Journal of Mechanical Engineering *Vol SI 7 (1), 91-102, 2018*

The effect of injection pressure on the droplet size distributions and micro-explosion

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ABSTRACT

Emulsion droplet size plays a key role in the micro-explosion occurrence as well as the stability of the emulsion. In a high-pressure common rail system, the water-in-diesel emulsion is subjected to intense pressure, temperature and shear when passing through the common rail and injector nozzle thereby altering the droplet size distributions as well as the number of droplets. Water emulsified diesel made with 15% of water content by volume was visualized under the microscope before and after the injector nozzle at an injection pressure of 1500 bar. The size and number of the dispersed water droplets were measured using a developed Matlab image processing code. The influences of the size of the dispersed water droplets before and after the injection on the micro-explosion phenomenon were examined using a hot plate technique. A high-speed camera and thermocouple were synchronized to record the images and the temperature of the emulsion droplet. The results indicate that micro-explosion of the emulsion droplets was significantly

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ISSN 1823- 5514, eISSN 2550-164X

Received for review: 2017-10-11
Accepted for publication: 2018-06-07
Published: 2018-11-30

affected by the injector shearing. Thereby the reduction in the size of the dispersed water droplets resulted in an increase in temperature required to initiate micro-explosion and delayed its onset.

Keywords: *Water-diesel emulsion; Micro-explosion; Common rail system; Injector shearing.*

Introduction

Diesel engines are keeping the lead in the fuel efficiency of the internal combustion engines. This is mainly due to the advantages of direct injection (DI) and compression ignition (CI) combustion. The diesel fuel is the dominant fuel used in a variety of applications, such as power generation, transportation, agriculture, drilling machines, and elsewhere as it offers fuel economy, efficient power, durability and heavy-duty applications. In contrast, the diesel fuel contradicts with the stringent emission regulations, correspondingly, interest is growing to research and improve the diesel fuel to reduce the exhaust emissions of the regulated pollutants. One of the possible and promising ways for reducing both nitrogen oxides (NOx) and particulate matter (PM) in diesel engines is the use of the water-in-diesel emulsions which have been investigated by different researchers [1], [2]. Study reports show that using water-in-diesel emulsions as one of the alternative fuels in CI engines can help in meeting the emission regulations as a result of reductions in the NOx emissions as well as in fuel consumption due to better combustion efficiency. Besides, when a water-in-diesel emulsion is subjected to high temperature, dissociation can form hydroxyl radicals which help to oxidize the soot thus reduce soot emissions [3]. When such fuel is subjected to high temperature, it is not only favorable to solve the problems of air pollution; it also provides an effective utilization of energy which is attributed mainly to the phenomena of micro-explosion as suggested by [4]. Micro-explosion is caused by the exposure of the primary emulsion droplet to a high-temperature environment whereby the small water droplets dispersed inside the fuel vaporize earlier than the fuel shattering the emulsion droplet into many smaller droplets known as droplets of secondary atomization [5]. The smaller droplets tend to evaporate more quickly and form a better air-fuel mixture.

However, the phenomena of micro-explosion were investigated by different researchers and were shown to depend on a number of parameters such as the water content in the emulsion [6], the temperature and droplet size [7]. [8] reported that the emulsion with a mean dispersed water droplet size of 2.1 µm combusted in a multi-cylinder diesel engine produced higher NO emissions An overview of experimental techniques for the investigation of water-diesel emulsion characteristics and droplets micro-explosion was reported by [9]. The authors remarked that the occurrence of the micro-explosion in spray combustion is sensitive to the injection pressure and ambient conditions.

The preparation method of the emulsion was also reported to significantly affect the occurrence of the micro-explosion phenomena. In this trend, a homogenizer and mechanical starrier blending were used for an emulsion preparation prepared [10]. The authors have observed that all samples of mechanically stirred exploded while no micro-explosion observed from the homogenizer. [8], used a magnetic stirrer and homogenizer to generate different dispersed water droplets size distribution and observed that for emulsions generated by the homogenizer (a narrow size distribution) cooperated to cause the micro-explosion phenomena. They stated that the small droplets evaporated simultaneously enhancing the phenomena. They concluded that for a high frequency of micro-explosion, the water volume fraction should not exceed 10% with narrow droplet size distributions. On the other hand, the droplet temperature played an important role in the occurrence of the micro-explosion. [11] showed that the temperature required for micro-explosion increased and decreased respectively with the decrease and increase of the size of the dispersed water droplets.

In the homogenizer, the emulsion subjected to high pressure, temperature, turbulent and shear stress lead to effect on the droplet size distributions as well as the number of droplets[12]. The production of final droplet sizes of the emulsion and the occurrence of re-coalescence depend on the pressure, temperature, surfactant and the movement of the droplets. Several studies on micro-explosion experiments (hot plate, free-falling and suspended droplets) on the occurrence of water-in-diesel emulsion indicated that coalescence and/or phase separation of the emulsion during heating were the main factors responsible for the occurrence of this phenomenon [6], [8], [13], [14].

In a high-pressure common rail system, the water-diesel emulsion is subjected to intense pressure, temperature and shear flow fields in the injector nozzle. These parameters lead to changes in the sizes of dispersed water droplets and their number in the emulsion. It is, therefore, reasonable to expect that these systems will have significant effects on the characteristics of the micro-explosion phenomena. Until now, these effects have not been investigated and only the effect of high-pressure homogenizer on the emulsion properties has been studied. Therefore, it is not known to what extent this new technology with high-pressure common rail and small hole injectors affect the emulsion properties as well as the occurrence of micro-explosion phenomena.

The current study aims to investigate experimentally the impact of injector nozzle shear on the major emulsion characteristics such as the size of the dispersed water droplets and hence the occurrence of micro-explosion phenomena. For this purpose, a common rail system, an Olympus microscope, a hot plate, a high-speed camera, thermocouple and data logger were used to visualize and analyse the sequences of micro-explosion phenomena.

Materials and Methods

Emulsion Preparation

A lipophilic surfactant Span 80 with a hydrophilic-lipophilic balance (HLB) = 4.3 was used to reduce the interfacial tension as well as to improve adherence between the neat diesel as a base fuel and the distilled water. The preparation procedure was as follows: a mechanical starrier driven at 1000 rpm was used for blending the neat diesel with the surfactant, and the distilled water was added drop by drop. The percentages of the emulsion made with 15% of water content by volume. The stability of the emulsion represents its ability to resist changes in the emulsifying layer when it is kept motionless or heated at a certain temperature for a specific time [15]. Cylindrical tubes were used to identify the stability of the water-in-diesel emulsion. After the emulsions were prepared, the samples were centrifuged for 10 minutes and kept motionless for 24 hours to record the volume changes for all the samples sediment layers as shown in figure 1. The density, viscosity and surface tension were measured using an Anton Paar density and Anton Paar, micro viscometer (lovis 2000M) and pendant drop method (OCA15EC) respectively. The heating value of the tested fuel was analyzed by an oxygen bomb calorimeter. All the samples were measured shortly (about 10 mins) after the preparation to ensure its an emulsion. In the current study, the percentage of water was 15% by volume and the emulsion properties are shown in Table 1.

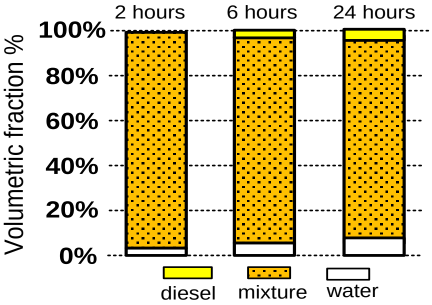


Figure 1 Volumetric fractions of various layers of a water-in-diesel emulsion made with 15% water content by volume after being kept motionless for different times.

Table 1 Properties of neat diesel and the Emulsion

Fuel/ Emulsion	Density at 25 °C (Kg/m3)	Viscosity at 40 °C (mm2/s)	Cal.value (MJ/Kg)	Surface Tension at 25 °C (N/m)
Neat diesel	825.01	3.21	43.20	27.08
15%W	856.12	9.44	37.20	26.75

Spray Collection System

A common rail system was used to generate high-pressure sprays into the samples collector. Figure 2 shows that the schematic experimental setup used in the present study is the same as that of the authors' previous work [16]. The injection timing and injection duration were controlled using the injector driver through lab view software. The fuel injection equipment included are listed in Figure 2. In the current study, the samples were collected from the injector (spray) and fuel tank only. The injection pressure was kept at 1500 bar. A k-type thermocouple was used to measure the fuel temperature inside the common rail during the spray (sample collection). The dispersed phase water droplets size was using a microscope (Olympus BX51) with 50× magnification.

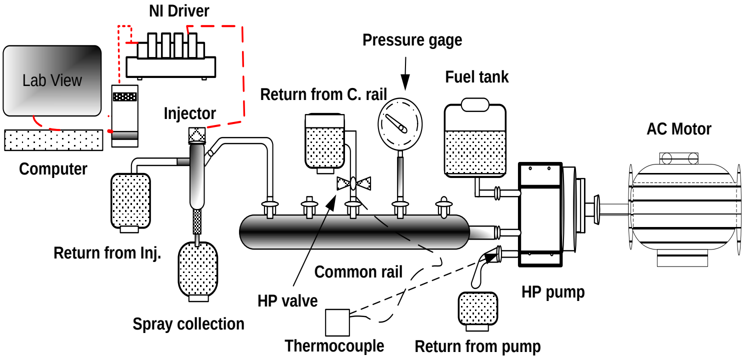


Figure 2 Impact. Schematic of the experimental setup (emulsion samples collection) [16].

Hot Plate Technique

The experimental set-up used in this study was the same as the previous study by [17]. A high-speed camera (8001-Phantom Miro M310), a K-type thermocouple and data logger were synchronized to evaluate the micro-explosion event and record the profile of droplet temperature during the phase change and micro-explosion phenomena. The camera triggering started before the droplet reached the thermocouple and continued until the end of the event for all emulsion samples. A controlled hot plate was fixed at 500 °C before dropping the droplet using a syringe with a diameter of 0.5 mm. The image acquisition rate was set at 509 fps with a resolution of 1280 × 800 pixels and exposure 300µs throughout all the experiment. A thermocouple wire of 0.3 mm diameter at a distance of 2 mm from the hot plate was used to suspend the droplet. The diameter of the suspended droplet was kept at 2.5±0.1mm. A direct visualization system was used to capture the images i.e. a Leica KL2500 light reflector lamp was used as the source of illumination in the same direction with the camera. The image sequences of the emulsion droplet, as well as the temperature history, were recorded.

The experiment began with the same emulsion samples which were collected from the fuel tank and the spray at the outlet of the injector nozzle at 1500 bar. The spray samples were immediately dropped on the hot plate after they were collected from the injector nozzle at 1500 bar injection pressure. To achieve Leidenfrost conditions, the hot plate was kept at a stable temperature of 500°C while the thermocouple recorded at 200°C. The emulsion droplet was then placed above the hot plate while suspended on the thermocouple, and the camera was started. The thermocouple temperature was recorded every 10ms using a National Instrument data logger.

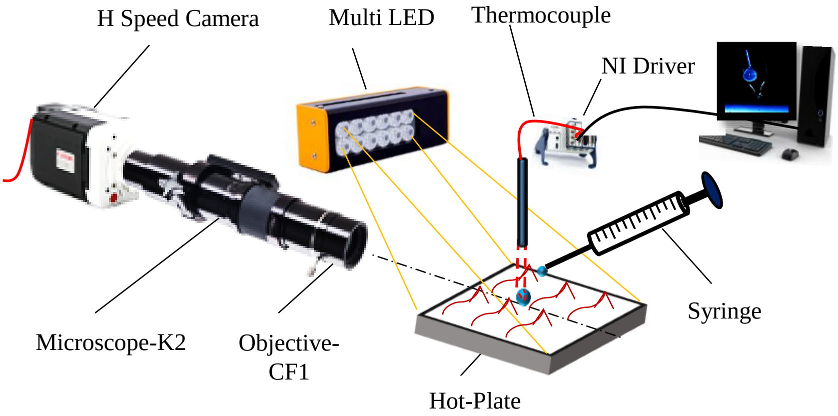


Figure 3 Experimental setup for the visualization technique.

Results and Discussion

The effect of injector shear on droplet size distribution

Figure 4 shows the effect of injector shear on a water-in-diesel emulsion made with 15%W at fuel tank (1 bar) and after injection at a pressure of 1500 bar as seen under an optical microscope at 50X magnification. It can be clearly seen that the sizes and numbers of the dispersed water droplets were significantly affected by the injector nozzle with the droplet sizes decreasing and their number increasing significantly as a result of the high injection pressure as the emulsion is subjected to high shear rate. This result is similar to the drop breakage of emulsion using homogenizers [18]. Also, both the viscosity and surface tension of the emulsion are affected by the rise in temperature of the fluid in the high-pressure pump and the fuel rail. It can also be seen in Figure 4 (b) that there were some large droplets due to coalescence. Other researchers also reported that emulsion heating causes a slight reduction in the interfacial tension between the oil and water phases resulting in the production of small droplets [19] and [20].

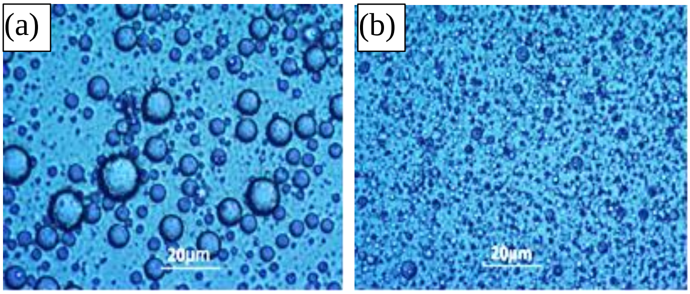
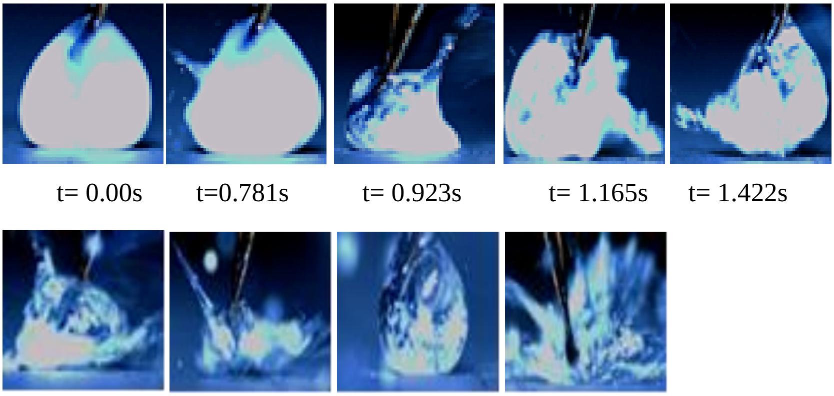


Figure 4 Images of 15%W water-diesel emulsion samples examined under an optical microscope at 50X magnification at (a) in the fuel tank and (b) after 1500 bar injection.

Micro-explosion phenomenon of fuel in the tank

Figure 5, shows a sequence of images of a droplet of emulsion taken from the fuel tank made with 15%W and suspended on the thermocouple over the hot plate. The images illustrate the evolution of the micro-explosion phenomena. The size of the droplet suspended on the thermocouple, measured from the first image at t=0.0s) was about 2 mm in diameter (± 0.1mm) and was kept constant throughout all the experiments. From the image sequence shown in figure 5, we can see that the droplet has gone into the partial micro-explosion



t= 0.00s t=0.781s t= 0.923s t= 1.165s t= 1.422s

t= 1.830s t= 2.381s t= 2.881s t= 3.11s

Figure 5 Sequence of images of an emulsion made with 15% water content taken from the tank showing micro-explosion behaviour.

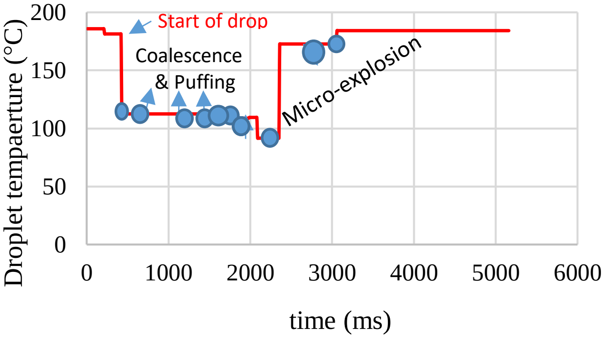


Figure 6 Evolution of thermocouple temperature.

and complete micro-explosion at 2.381s and 3.11s. respectively. After this time, the emulsion separated from the thermocouple. The mechanism of micro-explosion which consist of aggregation, coalescence, followed by puffing due to heating of the droplet as described by authors [8], [21]. Puffing was observed after a short time at (t = 0.78s) and followed by several times with coalescence and phase separation. The droplet temperature against time is shown in Figure 6. The dots on the figure represent the temperature of each droplet in Figure 5. At first, the effect of the 'cold' emulsion caused the thermocouple temperature to drop to 112°C when puffing and coalescence took place for 1.458s. After this time, the temperature dropped again to 91°C and tended to stabilize, at this value until micro-explosion occurred at 181ºC. The thermocouple temperature then increased as a result of heating by the hot plate until it reached its initial value of (200°C).

The effect of injection pressure on the micro-explosion behaviour

Figure 7 shows a sequence of images of a droplet of a 15%W emulsion taken after the injector and suspended on the thermocouple over the hot plate. The injection pressure was 1500 bar. Initially, the emulsion drop was milky white and turning transparent as it was heated. The droplets' transparency increased with the reduction of the sizes of the dispersed water droplet. This is due to the increase in coalescence with the larger droplets as well as the water content percentages, while small size droplets tend to evaporate rather than coalescence and prevent opacity of the droplet. The first puffing appeared after1.72s while for the fuel in the tank appeared after 0.78s. This can be attributed to the delay in evaporation of the smaller droplet sizes in this case while in the case of fuel tank emulsion (see figure 3), the larger and fewer droplets enhanced the puffing and reduced the time to achieve micro-explosion. It was also observed that the number of puffing events was higher in the fuel tank sample compared to that taken after injection.

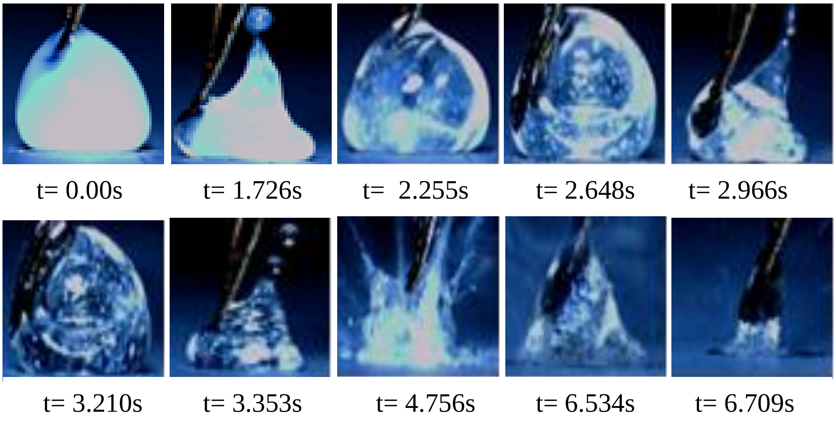


Figure 7 Sequence of images for a droplet collected after the injector nozzle at an injection pressure of 1500bar showing the micro-explosion behaviour.

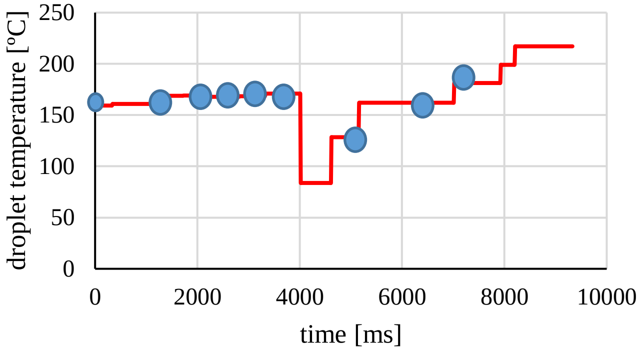


Figure 8 Thermocouple temperature for the 1500 bar injection emulsion droplet.

The droplet temperature against time is shown in Figure 8. The dots on the figure represent the temperature of each droplet in Figure 7. The image sequence and thermocouple temperature evolution confirm the different behaviour of the droplet in this case compared to that of the sample from the tank (Figures 4 and 5). The emulsion droplet showed a partial micro-explosion at 4.75s and continued until at 6.709s. The explosion temperature started at 162 °C and increased until it reached 182 °C.

Conclusion

The effect of different injection pressure of 1500 bar on the droplet size distribution and micro-explosion behaviour of emulsions made with 15% of water by volume with the neat diesel was investigated. The microscope images of the dispersed water droplets showed that the shearing of the emulsion resulting from the high injection pressure had a significant effect on both the droplet size distribution and micro-explosion behaviour of the emulsion. The number of droplets increased, and their size decreased with the increase in the injection pressure. This reduction in the droplet size of the dispersed water resulted in an increase in the time and temperature to achieve micro-explosion. This is believed to be due to the reduction in the rate of coalescence with the decrease in the dispersed water sizes.

Acknowledgements

The authors would like to acknowledge the support given by the Universiti Teknologi PETRONAS to the Centre for Automotive Research and Electric Mobility (CAREM) in performing this research. Authors also wish to thank the Ministry of Higher Education, Malaysia for their financial support under grant FRGS/1/2017/TK10/UTP/01/2).

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