"ANALYTICAL AND EXPERIMENTAL INVESTIGATIONS ON VARIABLE WATER EMULSIFIED CI ENGINE"

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Bhupendra S. Patil

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ABBREVIATIONS

bmep	:	Brake Mean Effective Pressure
C_{pa}	:	Specific heat of air
C_w	:	Specific heat of water
EN 590:2009	:	European standard of automotive fuel requirements
FAR	:	Fuel air ratio on mass basis
h_w	:	Specific enthalpy of water at T_w
h_a	:	Specific enthalpy of water at T_a
m_a	:	Mass of air
m_f	:	Mass of fuel
m_w	:	Mass of water in the emulsion
S	:	SPAN80
T	:	TWEEN80
T_a	:	Initial temperature of air
T_{comp}	:	Temperature at the end of compression process
T_m	:	Final temperature of mixture
VCR	:	Variable Compression Ratio
WDE	:	Water Diesel Emulsion
5% WDE	:	WDE fuel with 5% water + 95% Diesel
10% WDE	:	WDE fuel with 10% water + 90% Diesel
15% WDE	:	WDE fuel with 15% water + 85% Diesel
WFR	:	Water fuel ratio on mass basis
η_c	:	Combustion efficiency

ABSTRACT

The CI engine exhaust contains several hazardous components that need to be minimized. WDE fuel controls the emission of such poisonous gases and helps to minimize them. WDE fuel gives several special advantages including immediate reductions in emissions from all the generations of CI engines without changing its engine hardware. For India where most of the CI engines are more than 15 years old, WDE could contribute to instantaneous enhancement in air quality. The aim of this investigation is to formulate stable WDE fuel with different water content (0, 5, 10 and 15%) using proper surfactant and to analyze performance characteristics, emission and vibration analysis of single cylinder VCR diesel engine which is equipped with an eddy current dynamometer, gas analyzer and smoke meter under varying load conditions at 1500 RPM. The outcome of research can be concluded that high CR20 and CR19 are suitable for 10 to 15 % WDE with less BSFC, more BTHE and less NOx emissions. Conversely, low CR17.5 and CR18 are suitable with diesel and 5% WDE with least water content, lesser ignition delay and combustion duration.

1. Introduction

1.1Energy Scenario

The internal combustion engine plays a significant role in our society as means for converting liquid and gaseous fuels to other more useful energy forms. As diesel engines are the main prime movers for heavy duty vehicle applications worldwide due to their fuel efficiency. Presently, they are also used in light duty applications. They are also widely used as prime movers in the field of power generation, agriculture and transportation because of their simple mechanism, excellent performance, high thermal efficiency, durability and fuel efficiency. In developing countries like India whose economy depends to a large extent on agriculture, diesel engines play a major role. The rise in oil prices and depletion of petroleum reserves encourage researchers to focus on the effeciency of the engine as well the emissions coming out of the engine.

Emission of different hazardous automobile exhaust contents including unburnt HC, oxides of carbon (CO and CO_2), NO_x etc. are found responsible for global warming which is observed as one of the key problems from a worldwide environmental point of view. There are many ways available in previously published literature to control emissions of different hazardous pollutants. There are two significant ways of treatment inside and outside the cylinder. In the current study, treatment inside the cylinder is utilized. WDE technique is one of the promising methods to fulfil the objective of the current study. WDE is widely used to get expected engine performance and exhaust emission behaviour of CI engine with and without change in existing CI engine. [1]

1.2 WDE Fuel as an Alternative:

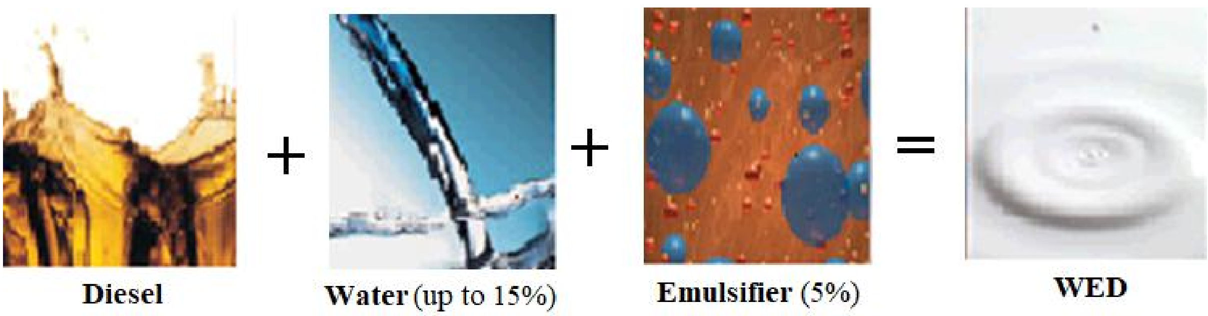

Figure 1: Formation of WDE

Water injection can be an effective strategy for reducing NOx because water's high specific heat allows it to absorb heat and lower system temperatures. Introducing water as an emulsion can potentially be more effective at reducing emissions than steam injection due to physical properties (such as micro explosions) that can improve atomization and increase mixing. The effect of water on combustion is twofold: on the one hand, the heat absorption for water evaporation will decrease the temperature of the chamber. On the other hand, more water vapour will increase the pressure of the cylinder and decrease the total enthalpy loss in exhaust gas, which may enhance the power output on the contrary. Because of the larger momentum of a water-blended oil jet, which leads to a larger air entrainment ability, the mixing between oil and fresh air will be improved. Once oil has a better mixing and wider distribution in the chamber, there will be a more complete burning and more rapid heat release process in the chamber and the combustion performance and power output will be improved greatly. The heat released near TDC will have a better work ability than released near BDC. This is just one of the main reasons for oil consumption saving for diesel engines using water-blended oil. [2]

1.3 History of WDE Technology:

The following time-line provides an overview of different water injection application over the last 100 years [3]:

1. In 1910, Otto Vollanhals carried out the first experiments with a mixture of air, atomized fuel and water in a petroleum fuelled hot bulb engine.
2. In 1940, a mixture of water and methanol was used in an air combat fighter Messerschmitt Bf109G-10. This system increased the engine power from 1700 to 2400 HP.
3. In 1983, Renault was the first formula 1 engine builder to use water injection in race engines to cool the compressed air so as to prevent knocking of the engine
4. In 1988, Saab started mass production of the first turbocharged car with an optionally available water injection system.
5. In 1992, ford introduced a water injection system in the world rally championship. all other teams followed by 1997 (except for Mitsubishi)
6. In 2007, the German engine tuning company MTM presented a water injection system to move the detonation limit in Otto engines. This system was developed together with Ingolstadt UAS
7. In 2014, the German company Exomission launched a fuel water emulsion system for marine diesel propulsion.
8. In 2015, BMW released its M4 safety car with an innovative water injection system at the Qatar Grand Prix.

2. Brief Description on the State of the Art of Research Topic

Emulsion is the mixture of two immiscible liquids, one is a dispersed phase and another is a continuous phase. In WDE, water is the dispersed phase and diesel is in the continuous phase. As the two liquids are immiscible, the mixture is thermodynamically unstable. A small amount of surface-active agents (surfactants) are used to increase the stability of the emulsion. Surfactant reduces the interfacial tension between the water and diesel by absorbing at the liquid interface. This alters the interfacial free energies and thus stabilizes water diesel emulsion. In the WDE, water remains suspended in diesel by surfactant; thus, it does not come in direct contact with the engine surfaces; thus, the risk of corrosion is less. The schematic illustration of diesel-in-water dispersion mechanism is shown in Fig. 2.a

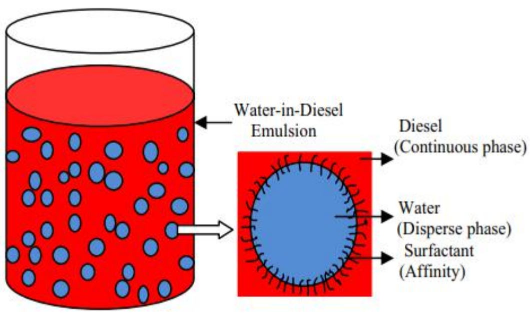

Figure 2.a: Illustration of Water-in-Diesel Dispersion Mechanism

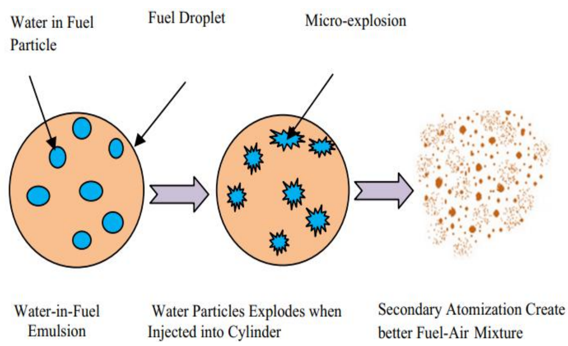

Figure 2.b: Combustion Phenomenon of Water Emulsified Diesel

In case of WDE, the low boiling point water is surrounded by high boiling point diesel. During compression stroke in diesel engines, the heat transfer takes place from diesel to water; thus, the low boiling point water goes to an unstable superheated state to form water vapor with a volume about 1000 times greater than that of the liquid water. The water vapor, therefore, explodes through the surrounding diesel oil layer leading to micro-explosion resulting in formation of even tinier diesel particles which is called secondary atomization (can be seen from the Fig. 2.b). It leads to increase the surface area of the atomized diesel particles which results in better mixing of fuel with air and thus improves the fuel combustion efficiency. [4]

The use of water in diesel engines has a number of possible benefits. It has been found that it has an influence on reducing the peak flame temperature and hence reducing the NOx emissions. The technique concerned with introducing water into the engine combustion chamber was proposed by Prof. B. Hopkinson in 1913, to make better internal cooling of the gas engine and to increase the engine output. Furthermore, the technique was developed to improve thermal efficiency and reduce exhaust emissions, or used as the safety fuel. [5]

For practical implementation of emulsion fuel, its stability plays a very crucial role. Harshal Patil et al. (2014) tried to optimize the whole process parameters like water concentration, surfactant concentration, HLB value, mixing time, and speed of the mechanical agitator to get the maximum stable emulsion fuel. They used a mixed surfactant system of span 80 and tween 80 to prepare the stable WDE fuel. They have used different percentage of water like 5%, 10%, 15%, 20%, 25%, 30%, 35% and 40% with different concentration of mixed surfactant like 1%, 3% and 5% with varying speed of high-speed mechanical agitator at 3000 RPM, 5000 RPM and 8000 RPM. They have prepared the samples of mixed surfactant having HLB value of 5, 7, 9 and 11. The stirring time varied like 5-minute, 10-minute, 15 minute, and 20 minutes. ultimately, they have concluded that the blend of span 80 and tween 80 (mixed surfactant system) with HLB of 9 with 5% concentration at 5000 rpm with agitation time 20 minutes gives the most stable WDE fuel for 5% and 10% water percentage and it lowers drastically beyond 25% water content and then remains stagnant. [6]

Water is not directly alone injected into the combustion chamber. It is in emulsion form and encapsulated by diesel means water particles are completely surrounded by the particles of diesel fuel. Harshal Patil et al. formulated the water diesel emulsion successfully by adding varying concentrations of water into diesel with a blend of Span 80 and Tween 80 surfactants at high-speed homogenizing mixing. The test results are shown in the table below.

Table 1: Corrosion test on mild steel and copper

Test Sample	Corrosion on mild steel and copper (days)				
	1 day	2 days	7 days	14 days	30 days
Diesel	No rust	No rust	No rust	No rust	No rust
Water	No rust	Rust	Heavy rust	Heavy rust	Heavy rust
Surfactant	No rust	No rust	No rust	No rust	Rust
10% WDE	No rust	No rust	No rust	No rust	No rust

They have reached the conclusion that the fuel emulsions are found to be non-corrosive even after 30 days of contact time. [7]

The emulsion fuel with different concentrations of water (5%, 10%, 15% and 20%) was prepared by Suresh V. (2016) with Sorbitan monolaurate at a speed of 15000 rpm and its properties listed in table 2.

Table 2: Comparison with EN 590:2009 specifications

Fuel Properties	Diesel	5% WDE	10% WDE	15% WDE	20% WDE	EN 590:2009	
						Min.	Max.
ρ at 15°C (Kg/m^3)	831.4	839.8	845.0	853.4	857.2	820	845
υ at 40 °C (mm^2/s)	2.4	4.2	4.4	4.7	4.9	2	4.5
Flash Point °C	62	69	74	78	83	above 55	
Heating Value (Mj/kg)	43.8	42.9	42.1	41.2	40.4	-	

From the measured values, it is observed that the density of emulsion fuel increases with the increase in water concentration due to the higher density of water over diesel. 5% and 10% water concentration in diesel fuel show 839.8 kg/m3 and 845 kg/m3 of density respectively that exhibit the permissible limits as per EN 590:2009. Water concentration with 15% and 20% surpasses the maximum limit. For neat diesel, the kinematic viscosity is 2.4 mm^2 /s. Increase in water concentration increases the interaction of water droplets resulting in high viscosity. Kinematic viscosity of 5% WDE and 10% WDE emulsion fuels fall within the range of fuel specifications, whereas, 15% WDE and 20% WDE emulsion fuels exceed the maximum limit. High value in fuel viscosity leads to poor atomization of droplets inside the combustion chamber. For neat diesel, the flash point is around 62˚C. The value is increased with increase in water concentration. The heating value of 5% WDE and 10% WDE emulsion fuels is reduced by 2.1% and 3.9% respectively over diesel, whereas 20% WDE emulsion fuel reduces the heating value by 7.7%. This may be due to heat absorption of inner phase water content in emulsion fuel during combustion. This lower heating value is compensated by a higher density and micro-explosion behaviour of W/D emulsion fuels. [8]

Introducing water to combustion systems can reduce emissions through a combination of thermal, chemical, and physical effects. The thermal effect has the greatest influence on NOx, while the chemical and physical effects play a small role and mostly influence CO, soot, and hydrocarbons. So, while all of these effects arise from the properties of water, not all of them play an equal role in emissions reduction. The effect of adding water on combustion are observed by Meagan Sung (2014) as follows: [9]

- **Thermal:**

Water's high specific heat allows it to act as a heat sink and absorb heat to lower flame temperatures resulting in lower NOx. Since a majority of NOx production is influenced by high temperature, the cooling effect of water can bring about an exponential decrease in NOx. The thermal cooling effect unfortunately can also cause increases in ignition delay because water's high heat capacity and high latent heat of vaporization can slow down the rate of temperature increase.

- **Chemical**

One benefit of water addition is that water vapour can suppress chemical reactions in the gas phase so that the rate of heat release is reduced. This is most pronounced in less volatile fuels. Water addition can also help reduce the concentration of CO and UHC by encouraging more complete reactions. As stated earlier, conditions that help reduce NOx tend to increase CO and UHC. So, while lower system temperatures reduce NOx formation by suppressing the thermal NO prompt, they also increase the concentration of CO and UHC by suppressing reactions. Wall cooling has been shown to "freeze" chemical reactions and lead to more CO by reducing the amount of time available for CO_2 oxidation. Also, if the temperature is too low (such as at low power conditions), CO production increases because of incomplete combustion and slow oxidation. Chemically, water addition reduces the concentration of O species and increases the concentration of OH radicals through:

$$H_2O + H \rightarrow H_2 + OH$$

$$H_2O + O \rightarrow OH + OH$$

$$H_2 + O \rightarrow OH + H$$

This subsequently increases the rate of CO2 production:

$$CO + OH \rightarrow CO_2 + H$$

The decrease in the concentration of O atoms can also reduce NOx. While a definite chemical effect exists when water is added to a combustion system, the overall influence may only be minimal. For example, since water vapor is already a by-product of every combustion reaction and forms combustion products with the propagated reaction, additional amounts of water may not significantly affect the chemical reaction.

- **Physical**

Adding water to the fuel system can increase the total pressure drop if the fuel flow rate is held constant, resulting in better atomization. Not only can this lead to reduced NOx, but the added mass momentum from water can also help encourage mixing and reduce CO and UHC. And since soot is most affected by atomization and mixing, the physical effects of water addition can encourage more complete combustion for the reduction of soot. Emulsions sometimes undergo a phenomenon called a micro explosion, in which water droplets inside oil droplets flash vaporize in heated environments, violently breaking up the original oil droplet into smaller droplets. This happens because the steam volume per weight of water (1.2 m^3/kg) is significantly higher than that of oil (0.06 m^3/kg). Sometimes micro explosions can even increase the combustible surface area up to 100 times, allowing for more efficient combustion. It has been hypothesized that if the internal phase diameter is large enough, the resulting energy from this secondary atomization can offer additional mixing energy and reduces carbon build-up.

The final thermodynamic equation for mean temperature that indicates the heat transfer between air and the water at the moment when both are mixed can be obtained as: [10]

$$T_m = \frac{m_w C_w T_w + m_a T_a C_{pa}}{m_a C_{pa} + m_w C_w}$$

Considering thermal equilibrium between the heat produced by burning the fuel and heat gained by the gases, the maximum temperature is calculated for diesel fuel combustion as follows: [11]

$$Q = m_f \times LCV \times \eta_c = m_a \times (1 + FAR) \times \left(T_1 - T_{comp}\right)$$

Mass of the products for diesel water emulsion combustion: [11]

$$m = m_a\,[1 + FAR(1 + WFR)]$$

The temperature at the end of combustion for diesel water emulsion combustion is given by [11]

$$T_2 = T_{comp} + \frac{FAR \times LCV \times \eta_c}{[1 + FAR(1 + WFR)]}$$

3. Motivation for Research

The motivation for research is presented below:

Need for energy is ever increasing and the quest for diverse energy sources is growing at a tremendous rate. For the last few hundred years the world primarily depended on non-renewable energy sources like petroleum, coal, wood etc. as they were reasonably easy to obtain and process to generate power. The whole world was in such a mad rush for a long time that it neglected the adverse effects of increased dependency on non-renewable energy sources affecting earth's existence due to pollution and underestimated how quickly these fuel sources can deplete. Oil producing nations took advantage of the demand for oil and they excavated oil at a tremendous rate that made huge sums of money in a short time. However, these nations now anticipate a day when they will not be pumping oil out of their wells and hence countries like Dubai are investing their wealth on a makeover to become a tourist attraction to keep their economy running.

Research carried out towards employing WDE as a diesel alternative returned several interesting results that caught the attention of alternate fuel technologists. These advantages included:

1. Concurrent reduction of both NOx and PM emissions
2. Significant emission reductions are possible by simply blending water into diesel fuel. Reductions of up to 80% in smoke opacity, 50% of PM emissions and 25% of NOx emissions are possible by switching over to WDE containing up to 20% water.
3. Instantaneous and immediate emission reductions are possible by switching to WDE. Changeover is as simple as charging the new fuel in the tank.
4. No engine hardware modifications or other changes are required to use WDE in the engine. Other emission reduction techniques require significant expenditures in converting existing engines.
5. No investment is required by vehicle owners since only the fuel needs to be changed.
6. No additional or complex fuel distribution infrastructure is required. Existing diesel fuel distribution networks can be used.
7. By using WDE all the vehicles will generate lower emissions. Therefore, lower emissions will be generated by both the older and latest generation, state of the art vehicles, avoiding all costs of engine modifications.
8. As the technology is neutral to fuel sulphur content, significant emission reductions become possible with both high and low sulphur fuels. Therefore, emission reductions do not depend on the availability of low sulphur diesel.

9. Water blended diesel fuels are very safe and easy to handle. Unlike some alternate fuels which involve significant fire and explosion hazards and several safety and handling issues, water blended diesel fuel is even safer than the diesel fuel from which it is made.
10. WDE is a particularly suitable emission control option for centrally fuelled big fleets of urban vehicles like city bus applications. By adopting WDE such operators can reduce emissions instantaneously with minimal capital expenditure cost.
11. WDE will provide synergistic emission reduction benefits with many exhausts after treatment devices like catalysts, particulate traps, etc.
12. It is possible for further reductions in emissions by suitably tuning the engines to operate with emulsified diesel fuels.
13. The increase in fuel consumption with a WDE containing 13% water is only 7 or 8%, depending on the application. In many cases, the operator does not notice any difference in the normal operation of equipment using WDE. [12]

4. Definition of the Problem

To study and analyze the performance characteristics (like BTE, BSFC, EGT etc.), emission characteristics (CO, CO_2, O_2, HC, NO_x and Smoke Density) and vibration analysis of VCR diesel engine fuelled with WDE fuel having different concentration of water (0, 5, 10 & 15%) and further to conclude the best suited blending ratio under varying load conditions at constant 1500 RPM.

5. Objective and Scope of Work

❖ Objective of the Research Work:

1. To carry out a literature search for a systematic review.
2. To perform the analytical study.
3. To develop of test plan, parameters and matrix.
4. To prepare performance, emission, combustion test facility with hardware and diagnostics.
5. To follow the standard procedure/method for generating well-mixed emulsions.
6. To conduct tests to compare the effects of WDE fuel (with different concentration of water) and diesel fuel in all aspects.
7. To analyze data to make relevant interpretations and conclusions.

❖ Scope of Research Work:

1. Find the best blending ratio/proportion (percentage of water concentration with diesel) to get the best results in a performance, emission and combustion perspective for BS-VI diesel.
2. Study effect of WDE fuel on engine at higher compression ratio.
3. Study WDE fuel on vibration of the engine.
4. Study the analysis of fuel Properties of WED with Standard Diesel in detail.

6. Original Contribution by the Thesis

Present research work has attempted to contribute following things:

1. Selection of the proper surfactant (from the literature review) which can make stable water diesel emulsion for a long time and can be used in a combustion chamber of the engine without any bad effects.
2. Various properties of the WDE fuel (from the literature review) at different concentrations of the water and its corrosive effect on the mild steel and copper was studied.
3. Thorough study of the effect of WDE on the engine performance, combustion, vibration and emission characteristics for BS-VI diesel.
4. The rated power output of the engine is 3.5 kW at 1500 RPM but we have studied the effect of WDE on the engine up to 4.375 kw.
5. The study of the effects of WDE was done at CR 17.5, 18, 19 and 20 with standard 17.5 CR engine.
6. The study of WDE fuel on engine vibration with the help of vibration senser was done.

7. Methodology of Experimental Investigation

The methodology of the present experimental investigation is divided into two phases:

Phases 1: Preparation of the stable emulsion

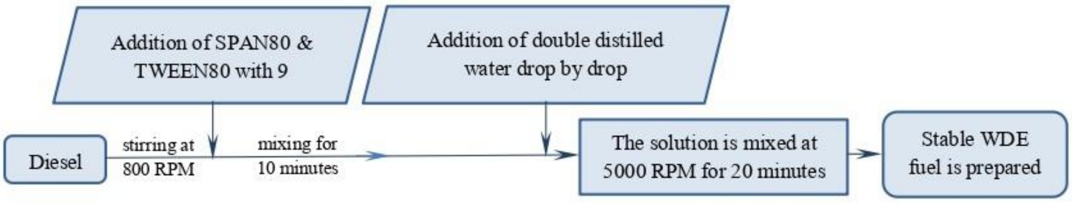

Figure 3: Flowchart showing stages of WDE fuel preparation by mechanical agitation

Mixtures of Span 80 and Tween 80 were used in such proportion that the resultant HLB value became 9. The resultant HLB value of the mixture was calculated as follows [8]:

$$HLB_{ST} = \frac{(HLB_S \times W_S) + (HLB_T \times W_T)}{W_S + W_T}$$

Phase 2: Engine preparation and evaluation

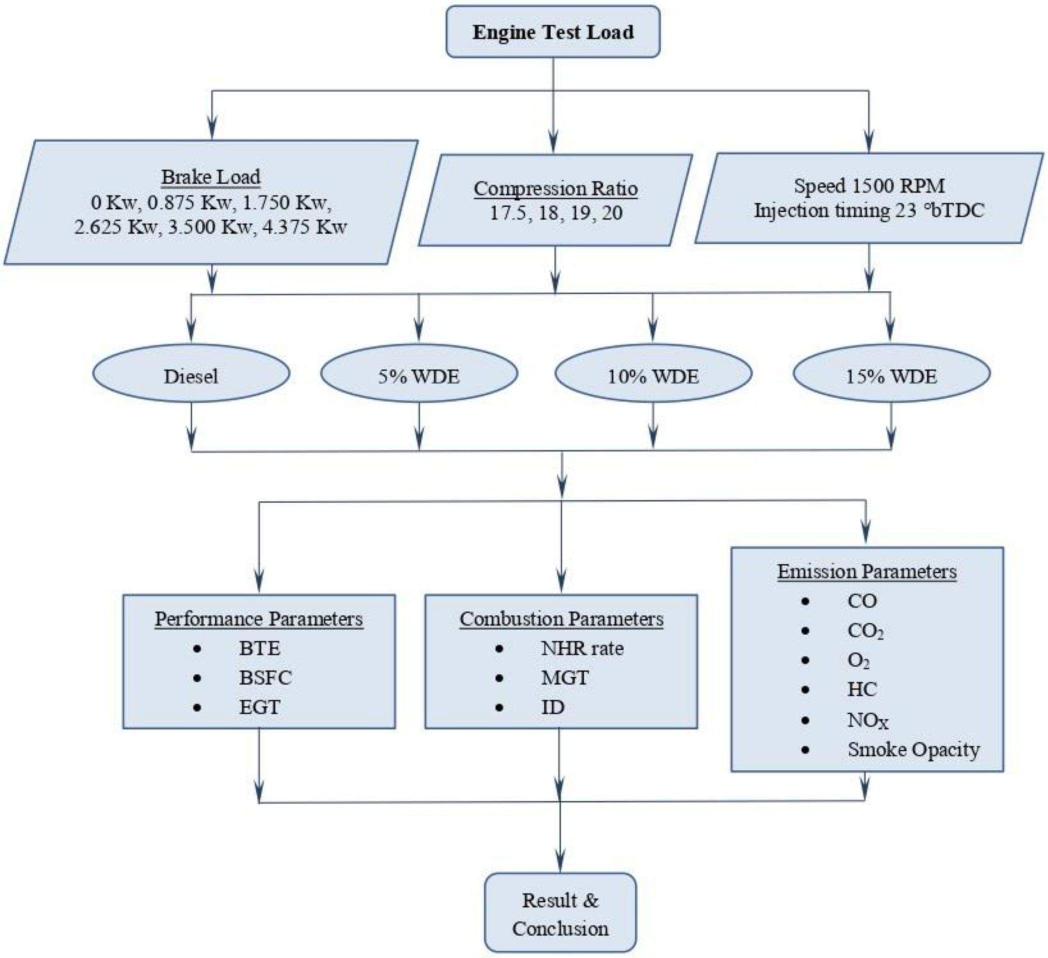

Figure 4: Methodology of Experimental Investigation for Water-Diesel Emulsion

8. Experimental Setup Details

Table 3: Specifications of the diesel engine

Parameter	**Specifications**
Manufacturer	Kirloskar Oil Engines Ltd., India
Model	TV1
Type of engine	4 Stroke, Single Cylinder, Water Cooled, Constant Speed, Direct Injection, Diesel Engine (Computerized)
Bore × Stroke	87.5(mm) × 110(mm)
Compression Ratio	17.5, VCR (CR variation between 12 to 20)
Power Output (Kw/HP)	3.5/5 @ 1500 RPM
Swept Volume (CC)	661
Dynamometer	Water Cooled Eddy Current with different loads (maximum load of 7.5 kw)
Injection Timing Starts	23° BTDC (injection duration depends on engine load)

Table 4: Specifications of the 5 Gas Analyzer and Smoke Meter

Measured Quality	**Range**	**Resolution**	**Accuracy Volume**
CO	0-10%	0.01%	±0.1%
CO_2	0-20%	0.1%	±0.3%
O_2	0-22%	0.01%	±0.2%
HC	0-20000 PPM	1 PPM	±10 PPM
NO	0-5000 PPM	1 PPM	±20 PPM
Smoke Intensity	0-100% Opacity	0.1%	±1% of full scale

9. Achievement with respect to objectives:

1. The brake specific fuel consumption (BSFC) reported by higher CR like CR20 and CR19 are lower. The BSFC 0.35 kg/kWhr and 0.33 kg/kWhr reported by VCR20 and VCR19 respectively are lesser at full load operation. This may be due to high compression and combustion produced sufficient heat utilization and increased bmep and imep effect might have reduced BSFC. The maximum BSFC are reported by lower CR17.5 and CR18 are 0.45 and 0.43 kg/kWhr at 4.375kW power operation. Also, BSFC reported by 10%WDE and 15% WDE at higher CR20 and CR19 are lower.

2. The maximum brake thermal efficiency (BTHE) 25.76% at 3.5kW power is reported by 15%WDE blend and CR20 operation. The water diesel emulsion with 10% and 15% water emulsion showed significant 14.5 % and 16.9% improvement in BTHE compared to 5% and diesel fuel operation. This relative improvement in BTHE may be due to use of high CR and water emulsion makes complete use of high compression and combustion conditions like higher pressure, temperature and heat utilization with controlled combustion.

3. Ignition delay is the time taken by fuel for physical and chemical preparation fuel to burn itself completely. Very interesting results found that the ignition delay period is decreasing with increase in CR. This may be due to rise in initial compressed air temperature and pressure of high CR. Also, this reduces time required for vaporization of fuel and hence physical delay period is reduced. Hence up to 30% decrease in ignition delay period is noted by all fuels with change in CR from 17.5 to 20.

4. Hydrocarbon emissions (HC) are lower for CR 20 and 19 compared to CR 18 and 17.5. HC emission more than 35% inferior is recorded by CR20 compared to CR17.5, 18 and 19. This may be due to high compression ratio perhaps having produced more imep, bmep, compression temperature and pressure. This led to more latent heat of vaporization of fuel and shortened ignition delay period. Thus, lesser HC emissions are reported. Further, diesel and 5% WDE fuel showed less HC emissions compared to 10% and 15% WDE. The HC emissions are very close for diesel and 5%WDE. It showed almost 18.8% less HC emission compared to 10% and 15% WDE.

5. Increased fuel consumption may be the reason for the rise in CO emissions. At high compression ratio, initial air temperature and pressures are increased. Hence, more utilization of latent heat from surrounding high compressed air and vaporization of fuel may be reasons for lower CO emission at high CR20. On the other hand, increasing CO emissions are observed though increase in CR at full and maximum power operation. Also 15 to 19% higher CO emissions are recorded at every CR by 10% and 15% WDE compared to diesel and 5%WDE operation respectively.

6. Nitric oxides (NO) emissions increase with output power requirement. This may be due to higher combustion pressure and temperature to meet desired power requirements. Also, as CR increases, NO emissions also have shown increasing trends. This may be due to high CR 19 and 20; higher compression pressure and temperature are reasons. Due to high CR, more combustion temperature for diesel and 5%WDE while 10% and 15% WDE showed less combustion temperature as more water emulsion.

7. Diesel and 5% WDE showed 26.5% and 19.2% smoke at CR17.5 and 3.5kW compared to 16.2% and 14.8% smoke emission at CR20 and same power operation. 15%WDE and 10%WDE showed 30% to 50% relative less smoke emission than diesel and 5%WDE. This may be due to low temperature combustion by higher WDE blends.

8. Engine vibration 41% raised from 643 Hz to 909 Hz at no load to maximum power operation is recorded. This may be due to more combustion pressure at full load operation compared to no load operation. As CR increases to 19 and 20 CR, engine vibrations are 4.5% higher compared to CR17.5 and CR18 may be due to more compression and combustion pressure and temperature.

10. Conclusion

The outcomes of the research from exhaustive experimentations can be concluded that high CR20 and CR19 are suitable for 10-15 % WDE with less BSFC, more BTHE and less NOx emissions. Conversely, low CR 17.5 and CR18 are suitable with diesel and 5% WDE with least water content, less ignition delay and combustion duration.

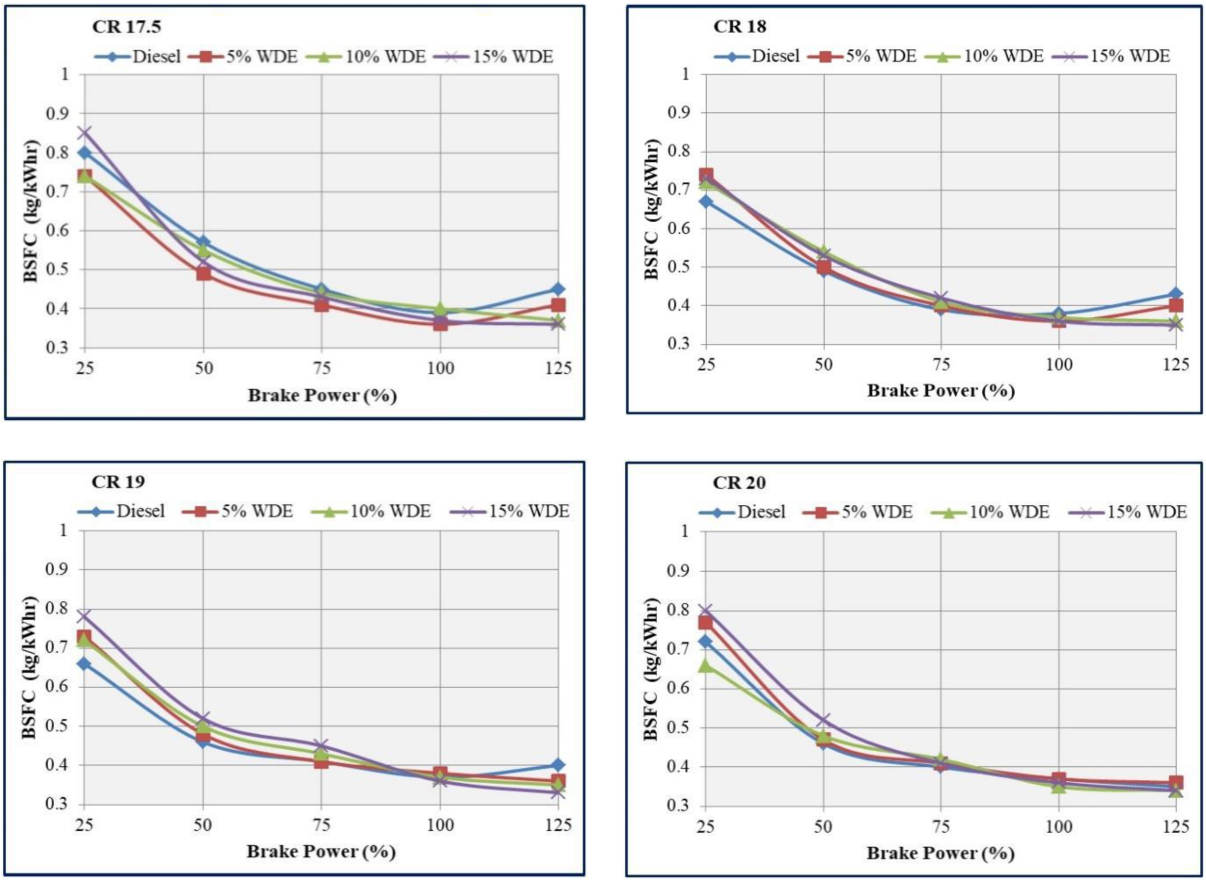

Figure 5: Comparative brake specific fuel consumption for VCR and WDE

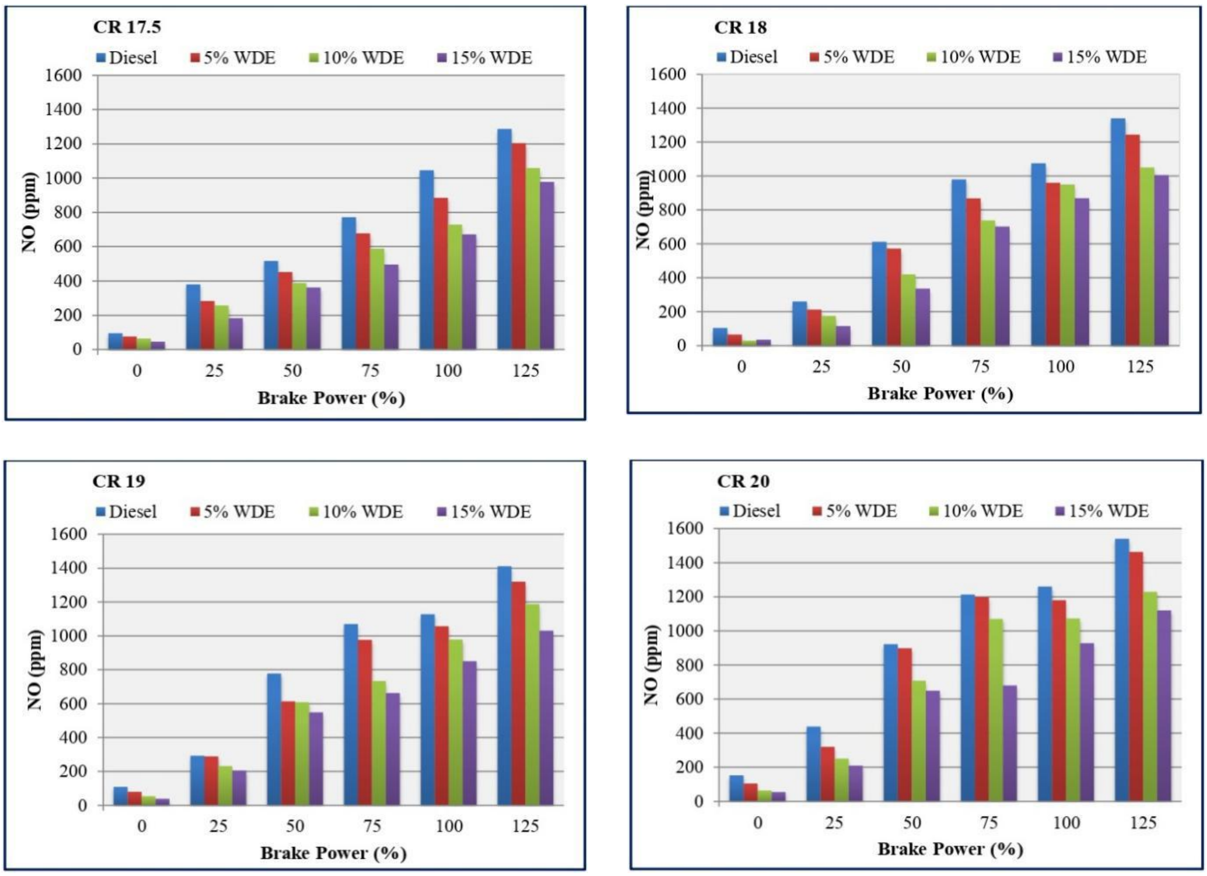

Figure 6: Comparative nitric oxides emissions for VCR and WDE

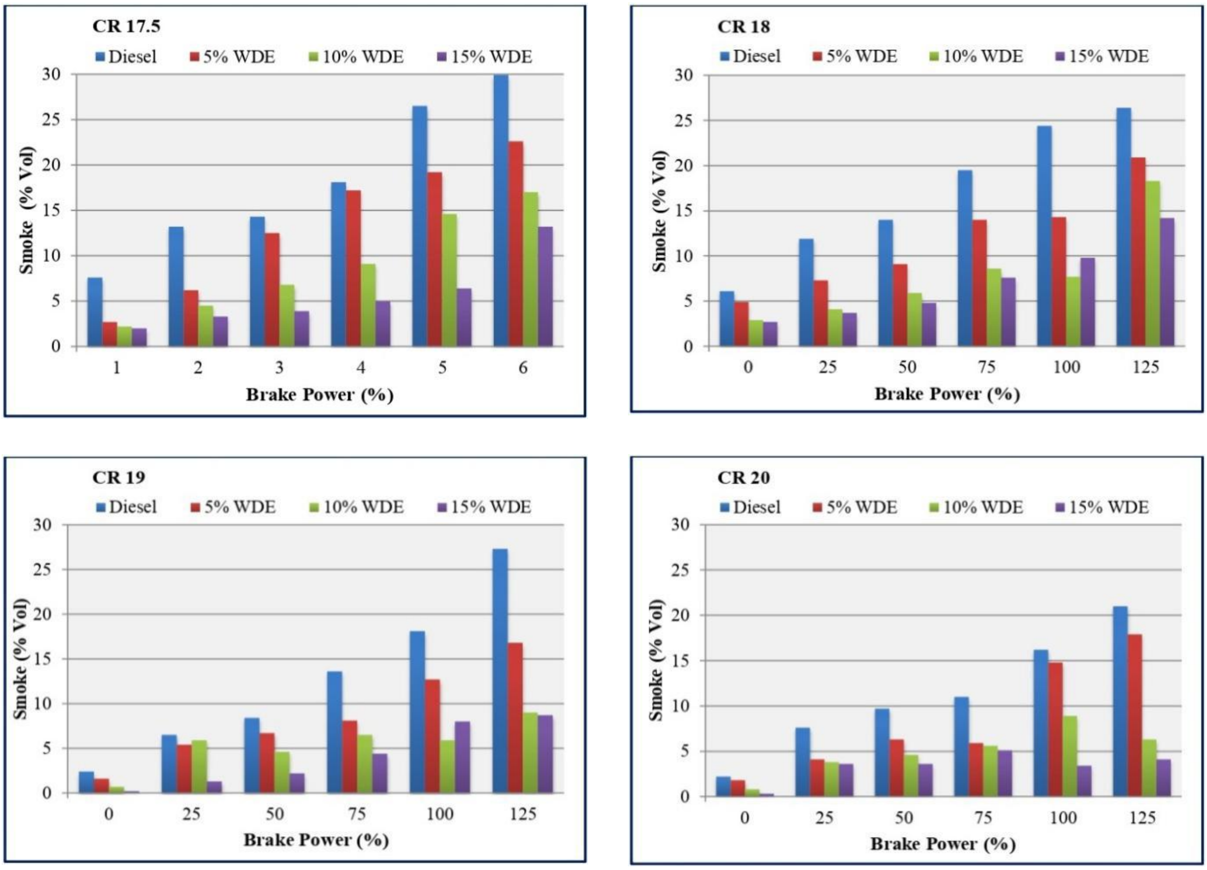

Figure 7: Comparative smoke opacity emissions for VCR and WDE

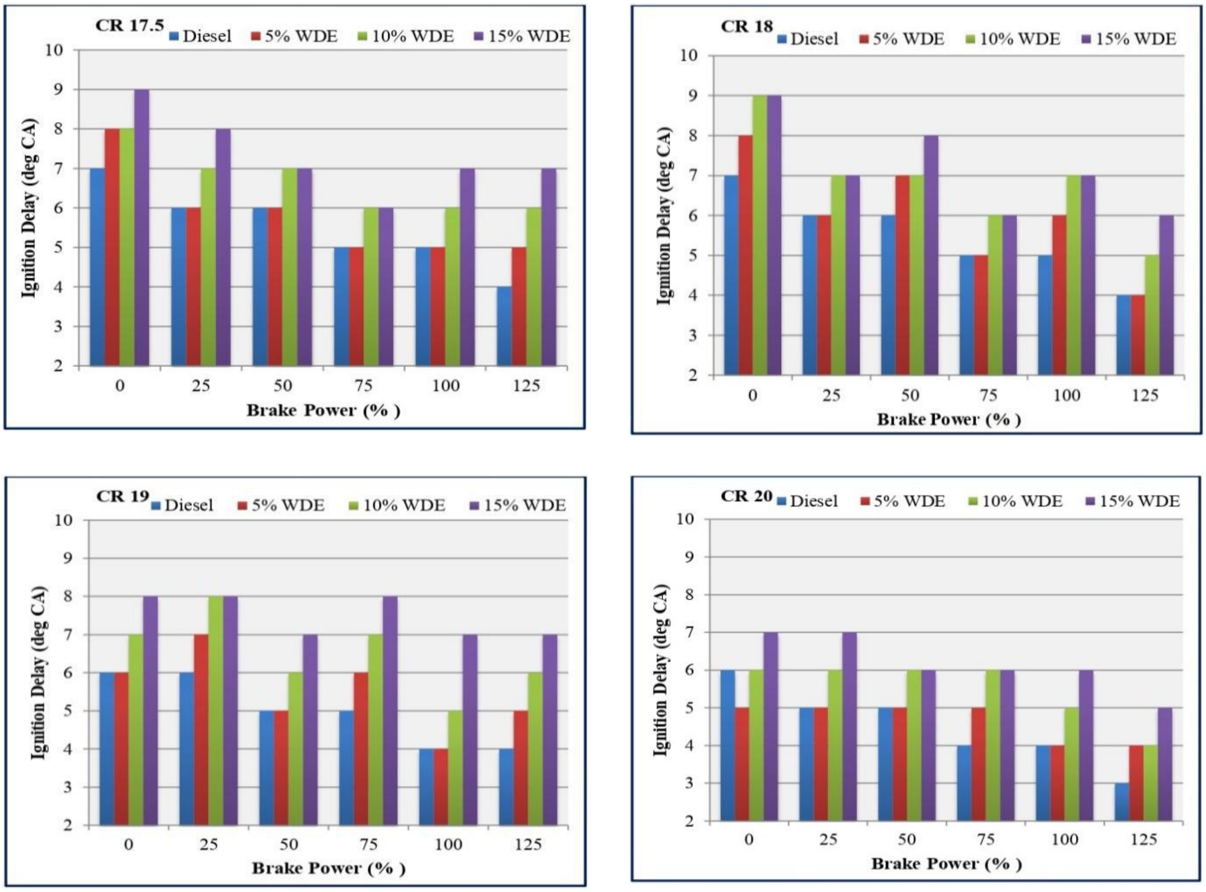

Figure 8: Comparative ignition delay period for VCR and WDE

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12. Publication Details

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