of D1 is greater than that of D2. The shock wave overpressures of two diesels also decrease with the increase of distance, but the overpressure decay rate of D2 is obviously less than that of D1, because part of the chemical energy that released by droplets of D2 in the droplet deformation – breaking-up – partial explosion process supplemented the frontier shock waves and delayed the decay speed of the shock waves.

4. Conclusions

In this study, static experiments of D1 and D2 were carried out in the experimental field. The maximum temperature, the minimum temperature and the average surface temperature of D1 fireball are higher than those of D2. Moreover, the duration of the maximum surface temperature of D1 fireball above 1000 ℃ is greater than that of D2 fireball. All the explosion shock wave overpressures of D2 are less than those of D1 in the same position away from the explosion center. The results illustrate that explosion property of D2 is poorer than that of D1, which is due to the higher viscosity of D2. The higher the viscosity of the fuel is, the bigger the grain diameters of the dispersion droplets are. At last, it is difficult for the combustion of the droplets.

Acknowledgements

This work is supported by International S&T Cooperation Program Major projects fund (Grant No.2013 DFR60080), Ministry of Science and Technology of the People's Republic of China.

The authors are grateful to WANG Xiwei, YANG Ke for their keen help throughout the course of this study.

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