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Investigation of the Effect of Water Diesel Emulsion Fuel on Heat Release in Direct Injection Diesel Engine

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Abstract

The main objective of this study is to investigate the effect of engine operating conditions (speed and load) on heat release characteristics as well as cylinder pressure and fuel injection using automotive diesel (AD) and water diesel emulsion (WDE) fuel. To achieve this objective, an experimental investigation was conducted on four-strokes, 4-cylinder, naturally aspirated direct injection diesel engine. Engine performance was assessed by collecting and storing data using two data acquisition systems. The collected data were then analysed to compute in-cylinder pressure readings and fuel injection. Combustion characteristics were derived in the form of heat release data based on the thermodynamic analysis of in-cylinder pressure measurements. Results clearly showed the presence of the two distinct combustion processes, premixed and diffusion. The cumulative apparent heat release increased proportionally with engine speed at constant load due to the lower heat transfer rates at high engine speed. The ignition delay was almost the same for all speeds and high load. whereas the rate of injection was higher for low speeds.

Keywords: Diesel engine, Direct injection, Cylinder pressure, Fuel injection, Heat release, Premixed combustion, diffusion combustion.

Introduction

Combustion process in compression ignition (CI) engines is different from that in spark ignition (SI) engines [1]. Combustion in SI engines is essentially a flame front moving through a homogeneous mixture whereas combustion in a CI engine is an unsteady process occurring simultaneously at many spots in a very non-homogenous mixture at a rate controlled by fuel injection. In diesel engines, the injected fuel break into very tiny droplets. The smaller the droplets, the quicker and more efficient is the mixing of fuel with air. The small droplets of fuel evaporate due to the high temperature of the compressed inducted air. Air surrounding the evaporated droplets will be cooled in what is called “evaporative cooling” [1]. however, near the core of the fuel jet, a combination of high fuel concentration and evaporative cooling will cause adiabatic saturation of fuel to occur. Figure 1 shows the non-homogenous distribution of air to fuel ratio that develops around the injected fuel jet. The Combustion can occur within the equivalence ratio (φ) limits of 0.8 (lean) and 1.8 (rich). In the given figure, the mixture` is very rich at the zone designated by symbol (A), and very leans at the zone designated by symbol (E). Self-ignition starts mainly at zone (B) and solid carbon soot is generated mostly at zones A and B.

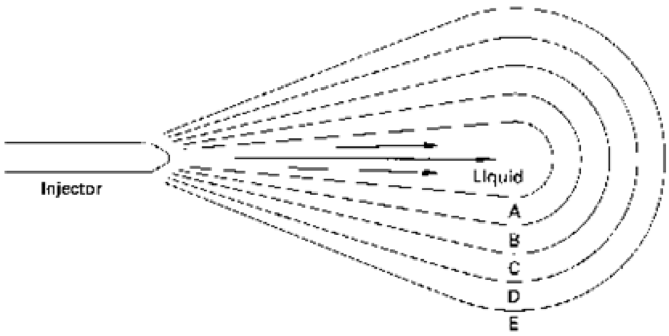


Figure 1: Fuel jet of CI engine showing zones of different air/fuel ratios.

Self-ignition of the air-fuel mixture starts near the top dead centre of the piston and continuous to a certain degree after the top dead centre. The delay in the commencement of self-ignition is due to the “ignition delay” or “ignition period”. This period comprises both physical and chemical delay components followed by two combustion phases as shown in figure 2.

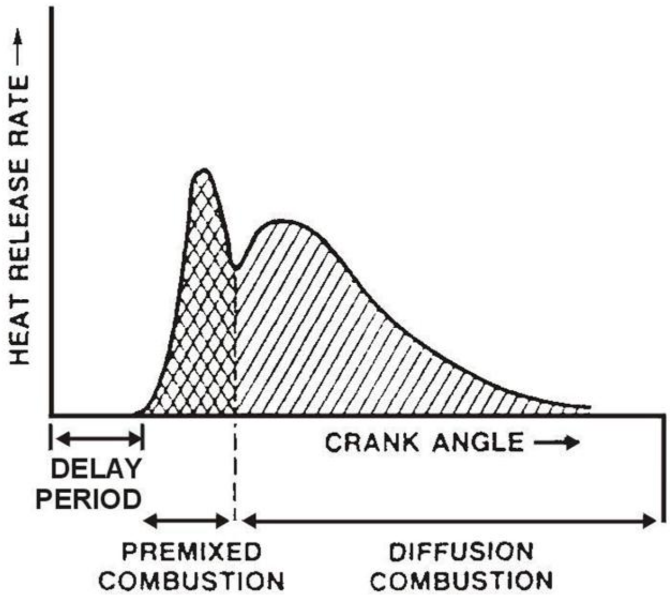


Figure 2: The delay period and the combustion phases [2].

The end of the delay period is designated by the departure of a firing pressure trace (trace produced because of fuel combustion) from the motoring pressure. The delay period depends upon the temperature and pressure that exists in the combustion chamber at that time, in addition to the chemical structure of the fuel. The higher the pressure and temperature within the combustion chamber, the shorter is the ignition delay. On the other hand, the degree of atomization of fuel and the quantity of fuel injected have a minor effect on the delay period [2]. During the delay period, the piston continues to move closer to the TDC causing the mixture temperature to reach the fuel ignition temperature causing rapid burning of the pre-mixed mixture. The speed of this reaction determines the rate of pressure rise in the cylinder. A high rate of pressure rise has a damaging effect on the engine parts. This high-pressure rise produces a violent pounding noise, which is known as diesel knock. The rate of pressure rise during the rapid combustion period is affected by the degree of atomization, how much fuel is evaporated during the delay period, how well the fuel is distributed through the cylinder and how much fuel is ignited during the delay period. Since fuel injection is continuing, the combustion becomes slow and is controlled by the rate at which fuel is injected, atomized, vaporized, and mixed with air in a proper air to fuel ratio. This phase of combustion is called diffusive combustion and is characterized by a slower rate of pressure rise and heat release. Although the rate of pressure in this phase is low compared to the pressure rise during premixed combustion, however, combustion lasts longer. This is because some fuel particles take longer time to mix with air in a proper condition. The apparent cumulative rate of heat release could be calculated using the first law of thermodynamics and the measured in-cylinder pressure data [3].

Literature review

May authors did research on the effect of water diesel emulsion, most results show that its can reduce pollution levels and improve engine performance. In this section a review of previous related work in the topic of water-diesel emulsion is presented.

Abu-Zaid [4] shows that the proper brake specific fuel consumption and gases exhaust temperature decrease as the percentage of water in the emulsion increases.

Ghojel [5] presented measurements of the performance of a diesel engine operating on a typical diesel oil emulsion and examine using heat release analysis differences found during its combustion relative to standard diesel, the result shows that brake specific fuel consumption is high.

Sangki Park [6] studied the diesel–water emulsified (DE) fuel that carried out the experiment for the characteristic of sprat using diesel water emulsified fuel in a diesel engine, and the possibility of its application to conventional diesel engines was evaluated from the fundamental characteristics of diesel–water emulsified fuel. The results showed that the experiments were confirmed as the spray atomization characteristics at the various emulsified fuels.

Abdurahman Nour [7] conducted an experimental investigation to examine the effect of water diesel emulsions on the performance of a TF120M Yanmar engine. The result shows an emulsion improves the combustion efficiency in the diesel engine, thus increasing the performance of the engine.

Zhe Kang [8] studied and investigated the effect of DWI temperature on combustion process and thermal efficiency within Internal combustion Rankine cycle.

Sudarshan Gowrishankar [9] modified and optimized an existing mechanical fuel injection system to an electronic common rail injection (CRDi) system for utilizing biodiesel-water emulsion. The results shows that utilizing biodiesel-water emulsion with a flexible injection system reduces engine exhaust emissions while simultaneously improving the performance characteristics.

In this paper, an experimental work of the effect of engine load and speed on cylinder pressure, fuel injection rate and fuel burn rate have been conducted.

EXPERIMENTAL ENGINE SET-UP

Tests were conducted on an industrial diesel engine (Table 1) with one cylinder instrumented for engine indicating purposes. A computerized data acquisition system was developed and used to gather performance data from the engine by means of an AVL high pressure transducer GU12P mounted in the unused glow plug, an AVL fuel line high pressure transducer SL31D-2000 and AVL Nozzle needle lift indicating set. A CODA exhaust gas analyser was used to measure NOx, CO, CO_2, HC and O_2 by means of chemiluminescence's and electro-chemical cells. Torque was applied to the engine through an eddy-current dynamometer. Three industrial fans were employed to constantly maintain the air temperature in the test cell. Fuel, engine inlet air, coolant, exhaust and oil temperatures were also recorded by K-type thermocouples. Engine coolant temperature was controlled and monitored by routing cooling water through an external heat exchanger. A fuel tank weight sensor was used to monitor the fuel consumption. A pressure transducer was mounted on the intake manifold for reading the absolute pressure. Test cell ambient conditions such as relative humidity and temperature were also recorded.

Table 1: Test engine specifications.

Type of Engine	Hino, Diesel, in-line, water cooled
No. of Cylinders/ No. Of Strokes	4 / 4
Rated Power (continuous)	62 kW @ 2800rpm
Prime Power (Generator Use)	33 kW @ 1500 rpm, 41 kW @ 1800 rpm
Maximum Torque (N.m)	258 @ 2800rpm
Bore x Stroke, mm	104 x 118
Displacement, litre	4.009
Compression Ratio	17.9:1
Combustion System	Direct Injection

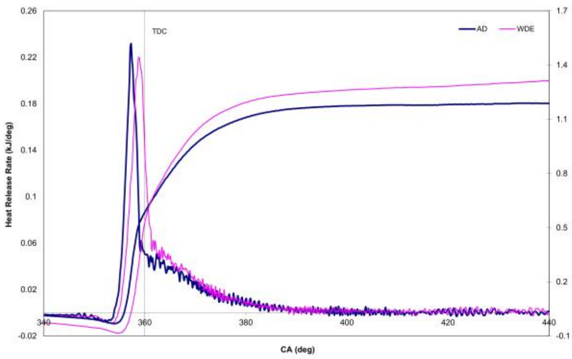
Table 2 shows the engine speeds and loads used in this test. All tests were carried out at steady state conditions.

Table 2: Speeds and loads considered in the present work.

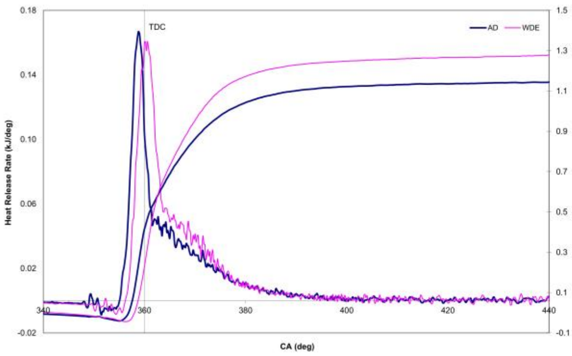
Speeds (rpm)	Torque (N. m)
1400	150 and 200
1600	
1800	
2000	

Results and Discussion

The in-cylinder pressure data has been used to calculate the heat release characteristics of the engine at all test points. Figure 3 shows the characteristics of heat release rate and cumulative for all speeds at 150N.m load for both fuels. The start of combustion (SOC) is considered to occur at the sudden rise heat release curve. Also, the two combustion phases of premixed and diffusion combustion phases can be identified clearly.



(a)



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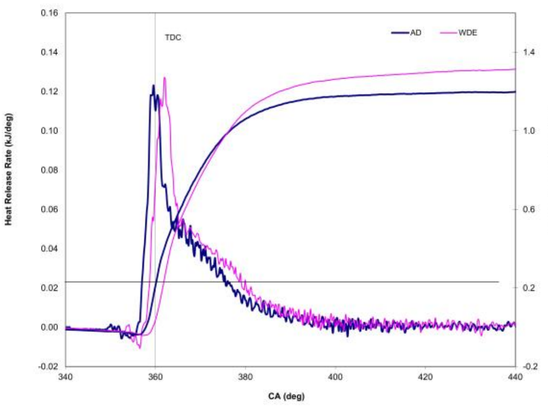

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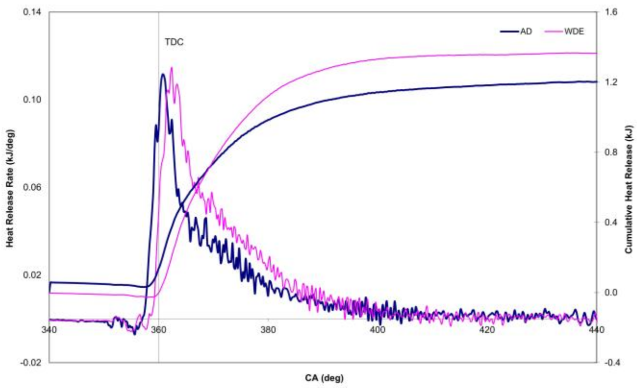

(d)

Figure 3: All speeds are at 150N.m; (a) 1400 RPM (b) 1600 RPM (c) 1800 RPM (d) 2000 RPM.

As engine speed increases, the premixed combustion process is retarded toward the TDC for both fuels, hence, retarding the gas peak temperature as well. This retard in the premixed combustion process would cause the diffusion combustion phase to occur mainly in the power stroke. This also means that the peak of the premixed combustion process would decrease as engine speed increases since most of the combustion process will be dominated by the diffusion combustion process. The small dip in the heat release rate curves at all engine speeds that occurs just before the SOC for both fuels implies that injected fuel is absorbing some of the heat within the cylinder to evaporate and become ready for combustion. Although the rate of evaporation is not within the scope of this study, however, it looks the same at all engine speeds with different evaporation time. The longer time of fuel to evaporate is due to the more amount of fuel injected which corresponds to the higher engine speed. At low engine speed, most of the fuel is injected within the premixed combustion phase which results in higher combustion temperature. The higher the value of premixed combustion, the more oscillating of pressure within the cylinder which causes the distinct knock of diesel engine. Furthermore, the peak of the premixed zone decreases with the increase of engine speed. While the amount of fuel injected for all speeds is the same at the same load (around 28.4 mg), however, the injection duration tends to increase with the engine speed. This causes the rate of premixed zone and rate of heat release at high speeds to decrease with decreasing speeds. In general, at high engine speeds most of the combustion happens in the diffusion zone whereas t low speeds, because the fuel injection starts and ends before the TDC the premixed zone also ends accordingly. When the injection duration extends beyond TDC, the premixed combustion zone is retarded, reaching its peak after TDC. The cumulative heat release tends to increase with engine speed while maintaining constant load. This is due to the lower heat transfer rates at high engine speed. The late rise of heat release rate curve for WDE fuel which corresponds to late start of combustion is due to the late start of injection for all engine speeds and loads as will be shown later. The higher cumulative heat release for WDE is since 13% of diesel fuel by weight is replaced with water to form the WDE fuel. This means that more WDE fuel is required to be injected to match the engine load of AD fuel. Table 3 shows the extra amount of fuel injected for WDE relative to AD fuel.

Table 3: Percentage of extra fuel injected for WDE relative to AD at engine speeds and both loads.

	1400	**1600**	**1800**	**2000**	**Avg.**
150 N.m	26.7%	27.1%	24.6%	15.3%	23.4%
200 N.m	21.0%	24.4%	23.6%	24.6%	23.4%

Although the extra amount of WDE fuel injected compared to AD fuel is different for each engine speed and load, however, the average extra amount of WDE fuel injected is the same for both loads. Although that WDE fuel is about 12% less in lower heating value than AD fuel, however, this means that the extra amount of the injected fuel is because water within the fuel is absorbing almost 11% of the combustion energy. This also means that using WDE fuel in diesel engine vehicles will result in more frequent stopping for refuelling than using AD fuel. This finding encourages to investigate the economic effect of using WDE fuel, however, it is out of scope of this study. The late rise of heat release curve for WDE is due to the late injection of fuel as shown in Figure 4.

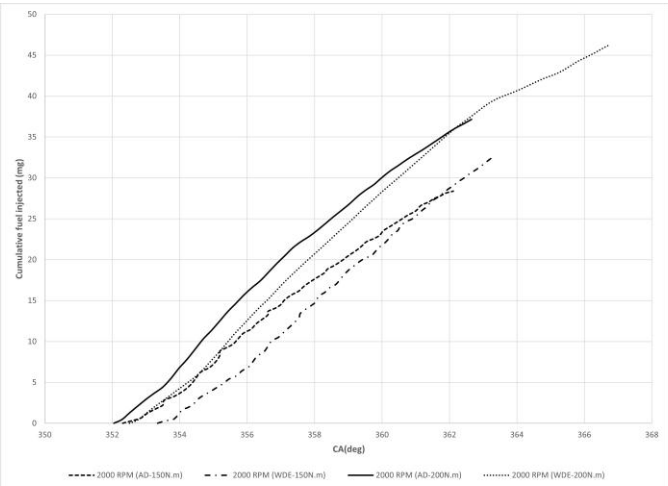

Figure 4: Cumulative fuel injected for AD and WDE at 2000 RPM and both loads.

It is evident that the start of injection for WDE always occurs late compared to AD and continuous for longer time. The higher density of WDE compared to AD which requires more pressure rise within the diesel injection pump to inject the fuel causing the fuel to be injected late. As mentioned before, the existence of water within the fuel absorbs enough heat during combustion which in turns reduce the maximum pressure within the cylinder as shown in table 4. On the other hand, because cylinder temperature is a function of cylinder volume and WDE combustion occurs later than that of AD (at higher cylinder volume), this causes the maximum temperature for WDE within the cylinder to be hire than that of AD in most cases.

Table 4: Sample of maximum combustion pressure and temperature at two speeds and both loads.

Speed (rpm)	Load (N.m)	Fuel	P_{max} (Bar)	T_{max} (K)
1800	150	AD	79.1	1669
		WDE	74.9	1635
	200	AD	85.7	1848
		WDE	83.2	1859
2000	150	AD	78.8	1645
		WDE	75.1	1667
	200	AD	81.6	1779
		WDE	80.4	1802

From the previous figures and tables, gas temperature and cylinder pressure depend mainly on engine load. This is because the amount of fuel injected within one cycle is directly proportional to engine load. Also, as the engine load increases, fuel injection starts earlier, giving more preparation time for the physical and chemical processes of fuel. However, ignition delay period becomes shorter which makes the fuel to be burned in the diffusion phase. Furthermore, as engine load increases, fuel injection period becomes longer which makes the maximum combustion temperature and cylinder pressure to retard (occurs after the top dead centre).

On the other hand, engine speed has a noticeable effect on heat release. The combustion pressure increases sharply during the premixed phase peaking at a lower rate of around 4.5 CA after the top dead centre (ATDC). Since the geometrical injection timing is fixed for the experimental engine, the start of combustion occurs between 2.9-7.2 CA before the top dead centre (BTDC) depending on load and speed. The variation of gas temperature with crank angle indicates that the increase of temperature is very steep following the start of combustion and reaches a peak at almost 15 degrees ATDC.

Then the temperature decreases gradually. This behaviour may be explained as follows: the rate of heat release (RHR) during the premixed combustion period is vigorous and, therefore, the gas temperature increases sharply. Accordingly, the rate of heat transfer increases suddenly, as well. During the diffusion combustion period, where the rate of heat release is more gradual and the gas expands during the expansion stroke, the gas temperature decreases gradually and therefore, the rate of heat loss decreases gradually, as well. As engine speed increases the premixed combustion zone shifts toward TDC causing the peak gas temperature to move away from TDC during the expansion process. Cycle parameter variations are summarized in Table 5.

Table 5: Variation of Cycle Parameters for AD.

Speed (rpm)	Load (N.m)	SOI (deg BTDC)	SOC (deg BTDC)	ID (deg)
1800	150	8.2	4.1	4.1
	200	9.1	5.6	3.5
2000	150	7.2	3.6	3.6
	200	7.7	5.3	2.4

The start of fuel injection occurs earlier at low engine speeds unlike higher speeds. Although the amount of fuel injected within the cycle is almost the same for all engine speeds at constant load, the fuel pressure increases with engine speed causing a fine fuel spray and hence better air fuel mixture. On the other hand, the injection duration increases as engine speed increases giving a lower rate of injection than at low engine speed. Fuel injection parameters are shown in Table 4.

Conclusion

An experimental investigation was performed on four-strokes, four cylinders naturally aspirated direct injection diesel engine for the purpose of examining the effect of WDE on heat release, in-cylinder measurements and fuel injection while varying engine speeds and loads. Based on experimental data, heat release was calculated using the first law of thermodynamics. Results showed that as the engine load increases, the maximum gas temperature and cylinder pressure tended to retard (shift away from TDC). Also, the fuel injection starts earlier giving more preparation time for the physical and chemical processes of the combustion of the fuel which reduce the ignition delay period. At low engine speeds, the start of fuel injection occurred earlier. The amount of fuel injected within a cycle was almost the same for all engine speeds at constant load. However, the fuel injection pressure increases with engine speed causing a finer fuel spray and hence a better air fuel mixing and combustion. The injection duration increased as engine speed increased giving a lower rate of injection than at low speeds (since the amount of fuel remained unchanged). The calculated heat release characteristics clearly showed the presence of the two distinct combustion processes, premixed and diffusion. The distinction tended to become more pronounced with increasing load. The premixed combustion phase shifted toward TDC as engine load was increased, which caused the peak gas temperature to move after TDC during the expansion process. The cumulative heat release increased proportionally with engine speed at constant load due to the lower heat transfer rates at high engine speed.

References

[1] Willard, W.P., 1997. *Engineering Fundamentals Of The Combustion Engine*. New Jersey.

[2] Alkidas, A.C., 1987. *Experiments with an uncooled single-cylinder open-chamber diesel*. SAE transactions, pp.280-290.

[3] Ghojel, J.I., 1994. *Computer time reduction in first law analysis of combustion systems.* In Proceedings International Conference on Fluid and Thermal Energy Conversion ‘94 (Vol. 1, pp. 335-342).

[4] M. Abu-Zaid., 2004. *Performance of single cylinder direct injection diesel engine using water fuel emulsions* Energy Conversion and Management. (Volume 45, Issue 5, Pages 697-705).

[5] Jamil Ghojel, Damon Honnery, and Khaled Al-Khaleefi 2006. *Performance, emissions, and heat release characteristics of direct injection diesel engine operating on diesel oil emulsion*. Applied Thermal Engineering. (Volume 26, Issues 17–18, Pages 2132-2141).

[6] Sang-Ki Park, Seungchul Woo, Hyungik Kim, and Kihyung Lee. *The characteristic of spray using diesel water emulsified fuel in a diesel engine*. Applied Energy. (Volume 176, Pages 209-220).

[7] N. H. Abdurahman, Y. M. Rosli, N. H. Azhari and A. Abdul Adam, 2016. *The Potential of a Water-in-Diesel Emulsion for Increased Engine Performance and as an Environmentally Friendly Fuel*. MATEC Web of Conferences Published by EDP Sciences.

[8] Zhe Kang a b, Shangsi Feng a b, Yang Lv a, Jingtao Wu c, Zhijun Wu. *Effect of direct water injection temperature on combustion process and thermal efficiency within compression ignition internal combustion Rankine engine*. Case Studies in Thermal Engineering Volume 28.

[9] Sudarshan Gowrishankar, Anand Krishnasamy, (2023). *Injection system modification and optimization for performance enhancement and emission reduction in a light-duty diesel engine fuelled by biodiesel-water emulsion*. Fuel Volume 337.