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Microexplosion of Three-Phase Diesel-Methanol-Water Emulsion Spray

DONGYIN WU[1,*], WUQIANG WANG[1], HONGZHI SHENG[2] and JI YAO[1]

[1]School of Energy & Power Engineering, Xi'an Jiaotong University, No. 28, Xianning West Road, Xi'an, Shaanxi, P.R. China
[2]Institute of Mechanics, Chinese Academy of Sciences, 100080 Beijing, P.R. China

*Corresponding author: Fax: +86 29 82667806; Tel: +86 29 82663910; E-mail: dongyinwu@mail.xjtu.edu.cn

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The development processes of the diesel-methanol-water emulsion sprays have been observed by a high-speed CCD camera at different temperatures and pressures. It is found that in the range of this experiment, the higher the ambient pressure the more beneficial to the occurrence of microexplosion. In the range of adequate temperatures, there is greater intensity of microexplosion. If the temperature is too high or too low, the microexplosion is very difficult to take place. At the same time, the delay of the microexplosion will decrease with the increasing ambient temperature. In this paper, using the high-speed CCD photography technology, we have verified that at an appropriate temperature and pressure, the microexplosion will inevitably take place in the three-phase diesel-methanol-water emulsion sprays. At different places all around the emulsion sprays, group microexplosions can be observed repeatedly. The microexplosion is able to greatly expand the spraying area.

Key Words: High-speed CCD camera, Emulsion, Sprays, Group microexplosion.

INTRODUCTION

The microexplosion of the two-phase diesel-water emulsion sprays has been experimentally verified[1-3]. The effect of microexplosion of the two-phase diesel (gasoline)-water emulsion, also termed "secondary atomization", improves the combustion and burn-out of the emulsion fuel. At the same time, due to the evaporation heat absorption of water in the emulsion, the temperature in the combustion area is decreased. This is conducive to the inhibition of NOx emission. The emulsion is, as a result, an ideal alternative fuel of the energy-saving and environmental-protection type.

Many researchers have done a large amount of fruitful work on the microexplosion of the emulsion to account for some physical phenomena in the process of microexplosion through experimental and theoretical studies[4-6]. In recent years, the three-phase emulsion which consists of diesel, methanol and water has attracted a great deal of attention. This is due to the fact that since methanol is an oxygenated fuel, its emission is relatively clean and moreover, it has an extensive source, it can be obtained from natural gas, coal, biomass, *etc*. The application of such emulsion is particularly suitable for regions which are rich in coal but deficient in petroleum. Obviously the study of alcohol-containing emulsions is of great significance. Nevertheless, the study of phenomena and characteristics of microexplosion of the three-phase diesel-methanol-water emulsion still needs experimental support as not much is reported therein.

The microexplosion of the two-phase diesel-water emulsion sprays was verified using the multi-pulsed ruby laser holography[3]. However, the whole system is very complicated because the multi-pulsed ruby laser holography needs to be closely matched with the multi-pulsed ruby laser mode, the holographic light path and synchronization trigger circuit, *etc*. Since the holocamera can only shoot a transient image, the successful rate of image-taking is low and additionally, the whole spray process can not been observed. There are few reports of using the dynamic laser holography to study the microexplosion of the emulsion sprays. With the advances in digital photography, the high-speed digital camera has been widely used in the study of microexplosion of the emulsion sprays because of its advantages of easy operation, convenient image processing and visualization. It is the former Soviet Union scholars, Ivanov and Nefedov[1] that proposed, at the earliest, the microexplosion investigation using the high-speed photography. Segawa *et al*.[7], observed the combustion and microexplosion of the *n*-hexadecane and water emulsion droplet under the microgravity condition by use of the high-speed photography. Mizutani *et al*.[8], successfully observed the microexplosion in the emulsion droplets in the sprays flame by using the schlieren optical system matching with the high-speed photography. In addition, many other researchers have successfully observed the microexplosion of emulsions using the high-speed photography and obtained satisfactory results[9-15]. In this paper the high-speed CCD photography is used to investigate the development processes of the emulsions diesel-methanol-water sprays and further confirm and analyze the microexplosion.

EXPERIMENTAL

The water-in-oil type emulsion, which consists of diesel, methanol and water, was tested in the present experiment. The mass fraction of diesel, methanol, water and emulsifier is about 69, 10, 20 and 1 %, respectively. The emulsion was prepared by ultrasonic emulsification. It is approximate to the Newtonian fluid in which the diesel acts as a continuous phase and methanol and water act as a dispersed phase[16].

Fig. 1 illustrates the schematic diagram of the high-speed photography experimental system. The entire system is composed of the liquid supply and injection system, constant volume combustion bomb (CVCB), control system, data acquisition and processing system, high-speed digital CCD camera *etc.*[17]. As shown in Fig. 1, the CVCB is designed to simulate a high temperature and pressure environment. A pair of quartz glass observation windows with a diameter of 120 mm are placed on the opposite side walls for optical access. The CVCB is filled with high-pressure nitrogen to form a high-pressure environment. Within the CVCB, the resistance wires uniformly placed at the external cylindrical part of the CVCB heat the nitrogen inside to form a high-temperature environment in a heating mode with an extreme temperature (873 K) and pressure (5.0 MPa). The ambient pressure and temperature of the CVCB are recorded by the spring-type pressure gauge and thermocouples, respectively. The fuel injection system consists of the fuel supply system, speed regulation motor, high-pressure fuel pump, injectors and so on. The high pressure fuel pump, which is of the B series completed with of 6135 type diesel engines, is driven by a motor whose rotational speed can be regulated. A crank angle encoder which is capable to give pulse signals in the set phase is installed on the driving shaft of the high pressure fuel pump. In the present experiment, the rotational speed of the speed regulation motor is set at 750, 550, 500 and 300 rpm separately. This equals to the working condition that the four-stroke diesel engine operates at the speed of 1500, 1100, 1000 and 600 rpm separately. The injector for the 6135 diesel engine is used as the injector. According to the experimental requirements, a diesel nozzle with a single orifice 0.34 mm in diameter ordered from the manufacturer is installed on the upper wall of the CVCB.

During the experiment, it is needed to implement synchronization of the high-speed CCD camera, single injection pump and data acquisition system. The entire experimental system is controlled by a TP801B type single board computer (hereinafter referred to as "SBC"). The time sequence of the control process is as follows. When the injection pump, optical path, data acquisition and processing systems as well as the high-speed digital camera enter into the standby mode of the normal working, the SBC starts and enters into the state waiting to trigger signals.

Subsequently, the high-pressure oil pump is started up by pressing the manual button. When the pump rotates to an appropriate phase, a crank angle encoder on the driving shaft will send the signals to trigger the SBC. The trigger circuit of the SBC can send two positive pulses. One pulse makes the electromagnet pick up and then actuate the high-pressure injection pump plunger, so as to allow the fuel pump to achieve

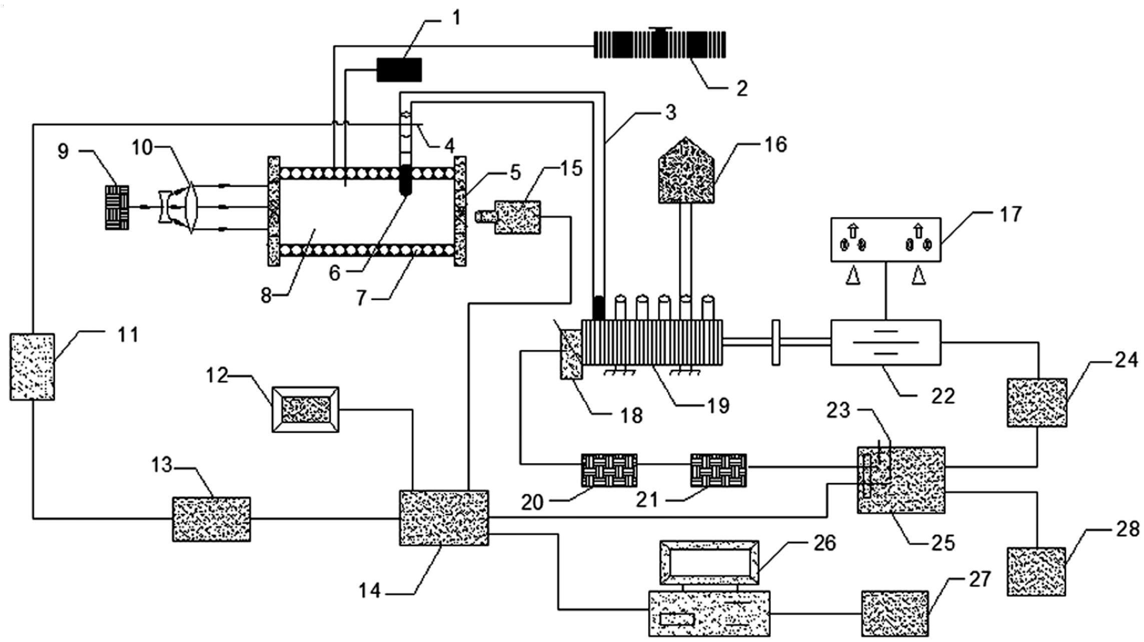


Fig. 1. Schematic diagram of experimental system. 1. Thermometer; 2. Voltage thermoregulator; 3. High pressure fuel tube; 4. Pressure sensor; 5. Quartz observation window; 6. Nozzle; 7. Heater; 8. Constant volume combustion bomb; 9. He-Ne laser; 10. Beam expander collimator; 11. Charge amplifier; 12. Monitor; 13 Multi-channel data link; 14. Mainbody of high-speed digital camera; 15. CCD camera; 16. Fuel reservoir; 17. Speed regulating device; 18. Throttle; 19. High-pressure fuel pump; 20. Electromagnet; 21. Control circuit; 22. Motor; 23. Trigger switch; 24. Subscript generator; 25. TP801B single board computer; 26. Computer; 27. Printer; 28. Manual trigger

a single or multiple injections; the other pulse triggers the data acquisition and processing system and high-speed CCD camera to record the experimental data. After the set injection is completed, the electromagnet is reset, the high-pressure injection pump stops and the data acquisition and processing system ends operation, waiting for the next work cycle. The time sequence of work is shown in Fig. 2.

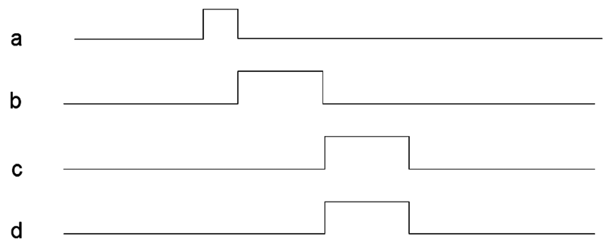
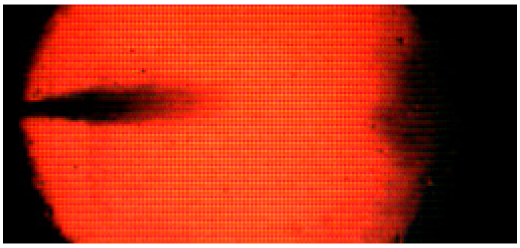


Fig. 2. Experimental process of the work of timing. a. Subscript signal; b. Trigger signal of single board computer; c. Suction signal of electromagnet; d. Trigger signal of high-speed camera and data acquisition system

The development process of the three-phase diesel-methanol-water emulsion sprays was obtained at different motor speeds (750, 550, 500 and 300 rpm, respectively), different ambient temperatures (373, 573, 673 and 773 K, respectively) and ambient pressures (0.1, 1.1, 2.1 and 3.1 MPa, respectively) in this experiment. For simplicity, only part of experimental results of high-speed CCD photography is presented to analyze the microexplosion of the three-phase diesel-methanol-water emulsion sprays in the high pressure and temperature environment.

Figs. 3-6 show the development processes of the diesel-methanol-water emulsion sprays, in the spray time from 0-1.5 min at a 0.5 min interval, at the ambient pressure of 3.1 MPa and temperature of 373, 573, 673 and 773 K, respectively. The shooting speed of high-speed camera is 2000 fps, the nozzle injection pressure is 20 MPa and the rotational speed of the injection pump is 750 rpm. In the following are given the plots of the development process of the sprays within 1.5 min. The process is recorded from the moment when the timing starts up as soon as automatic spraying appears in the field of view.



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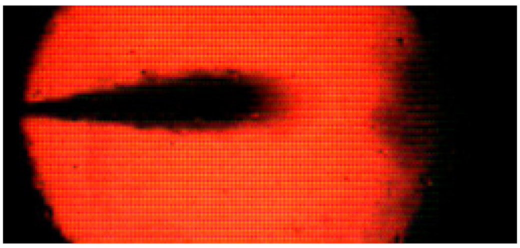

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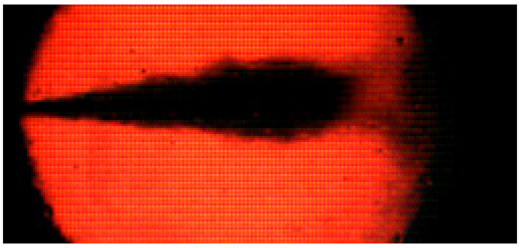

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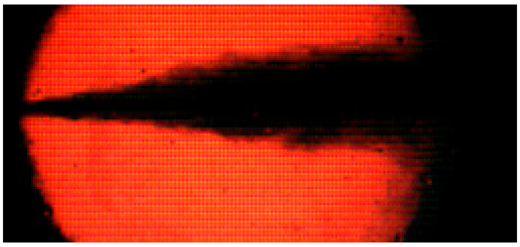

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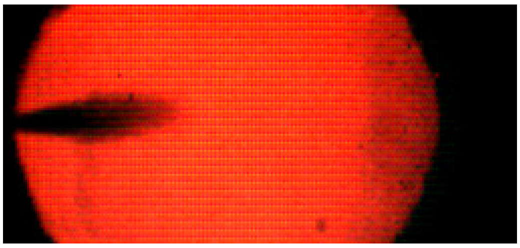
Fig. 3. Development process of the emulsion spray at ambient temperatures of 373 K and ambient pressure of 3.1 Mpa



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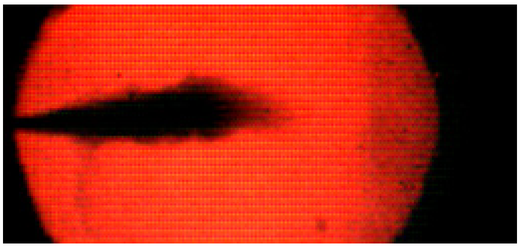

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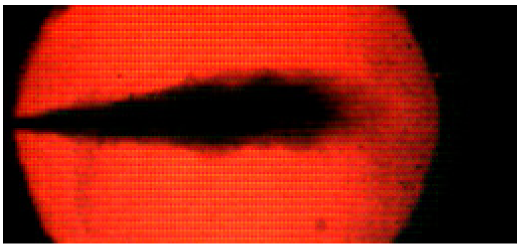

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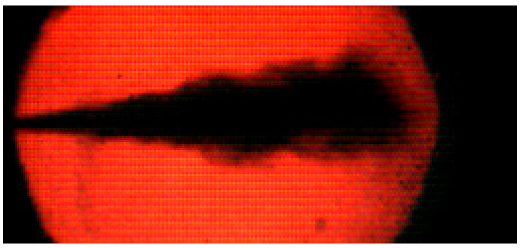

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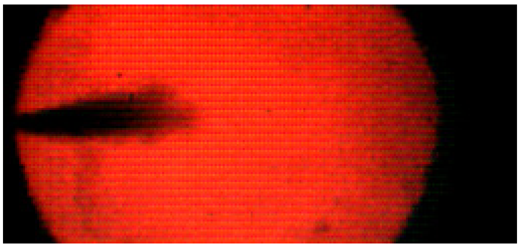
Fig. 4. Development process of the emulsion spray at ambient temperatures of 573 K and ambient pressure of 3.1 Mpa



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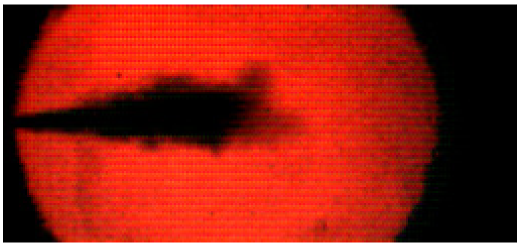

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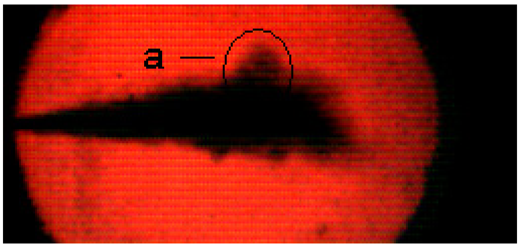

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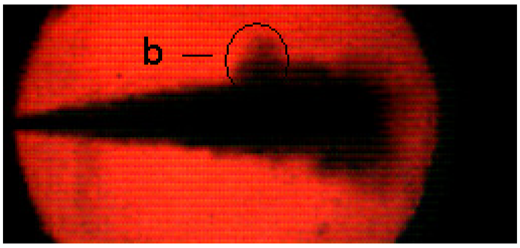

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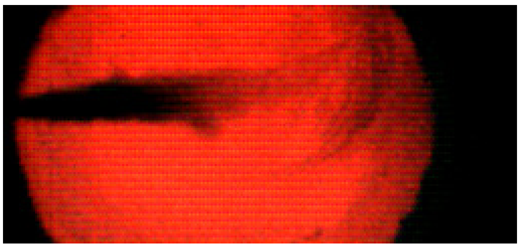
Fig. 5. Development process of the emulsion spray at ambient temperatures of 673 K and ambient pressure of 3.1 Mpa



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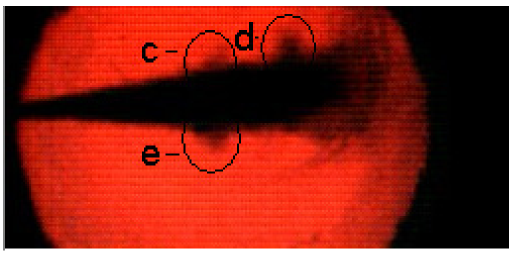

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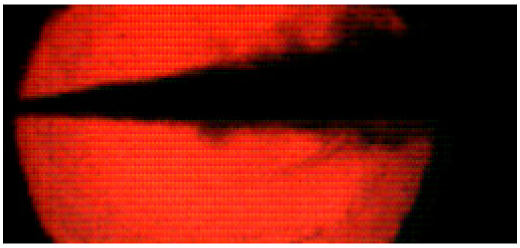

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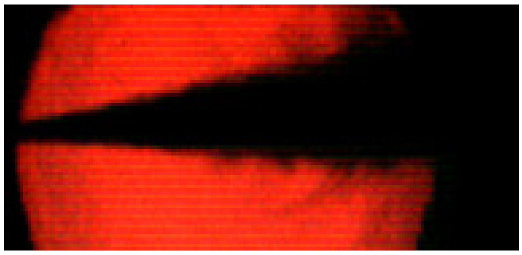

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Fig. 6. Development process of the emulsion spray at ambient temperatures of 773 K and ambient pressure of 3.1 MPa

RESULTS AND DISCUSSION

Compared with the spray snapshots shown in Figs. 3-6, it is found that the microexplosion of three-phase emulsion would happen under high temperature and pressure conditions. The results are similar to those of the two-phase diesel and water emulsion sprays observed previously through multi-pulse laser holography[3]. The experiments further confirm that the ambient temperature and pressure have greater impact on the occurrence of microexplosion of the emulsion sprays. The higher the ambient pressure, the more profitable for the occurrence of microexplosion of the emulsion sprays. The microexplosion of three-phase diesel-methanol-water emulsion sprays inevitably occurs at an appropriate ambient temperature and pressure. The microexplosion is in the lump fashion also termed "group microexplosions". The phenomena of "group microexplosions" for the three-phase emulsion sprays will be analyzed according to the experimental results.

Microexplosion temperature range: The three-phase diesel-methanol-water emulsion spray is of the water-in-oil type and its spray jet is formed of many droplets. Diesel (oil phase), as the continuous phase, is in the outer layer of droplets and a certain number of methanol and water tiny droplets (water phase), as the dispersed phase, are contained within droplets. When the spray stays in the high temperature and pressure environment, there is a droplet temperature gradient as the droplet temperature increases. Since the boiling point of the "water phase" is lower than that of the "oil phase", water and methanol in the thin layer on the surface of the emulsion droplets will evaporate first. When the evaporation of water and methanol in the thin layer on the surface of the emulsion droplets is ended, a "none-water layer" on the droplet surface is formed. Then, the droplets continue to absorb heat. Due to the presence of a "none-water layer", the "water phase" within droplets cannot evaporate in time so that the "water phase" temperature rises rapidly. After the temperature of the "water phase" within the droplets rises, the motion is speed up. The tiny moving droplets collide with each other resulting in forming larger droplets. The probability for forming large droplets through mutual collision is greater than that for splitting into tiny droplets from large droplets. Finally, it is possible to form one or several droplets with a relatively large volume. As soon as the pressure of a larger droplet after evaporation exceeds the sum of the ambient pressure and surface tension when the temperature reaches the superheat limit of "water phase" and the homogeneous nucleation of "water phase" within droplets, the "water phase" vapour will tear up the "non-water layer" and then the microexplosion results. The microexplosion process has a certain delay which is associated with a vast number of factors such as ambient temperature and pressure, boiling point of water and methanol, latent heat of vaporization, droplet diameter and so on.

From Figs. 3-6, it is clear that when the ambient pressure is 3.1 MPa and the ambient temperature in a suitable range, the microexplosion of three-phase diesel-methanol-water emulsion sprays may occur, thus resulting in an obvious "protuberance" of the spray boundary and expanding the spray area. The delay and intensity of microexplosion are different at diverse ambient temperatures.

It is indicated in Figs. 3 and 4 that as the ambient temperature range is from 373-573 K and the water and methanol do not reach their boiling points of 3.1 MPa so that water and methanol on the droplet surface cannot evaporate rapidly, the "non-water layer" is not formed and water and methanol within the droplets can not reach the superheat limit. In this case there is no microexplosion in droplets. So the spray boundary is smoother in appearance.

As shown in Fig. 5, in the temperature of 673 K, due to a lower ambient temperature, it is required for tiny droplets within the water and methanol droplets to take a delay in order to grow into large droplets and reach the superheat limit by absorbing heat. So there is a microexplosion only in the later period of spraying as the delay for microexplosion is relatively long. Most methanol and water tiny droplets remain in the droplets due to an earlier formation of the "non-water layer" and consequently the probability of forming bigger vaporizing droplets of methanol and water is larger and so are the corresponding vaporation pressure and the intensity of microexplosion. There are noticeable protuberances on the spray boundary. As shown in Fig. 5, there is larger protuberance on the spray boundary, that is, the "group microexplosions". The mechanism for forming "group microexplosions" will be dealt as below.

In Fig. 6, there are three relatively apparent protuberances at the upper and lower boundary in the spray snapshots of 0.5 min when the ambient temperature is relatively high. The protuberances are attributed to the "group microexplosions". Of them, in the front side of the upper boundary of the spray snapshot, there are relatively distinct protuberances with a greater intensity, indicating the early stage of the microexplosion process (Fig. 6d). In the front side of the upper and lower boundaries of the spray snapshot, there are protuberances with weaker intensity, showing the later stage of the microexplosion process (Fig. 6c-e). At the moment of 1 min, the above mentioned protuberances (*i.e.*, group microexplosions) gradually evaporate with the volume lessened. At the moment of 1.5 min, there are still traces on the boundary of the spray, which results from the continuous evaporation of the fragments cast from the above group microexplosions. The lower boundary of the spray is relatively smooth. Apart from the reason that the fragments cast from the group microexplosions in the early stage of the spraying have been evaporated completely, there are still three other reasons as follows:

(1) In the later stage the methanol and water tiny droplets cannot form larger droplets in motion due to the steep temperature gradient within droplets. Meanwhile, a number of tiny droplets cannot exist as superheated water. When the outer layer water is in the superheated state, a small amount of methanol and water vapor cannot overcome the surface tension and ambient pressure to tear up droplets so that it is only able for them to tear up some tiny gaps of the droplets causing some tiny droplets to leak into the air and the microexplosion does not happen, as a consequence.

(2) In the later stage of spraying, only part of water and methanol is likely to participate in the microexplosion. There is a greater frequency of microexplosion and the intensity is weaker as well. Moreover, there is a relatively long delay of microexplosion. The weaker microexplosion effect results in a smaller number of the fragments flying off the boundary area of the spray. The fragments evaporate rapidly in the high-temperature environment. So the boundary of the spray still appears to be smoother.

(3) The occurrence of the microexplosion of emulsion droplets requires a certain droplet diameter. If the diameter is too small, the droplets may evaporate rapidly at a high ambient temperature. In this case, it is very hard to invoke microexplosion.

Consequently, the occurrence of the droplet microexplosion requires an ambient temperature in the adequate temperature range. If the ambient temperature is too low (Fig. 3), there will be no droplet microexplosion. If the ambient temperature is too high (as shown in the later stage in Fig. 6), there is a lower probability of the occurrence of microexplosion. Even if the microexplosion takes place, the strength remains weaker.

Impact of ambient pressure: As shown in Figs. 3-6, the experiment was conducted at an ambient pressure of 3.1 MPa and the spray snapshots in an ambient pressure of 2.1 MPa, 1.1 MPa and atmospheric pressure were also obtained in the experiment. It is found that a high ambient pressure is conducive to the occurrence of microexplosion of the emulsion droplets. This is because when the ambient pressure rises, the difference of boiling points between the components of the emulsion increases and the accumulation of energy is large during microexplosion and therefore the intensity of microexplosion is also high.

Place of group microexplosions and microexplosion: It can be seen from the images of high-speed photography that microexplosion of three-phase diesel-methanol-water emulsion is lump fashion at the high temperature and pressure. The volume of microexplosion region indicates that this is not the outcome of the action of a single tiny droplet, but that of the common action of a couple of droplets. This is due to the fact that in the spray there are several micro-groups composed of a larger number of tiny droplets whose heating and moving process are similar to each other. If a tiny droplet within a micro-group triggers a microexplosion, this may provide impetus to the "chain" explosion of other droplets within the micro group. So a number of tiny droplets are subjected to microexplosion in the lump form, termed "group micro-explosions". The continuous "group microexplosions" may substantially increase the volume of the spray. This phenomenon not only verifies the viewpoint that there is a "group microexplosions" in the two-phase emulsion spray in the environment of high temperature and pressure[3], but also confirms the existence of "group microexplosions" in three-phase diesel-methanol-water emulsion sprays at the high temperature and pressure in this experiment and moreover, there is a multiple "group microexplosions". It can be confirmed that whether the two-phase diesel-water emulsion sprays or the three-phase diesel-methanol-water emulsion sprays is concerned, the "group microexplosions" of the sprays will take place inevitably so long as the conditions are suitable.

The microexplosion occurs in the area of the outer layer of sprays where there is a higher temperature. The shadow images obtained in this experiment are two-dimensional projections of the spray, which only provide the microexplosion information of the boundary on two sides of the spray. So it can be predicted that a number of microexplosions will take place in a number of places around the entire spray. This means that a number of microexplosions arise in the entire spraying process at different moments and places.

Affecting area of microexplosion: As shown in Figs. 5 and 6, under the condition that the temperature ranges from 673-773 K and the ambient pressure is 3.1 MPa, the size for the microexplosion group projecting from the spray boundary is about 7-10 mm, which has already reached 1/3 to 1/2 of the radius of the spray in the place. So the continuous "group microexplosions" can greatly increase the volume of the spray. This phenomenon can make mutual authentication with the conclusion arrived at by the laser holography of the two-phase diesel-water emulsion. It is observed in the holography that at the same temperature and pressure, the fragments of tiny droplets tore up by microexplosion will fly for a distance of 5-7 mm[18]. As seen from the continuous high-speed photographic images of the three-phase diesel-methanol-water emulsion, the visible region is gradually reduced and subsequently disappears along with the evaporation of the fragments of droplets.

When judging from the spray images of the diesel and water emulsion at the normal and high temperature, it is impossible to get a clear boundary contour of the gas phase with the shadow method because of the lower density of the fragments farther from the explosion center. It is, therefore, difficult for the fragments of tiny droplets after rapid evaporation during explosion to leave traces on the high-speed photographic images. It can be inferred that the effect of the increase of the spraying area caused by actual microexplosion is definitely greater than the results displayed on the images and the effect of "secondary atomization" is relatively distinctive instead.

Comparison with laser holography: Laser holography can provide details of the microexplosion of the emulsion sprays. However, it only provides some transient information in the injection process rather than the whole process of the injection. It, consequently, misses opportunities to capture the microexplosion so that the successful rate is not high. Furthermore, even if the microexplosion is captured, it is impossible to track and obtain all trajectories of the fragments during microexplosion, thus resulting in a smaller observed spray area extended by microexplosion.

On contrary, high-speed CCD photography can provide all the information of the progress of microexplosion of the spray. The observation of the macro impacts and the entire process is one of the effective means to study the micro-explosion of the emulsion spray. From analyzing a vast number of high-speed photographic images, it can be concluded that a number of "group microexplosions" take place in the entire development process of the three-phase diesel-methanol-water emulsion spray.

Moreover, in each injection, there are microexplosions in the range of appropriate temperature and pressure and a larger scope of the spray area expended by the microexplosion. This is impossible for the experiment with the laser holography. While the resolution of the images obtained with the high-speed photography is impossible to distinguish micro details of the tiny droplet fragments and the blasting center after explosion, it is able to observe the macro impacts and the entire process and the successful rate is higher than the laser holography as well.

Conclusion

The development process of the emulsion diesel-methanol-water sprays was observed by a high-speed CCD camera and a lot of snapshots of three-phase diesel-methanol-water emulsion sprays were obtained at different ambient pressure and temperature. Experimental results show that the ambient temperature and pressure have greater impacts on the microexplosion of the emulsion sprays. The higher the ambient pressure, the more beneficial to the occurrence of microexplosion. In the range of the suitable temperature, the intensity of microexplosion is relatively high. If the ambient temperature is too high or too low, the microexplosion is difficult to happen. Even if the microexplosion happens, its intensity will be very weak. The experiments show that the microexplosion of three-phase diesel-methanol-water emulsion sprays will inevitably occur at suitable temperatures and pressures and the microexplosion is in the lump form, termed "group microexplosions" and there are multiple microexplosions in different moments and places of the entire development process of sprays.

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