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Behavior of Water-Waste Cooking Oil Biodiesel Emulsion for Diesel Engine Performance, Engine Roughness and Exhaust Emissions

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***Abstract*:- The current work involved the use of waste cooking oil (WCO) to produce a biofuel for diesel engine and to generate/prepare a new set of fuels, by emulsifying the WCO biofuel with different water amounts of 5%, 10% and 15%. Important conclusions about the performance of the diesel engine and its exhaust emissions as affected by the water addition have been drawn. All results have been compared with the basic case where the pure diesel fuel is used. It may be highlighted that the engine produced slightly less output torque when the WCO biofuel or its emulsions with water are used, hence the brake specific fuel consumption was slightly increased. On the positive side, the use of water in the biofuel emulsion reduced the dangerous emissions of Nitrogen Oxides gases.**

1. INTRODUCTION

The dangerous exhaust gases emitted from diesel engines pollute our environment hence affects the human's health directly and indirectly. It is evident [1] that the gases / particulate matter emitted from such engines not only affects the environment but also generate green house effect. It has been a challenging goal of engineers to reduce the level of dangerous gases such as Nitrogen Oxides in the diesel exhaust by different means. The most promising method of such efforts is producing emulsion of the liquid fuel and the water (Water / Diesel emulsion). It has proved effective to reduce such dangerous gases from diesel exhaust when added to the diesel fuel [2-4].

Adding water to diesel to produce fuel emulsion is also known in other applications e.g. oil spills [5] or transporting heavy crude oil through pipelines [6] or in food production e.g. mayonnaise, or in drug emulsion and even in cosmetics industry (skin lotion). When water is added to the oil (or fuel) it shall separate after short period of time and this will not help in diesel engine fuel system and shall prevent the use of water in combustion chamber associated with the fuel to reduce the dangerous gases which form at high temperature, hence researchers found a method to keep them joining for a longer period of time. That is by adding a surface active agent with to be added within the emulsion to decrease the interfacial tension between the water and diesel phases and to form the stable emulsion. Another use of the agent is to reduce the lumping of the water droplets [7, 8] where it accumulates the film between the water and the fuel particles and make them connected to a longer period of time. The amount of the emulsified agent is critical to keep the emulsion stable [9-10].

The Nitrogen Oxides gases which formed at high temperature from the atmospheric Nitrogen and Oxygen [11] may be reduced by reduced if the maximum combustion temperature is reduced by injecting water to the combustion chamber or adding water to the diesel fuel; e.g. in numbers, adding 20% water to the diesel cuts down the NOx gases by about 57% [12].

The mechanism of water involvement in the combustion is well explained before as the layer of boiled water (at lower temperature) explodes through the outer layer of the fuel oil causing a micro-explosion behavior where the fuel droplets are further atomized in a finer droplets and mixing the fuel with more surrounding air [8]. This produces more complete combustion as well as reducing the maximum combustion temperature. These two effects both reduce the NOx and also reduce the smoke / soot significantly [13-18].

Producing a biofuel may be costly and not attractive, hence it may be more interesting and attractive to reduce the cost of the production or using waste materials to produce the biofuel. One example is using waste or used frying cooking oil as compared to using raw oils [19-20].

Few studies investigated the effects of emulsifying the biofuel with water e.g. [21-22]. In these two studies, the researchers investigated the effects of adding water & alcohol (e.g. Methanol or DEE) to the biofuel. The use of neat biofuel as emulsified to the water is lacking.

Therefore, it is found important to examine the effects of emulsifying the neat biofuel derived from waste cooking oil, with different amount of water, and after stabilizing the emulsion, it was used in a diesel engine. No other additives (e.g. alcohols) was added to the emulsion before testing it in the diesel engine, nor was the diesel engine modified. The objectives of adding the water to the biofuel were to reduce the NOx exhaust emissions and show the effects on the power / specific fuel consumption of the diesel engine. This is to have double advantages of running the engine on alternative source of energy and at the same time reduce the environmental pollution problem.

2. EXPERIMENTAL WORK

2.1 BIOFUEL PREPARATION

The fuel used in this study is biofuel made from waste cooking oil transesterified with methanol at the ratio of 20% by volume methanol. The yield obtained was 85% of the raw waste cooking oil. The mixture of raw oil and methanol was heated at 60ºC with the NaOH catalyst under continuous magnetic stirring of 300 rev/min for one hour. The mixture was left to cool down to the room temperature for 24 hours and then filtered. Diesel fuel obtained locally was used as a reference fuel for all experiments. The physical properties of the used diesel fuel, raw WCO and its biofuel are shown in Table 1.

Viscosity measurements of raw waste cooking oil and its biofuel are carried out by employing Fann Rheometer. Figures 1 and 2 display the effect of shear rate and temperature on the viscosity behavior of waste cooking oil and its biofuel. Figure 1 shows Newtonian behavior for both tested fluids since the viscosity profile does not change with shear rate as reported by Diamante et *al.* [23]. Heating the waste cooking oil and its biofuel is shown in Figure 2 as viscosity versus temperature at constant shear rate. Both tested fluids of waste cooking oil and its biofuel are strongly affected by temperature influence, for example the viscosity of WCO drops from 95.5 to 29.3 mPas while the biofuel declines from 8.2 to 4 mPas over the examined temperature. The diesel fuel was utilized for comparison purposes.

2.2 EMULSIONS PREPARATION

To produce a stabilized water-biofuel emulsion, it was necessary to add a surf-acting agent to produce immiscible fluids in the continuous phase. The water in biofuel emulsion was prepared by slow addition of water into the biofuel liquid with 0.2% by volume of surfactant agent with high speed mixing [8]. This is explained in a previous work of the authors [24] where it was done on preparing water-in-diesel emulsion.

In the current work, three samples of water / biofuel (W/B) mixture were prepared using 5%, 10% and 15% by volume water. Optimum mixing speed with mixing times were used to prepare stable emulsions [25]. The prepared samples of emulsion were placed into graduated glass cone-containers to check the stability of the sample. The main criterion for the stable emulsion is the presence of only one phase. If more than one layer is found, it must be considered as unstable emulsion as explained in previous work [25]. The complete details of the preparation of the diesel-water emulsion may be found in [24, 25].

2.3 EXPERIMENTAL SETUP

The waste cooking oil emulsified with water and compared to the base case is tested in a research engine which has a single cylinder variable compression diesel engine. All running parameters can be measured and stored. It was not needed to modify the engine to run with the biodiesel nor with its emulsion with water. The physical data of the engine is given in Table 2. The fuel flow is measured with an error of 0.1 Pa in measuring the pressure difference. The engine combustion pressure, torque and speed are also measured by high speed data acquisition system.

It is needed to scrutinize the effects of adding water to the biodiesel on the engine perfroamcne, roughness and emission. To carry out this objective, it was needed to do the following tests:

1- Effect of engine speed over the range of 20 to 30 rev/s. During these tests other parameters of the engine were kept constant e.g. injection timing (IT) was kept at 35 ºBTDC, and the compression ratio was kept constant (during all experiments) at 22.
2- Effect of load over the range of 0.1 Nm to 15 Nm. During these tests, the engine speed of 20 rps and IT of 35ºBTDC were kept constants.
3- Effect of fuel injection timing over the range of 20 to 45 ºBTDC. During these tests, the engine speed of 20 rps was kept constant.

The engine output brake power (BP) and brake specific fuel consumption (bsfc) are calculated from the measured output torque, engine speed and fuel flow rate [26].

The NOx emission is measured using a gas analyzer known as VARIO plus SE instrumentation which is manufactured by MRU Instruments which have accuracy of ±1 ppm. Other experimental errors are listed in Table 3. The exhaust gasses opacity is measured by AVL Opacimeter which can get the opacity continuously.

3. RESULTS AND DISCUSSION

The exhaust emission results of the effect of adding water to the biofuel in the three ratios of 5%, 10% and 15% on the NOx gases are shown in Figs. 3, 4 and 5 as a function of the engine speed, load and fuel injection timing. Figure 3 shows the increase in the NOx with the engine speed as expected trend as the fuel burned flow rate increases and the energy released per unit time increases, hence all the cycle temperatures and the NOx go up. Using the biodiesel derived from the WCO reduced the NOx emission as compared to pure diesel as shown in Figs. 3, 4 and 5. The main reason for this reduction in the NOx level may be the lower heating value of the WCO biofuel; see Table 1 for properties; which means less heat is released under the same conditions compared to diesel fuel and less maximum combustion temperature and NOx levels. Also, the WCO biofuel may have a bit more water content as shown in Table 1 which tends to decrease the maximum combustion temperature and the Nitrogen Oxides level.

Figures 3, 4 and 5 also show the effect of adding 5%, 10% and 15% water to the WCO biofuel at different speeds, loads and injection timings. The general trend for all conditions that adding more water reduces the NOx level in the exhaust gasses as shown in Figures 3-5, as reported before in all previous works for *diesel – water* emulsified fuel (e.g. Lin et *al.* [12]). At all engine speeds, all injection timings and at most loads, adding more water reduced the NOx level compared to pure biofuel case as well as to pure diesel fuel case. This is due to lower combustion temperature when water is added.

Adding more water, did not increase the exhaust gasses opacity, as shown in Fig. 6. The exhaust gasses opacity did not change much in case of biofuel and its emulsions compared to the diesel case, nor when water was added at 5, 10, or 15%. This is agreement to previous findings for pure diesel fuel case. Some previous works reported a reduction in the soot emissions as water is added to the diesel fuel combustion [27-30].

Figures 7 and 8 show the brake specific fuel consumption and output torque for the WCO biofuel and its emulsions compared to pure diesel. It may be seen that the WCO biofuel produced less output torque (at the same mass flow rate of fuel) and hence higher brake specific fuel consumption. This may be due to the lower heating value of the WCO biofuel; see Table 1 for properties. Adding more water to the WCO biofuel, reduced the output torque and hence increased the bsfc. It has reported by [31] that the micro-explosion phenomena and the associated reduction in the reaction time may improve the combustion in terms of brake specific fuel consumption or thermal efficiency. This was proved valid for low amounts of water e.g. at 10% water in the diesel emulsion. However, for higher water contents, the brake specific fuel consumption was increased.

Figures 9 and 10 illustrate the maximum combustion pressure and maximum combustion pressure rate (which are related to diesel engine roughness [26]) at different fuel injection timings and for different fuels (pure diesel and WCO biofuel and its emulsion). Advancing the injection timing causes the maximum combustion pressure rise rate as the fuel would be injected at lower pressure and temperature which have been shown before to increase the ignition delay period and increases the combustion pressure rise rate. Increasing the combustion pressure rise rate tends to increase the maximum combustion pressure especially before the top dead center point in the compression stroke. Figure 10 shows the WCO biofuel produced less maximum combustion pressure rise rate compared to the pure diesel case. This may be due the lower heating value of the WCO biofuel compared to the pure diesel fuel. However, adding more water (from 5 to 15%) produced higher pressure rise rates compared to the pure WCO biofuel. This is in agreement to the concept of micro-explosions of water-diesel emulsion which tends to increase the reaction rate and reduce the reaction time [31].

CONCLUSIONS

The WCO biofuel and its emulsions with 5%, 10% and 15% water have been used in a diesel engine which was tested under different engine speeds, loads and injection timings. The following conclusions may be summarized:

- The engine ran very smoothly with WCO biofuel and at the three emulsions with water up to 15% by mass, with no modifications to the engine.
- The WCO biofuel is comparable to diesel in terms of combustion, engine efficiency and exhaust missions.
- Adding more water (from 5% to 15%) to the WCO biofuel reduces NOx emissions under all testing parameters.
- Adding more water to the WCO biofuel did not increase the smoke but increased the rate of combustion pressure rise which leads to increasing the combustion noise too. It increases bsfc as well.
- Using WCO biofuel and its water emulsions didn't cause the power to be reduced much. Therefore, the biofuel (out of waste cooking oil) and its emulsions may be considered as promising renewable fuel.

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Table 1 Basic properties of diesel / biodiesel fuels

Properties	Diesel fuel No. 2	Raw WCO	WCO Biofuel	Diesel Standard [33]	Biodiesel Standard [32, 33]
Density at 25 ºC, kg / m^3	833	902	792/910	850 (at 15.5ºC)	0.88 (at 15.5ºC)
Mass high heating value, MJ / kg	51.76	41.4	42.65	42.64	
Kinematic viscosity at 40 ºC, mm^2 / s	4.16	54.53	3.29 / 4.2	1.3-4.1	1.9-6
Calculated cetane number	55/56	49	54	41-60	Min 40-51
Cloud point, º C	8	12	0	-15 to 5	-3 to12
Pour point, º C	-34	6	-3	-35 to -15	-15 to 10
Moisture content, %	0.161	0.02	0.12 / 1.9	0.161	0.05
Flash point, º C	>52	164	150	60-80	100-170

Table 2 Physical data of the research engine at UAE University

Number of cylinders	1
Bore	76.2 mm
Stroke	111.1 mm
Swept Volume	0.607 liters
Max. Speed	60 rev/sec (3000 rpm)
Max. Power, Diesel (CR = 20.93)	9.0 kW, Naturally Aspirated
Compression Ratio (CR)	Max. 22
Injection Timing	Variable, 20°- 46° BTDC

Table 3 Experimental errors

Parameter	**Max Error**
Torque	±0.1 Nm
Opacity	± 1%
NOx	±1 ppm
Speed	± 0.1 rps
Volume	± 1 ml
Time	± 1 sec

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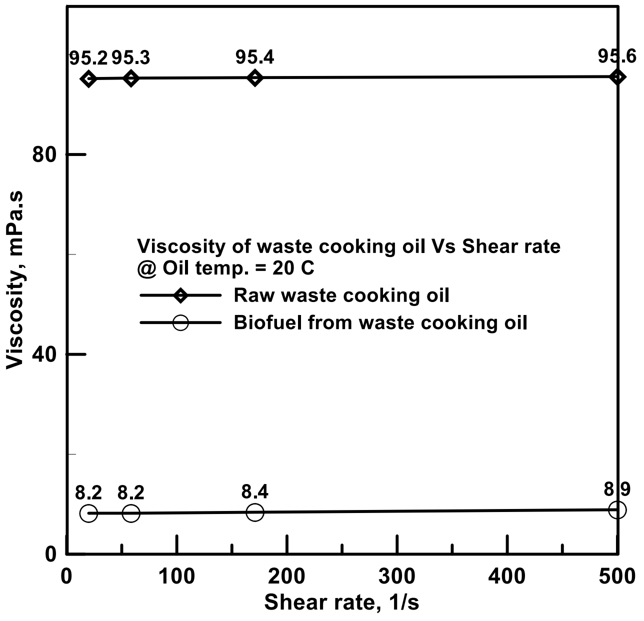

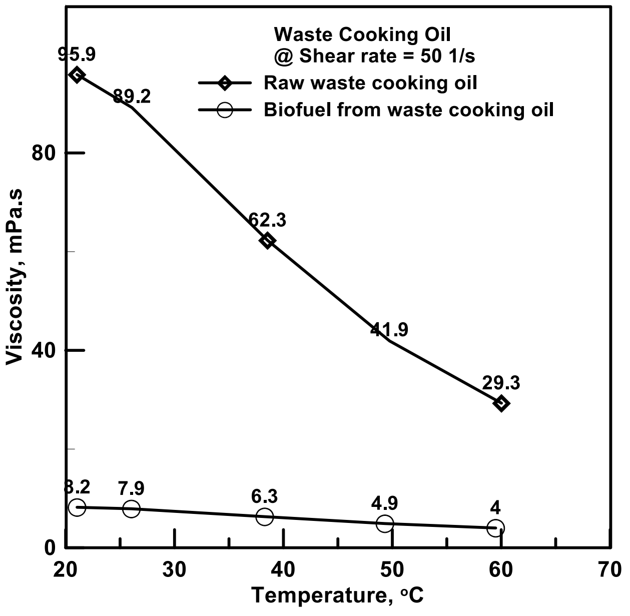

Figure 1 Viscosity of waste cooking oil and its biofuel

Figure 2 Viscosity of waste cooking oil and its versus shear rate biofuel versus temperature

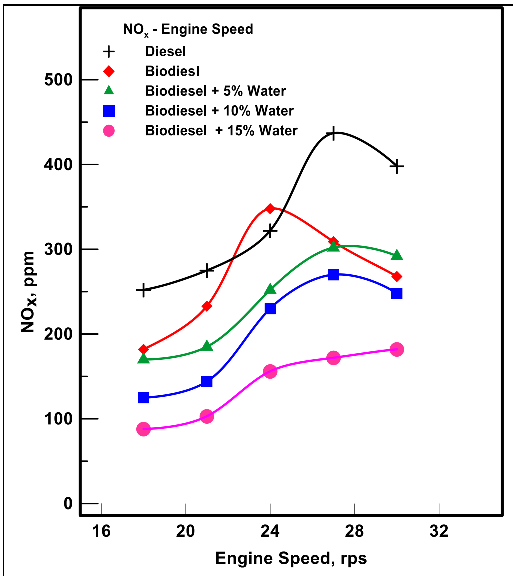

Figure 3 Effect of engine speeds and water amounts on Nitrogen Oxides, IT=35° BTDC

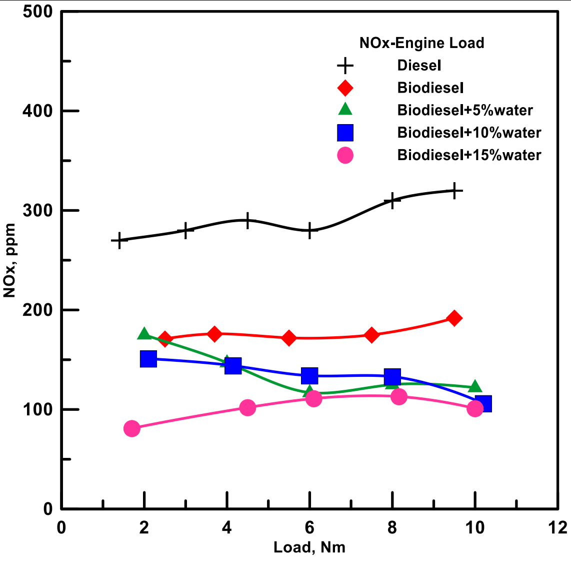

Figure 4 Effect of engine load and water amounts on Nitrogen Oxides, N = 20 rev/s, IT = 35° BTDC

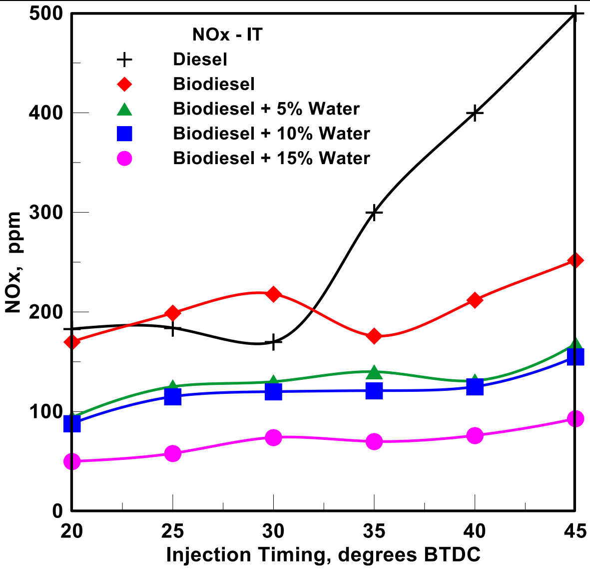

Figure 5 Effect of fuel injection timing and water amounts on Nitrogen oxides, N = 20 rev/s

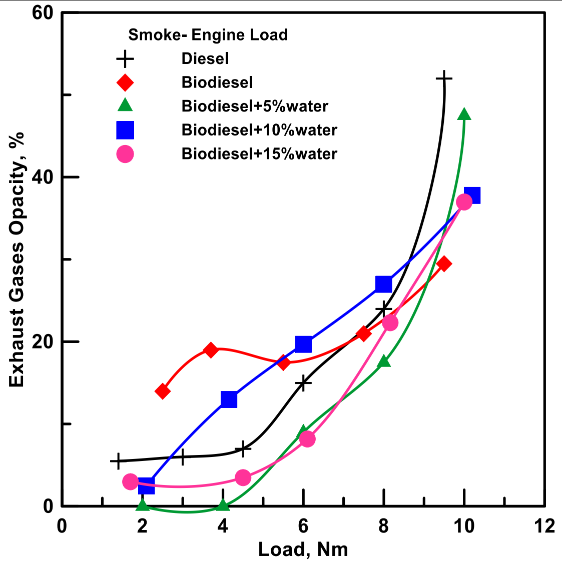

Figure 6 Effect of engine load and water amounts on exhaust gas opacity, N = 20 rev/s, IT = 35° BTDC

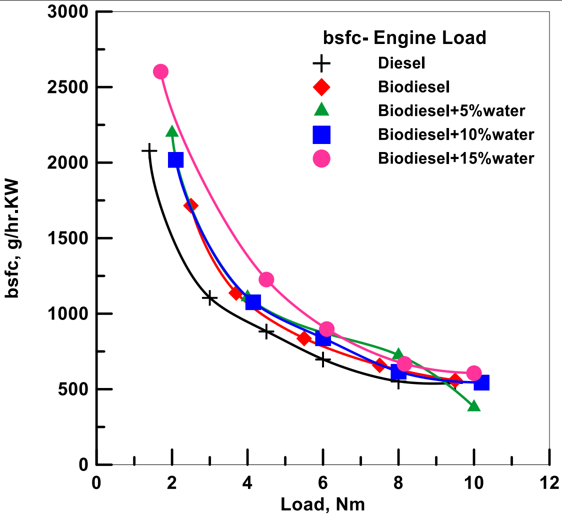

Figure 7 Effect of engine load wand water amounts on brake specific fuel consumption, N = 20 rev/s, IT = 35° BTDC

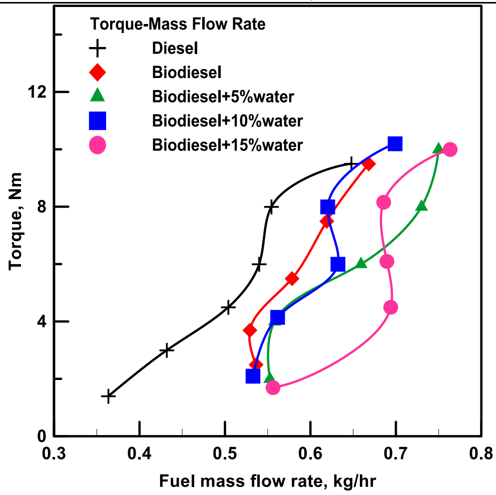

Figure 8 Effect of fuel mass flow rates and water amounts on engine torque produced, N = 20 rev/s, IT = 35° BTDC

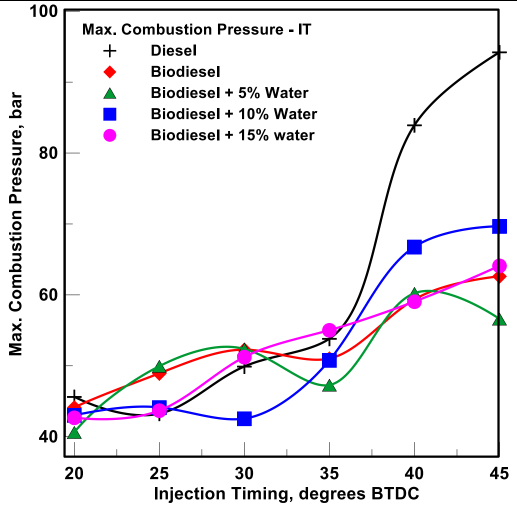

Figure 9 Effect of fuel injection timing and water amounts on maximum combustion pressure, N = 20 rev/s

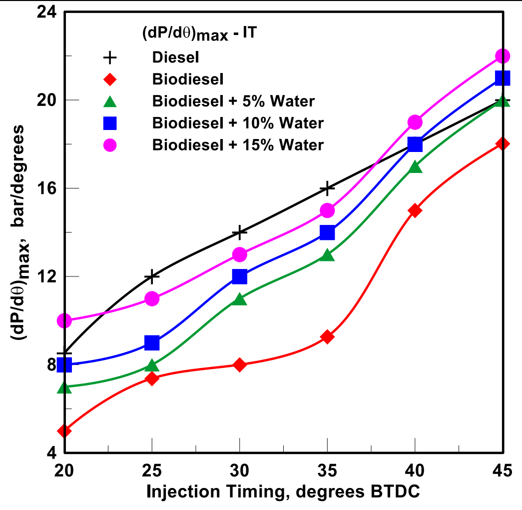

Figure 10 Effect of fuel injection timing and water amounts on maximum combustion pressure rise rate, N = 20 rev/s