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The Droplet Group Micro-Explosions, Viscosity and Atomization Characteristics of W/O Emulsions

Hongzhi Sheng, **Xiaobo Li**, **Xiaolin Wei and Dongyin Wu**

Division of Engineering Sciences, Institute of Mechanics, Chinese Academic of Sciences, hz_sheng@imech.ac.cn

ABSTRACT The spray of emulsified fuel, composed of diesel fuel, water and methanol can make micro-explosion under high temperature conditions, and the viscosity and the atomization characteristics of emulsion have significant effects on the micro- explosion of emulsions.

To clarify the combustion mechanism of water-in-oil emulsion sprays, combustion bomb experiments were carried out, and the droplet group micro- explosions in W/O fuel emulsion sprays in a high-pressure, high-temperature bomb were observed clearly by a multi-pulsed, off-axis, image-plane ruby laser holocamera and continuously by a high-speed CCD camera.The viscosity and atomization characteristics of emulsions were also studied experimentally. The experimental results show that the higher concentration of the aqueous phase (water-methanol) (<50%) increases the viscosity of the emulsions, especially for higher agent concentration, and higher aqueous phase concentration and higher viscosity results in lager Sauter Mean Diameter (SMD). The experiment results also show that the different kinds of emulsifying agents, with different Hydrophile-Lipophile Balance (HLB) values, have significant influence on the viscosity of the emulsions.

Keywords: Emulsion, Micro-explosion, Viscosity, Atomization

1. INTRODUCTION

The emulsified fuel made of diesel, water and methanol is a kind of clean fuel with lower soot and NOx emissions. Recently, much attention has been paid to the preparation and use of water-in-oil (W/O) emulsified fuels with/without stabilizer, to improve the engine efficiency and exhaust emissions, or as safety fuels [1-4]. Micro-explosion of water-diesel system was firstly observed in 1965 [5]. This phenomenon is so called “secondary atomization”. Micro-explosion can improve the mixing and combustion process in macro- and micro-scales, and reduce the flame temperature for better NOx emission, due to high latent heat of added water and methanol. Many questions cannot be well answered by the existing knowledge, since previous fundamental research on emulsions mainly emphasized droplet micro- explosion at room pressure and the results from engine tests were often contradictory.

Which is the key factor controlling the emulsified fuel combustion, micro- explosion? Do micro-explosions take place in diesel engine cylinder where the ambient temperature and pressure are very high? What are the detailed features of the explosion in spray combustion? The interaction of droplets in sprays, the droplet size, the ambient pressure, and the heating history have significant effects on the combustion process, so the micro-explosion in dense emulsified sprays under diesel engine combustion conditions needs further study for clarifying these issues.

In order to evaluate the potential energy saving by the use of emulsified fuels on a large scale, research was started several years ago to understand the mechanism of the micro-explosion in sprays and its application in engines. In order to link the broken chain between droplet combustion and engine application for emulsions, experiments in a combustion bomb, dynamical engine tests, combustion modeling, emulsion fuel characteristics and theoretical work were carried out [6, 7 and 8].

The "lump-fashioned" droplet group micro-explosion (in earlier publications, droplet group micro-explosion was called “lump-fashion micro-explosion”) and a no-water layer in emulsion droplets were observed in the bomb by a multi-pulsed ruby laser holocamera and continuously by a high-speed CCD camera. The advantage of laser holocamera is that it can take very high resolution and shows many details of the droplet group micro-explosion. The high-speed CCD camera can provide the movie of whole process, even though the resolution is limited. The combination of laser holocamera and the high-speed CCD movie give us clear information of micro-explosion. The observations also show that the explosions were strong enough to expand the spray region and speed up flame propagation.

As known, combustion process of the liquid fuel depends fully upon the atomization and spray characteristics in many applications, and the atomization and spray of fuel depend upon the viscosities and surface tension in many cases. And the emulsion preparation, the property and the quantity of emulsifying agent, and the quantity of water in the emulsion may have significant influence of on the viscosities and surface tensions of emulsions. According to our investigation, there are no enough research results to indicate the physical properties of emulsion, such as viscosity and surface tension of diesel, water and methanol emulsions. To clarify the viscosity and atomization characteristics of emulsions, the experiments for water- methanol and diesel emulsions were carried out and reached some useful conclusions.

2. MICRO-EXPLOSION IN SPRAY UNDER DIESEL ENGINE CONDITIONS

The early fundamental research was focused on the combustion of either isolated droplets or arrays of single droplets (h=0.3-1.0mm) suspended on quartz filaments or fine thermocouples under atmospheric pressure. Since the suspending filaments may be particularly detrimental to the study of combustion characteristics of evaporating emulsions, a droplet generator was employed to generate small droplets floating in an upward heated gas stream [9]. The size of the dispersed phase in emulsion may affect micro-explosion [10]; the higher cylinder pressure may suppress the occurrence of micro-explosion [11]. The theoretical work was also carried out based on the experimental results, even for a multi-compound liquid.

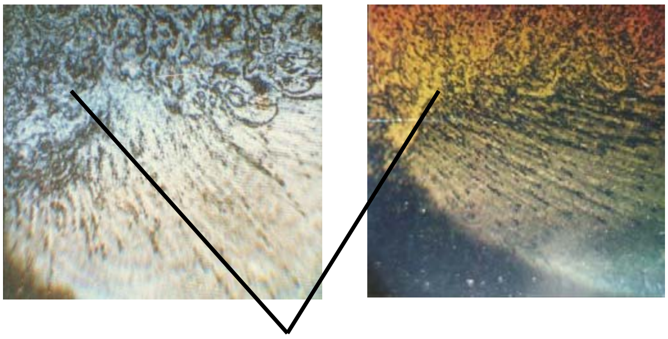
2.1 Laser Holography and High-Speed CCD Camera

Previous work on fuel spray research emphasized the spray, penetration and entrainment using hot-wire anemometer, particle tracing, high-speed photograph, single-flash photography, instantaneous microphotography, schlieren photography, shadowgraph, Fraunhofer diffraction particle analyzers, and single-pulsed Gabor laser holography. However, these methods cannot measure the droplet velocity and trajectory and the micro-explosion of the micron-sized, fast moving particles in sprays, since the measurement needs very high resolution in a large field of view.

To observe the very weak diffraction from small moving droplets in a spray inside the high-pressure bomb, by a multi-pulsed, off-axis, ruby laser holocamera [6-7] and a high-speed CCD camera, the testing conditions simulate the cylinder pressure and temperature.

2.2 Droplet Group Micro-explosions in Emulsion Sprays

The droplet group micro-explosions take place in eddy scale near the outer layer of the emulsion sprays. Figure 1 taken at different moments show various strengths of the micro-explosions. Series studies show that the ambient temperature has the most important influence on the occurrence and violence of the micro- explosion. Figure 2 shows micro explosion captured by high speed CCD photography. Comparing with Figure 1 and Figure 2, it can be sure that the group micro-explosion takes place in W/O sprays. And Figure 2 also shows the micro-explosion takes place several times during every spray process if the condition is proper, which cannot be observed by holography since the holography can make a few pictures during the spray process, and some micro-explosions cannot be captured. The droplet group micro-explosion is strong enough to eject fragments of torn droplets to a distance several millimeters away from the spray boundary at much higher speed, and rapidly evaporated, greatly expanding the spray zone and improving air-fuel mixing.



Micro-Explosion Center

Fig 1 the droplet group micro-explosion (high-speed laser holography, very lager magnification)

Fig 2 partial process of droplet group micro-explosion (high-speed CCD movie)

The coherent structure of spray and the eddies were observed by off-axis, ruby laser holography in 1980s[6], perhaps the droplet group micro-explosion occurs mainly in the turbulent eddy in which the droplets more or less have homogeneous size, similar heating history, and superheated state. If a droplet is exploding, the pressure wave may induce all the droplets in the same eddy to explode, an avalanche of micro-explosions of droplet group. Different eddies have different superheated histories, so the explosions are also very different from one to another. The explosion region is near the spray head and outer layer, where the gas temperature is high enough and the droplets go through sufficient heating time to be superheated. No explosion was observed in the spray core with higher density and lower temperature.

If the ambient temperature is not high enough (733 K in the test), the water dots (internal phase of W/O emulsion) in the droplets will not be superheated and will evaporate and vanish before being heated into superheated state, and no micro-explosion takes place. If the ambient temperature is proper, all the water dots in droplets rapidly go over the saturation temperature (523.5 K at 4.0 MPa) and into s superheated state, a pseudo-stable state, and vaporizes and explode at the same time when the outer water dots achieve the limit of superheat (583 K at 4.0 MPa). This tears up the droplet and greatly expands the spray region. If the temperature is too high (823 K), the heat transfer between gas and droplets is strong enough, some water dots near the outer layer are over the limit of superheat, but central water dots are not in superheated state in this case, the explosion occurs earlier and closer to the injector, and the violence of explosion is not very strong since all water dots do not explode at the same moment.

The torn droplets fly much faster in a lower gas density, causing a larger flame angle and stronger micro-explosions. If the gas density is constant, gas pressure may have little effect on explosion violence. The injection pressures between 18 and 24 MPa have little effect on atomization and micro-explosion of emulsions.

3. VISCOSITY AND ATOMIZATION CHARACTERISTICS OF EMULSIONS

The spray of emulsified fuel, composed of diesel fuel, water and methanol (DWM), can make micro-explosion under high temperature conditions. And the viscosity and the atomization characteristics of emulsion have significant effects on the micro-explosion of emulsions. So the rheology and atomization of the emulsions (DWM), was studied experimentally. The Span 80 and Tween 60 are employed to make three emulsifying agents Y01, Y02 and Y03, the agents Y01 and Y02 are approximately Newtonian fluids, and Y03 is a Newtonian fluid. All the emulsions are Newtonian fluid, in which the percentage of the water phase is in the range of 10% and 50%, the concentration of emulsifying agent added is 0.8~8.0%, and the viscosity is 0.004~0.02 Pa•s.

The emulsion mainly studied here is a kind of water-in-oil (W/O) emulsion, made of the water phase and the oil phase. The water phase here means water and methanol, since the two components are soluble. The water and oil phase are insoluble, so the additives were employed as emulsifying agents to obtain stable emulsions. The HLB value can describe the property of the agents, lower HLB value (3~6) is easy to form W/O emulsion, and higher HLB value (8~18) is easy to form O/W emulsion. Three compound emulsifying agents Y01, Y02 and Y03 with HLB values of 5.36, 4.83 and 4.51 respectively, were prepared for the experiments, by mixing Span 80 (HLB=4.3) and Tween 60 (HLB=14.9). The emulsion made by the agents can be kept for more than three months at room temperature, without deformation and break up, since the agents used make strong interfacial membrane between two phases.

The rheological characteristics and viscosities of three agents are shown in Fig.3. The Y03 has highest viscosity and is a Newtonian fluid, but Y01 and Y02 are approximately Newtonian fluid. The viscosity of Y03 is 1.5 Pa•s, about380, 1500, and 1200 times of that of diesel fuel, water and methanol, which are and 0.004 Pa•s, 0.001 Pa•s and 0.00123 Pa•s, respectively. The viscosities of Y01 and Y02 are 88% and 92% of Y03, when the shear rate is faster enough during the test.

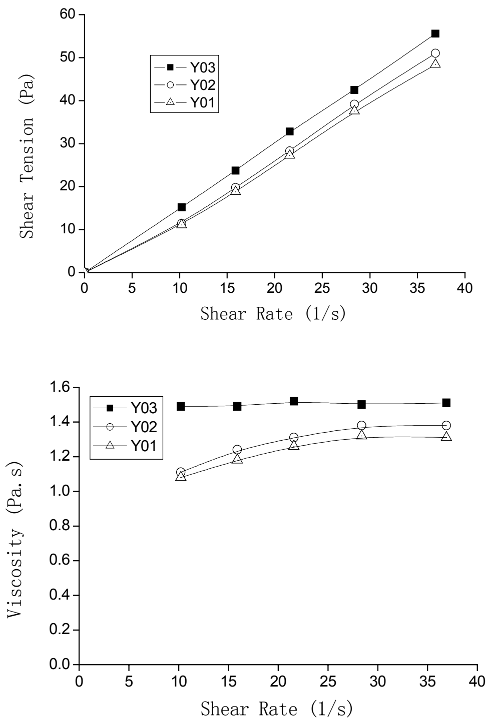


Fig.3 Rheological Property and Viscosity of Three Emulsifying Agents

3.1 The Rheological Property of Emulsions

Three compound emulsifying agents mentioned above were employed to prepare the emulsions, 5 percentages of each three agents are applied as following: 0.8%, 2.0%, 4.0%, 4.8%, 8.0%, the percentage of the water phase is in the range of 10% and 50%, the diesel fuel, water and methanol concentrations in the emulsions are listed in table 1, where the capital letters D, W, M and the following digitals stand for the percentages of the diesel fuel, water and methanol in the emulsions in weight. For example, D80W10M10 means 80% of diesel fuel, 10% of water, and 10% of methanol in the emulsion:

Table 1 The Diesel fuel, Water and Methanol Concentrations in the Emulsions

D90W5M5	D80W10M10		D70W15M15	D60W20M20	D50W25M25
			D70W20M10		
D90W10	D80W20	D75W25	D70W30	D60W40	

Because the diesel and water/methanol are put together at first and the agents are added later, so the concentration of the agents cannot be marketed in this naming system. An ultrasonic facility was employed to make the emulsions.

The rheological characteristics of the DWM and DW emulsions are measured, and the results show that all the two sorts of emulsions appear as Newtonian fluids, but not the pseudo-plastic fluid. The detailed figures for rheological properties are shown in reference [8,13].

Each data point shown in the following figures is an average of 5 measurements and averaged for 5 different shear rates, since the emulsions are Newtonian fluids. From the figures, the followings are clearly:

The viscosities of the emulsions are in the range of 0.004 and 0.02 Pa•s. when the emulsion has little emulsifying agent and water phase in it, the viscosities of the emulsions are little higher than that of diesel fuel, but when the water phase concentration is near 50% and the agent concentration is more than 4.8%, the viscosities of emulsions is about 4 to 5 time of that of diesel fuel and 20 times of that of water. In this case, the atomization and mixing process of emulsions will be different form that of diesel fuel, which will be mentioned later.

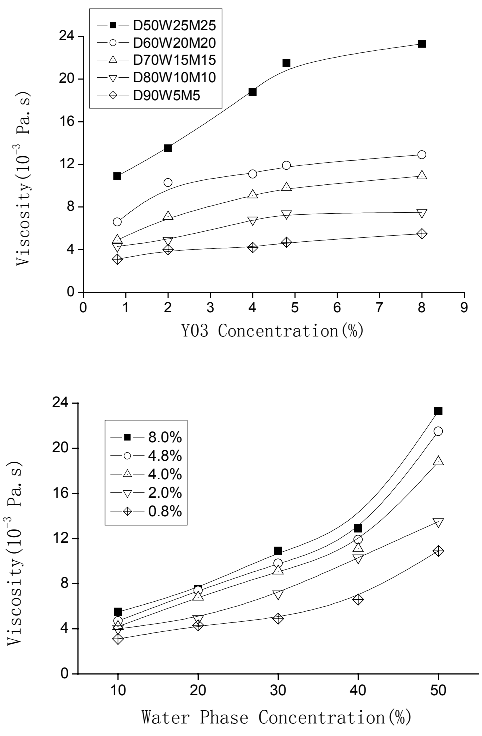


Fig.4 the Viscosities of DWM Emulsions with Y03.

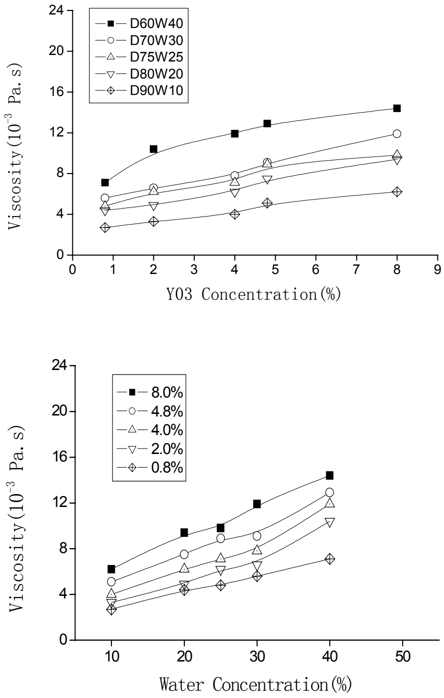


Fig.5 the Viscosities of DW Emulsions with Y03

The viscosity of emulsifying agent with different HLB values has significant influence on the viscosity of the emulsion; even through the agent concentration is very little. Increasing the agent concentration will greatly increase the viscosity of emulsion if water phase concentration is more than 40%. If the water phase concentration is less than 30%, there is no significant influence on the viscosity of emulsion.

Figure 4 shows the viscosity of DWM emulsions with Y03. The viscosity of the agent Y03 is only 14% higher than that of Y01, but the viscosity of emulsion with 8% of Y03 is 40% more than that with 8% of Y01, when water phase concentration is more than 40%. It is true that, if the water phase is as much as oil phase in volume, the agent plays a more important role for the viscosity of emulsions.

If fixing the ratio of water to methanol and the agent concentration, the viscosities of emulsions are increasing with increasing water phase concentration. Is the water phase concentration is higher than 40%, the trends of viscosities of emulsions with less than 2% of the agents are different from that with more than 4% of the agents. In this case, the viscosity increases gently with the water phase concentration increasing, if the agent concentration is lower. It is shown that the emulsifying agents play a very important role for changing the viscosity of emulsions, especially for higher water phase concentration.

3.2 Atomization Characteristics of Emulsions

Atomization of emulsions was performed by Series 150435 pressurized nozzle made by Shanghai Diesel Engineer Ltd., and it consists of four apertures of 0.34mm Diameter. Operating pressures was set on the value of 31MPa, 29 MPa, 25MPa, and 22MPa respectively. Series 2600 Malvern separator-size analyzer was applied to measure the distribution of the sizes of emulsion droplets in Spray at room temperature and pressure.

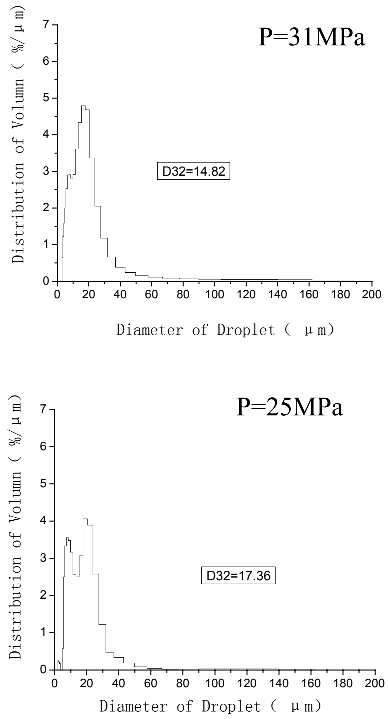


Fig.6 SMD Distribution of D70W20M10 with Y03

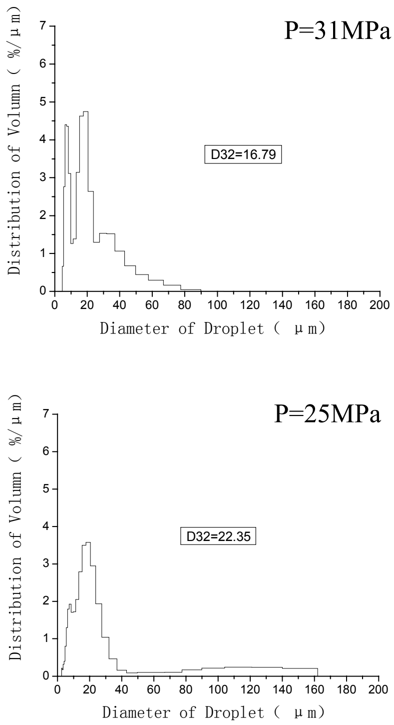


Fig.7 SMD Distribution of D50W30M20 with Y03

The distributions of SMD of two kinds of emulsions with different agent under different operating pressures are shown in Figure 6 and Figure 7, and the distribution of SMD of diesel is shown in Figure 8 for comparison. The SMD of emulsions with different water concentration is shown in Figure 9.

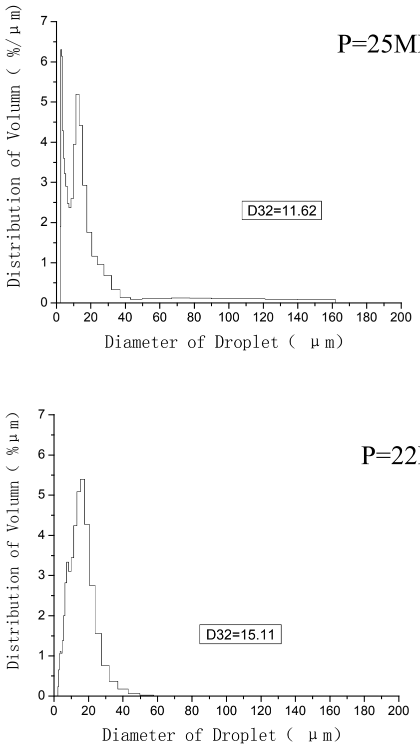


Fig.8 SMD Distribution of Diesel

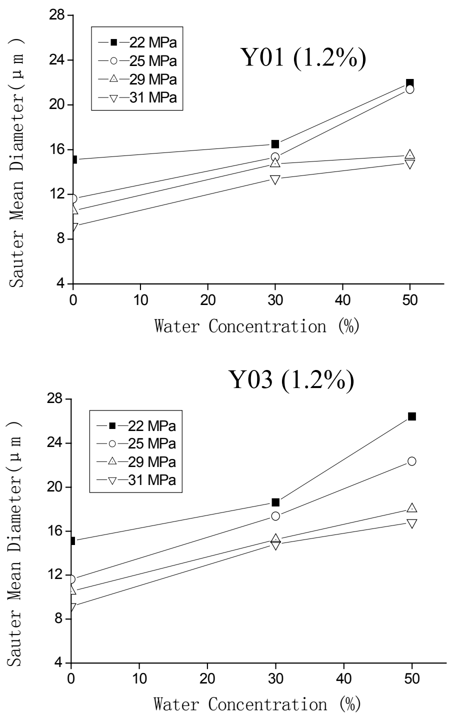


Fig.9 SMD of Emulsions with Different Water Concentration

The experimental results show that the surface tension and viscosity of the emulsion is closed to that of diesel fuel, but the SMD of emulsion droplets is larger than that of diesel droplets, and the injection pressure, the content and the viscosity of emulsions have significant effects on the SMD of emulsions droplets. When the injection pressure increasing, the SMD of emulsions decreases very much, and the SMD increases when the aqueous phase fraction increasing, if the injection pressure is constant. When a little ore viscous emulsifying agent with lower HLB was employed, the SMD of emulsions is much larger. It suggests that the interfacial condition and the agents between dispersed phase and continuous phase plays a very important role on SMD.

4. CONCLUSIONS

According to the experimental studies for micro-explosion and the characteristics of emulsions fuel, it is clearly that the droplet group micro-explosion takes place several times during every spray process if the condition is proper, which captured by high speed CCD camera. The droplet group micro-explosion is strong enough to eject fragments of fuel droplet to a distance of several millimeters away from the spray boundary at very high speed, which greatly expands the spray boundary, spray angle, improves air-fuel mixing.

The viscosity, surface tension, and atomization characteristics of emulsions have very important influences on spray characteristics. The higher concentration of the aqueous phase (<50%) increases the viscosity of the emulsions, especially for higher agent concentration. Interfacial membrane and HLB values of the agents can explain all these phenomena. Higher aqueous phase concentration and higher viscosity results in lager Sauter Mean Diameter (SMD). The different kinds of emulsifying agents, with different HLB values, have significant influence on the viscosity of the emulsions.

5. ACKNOLEDGEMENTS

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