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A Review on Micro-Explosion Phenomena in Water-in-Diesel Emulsion Fuel

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ABSTRACT

Water-in-diesel (W/D) emulsion fuel is the potential alternative fuel that could fulfill the world's needs: more efficient energy usage and less polluting emission. It is capable to improve the combustion efficiency of a diesel engine and reduce harmful exhaust emission, especially nitrogen oxide (NOx) and particulate matter (PM). A micro-explosion phenomenon is the key to the improvement of those measurements. It defined as the secondary atomization of the initial spray as a result of the rapid evaporation process of water that is initially contained in an oil drop. Fuel droplets exploded and tear into fine particles, leading to increase the air-fuel mixing process, thus promotes to better combustion. Numerous studies have been conducted experimentally and numerically in order to observe and investigate the behavior, onset and strength of the micro-explosion process, which include single droplet on hot plate, fine wire in the hot furnace, spray flame in the burner and bomb experiments techniques. Factors that affect the onset and the strength of micro-explosion are the size of the dispersed water particle, droplet size of the emulsion, water-content in the emulsion, ambient temperature and ambient pressure.

Keywords:
Combustion efficiency, diesel engine, exhaust emission, micro-explosion, water-in-diesel emulsion fuel

1. Introduction

The need for more efficient energy usage and a less polluted environment are the prominent research areas that are currently being investigated by many researchers worldwide. Water-in-diesel emulsion fuel (W/D) is a promising alternative fuel that fulfills such requests in that it can improve the combustion efficiency of a diesel engine and reduce harmful exhaust emission, especially nitrogen oxide (NOx) and particulate matter (PM). The term emulsion is a mixture of two or more immiscible liquids which are unblended in nature, one present as dispersed droplet throughout the other liquids which present in continuous phase. The dispersed droplet is called internal phase (water), and the other liquids is the external phase (diesel fuel) [1,2]. Generally, in the emulsion fuel production process, the percentage of water being added to the mixture is between 5-40 %. The

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emulsion is formed by the help of mechanical agitation together with the chemical additives so called surfactant to keep the immiscible liquids being tied together forming one solution. Example of surfactant that widely used by researchers and expertise is Span 80 [3] and normally the percentage of surfactant that added in the mixtures is between 0.1-2% .The W/D emulsion fuel can be used directly to the diesel engine without required any modification on the engine [3]. A popular aspect of W/D emulsion fuel is the micro-explosion phenomenon, which is a special occurrence that intrigues researchers worldwide as it is nonexistent in the normal diesel combustion process in a diesel engine. In addition, this phenomenon is the main factor that brings to the improvement of the combustion efficiency and reduction of harmfull exhaust emissions. This paper reviews the micro-explosion phenomena consisting of fundamental of the occurrence of micro-explosion process, recent advance in micro-explosion studies and factors that influence the onset and the strength of micro-explosion in diesel engine.

2. Fundamental of Micro-Explosion Process

The micro-explosion process was first discovered by Ivanov and Nevedov [5] in 1965. They reported that the suspended droplets of residual W/O emulsion underwent a spontaneous explosion during the combustion and suggested that this phenomenon be called micro-explosion. Subsequently, this phenomenon has attracted considerable research interest worldwide to explore and investigate in more detail. There are a variety of explanations to describe the micro-explosion process. However, all of them reflect the same meaning. Micro-explosion is the secondary atomization of the initial spray as a result of the rapid evaporation process of water that is initially contained in an oil drop [6]. For a specific description, the water in the emulsion fuel is located in an inner phase of the emulsion. As the emulsion fuel is sprayed into a high temperature environment, such as the combustion chamber, the heat will be convected to the surface of the emulsion droplet. However, the volatility and boiling temperature of water and diesel liquids are different in nature. Due to the finite diffusion velocity of a liquid, the diesel fuel will cover the surface of the droplet, surrounding and keeping the dispersed water droplet inside. Once the temperature of the water inside the emulsion droplet reaches to the superheat temperature, rapid bubble nucleation occurs resulting in the expansion and explosion of the whole droplet. Thus, tearing up the droplet into very fine particles [3,4,7-12]. Consequently, more surface area of the fine droplets can be exposed to the air leading to an improvement in the fuel and air mixing process. As a result, the combustion efficiency will increase [11].

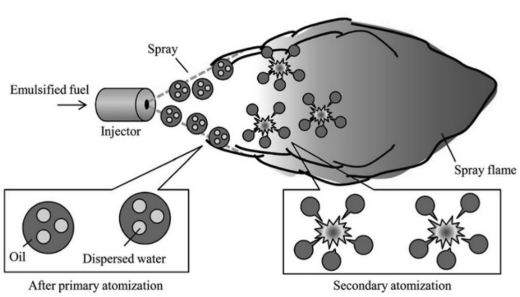

Fig.1. Schematic diagram of the occurrence of micro-explosion process [4]

Figure 1 displays the schematic diagram of how the micro-explosion process occurs. According to W.B. Fu [7], the micro-explosion is usually violent due to the great energy storage of the nucleation. Sheng *et al*., [12] reported that, from their observation of flame characteristics, the flame angle of W/D emulsion fuel is much wider and the flame is much larger than that of neat diesel fuel. This is due to the effect of micro-explosion during the combustion. Furthermore, the presence of glowing spots was observed in the emulsion flame, but unnoticed for neat diesel flame. This is believed to be caused by rapid vaporization of water in the emulsion. The water is expected to rapidly become superheated steam after being introduced into the combustion chamber leading to the occurrence of the micro-explosion [13].

3. Current Approaches in Micro-Explosion Studies

Numerous studies have been conducted to investigate the micro-explosion phenomena ever since it was first discovered. Different kinds of approaches have been explored by researchers and experts in understanding the occurrence, behavior, and fundamentals of the micro-explosion process. Some studies use the single droplet method to investigate the occurrence of the micro-explosion process [4,14]. Generally, in the single emulsion droplet method, the droplet is put on a hot plate in which the temperature can be measured and controlled, and then the vaporization process of emulsion and the occurrence of the micro-explosion is captured by a high-speed camera and presented as a shadowgraph. A high speed Charge-Coupled Device (CCD) was used to capture the time resolved shadowgraph of the droplet during heating [15]. One study used different hot plates (stainless steel and aluminum) to determine the evaporation time of the droplet [14]. Instead of using the heating surface technique, Watanabe *et al*., [4] used the fine wire technique to study the breakup characteristic of the secondary atomization. Figure 2 shows the schematic diagram of an experimental setup for the fine wire technique. The droplet is suspended from the fine wire and inserted into the electric wall furnace with the temperature wall at 973 Kelvin. The onset of micro-explosion was captured by a high speed camera and the thermal history inside the droplet is recorded by the data logger. The fine wire used is a ceramic fiber wire. Another study varied the pressure to determine the effect of pressure on the onset of the micro-explosion process [16].

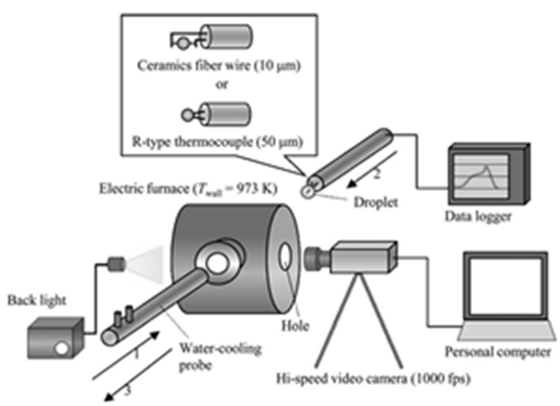

Fig. 2. Schematic diagram of experimental setup for fine wire technique [4]

In other research, the effect of multiple droplets arranged in one-dimensional arrays with various droplet spacing, number of droplets and surrounding temperature on the micro-explosion behavior was also explored [10]. The observation of the micro-explosion process in the flame and combustion characteristic is also the favored approach studied by researchers and experts. The occurrence of micro-explosion in the spray flame that was tested in the burner was observed and recorded in the optical system called a simple Mie scatter imaging system and high speed video camera [17]. A study has tested this in the bomb experiments using a high speed multi-pulsed ruby laser holographic camera with image plane optical path [12]. Other than experimental studies, many numerical researches have been conducted, predicting the onset, behavior and strength of the micro-explosion [7,18]. W.B. Fu *et al*., [7] modeled a general model of the micro-explosion that predicts the onset and strength of micro-explosion by considering various parameters, such as water percentage, droplet size, dispersed droplet size, and ambient pressure and temperature. In addition, the authors concluded that the general model agreed with the experimental studies. Unlike the numerical modelling created by Zeng *et al*., [18], the numerical model of micro-explosion consists of two parts. The first part addresses the bubble growth, mass and temperature inside the droplet. The subsequent bubble growth leads to the explosion. The bubble generation process is described by the homogeneous nucleation theory. The second part of the model determines when and how the explosion process occurs. The authors claimed that the developed model was first used to study the effects of the various parameters on the onset of micro-explosion after it is validated against the experimental data for bubble growth and homogeneous nucleation.

4. Factors Influences the Onset and Strength of Micro-Explosion

Variety of the onset and strength of micro-explosion may give different impact and effectiveness of W/D emulsion fuel to the diesel engine. The onset of the micro-explosion is defined as the time period from the time fuel is injected until the micro-explosion starts to occur. Although no measurement can define the strength of the explosion, it is being done by comparing the explosion of the droplet, breaking and ejecting away into fine particles as presented in the shadowgraph. This section discusses the factors that influence the onset and the strength of the micro-explosion process.

4.1. Size of Dispersed Water Particle

The size of the dispersed water particle may affect the strength of the micro-explosion, which has been revealed by many researchers. Nicholas *et al*., [19] tested different mean water particle sizes of W/O emulsion ranging from 2.1 micron to 4.5 micron. The result shows that the 4.5 micron water particle shows the most crucial explosion. The increasing particle size results in an increase in the ability of emulsified water to disperse the oil droplet. According to the authors, if the water is distributed throughout the oil in very small particles, the droplet only experiences a weak explosion. Plus, only a few fuel fragments are ejected from the primary droplet. Consequently, after the last of the water is evaporated, the droplet still remains but has lost little of its heavy component. This finding agrees with W.B. Fu *et al*., [7]. From the author's micro-explosion modelling, the strength of micro-explosion is calculated to be weak if the water particle is too small. Plus, only weak expansion and puffing occur. However, the authors stated that, if the particle size is too big, too much water will evaporate, and, thus, insufficient residual water is left. Thus, it will affect the strength of the explosion. Furthermore, Mura *et al*., [20] reported that from their experimental finding, the optimum dispersed water droplet size is 4.7 microns. After this point, the strength of the explosion begins to fall. Figure 3 shows the comparison of the explosion by using a different dispersed droplet size. The 4.7 micron meters dispersed droplet size (A) shows a rapid and strong explosion compared to the 17.4 micron meter size (B). In addition, if the dispersed droplet size is too big, the coalescence phenomenon is predominant [15].

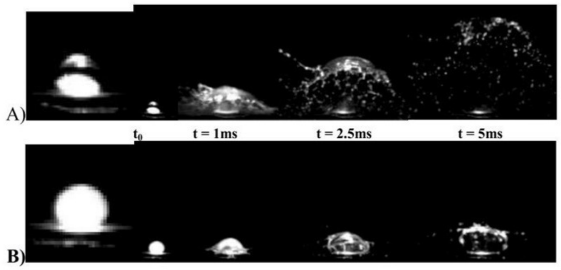

Fig. 3. Sequence of micro-explosion using different dispersed droplet size: A) 4.7 micron meter, B) 17.4 micron meter [20]

4.2. Droplet Size of the Emulsion

The droplet size of the emulsion during the spray of fuel into the combustion chamber also influences the strength of micro-explosion. If the initial droplet is too small, the residual water mass is too low or will vanish even before the droplet is heated up to the saturation temperature leading to form a weak micro-explosion [18]. The onset of the micro-explosion process is also affected by the initial emulsion droplet size. With the increased droplet size, the micro-explosion occurs relatively earlier. This is due to mass fraction difference of the centre and the surface which is larger for bigger droplet. Thus, the superheat region is easier to be formed, resulting in the micro-explosion to occur relatively earlier [10]. In addition, some study reported that micro-explosion will not occur if the droplet is too small due to high difficulty to form a sufficient thick oil membrane. Plus, based on the numerical calculation from the micro explosion modelling, the minimum of droplet size should be at least twice bigger than the size of the dispersed droplet [7].

4.3. Water-Content in the Emulsion

The percentage of water in the emulsion does have an influence on the onset and the strength of the micro-explosion. From the study reported, if the water content is too small in the emulsion, resulting in less storage energy of nucleation, thus forming weak micro-explosion [7]. From the experiment conducted by Jeong and Lee [10], the authors observed that when the water content in the emulsion is higher, the intensity of the micro-explosion seems to become vigorous and the duration of the explosion is elongated. According to the author, this is due to the flame becoming normal after making a lump when the micro-explosion is finished. However, some studies Sheng *et al*., [12] found that water ranging from 8-12% has no significant influence on the violence of the explosion. The authors added that, maybe, 8% of water already has enough energy storage to experience micro-explosion. In another study, it is found that the onset and the intensity of the micro-explosion can be enhanced by increasing the water content to a maximum value of 30% [21]. However, in the experiment conducted by Sheng *et al*., [12], if the water content is too large, it will lead to a negative effect. According to the author, if the initial diameter of the emulsion is held constant, the emulsion with larger water content will lose more water due to the existence of a vortex and no-water layer, leading to lower surface temperature. Furthermore, with large water content in the emulsion, more water evaporation is needed to form an oil membrane, and, consequently, will lead to only a small amount of water remaining in the droplet. This indicates that there is optimum water content in gaining the high energy storage inside the droplet. With the increase in water content to the optimum value, the violence of the micro-explosion can be increased, resulting in smaller fragments and shorter burnout-time after the onset of the micro-explosion [7].

4.4. Ambient Temperature

According to Watanabe *et al*., [4], the micro-explosion process is strongly affected by the superheat temperature just before the occurrence of the micro-explosion. Sheng *et al*., [12] found that the micro-explosion will not occur when the ambient temperature is too low. The author stated that if the ambient temperature is inadequate (733 Kelvin in the test) the water, which is located in the internal phase of the emulsion droplet, will evaporate before it reaches the superheated state, thus no micro-explosion can occur. Nonetheless, the author added that if the temperature is too high (823 Kelvin in the test), the heat transfer between the droplets and gas is so rapid that the water located near the outer layer will go over the limit of superheat. However, the dispersed water droplet that is located in the centre of the emulsion droplet has not yet reached the superheat state. Consequently, the explosion occurs early and only a weak explosion is achieved since the dispersed water droplet inside the emulsion droplet did not explode at the same time. If the ambient temperature is correct (773 Kelvin in the test), all the dispersed water droplets inside the emulsion droplet will rapidly exceed the saturation state, superheated state and pseudo-stable state, which leads it to experience the vaporization process and explode at the same time when the dispersed water located near the outer layer reaches the superheat limit. Thus, the vigorous explosion will tear up the droplet and greatly expand the spray volume. In another study [7], it was also found that the effect of ambient temperature speeds up the micro-explosion process. According to the authors, if the temperature is relatively high, the heat flux is larger, leading to the transference of a higher rate of heat transfer, and, hence, leading to a quicker onset of micro-explosion.

4.5. Ambient Pressure

A few studies have been conducted to investigate the effects of ambient pressure on the micro-explosion process. W.B. Fu *et al*., [7] reported that pressure has no direct effect on the micro-explosion process. Nevertheless, the authors contended that a higher pressure will increase the boiling point of the heavy component, thus making the micro-explosion easier to occur. The authors added that, as the pressure increases, the solubility of the gas also tends to increase, which then accelerates the occurrence of the micro-explosion. This finding is agreed by Tanaka *et al*., [22]. From their calculation of the derived formula, they found that the occurrence of the micro-explosion is quicker when the ambient pressure is higher, and with the increase of other factors, such as the saturation temperature of the base fuel, the water content and the surface temperature.

However, another study Sheng *et al*., [12] found that an increase in the pressure will make the penetration of the torn droplet much shorter due to the higher gas density. As a result, it will weaken the effect of the explosion.

5. Conclusion

Water-in-diesel emulsion fuel is the alternative fuel that has the potential to be commercialized worldwide as it has the ability to increase the combustion efficiency and reduce the harmful exhaust emissions. Micro-explosion phenomena is the key to the improvement of those measurements as it can explodes the fuel droplet into fine particle, leading to increase the air-fuel mixing process, thus promotes to better combustion. Numerous studies have been conducted experimentally and numericaly in order to observe and investigate the behavior, onset and the strength of the micro-explosion process. The factors that affect the onset and strength of micro-explosion include the size of the dispersed water particle, droplet size of the emulsion, water-content in the emulsion, ambient temperature and ambient pressure. It will be a good research prospect in future, if the micro-explosion process can be observed and investigated in the real diesel engine. Thus, the findings and the measurements of the occurrence, onset and the strength of the micro-explosion in the diesel engine can strongly be validated.

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