Journal of Mechanical Engineering and Automation 2022, 11(2): 27-42
DOI: 10.5923/j.jmea.20221102.01

Investigation of In-cylinder and Fuel Injection Characteristics of Direct Injection Diesel Engine Using Water Diesel Emulsion

Alardhi M.[1,*], Alrajhi J.[1], Alkhulaifi K.[2]

[1]Automotive and Marine Dept., College of Technological Studies, PAAET, Kuwait
[2]Mechanical Power and Refrigeration Dept., College of Technological Studies, PAAET, Kuwait

Abstract Experimental results of in-cylinder and fuel injection characteristics measurements in direct injection diesel engine using automotive diesel (AD) and water diesel emulsion (WDE) have been investigated at two engine speeds and loads. Experimental results have shown that the magnitude of cylinder pressure of WDE during most of the cycle and peak pressures are close to those observed for AD at both speeds and loads. The late SOC for WDE causes the fuel energy to be released during most of the expansion stroke resulting in a higher cylinder pressure. Differences in WDE fuel properties such as bulk modulus, density and viscosity cause the start of fuel injection pressure rise to occur much earlier than that of AD. Although the higher bulk modulus of WDE should result in an earlier SOI, however, the opposite has been noticed here. In terms of exhaust emissions, the lower combustion temperature of WDE is expected to cause a lower NOx emission.

Keywords Direct injection, Diesel engine, In-Cylinder, Fuel injection, Water diesel emulsion

1. Introduction

The use of WDE in diesel engines is an easily applicable alternative fuel for the existing vehicle fleet. There is a growing interest in the use of WDE in which environmental aspects are the main driving force [1]. There may be a certain loss in engine performance due to the presence of water due to the fact of replacing fuel by water, but fuel consumption is often reduced. WDE has been shown to give several interesting effects such as reduced NOx emission and lower PM in the exhaust and improve combustion efficiency. The influence of water on the performance parameters and exhaust emissions of diesel engines has been studied by many researchers [2-7]. It has also been shown that WDE can improve engine thermal efficiency and reduce brake specific fuel consumption [8]. In all previous studies reviewed, specific fuel consumption considers the diesel component of the fuel only not the water diesel mixture.

Samec et. al. [9] have made a numerical and experimental study on some of the chemical and physical properties of WDE on the combustion process of a four cylinder air-cooled DI diesel. A comparison of the exhaust emission data and specific fuel consumption for three different fuels (neat diesel fuel, 10% WDE and 15% WDE) at different operating conditions were made. NOx concentration in exhaust gas was reduced by nearly 20% and soot concentration by up to 50% with no worsening in specific fuel consumption. Their WDE results showed a better reduction in NOx and soot compared to their earlier experimental work when water was added to the fuel separately via single and multi-point injection [10-11] and with the results of other authors when other modes of water addition were applied [12].

In a similar study, Abu-Zaid [8] investigated an emulsified diesel fuel with different percentages of water by volume (0,5,10,15 and 20%) in a single cylinder DI diesel engine. He showed as the percentage of water in the emulsion increased the torque produced increased. As a result, engine power increased with the increase of water percentage. Furthermore, the 20% water emulsion improved the brake thermal efficiency about 3.5% over the use of neat diesel fuel. The BSFC and exhaust temperature were decreased as the percentage of water in the emulsion was increased. In addition, the exhaust temperature for the emulsion was always lower than that of standard diesel. It is clear, as the percentage of water in the emulsion increased, the exhaust temperature decreased.

Tsukahara and Yoshimoto [13] investigated standard diesel fuel and WDE (51% by mass water) on a single cylinder direct injection diesel engine at three different compression ratios and various inlet air velocities and fuel injection timing. With WDE, the concentration of NOx was lower than standard diesel fuel for all inlet air velocities.

* Corresponding author:
alardhi@paaet.edu.kw (Alardhi M.)
Received: Nov. 18, 2022; Accepted: Dec. 5, 2022; Published: Dec. 14, 2022
Published online at http://journal.sapub.org/jmea

Also, the BSFC decreased with WDE for low inlet air velocity whereas at high air velocity BSFC has increased. Furthermore, the BSFC and NOx for WDE decreased below standard diesel fuel values at all injection timings. Within the range of their experimental work, the BSFC for both fuels tends to increase with decreasing compression ratio whereas the concentration of NOx was almost constant. Other experimental work with emulsified fuel [13-16] also showed a reduction in NOx and smoke with no noticeable increase in the BSFC.

2. Results and Discussion

In-Cylinder Pressure and Fuel Injection

The in-cylinder pressure data were used to calculate average exhaust gas temperature of the engine at different test points. Pressure traces were smoothed using a five-point moving. Fuel injection pressure and needle lift have been used to calculate the rate and cumulative fuel injected within the cycle. Due to the large amount of data available for each test point, only two test points (1800 and 2200 RPM) are presented here in detail for discussion purposes. Before going into the explanation of WDE combustion behavior it is important to see the difference in fuel injection characteristics for both fuels.

Effect of WDE on Fuel Injection Characteristics

Figures 1 to 16 show fuel injection pressure, instantaneous rate of fuel injection and cumulative fuel injected for the two fuels at different engine speeds and both loads. In some other WDE studies [17,18] the fuel injection timing was retarded in order to obtain the highest reduction in exhaust emissions (NOx and HC) and obtain the best engine performance. In this work injection timing was kept at its standard timing (14° BTDC). This does not change the fact that a shift from the standard injection timing was observed from test point to another during the experimental work. Fuel injection pressure duration increases with the increase of engine speed and decreases with the increasing of engine load, Figures 1 to 4. Engine load has a major effect on increasing the magnitude of fuel injection pressure due to longer effective plunger stroke. A sample of needle lift curves are also shown in Figures 1 and 2. However, fuel injection rate will be used instead of needle lift since it accounts for both fuel injection duration and the rate.

From Figures 1 to 4, the main differences between the two fuel injection pressure curves are the earlier fuel injection pressure rise for WDE at all engine speeds and loads and its longer duration. The higher bulk modulus of WDE results in an earlier fuel injection pressure rise and longer injection duration. Also, the higher viscosity (9%) of WDE leads to reduced fuel leakage during the injection process and thus faster fuel pressure rise. However, the start of injection (SOI) retards for WDE which might be the reason of having different behavior between stabilized and unstabilized emulsions when subjected to high pressure.

The fuel injection rate is calculated using *(Eq. 1)*

$$\dot{m}_i = C_D A_n \sqrt{2\rho_f \Delta P} \qquad (1)$$

Where C_D is the nozzle discharge coefficient, A_n is the nozzle hole area, ρ_f is the fuel density and ΔP is the pressure drop across the injector nozzle. From the above relation, the cumulative fuel injected during each increment of the injection process can be estimated as,

$$m_{f(cum)} = \dot{m}_i \ \Delta\theta_{inj} \qquad (2)$$

Figures 5 to 8 show the fuel injection rate for both fuels.

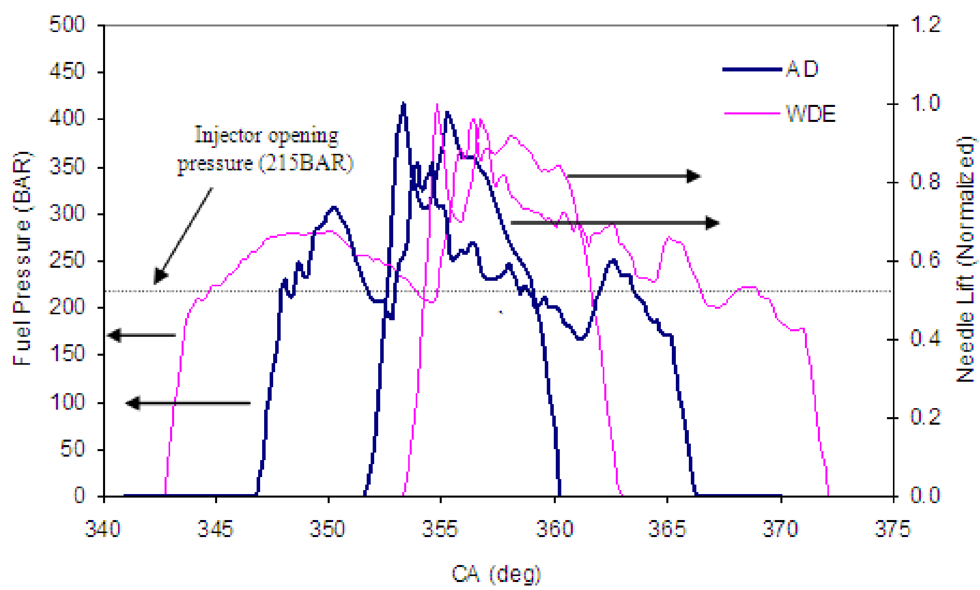

Figure 1. Fuel injection pressure and needle lift for both fuels at 1800RPM and 150N.m.

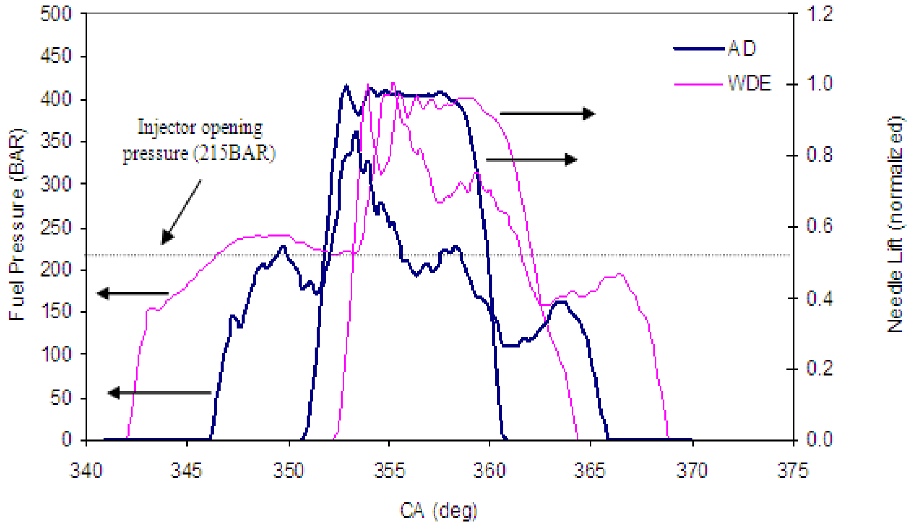

Figure 2. Fuel injection pressure and needle lift for both fuels at 1800RPM and 200N.m.

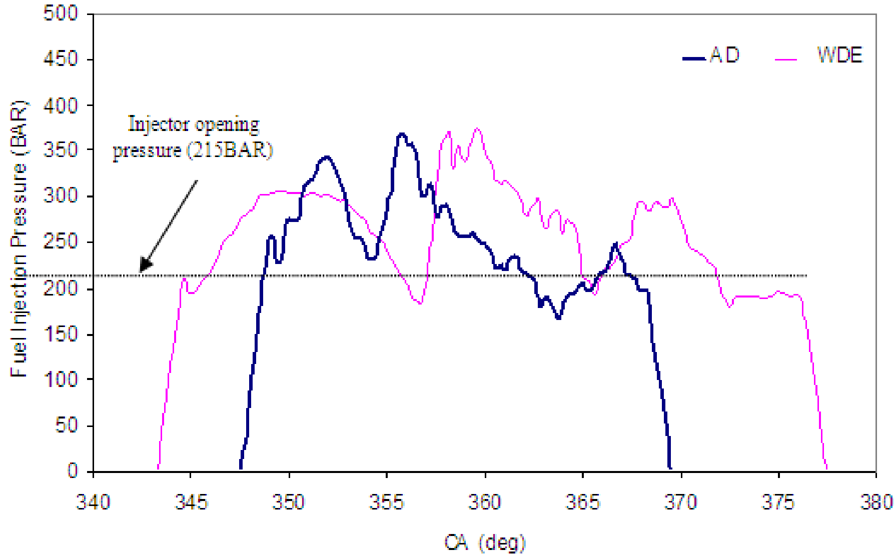

Figure 3. Fuel injection pressure for both fuels at 2200RPM and 150N.m

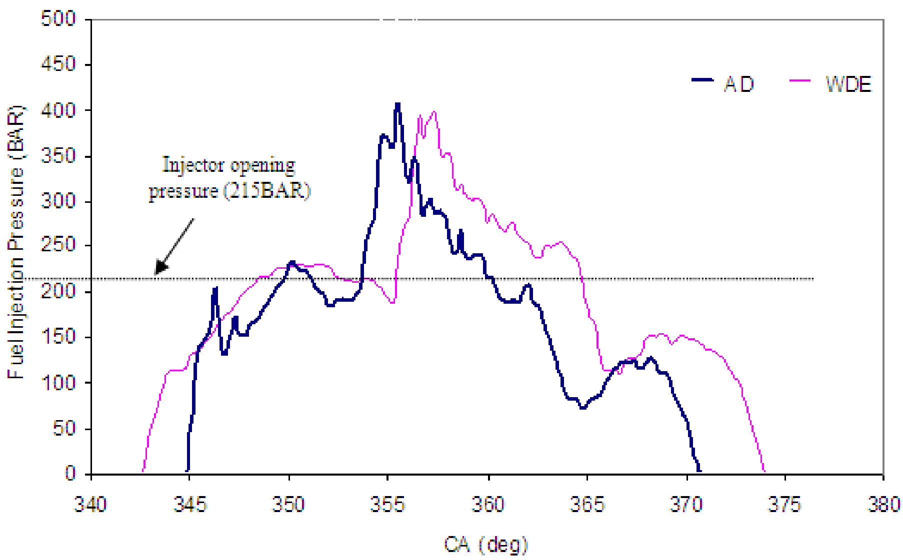

Figure 4. Fuel injection pressure for both fuels at 2200RPM and 200N.m

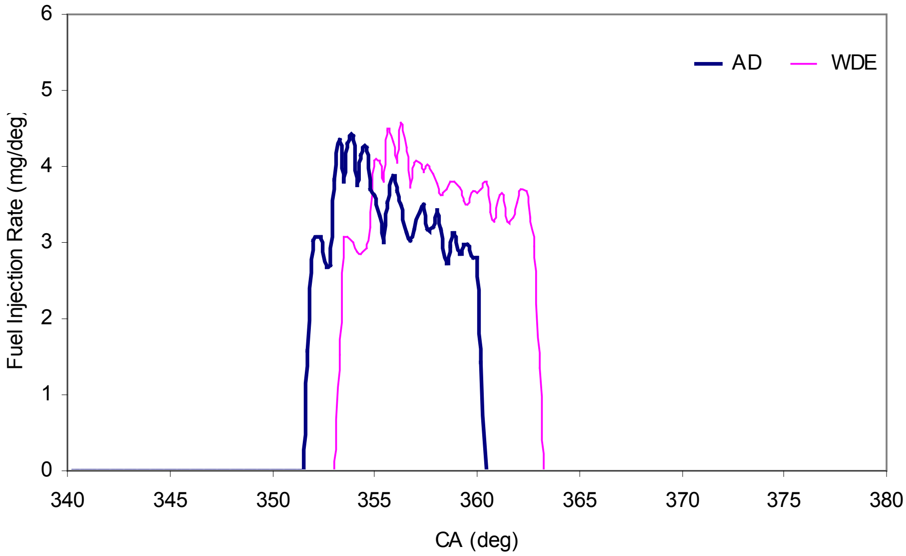

Figure 5. Instantaneous Fuel injection rate for both fuels at 1800RPM and 150N.m

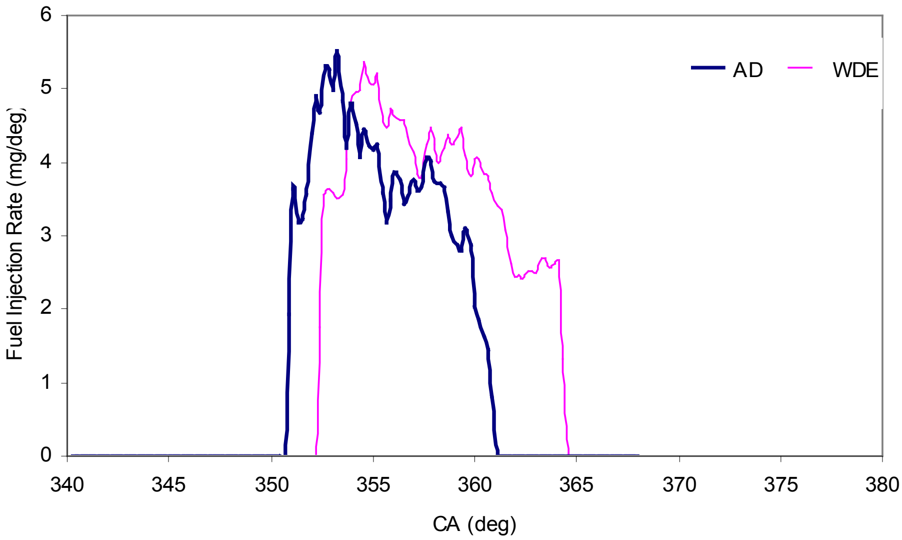

Figure 6. Instantaneous Fuel injection rate for both fuels at 1800RPM and 200N.m

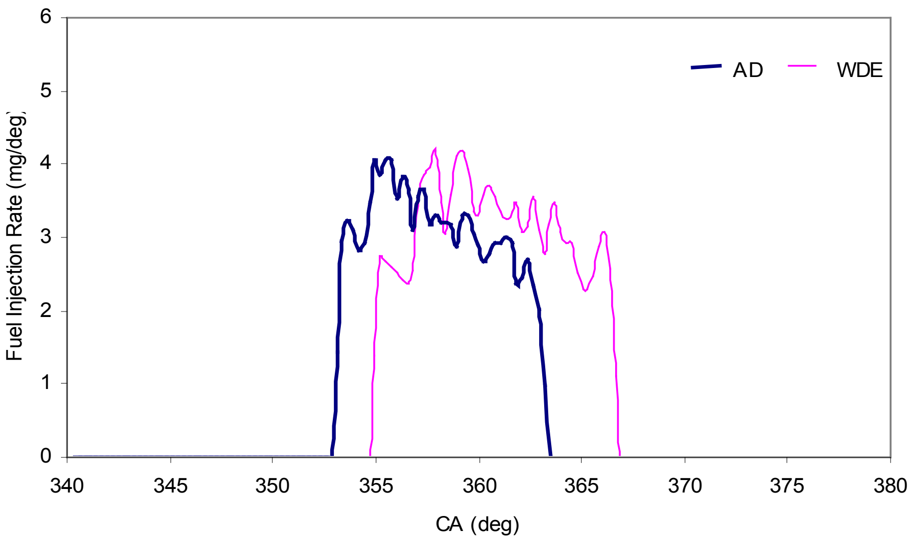

Figure 7. Instantaneous Fuel injection rate for both fuels at 2200RPM and 150N.m

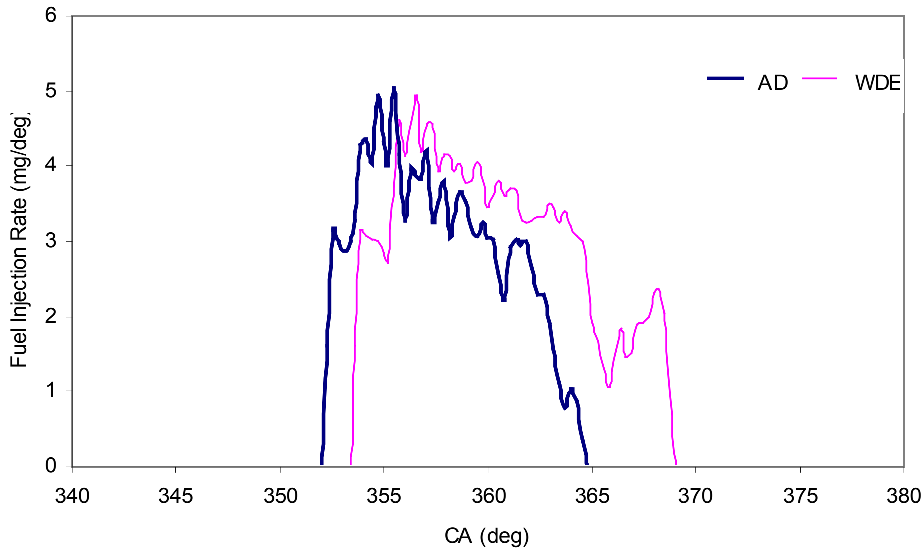

Figure 8. Instantaneous Fuel injection rate for both fuels at 2200RPM and 200N.m

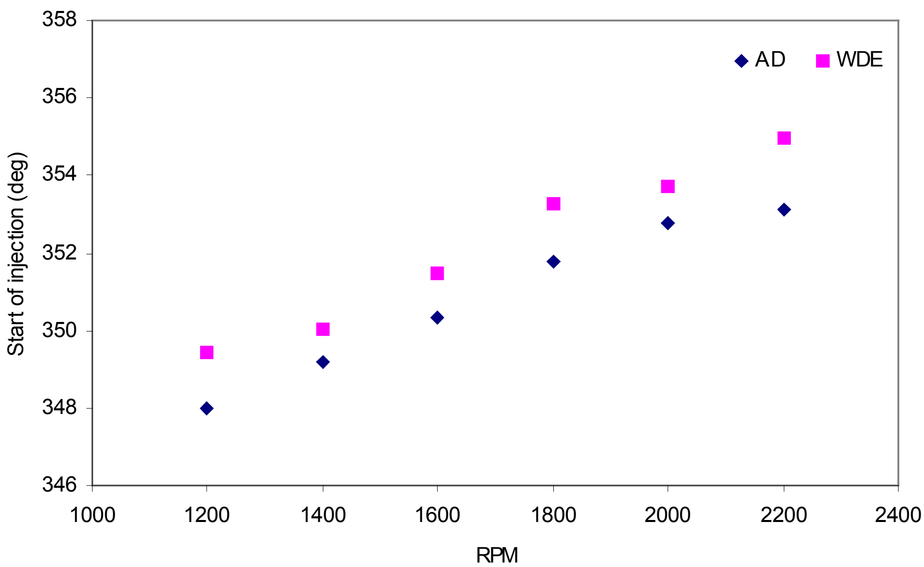

Figure 9. The Start of Injection (SOI) for the two fuels at all engine speeds and 150N.m

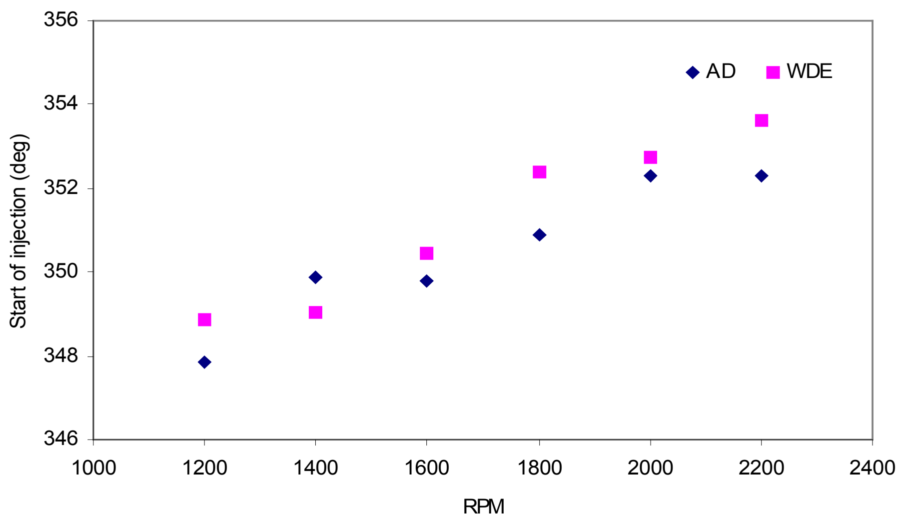

Figure 10. The Start of Injection (SOI) for the two fuels at all engine speeds and 200N.m

The increase in engine load has greater effect on increasing fuel injection rate than the change in speed (Figures 5 to 8). Furthermore, the variation in SOI is smaller when changing engine load than with the change of engine speed. For both fuels, increasing engine speed for fixed load causes a decrease in the average injection rate, delay in SOI and increase in injection duration. Increasing the load causes an increase in injection rate, advance of SOI and increase in injection duration. Although the higher bulk modulus would means an earlier rise of needle lift and SOI as shown in some literature [19], however this is not the case here as explained earlier, Figures 9 and 10.

Increasing engine load causes the instantaneous fuel injection rate to increase in magnitude and duration while increasing engine speed increases the fuel injection rate duration and has small effect on the magnitude. Although the maximum instantaneous fuel injection rate of WDE looks similar to that of AD at all engine speeds and loads, the overall average fuel injection rate for WDE is higher during most of the engine operating conditions, Figures 11 and 12. Increasing engine load causes the average rate of fuel injection to be higher, which causes the pressure in the fuel line to drop at faster rate than at lower load.

The overall trend of the average fuel injection rate for both fuels is similar. They both tend to decrease as engine speed increases. WDE has higher fuel injection rate than AD at all test points except at 2000RPM and 200N.m. The average fuel injection rate difference between the two fuels throughout the whole engine speed and load range is 8%. For AD fuel the maximum average fuel injection rate at 1400RPM is always higher at the two loads than other test points. This can be and expected reason of having higher HC emission index values. Also, it can be said as the fuel injection rate gets higher injection pressure duration become shorter.

Figures 13 to 16 show the cumulative fuel injected for the two fuels at different engine speeds and loads.

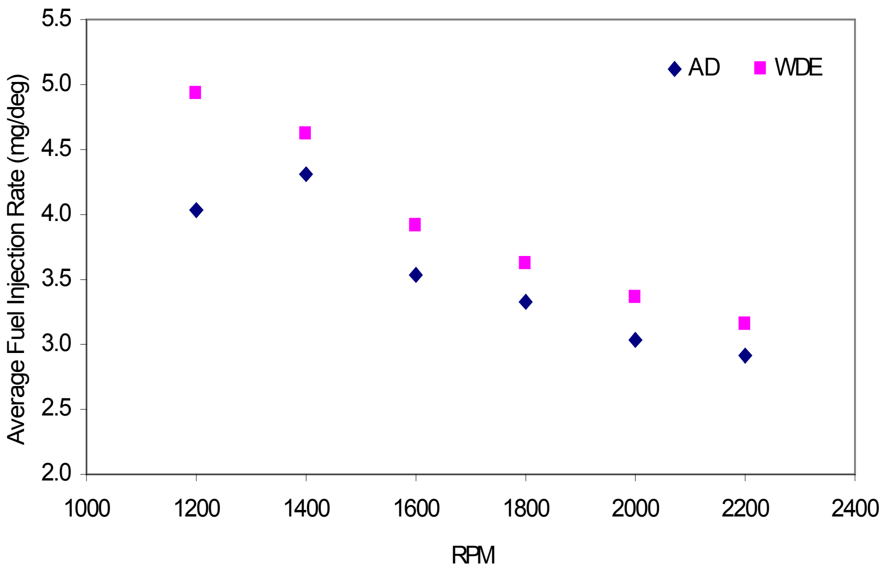

Figure 11. The overall average fuel injection rate for both fuels at all engine speeds and 150N.m

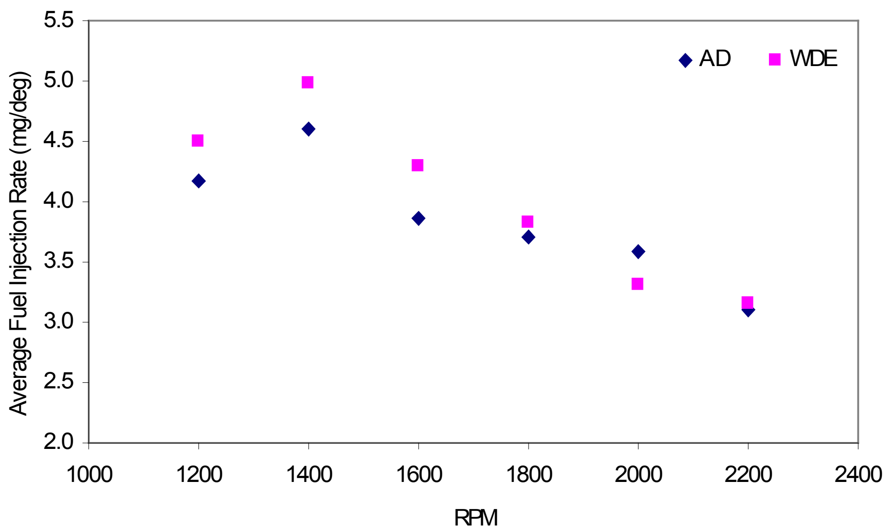

Figure 12. The overall average fuel injection rate for both fuels at all engine speeds and 200N.m

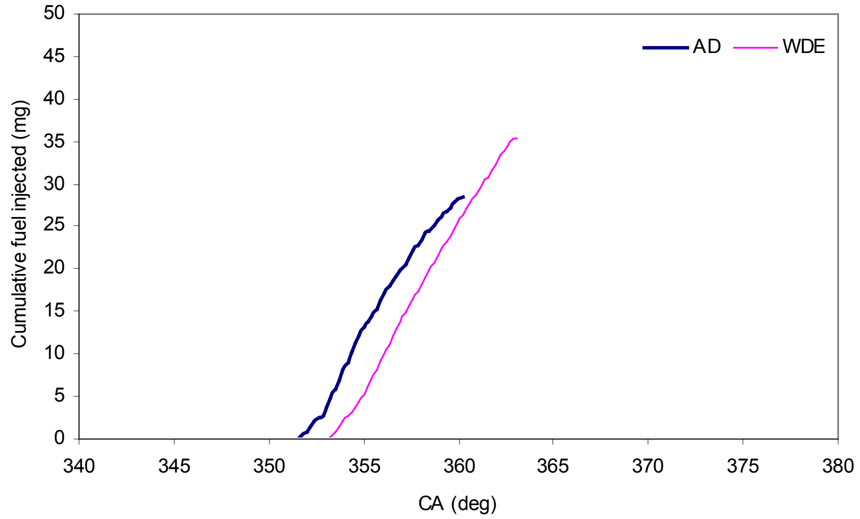

Figure 13. Cumulative fuel injected for both fuels at 1800RPM and 150N.m

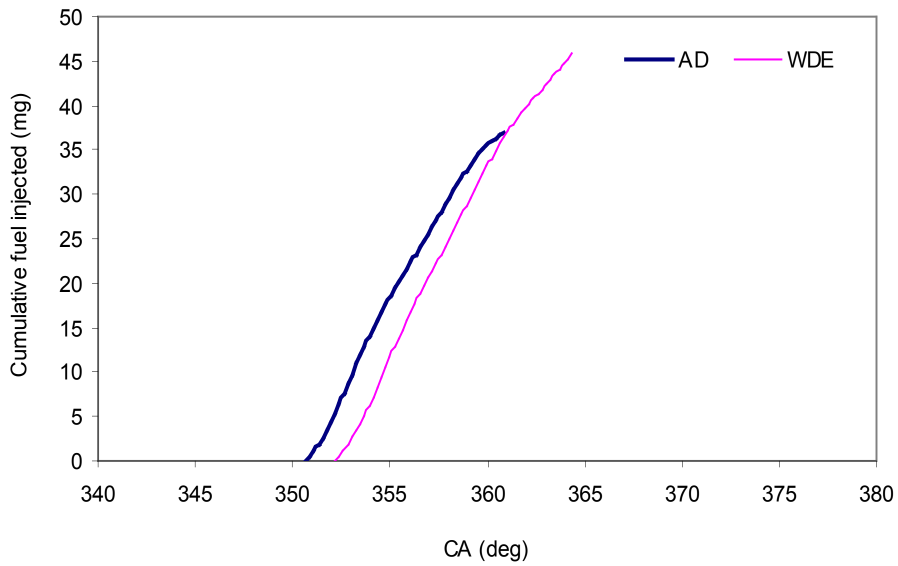

Figure 14. Cumulative fuel injected for both fuels at 1800RPM and 200N.m

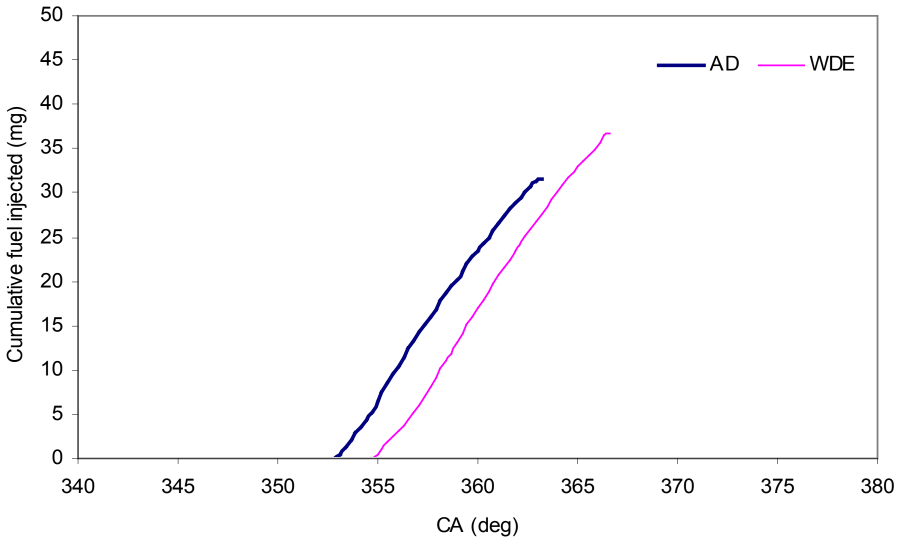

Figure 15. Cumulative fuel injected for both fuels at 2200RPM and 150N.m

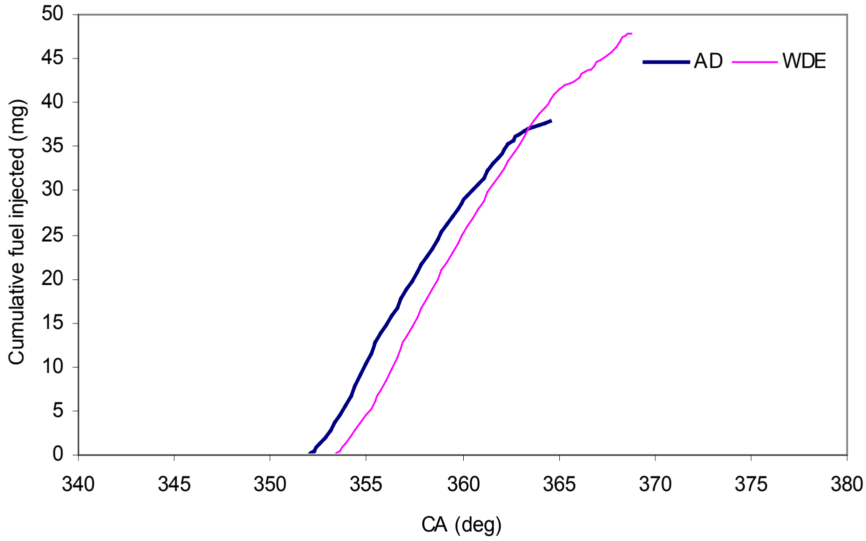

Figure 16. Cumulative fuel injected for both fuels at 2200RPM and 200N.m

Table 1. Fuel injection parameters for the two fuels

Engine speed (RPM)	Load (N.m)	Start of Injection (deg) BTDC		Injection Duration (deg)		Start of Combustion (deg) BTDC		Average injection rate (mg/deg)		Amount of fuel injected per cycle (mg)	
		AD	WDE	AD	WDE	AD	WDE	AD	WDE	AD	WDE
1800	150	8.2	6.7	8.5	9.8	4.1	2.4	3.3	3.6	28.4	35.3
	200	9.1	7.6	10.0	11.9	5.6	4.3	3.7	3.8	37.0	45.7
2200	150	6.9	6.3	10.1	10.9	3.2	1.1	2.9	3.1	29.4	36.7
	200	7.7	7.2	12.2	14.0	5.3	2.9	3.1	3.1	37.8	47.8

These Figures indicate that more mass (27%) of WDE is injected per cycle than AD in order to deliver the same brake power, the greater gradient of the WDE curve indicates a higher fuel injection rate as shown earlier. In general, increasing engine load at constant engine speed means earlier SOI, longer injection duration and almost similar injection rates (although slightly higher) occurring for both fuels. For WDE relative to AD, the SOI happens later than that of AD, longer injection timing and greater injection rate due to the higher fuel density. Table 1 shows the fuel injection parameters for both WDE and AD at different engine speeds and both loads.

The higher fuel injection pressure and duration of WDE was also seen by Tajima et al. [4]. They found an increase in the injection duration and pressure of 5 degrees and 5 Mpa respectively when using 25% emulsified fuel.

Effect of WDE on Cylinder Pressure Measurements

Figures 17 to 20 show the effect of engine speed on cylinder pressure and temperature readings for both fuels with the location of start of combustion (SOC). At both engine speeds and loads the SOC of WDE occurs later than that of AD. SOC for both fuels tends to advance with an increase of engine load and retards with an increase of engine speed as will be shown shortly. Increasing engine speed shifts the cylinder peak pressure away from TDC while increasing engine load has the opposite effect. The WDE peak pressure shift is more sensitive to engine load than AD. Peak pressure values for the two fuels approach each other at higher engine load. At 1800RPM WDE has a higher cylinder temperature than AD during much of the expansion stroke. This difference gets higher at 200N.m load. Cylinder peak pressure decreases with the increase of engine speed and increases as engine load increases, Figures 21 and 22. Peak pressure values for AD are mainly higher than WDE at all engine speeds and loads. The minimum difference in peak pressure values between the two fuels is 1.2% at 1200RPM and 200N.m while the maximum difference is almost 9% at 2200RPM and 150N.m load. The change in cylinder pressure readings for both fuels as engine speed increases is very small compared to the change in engine load. For 1800RPM and 200N.m, the calculated average bulk cylinder temperature for WDE exceeds that of AD. This is because the WDE peak cylinder pressure occurs later than that of AD causing the combustion process to occur during most of the expansion stroke.

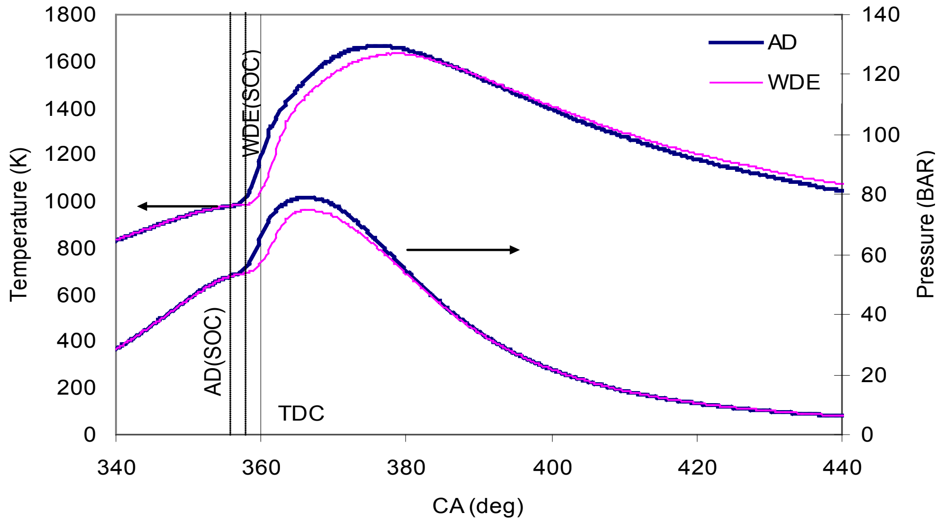

Figure 17. In-cylinder pressure and temperature measurements for both fuels at 1800RPM and 150N.m

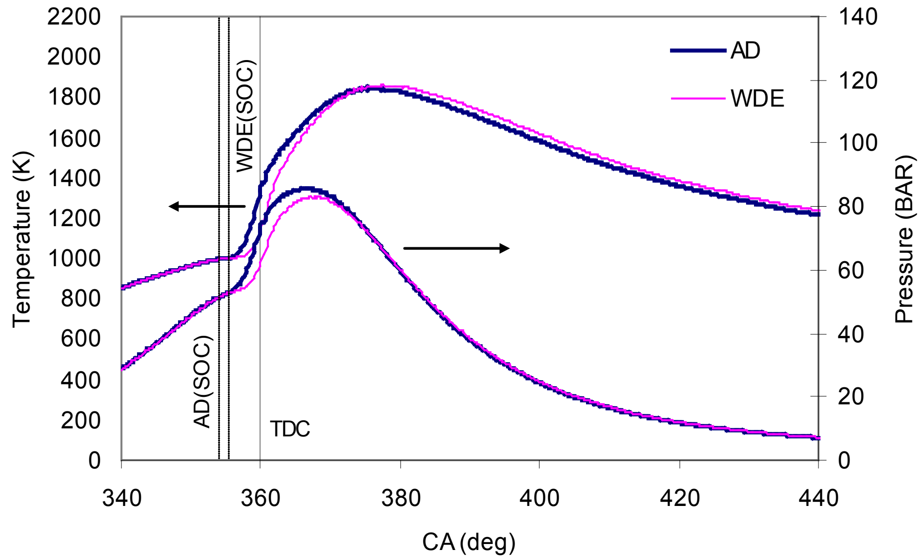

Figure 18. In-cylinder pressure and temperature measurements for both fuels at 1800RPM and 200N.m

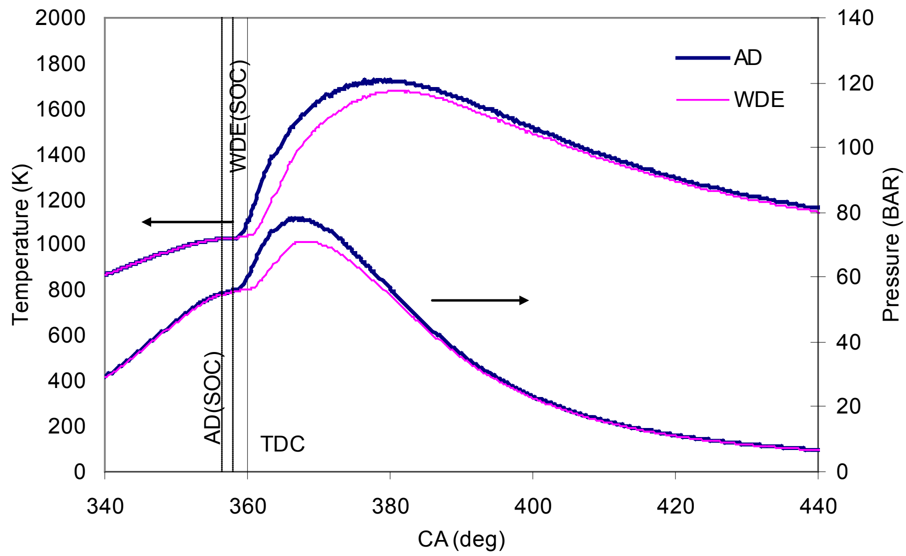

Figure 19. In-cylinder pressure and temperature measurements for both fuels at 2200RPM and 150N.m

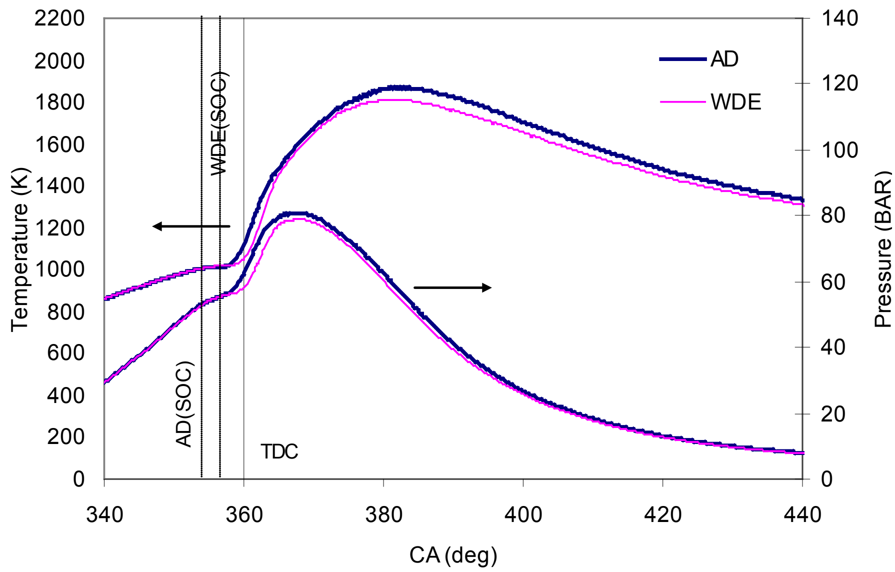

Figure 20. In-cylinder pressure and temperature measurements for both fuels at 2200RPM and 200N.m

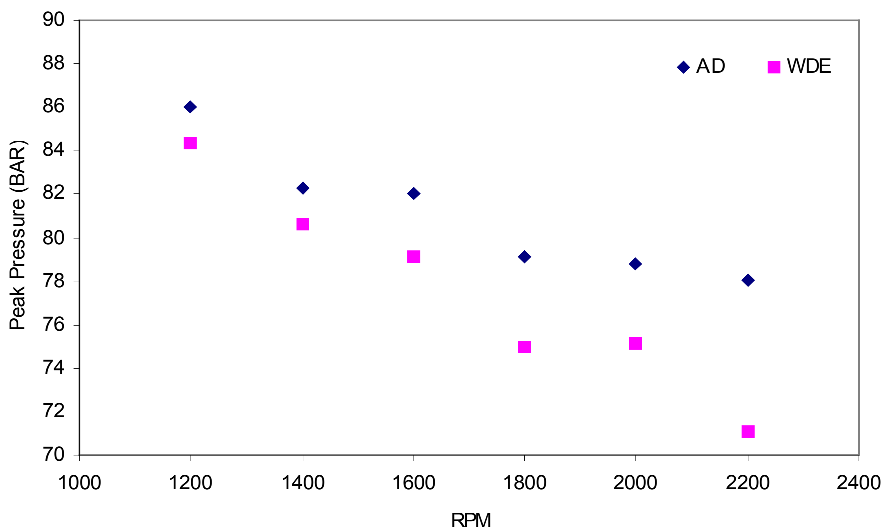

Figure 21. Cylinder peak pressure values at all engine speeds for both fuels and 150N.m

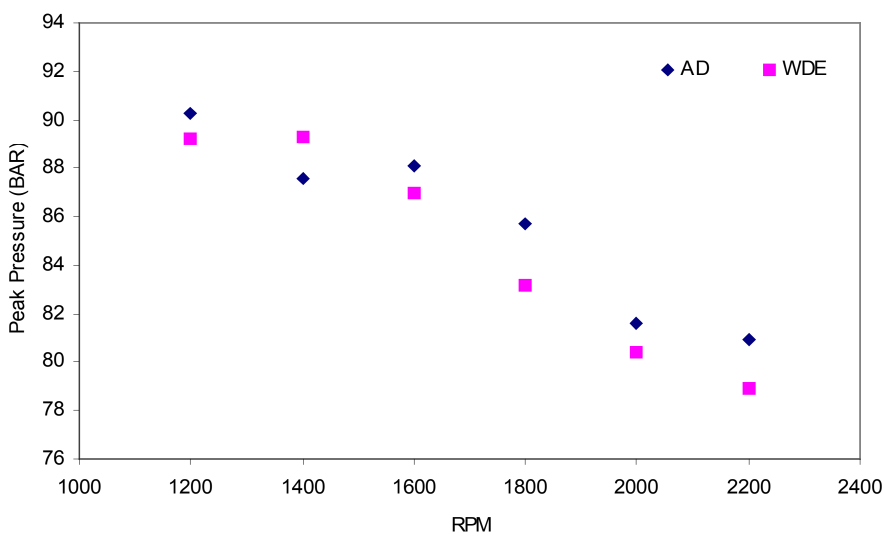

Figure 22. Cylinder peak pressure values at all engine speeds for both fuels and 200N.m

Park et al. [18], have shown that as water percentage increases in an emulsion, peak cylinder pressure is higher than standard diesel fuel peak pressure and the peak occurs further away from the TDC mark. Nazha et. al. [17] and Kumar et al. [21] found the same results as Park et al. [18] when they used 20% WDE and 10% seawater emulsion respectively.

The combustion of the fuel injected during ignition delay causes a sudden rise in cylinder pressure which results in a noticeable change in cylinder pressure gradient, Figures 23 to 26. Since the SOC for WDE is occurring later than that of AD, as a result, the rate of pressure rise is lower for WDE since the fuel energy is released during the expansion stroke. The maximum peak rate of pressure rise for AD at both speeds is higher than WDE at 150N.m whereas at 2200RPM and 200N.m the rate of pressure rise for both fuels is the same. WDE peak rate of pressure rise at all engine speeds and loads is always lower than that of AD. This could be the reason of having slower flame propagation for WDE which takes a longer time to propagate over the premixed phase than that of AD. This explains the noticeable decrease in engine noise with WDE. As engine load increases, WDE peak rate of pressure rise approaches that of AD.

Park et. al. [22] investigated the combustion characteristics of 17% and 29% WDE in a rapid compression machine. Pressure traces and high-speed photography indicated that there was a lower rate of pressure rise. However, Tsukahara and Yoshimoto [23], and Subramanian and Ramesh [24] found that the longer ignition delay resulted in higher rate of pressure rise.

The late SOI of WDE as shown previously (Figures 9 and 10) is causing the SOC to occur at a later position than AD, Figures 27 and 28, for all test points except the 1400RPM and 200N.m case. Increasing engine load has an opposite effect of speed. It tends to advance the SOC to occur much earlier. This is true for both fuels, however, at high engine speed and load (2200RPM and 200N.m), the WDE SOC shifts away from AD. Although the SOC of both fuels at any specific test point are different, this difference in SOC between the two fuels has almost the same difference as the SOI at that speed and load.

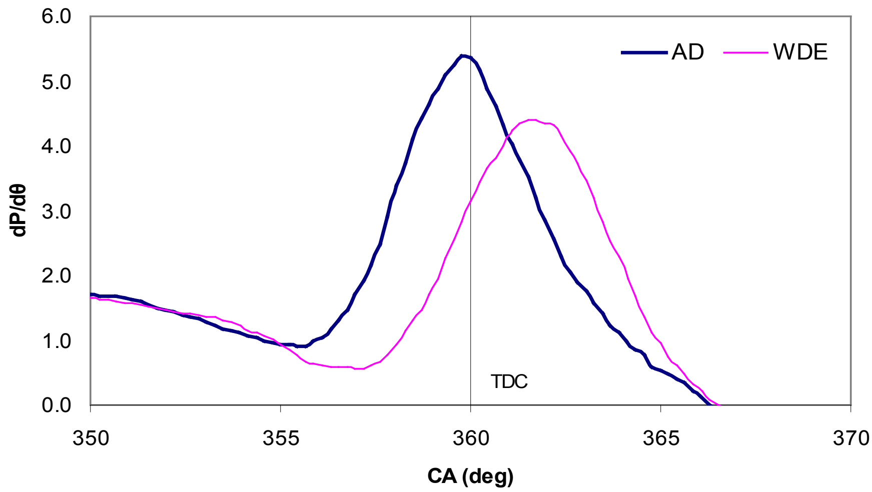

Figure 23. Rate of pressure rise for both fuels at 1800RPM and 150N.m

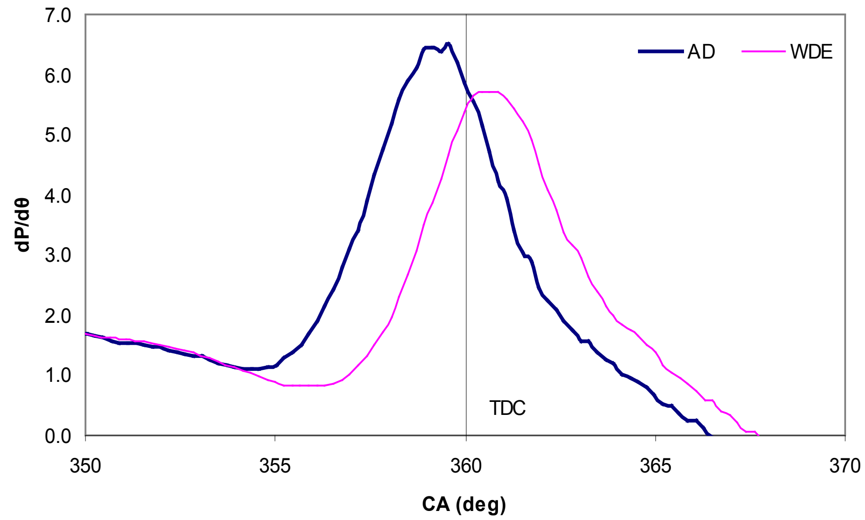

Figure 24. Rate of pressure rise for both fuels at 1800RPM and 200N.m

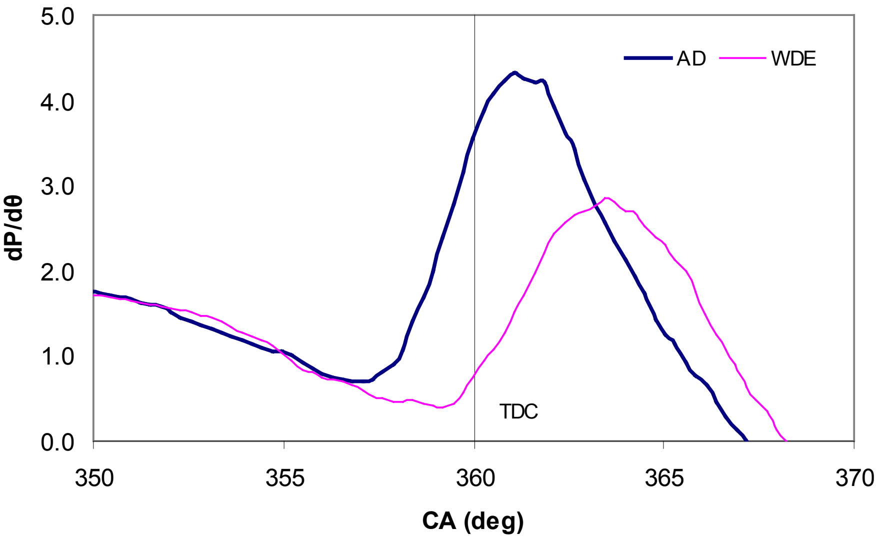

Figure 25. Rate of pressure rise for both fuels at 2200RPM and 150N.m

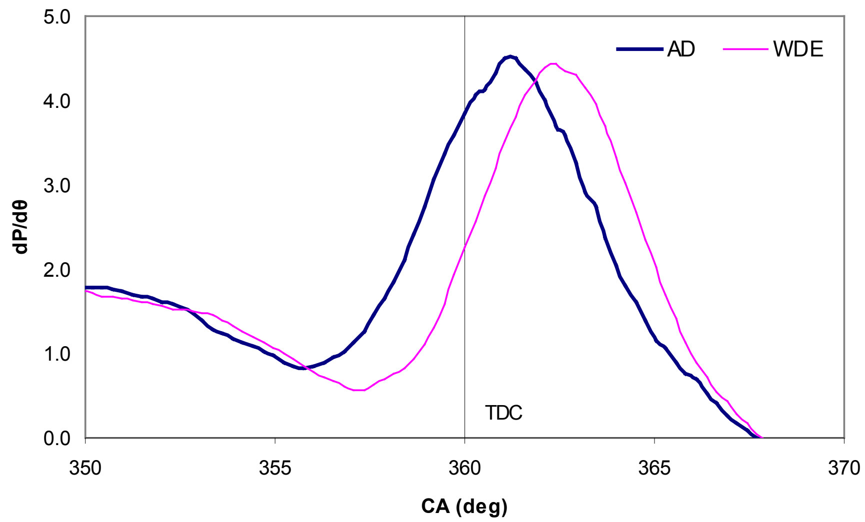

Figure 26. Rate of pressure rise for both fuels at 2200RPM and 200N.m

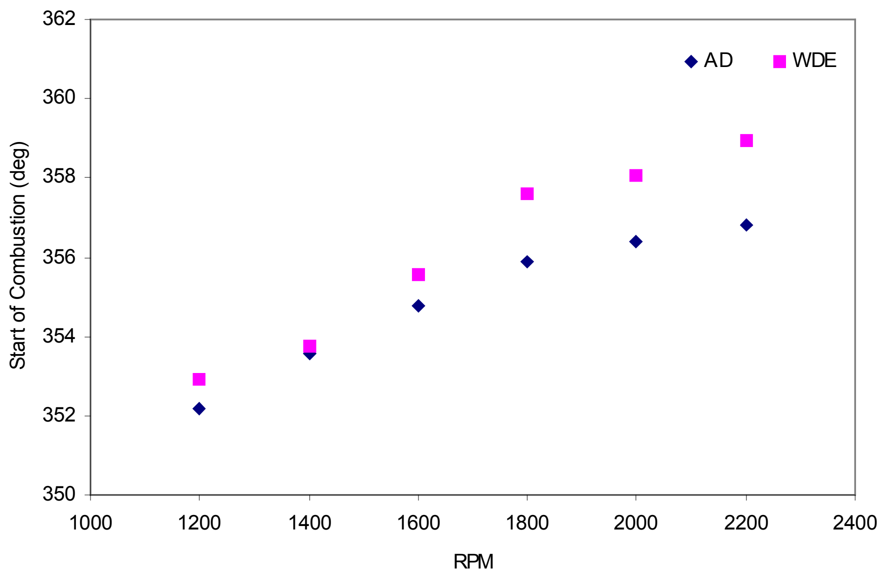

Figure 27. The Start of combustion (SOC) for the two fuels at all engine speeds and 150N.m.

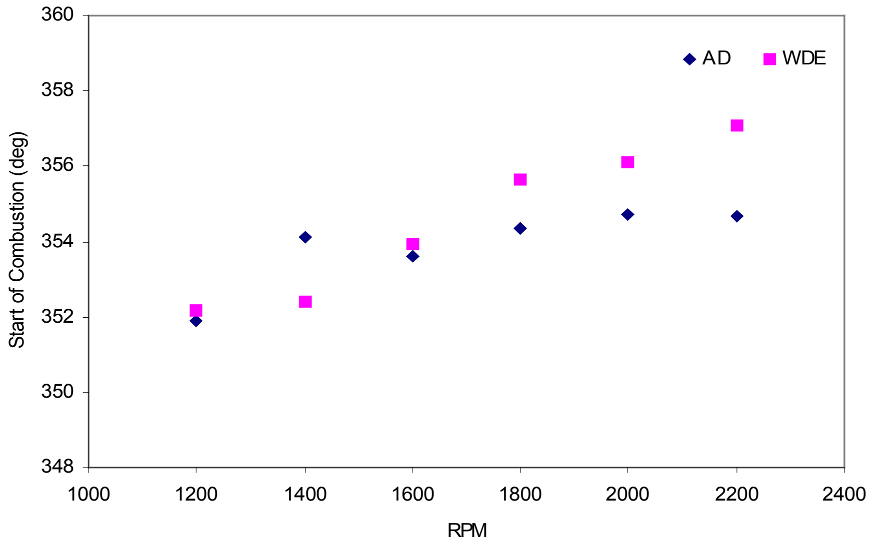

Figure 28. The Start of combustion (SOC) for the two fuels at all engine speeds and 200N.m

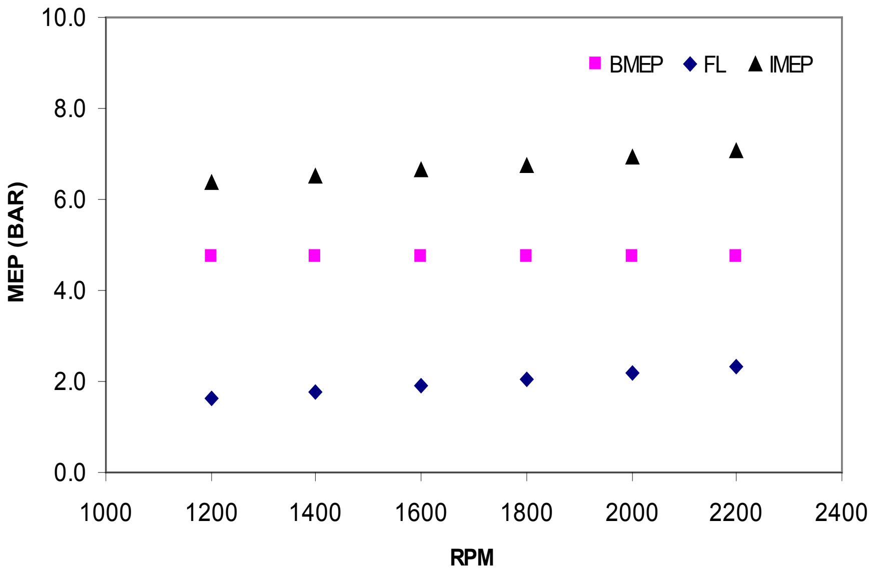

Figure 29. Experimental IMEP, BMEP and FL at all engine speeds and 150N.m using AD

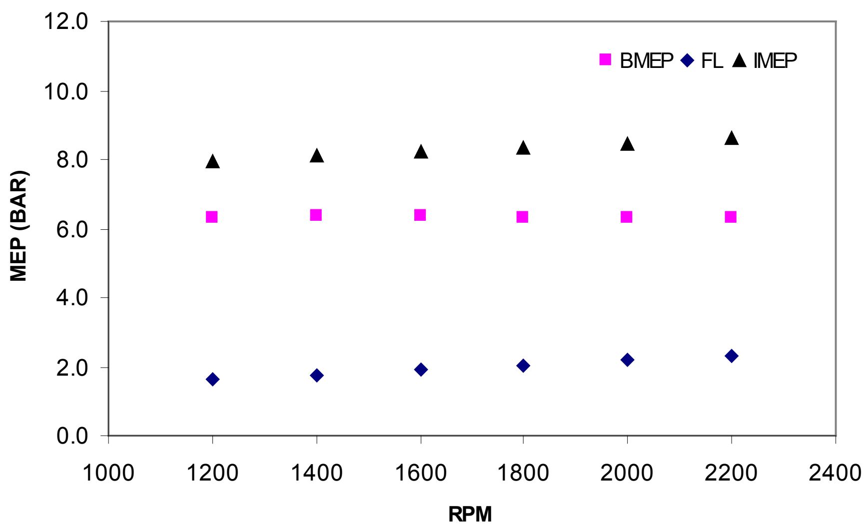

Figure 30. Experimental IMEP, BMEP and FL at all engine speeds and 200N.m using AD

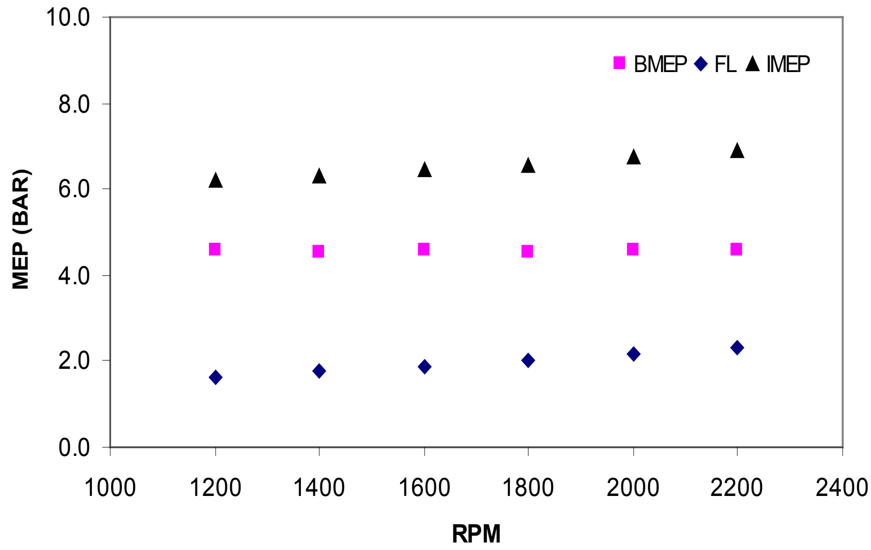

Figure 31. Experimental IMEP, BMEP and FL at all engine speeds and 150N.m using WDE

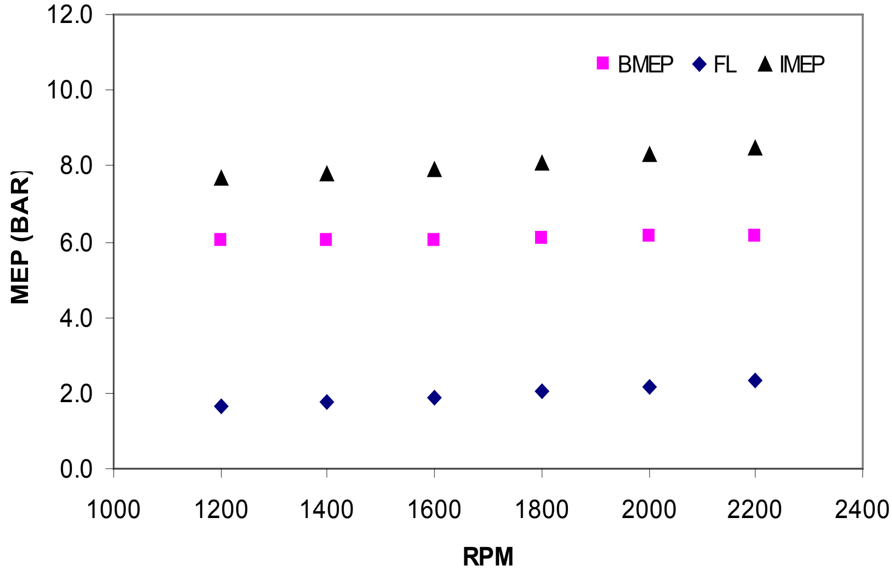

Figure 32. Experimental IMEP, BMEP and FL at all engine speeds and 200N.m using WDE

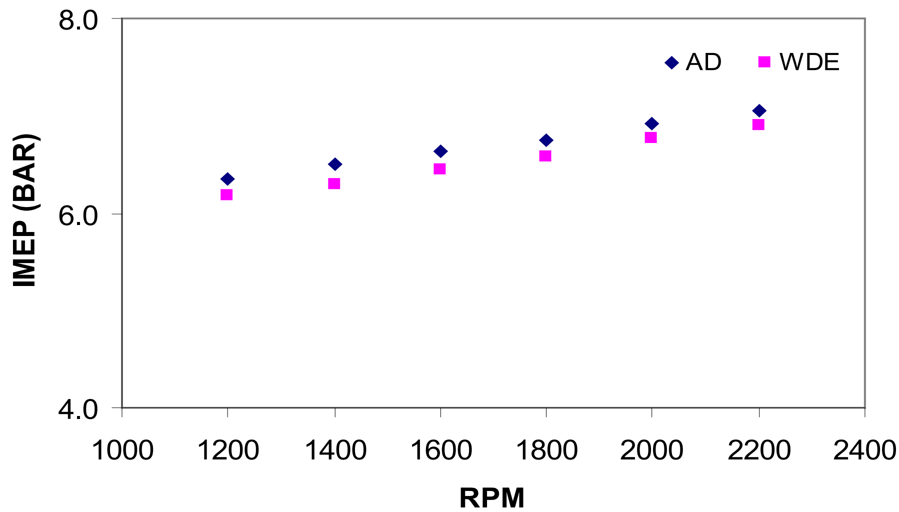

Figure 33. The difference in the IMEP between the two fuels at all engine speeds and 150N.m

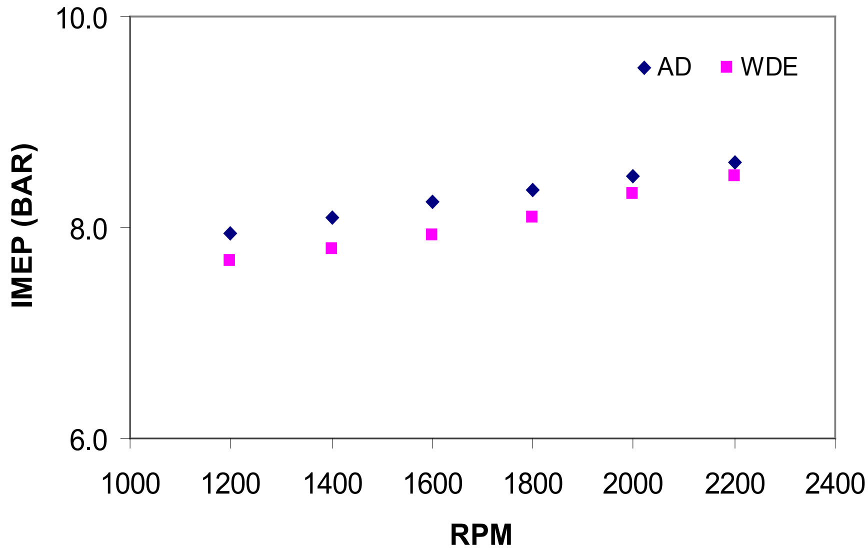

Figure 34. The difference in the IMEP between the two fuels at all engine speeds and 200N.m

Mean Effective Pressure

The experimental brake mean effective pressure (BMEP) have been calculated using Millington and Hartles [25] friction loss (FL) model and the indicated mean effective pressure (IMEP) at all engine speeds for both fuels and loads, Figures 29 to 32.

The FL as described by Millington and Hartles is dependent on compression ratio, engine speed and mean piston speed. In this case, the FL at any specific engine speed for both fuels and loads are the same. The BMEP is then dependent on IMEP. At 150N.m (Figures 29 and 31), the BMEP for WDE at any specific test point is slightly lower than that of AD, Figure 33.

As engine speed increases (2000RPM and 2200RPM), the BMEP for WDE approaches that of AD. This is more evident at 200N.m load, Figure 34.

From the above Figures, WDE produces almost similar engine performance as that of AD. Although the peak cylinder pressure for WDE is lower than that of AD for most of the test points, however, the longer fuel injection duration resulted in a higher cylinder pressure during most of the expansion stroke and hence an overall similar engine performance as AD.

3. Conclusions

Experimental work on direct injection diesel engine using AD and WDE at two engine speeds and loads have been investigated. In terms of combustion behaviour, WDE can be regarded as an alternative for automotive diesel fuel. The magnitude of cylinder pressure during most of the cycle and peak pressures are close to those observed for AD at any speed and load. WDE cylinder pressures get closer to that of AD at higher engine load (200N.m). The late SOC for WDE causes the fuel energy to be released during most of the expansion stroke resulting in a higher cylinder pressure. Because WDE has lower energy than AD (12% less), more fuel volume is required per cycle in order to deliver the same engine brake power. The fuel injection characteristics of WDE are quite different to that of AD. Differences in WDE fuel properties such as bulk modulus, density and viscosity cause the start of fuel injection pressure rise to occur much earlier than that of AD. Although the higher bulk modulus of WDE should result in an earlier SOI, however, the opposite is occurring here. It is causing a late SOI for WDE and consequently late SOC. In terms of exhaust emissions, the lower combustion temperature of WDE is expected to cause a lower NOx emission.

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