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Experimental Study on the Combustion Characteristics of Emulsified Diesel in a RCEM

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Combustion characteristics of the emulsified diesel fuels are investigated in a Rapid Compression and Expansion Machine(RCEM). Among the test cases the 40 W/O fuel injected at BTDC 20° has shown the best performance with respect to the efficiency and NOx and soot emissions. The pressure trace of the 40 W/O fuel is characterized by a longer ignition delay and a lower rate of pressure rise in premixed combustion. High speed photographs show reduced flame luminosity and lower flame temperature with the increasing W/O ratio. Micro-explosions of emulsified fuel droplets which affect the local shape and brightness of the flame are identified in magnified flame images.

Keywords: emulsified diesel, RCEM, high speed photographs, micro-explosions

INTRODUCTION

Environmental concerns on pollutant emissions such as NOx and soot are growing while available petroleum resources are limited around the world. Automotive manufacturers are trying to find ways to reduce pollutant emissions and improve fuel conversion efficiency of internal combustion engines. One promising method may be use of water emulsified diesel which can economically accomplish both of these goals. Previous researches[1, 2] have shown that it is possible to reduce NOx and smoke with no loss of power and efficiency in a normal diesel operating condition. There may be several ways of introducing water into a combustion chamber; a specially devised separate injection system[3], an emulsion mixer without any stabilizer and use of emulsified fuel with a stabilizing agent. Among these the last one may be the simplest and most practical in laboratory experiments, although corrosive side effects of water and stabilizing agent on metallic parts of an engine are not yet solved. In Tsukahra et al.[4] reduction of the specific fuel consumption with water emulsified diesel is attributed to the following effects; (1) formation of a finer spray due to rapid evaporation of water(micro-explosion), (2) more air entrained in the spray due to increased momentum and penetrating force, (3) more fuel burning in premixed combustion due to a longer ignition delay, (4) increase in the local excess air ratio due to the water content, (5) decrease in cooling loss due to a lower flame temperature, (6) suppression of thermal dissociation and (7) more combustion product gas due to water vapor. In recent years more experiments have been performed with emulsion fuels to confirm improved fuel economy[5] and significant reduction in NOx and soot[6]. Increase of the ignition delay due to added water is shown to result in a small negative effect for NOx although it shows a positive effect for reduction of smoke[7]. However no systematic investigation has been made on the effects of the parameters such as the injection timing and the W/O ratio of the emulsion fuel in well defined environment. This paper investigates the combustion characteristics of emulsified diesel fuels in an engine-like environment of a RCEM for better understanding of the fundamental mechanisms listed in the above. Both the pressure curves and successive flame images by a high speed camera are acquired simultaneously for different W/O ratio fuels with electronically adjusted injection timings.

EXPERIMENTAL SETUP

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Figure 1 shows a schematic diagram of the RCEM and its experimental setup. The RCEM is different from a RCM[8] in that it rotates at a constant speed and can simulate the whole combustion process including the late combustion phase. The RCEM consists of four parts; a driving part, a rotational part, a compression part and a combustion chamber. Motion of the rotational and compression parts is similar to that of an ordinary engine. The piston compresses the chamber at the peak motoring pressure of about 38*bar* with no effect of the turbulent intake flow in the cylinder. The rotational speed of the RCEM is fixed at 700*rpm* for all test cases. The bore and stroke of the RCEM are 100mm and 110mm respectively with the compression ratio of 15.0

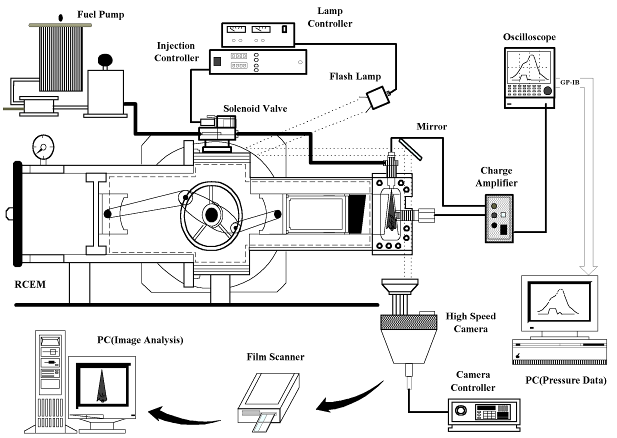

Figure 1 Schematic diagram of the RCEM

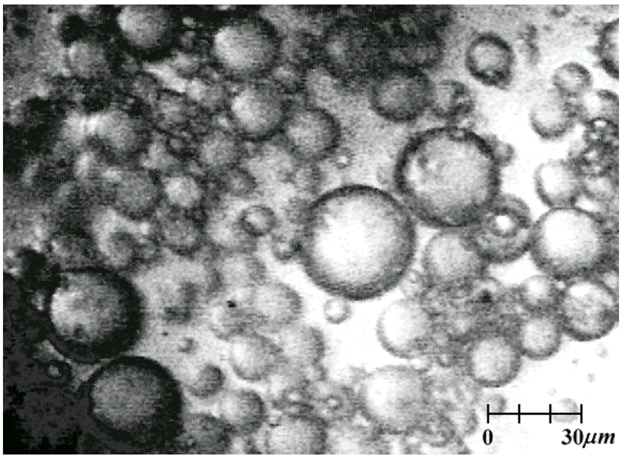

Figure 2 Microscopic photograph of the 40 W/O fuel with 0.1% stablizing agent

The wall temperature of the combustion chamber is maintained at about 80°C. The Model 350 Cordin rotating drum framing camera records 225 frames in two columns on a 35mm nega-color film at the rate of 20,000 frames per second. The time interval between each frame is 50μs for the total recording time of about 11.2ms. The mechanical delay of the shutter(2.0 - 2.25ms) and ignition delay are taken into account in triggering high speed camera. The crank angle marked on the axis of the rotating part is captured through an optical path simultaneously with flame images. A special delay and pulse width modulation system is designed to confirm the exact injection timing. It consists of an angle delay and a pulse width modulation circuit, a fuel pump, a high-pressure solenoid valve and a pintle type injector with a needle lift sensor. Since all mechanical parts of the injection system have their own time delays, an injection signal confirmed by the needle lift sensor must be sent to the solenoid valve in advance to compensate for these delays. Four data sets of the pressure, needle lift, crank angle and flame images are acquired with the crank angle resolution of 0.1°.

W/O ratio	Volume fraction of water/oil	Mass fraction of water/oil
0	0/100	0/100
20	16.7/83.3	19.4/80.6
40	28.6/71.4	32.5/77.5

Table 1 Volume and mass fractions of water and oil in emulsion fuels of different W/O

The emulsion fuels with the W/O ratios of 0, 20 and 40 represent the volume ratios of water to diesel of 0/100, 20/100 and 40/100 respectively. For example, 140*cc* of 40 W/O emulsion fuel consists of 40*cc* of water and 100*cc* of oil. The volume and mass fractions of water and oil in different W/O ratio emulsion fuels are listed in Table 1. The minimum amount of stabilizing agent is added to the fuel to avoid any unknown effects on combustion. The stabilizing agent, Sekiemal SA, is added by 0.1% and mixed with water in a mixer of a centrifugal type. Additional stirring fans and circulating pipelines are installed at the fuel tank and just ahead of the injector, as water drops tend to combine and submerge in the inherently unstable emulsion fuel. Figure 2 shows a microscopic photograph of the injected emulsion fuel of the 40 W/O ratio with the droplet sizes in the range of 5 to 40μm. The droplet sizes of emulsion fuel are one of the most important factors to determine the subsequent combustion characteristics.

RESULTS AND DISCUSSION

3.1 Pressure Data

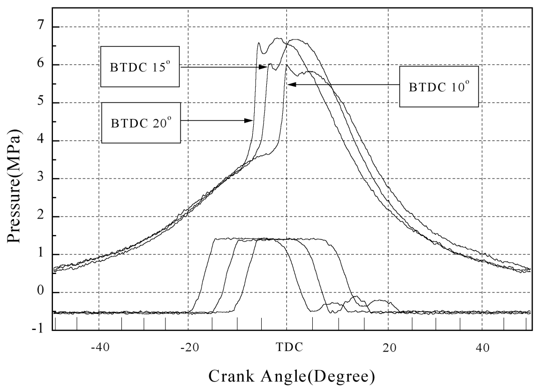

Figure 3 Pressure and needle lift data for the diesel fuel(0 W/O) with the injection timings of BTDC 10, BTDC 15 and BTDC 20

Figure 3 shows the pressure and needle lift data for the diesel fuel of the 0 W/O ratio, with the injection timings of BTDC 10°, 15° and 20°. As the injection timing is advanced, ignition occurs earlier with increase in the ignition delay. It results in steeper rise of the pressure at ignition as the amount of fuel involved in premixed combustion increases with a longer ignition delay. A small secondary peak in the pressure trace is noted for the injection timing of BTDC 20° in Fig. 3, as more fuel burns in premixed combustion with an advanced injection timing. Figures 4 shows the pressure and needle lift data for the 20 W/O fuel also injected at BTDC 10°, 15° and 20°. Although the ignition delay increases with the W/O ratio, the overall combustion characteristics are similar to those of the diesel fuel in Fig. 3.

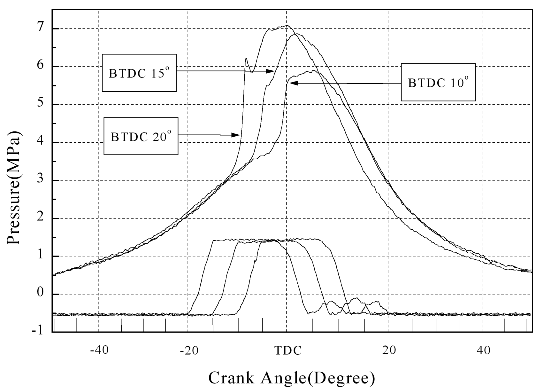

Figure 4 Pressure and needle lift data for the diesel fuel(20 W/O) with the injection timings of BTDC 10, BTDC 15 and BTDC 20

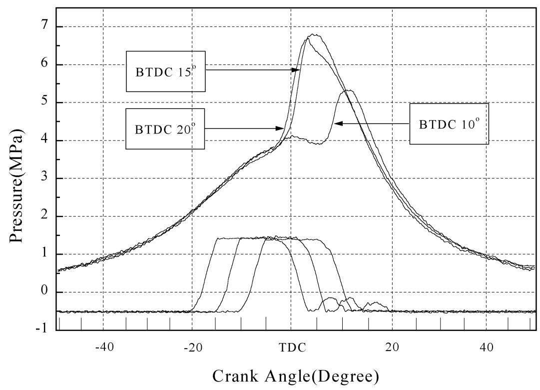

Figure 5 Pressure and needle lift data for the diesel fuel(40 W/O) with the injection timings of BTDC 10, BTDC 15 and BTDC 20

Small secondary peaks are noted for all three injection timings in Fig. 4 with more fuel burning in premixed combustion after longer ignition delays for the 20 W/O fuel. Figure 5 shows that the 40 W/O fuel results in the longest ignition delays, while the rates of pressure rise at ignition are lower than those in Fig. 3 and 4. There are no secondary peaks observed in the pressure traces in Fig. 5.
This is because the flame propagation speed in premixed combustion decreases with a higher content of water in the 40 W/O emulsion fuel. Note that the peak pressure of the 40 W/O fuel in Fig. 5 is comparable to those of the diesel fuel in Fig. 3. The emulsion fuels require less pumping work than the diesel fuel due to a longer ignition delay during the compression stroke. The longer ignition delay also helps to reach a higher peak pressure after the TDC to produce more work output during the expansion stroke.

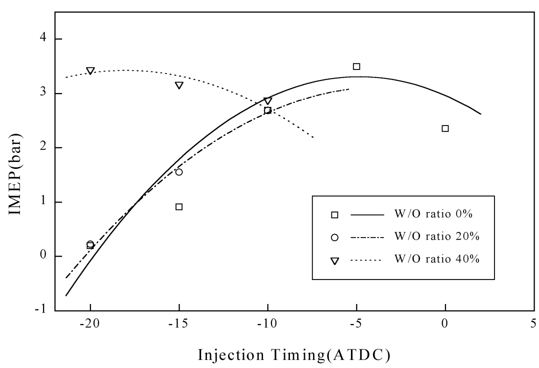

Figure 6 IMEP of the 0, 20 and 40 W/O fuels with respect to the injection timing

Figure 6 shows variation of the imep for all the fuels and injection timings tested. The curve for the diesel fuel reaches the maximum at the injection timing of BTDC 5°. Variation of the imep for the 20 W/O fuel is similar to that of the diesel fuel, while the 40 W/O fuel shows a different behavior in Fig. 6. The maximum imep for the 40 W/O fuel occurs at the injection timing of about BTDC 20°.

Early injection is required due to a longer ignition delay and a slower flame propagation speed for a higher W/O ratio fuel. The maximum imep of the 40 W/O fuel is comparable to those of the diesel and 20 W/O fuel in Fig. 6. However the fuel conversion efficiency of the 40 W/O fuel is the highest among the three fuels since the 40 W/O fuel is composed of 71.4% of diesel and 28.6% of water by volume. Among the test cases the 40 W/O fuel with the injection timing of BTDC 20° has shown the maximum fuel conversion efficiency.

3.2 High-speed Photographs

Figure 7 shows high-speed photographs taken for the following three cases; the diesel, 20 W/O and 40 W/O fuel all injected at BTDC 20°. Luminous flames propagate faster over the chamber after a longer ignition delay, as the injection timing is advanced with the diesel fuel. Photographic images for ignition and flame propagation of the 20 W/O fuel are not much different from those of the diesel fuel. The 20 W/O fuel shows minor reduction in flame luminosity, while the 40 W/O fuel shows remarkable reduction in flame luminosity with the longest ignition delay in Fig. 7. The images in Fig. 7 are taken from ignition until the peak luminosity and pressure are reached during the whole combustion process. The flames of the 40 W/O fuel are dark red, while those of the diesel fuel are bright yellow. It means the flames of the emulsion fuel are less sooty and at a lower temperature due to its water content[9, 10]. Less formation of soot is confirmed as the engine components are disassembled for cleaning after each run of the experiment.

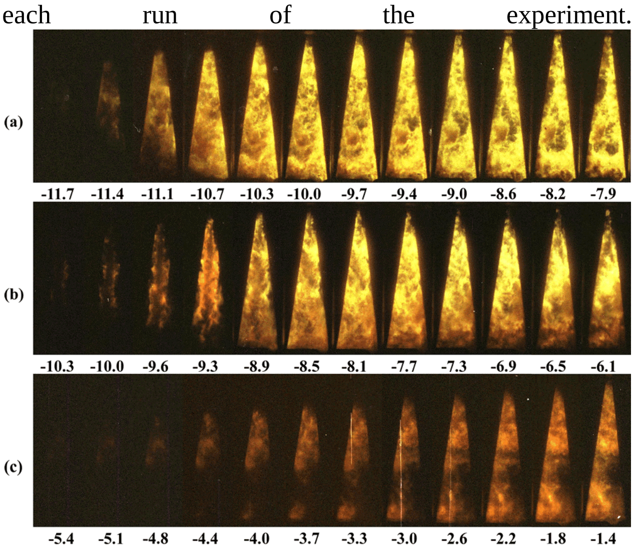

Figure 7 Flame images for (a) the diesel fuel with the injection timings of BTDC 20, (b) the 20 W/O fuel with the injection timings of BTDC 20, (c) the 40 W/O fuel with the injection timings of BTDC 20 (The negative numbers below images represent the crank angle

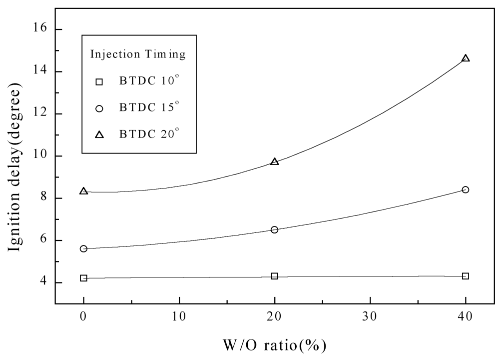

Figure 8 Ignition delay with respect to the W/O ratio

The ignition delay in Fig. 8 is determined as the period from the beginning of fuel injection until detection of luminosity in the flame images. Note that the ignition delay increases as the injection timing is advanced for any given fuel. At the injection timing of BTDC 10° the W/O ratio does not have much effect on the ignition timing due to the high pressure and temperature in the chamber near TDC. At the injection timings of BTDC 15° and 20° the ignition delay increases with the W/O ratio, reflecting difficult ignitability of the emulsion fuel. The 40 W/O fuel injected at BTDC 20° results in the longest ignition delay of about 15° crank angle. It is likely that incomplete combustion may occur for the 40 W/O fuel with the late injection timing of BTDC 10°. Ignition locations of the emulsion fuels are different from those of the diesel fuel. Ignition occurs in the middle of the combustion chamber with the diesel fuel, while it occurs in the bottom region or at multiple points in the middle simultaneously with the 40 W/O fuel. Flame propagates slowly from the ignition locations so that it]takes twice as long or longer for the luminous flame to propagate over the whole chamber for the 40 W/O fuel.

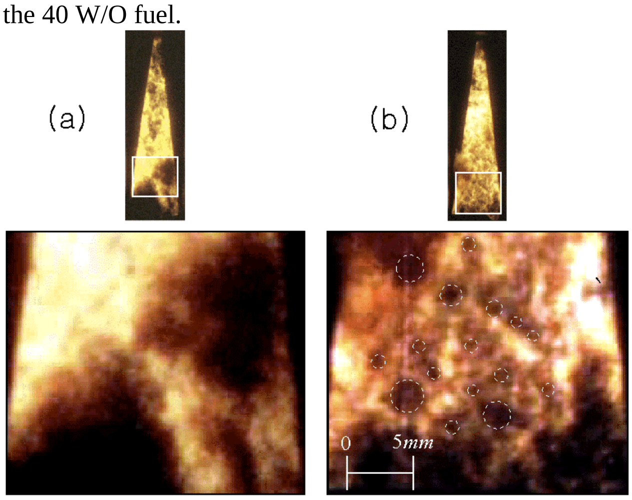

Figure 9 Magnified images for the (a) diesel and (b) 20 W/O fuel both with the injection timing of BTDC 10

Figure 9 shows magnified flame images of the diesel fuel injected at BTDC 10° and the 20 W/O fuel also injected at BTDC 10°. The image for the 20 W/O fuel shows that strong micro-explosions occur in the bottom region of the luminous flames near the spray tip. There are numerous small, round regions due to explosion of superheated water in the droplets. These spherical regions may grow bigger, collapse with new flames or convect with the mean flow motion. There is a range of the sizes, from small ones that are barely identifiable to those of the diameters of a few millimeters. The luminous flames of the diesel fuel are more homogeneous, brighter and yellow in color with no micro-explosions observed. Micro-explosions of a group of droplets of the emulsion fuels are strong enough to eject fragments of torn droplets to expand the tip and angle of the spray, enhancing mixing of fuel with surrounding air[11].

CONCLUSION

1. Combustion characteristics of the emulsified diesel fuels of 0, 20 and 40 W/O ratios are investigated with the injection timings of BTDC 10°, 15° and 20° in an engine-like environment of a RCEM operating at 700*rpm*. According to the pressure traces and their imep's the 40 W/O fuel injected at BTDC 20° has given the best fuel conversion efficiency among the test cases.

2. According to the measured pressure traces the ignition delay increases as the injection timing is advanced or as the W/O ratio increases. A longer ignition delay combined with slower flame propagation and evaporated water content results in improvement in the efficiency of the emulsion fuels. While the peak pressures and maximum imep's are comparable for the three fuels tested, the 40 W/O fuel gives the highest fuel conversion efficiency due to its water content.

3. According to the high speed flame images the 40 W/O fuel shows remarkable reduction in flame luminosity with the longest ignition delay, while the 20 W/O fuel shows little difference from the diesel fuel. It confirms a lower flame temperature and less sooty flames of the higher W/O fuels to reduce the NOx and soot emissions. Ignition tends to occur at multiple points simultaneously in the bottom region of the chamber with a longer ignition delay and slower flame propagation from the ignition locations for the higher W/O fuels.

4. Micro-explosions of a group of droplets of the emulsion fuels can be observed in the luminous flames near the tip of the spray. They affect the local shape and brightness of the flames as small, dark round regions due to explosion of superheated water in the droplets. The sizes of micro-explosions range from barely identifiable small ones to those of diameters of a few millimeters. Micro-explosions of the emulsion fuels seem to enhance mixing of fuel with surrounding air for faster and more efficient combustion.

NOMENCLATURE

rpm revolutions per minute
BTDC before top dead center
RCEM rapid compression and expansion machine
TDC top dead center
W/O water to oil ratio by volume

ACKNOWLEDGMENT

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