Effect of direct water injection at different crank angles on diesel engine emission and performance

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Abstract. It is well known that in DI diesel engines the formation of NOx is chiefly due to the prevailing high pressure and temperature in the combustion chamber. The methods used for lowering NOx is by induction of water which is blended with diesel oil, which leads to longer delay period, improper combustion and lowered release of thermal energy of fuel thus lowering the efficiency of the engine. In overcoming above problems, a novel approach is proposed in this work in which water is directly injected into the combustion chamber just when the temperature and pressure of gases inside the combustion is about to rise to a peak value. This lowers the formation of NOx very effectively. Adding to this aspect, the water sprayed absorbs heat from the hot gases as well as from the hot metallic surfaces of the combustion chamber and becomes super-heated steam, which augments the pressure built up at a lower temperature. This will help in increasing the power output of the engine. Experiments have been conducted spraying water at different injection timings such as: at 0 degree and at 8 degrees before and after TDC. The quantity of water injected is varied in the ratio of diesel to water from 1:1 to 1:4. The study shows that injection of water before TDC has yielded better results. NOx has reduced by 85 % at 1:4 diesel to water ratio and also injection at 24 degree BTDC. Drop in brake thermal efficiency by 10% to 20% is observed when water ratio is increased from 1:1 to 1:4.

1. Introduction

With the world of automotive industry moving forward with new emission norms leading towards the production of vehicles with zero emission. Researchers across the globe are developing new techniques to reduce harmful emissions like; NOx, Particulate Matter, CO and Unburned HC. Compared to petrol engines, diesel engines are suffering big setbacks due to emission related issues even though they have a potential to be the most fuel efficient. Of the several methods employed to eliminate harmful emissions, introducing water into the combustion chamber is found to be very promising. There are different methods of introducing water into the combustion chamber like fumigation, emulsions, parallel injection systems and direct water injection, each of these methods claiming their own set of advantages and drawbacks.

2. Literature Review

As already stated there are different methods of introducing water into the combustion chamber. In this section an attempt is made to revise the outcome of each method.

2.1 Emulsion technique

Emulsion is a mixture of two or more liquids similar immiscible in nature, one present as droplet, or distributed throughout the other, in dispersed/continuous phase [1]. It is generated by means of a mechanical agitation in the presence of surface active agents, called emulsifiers or surfactants, for
stability. A test conducted using water-in-diesel emulsion with conventional (sorbitanmonooleate) and gemini surfactants [2] in a four stroke four cylinder engine test bed for 15% water content showed 71% reduction in PM emission. Another study [3] reported a power loss of 7-8% with 10% water content. Samec et al. [4] reported 52% reduction in HC at 10% emulsion and reduced to 33% at 15% emulsion.

2.2 Fumigation
Fumigation refers to inlet manifold water injection method. It is easier way of supplying water into combustion chamber because of its simplicity and less modification required to integrate this system into the existing engines. But the drawback is that the water required is very large when compared to water in diesel emulsion system. To achieve 50% reduction in NOx, water mass of about 60-65% of fuel is needed [5, 6]. It was also observed that there is no significant change in cylinder pressure and indicated power with fumigation method [7]. Also it does not affect CO and HC emission considerably [8].

2.3 Direct Water Injection
Drawback of fumigation method is that water cannot be injected at the end of compression stroke. Thus direct water injection offers more flexibility in terms of injecting water at different crank angles. Research in this area is slowly progressing due to difficulty involved in modification of cylinder head to mount additional injector for water and provisions to operate it. In the attempt [9], water and diesel was mixed in injector tip so that initial portion of diesel injected contain mostly diesel. A CFD model used for this purpose, showed reduction in NOx and PM emissions at 46% load. In another study, researcher [10] developed a real time water injection system and applied to a heavy duty diesel engine. Using real time water injection system alone, NOx emissions were reduced by 42%. Use of EGR with real time water injection increased the reduction of NOx to 82%. They concluded that using water injection system substantial decrease in NOx, PM and CO emissions were found during steady state operation. At high loads, best performance of real time water injection system was demonstrated when the water injection was equal to 30% of the diesel injection.

Kohketsu et al. [11] used a modified injector which employed a modified water supply system together with the fuel pump system. Modification was done in fuel injector to inject water also. The fuel and water supply systems were designed in such a way that fuel and water layers could be stratified in the injection nozzle. During injection, water and fuel are successively injected into the combustion chamber. They conducted tests in a typical engine of an urban bus under medium and high load conditions. The results were highly promising. As the water/fuel ratio increased, NOx concentration in the exhaust gases decreased linearly. The reduction of NOx was nearly one-to-one with the volumetric content in the total injected fuel. The study also confirmed the hypothesis that NOx reduction is caused by reduced flame temperature.

Researchers also reviewed effectiveness of different methods introducing water into combustion chamber of Marine diesel engines [12]. In the direct injection method employed, a specially designed nozzle containing two needles were used, one for fuel and other for water respectively. Also cylinder head and pistons were made with stainless steel alloy material to provide sufficient strength and high resistance to corrosion. Fuel to water ratio was kept below 1:1 and water was injected before diesel injection so that it does not affect the combustion process. Experimental result showed 40-60% reduction in NOx. But due to operational problems, this method could not be implemented successfully.

A CFD study of water injection on the performance and emission of Gasoline Direct Injection (GDI) [13], showed 34.6% reduction in NOx for 15% of water injection by mass. Injection timing of water was set at about 40° before TDC for duration of 20° crank angle so that it ends before fuel injection. It was seen that mean indicated pressure at combustion stroke increased leading to an increase in indicated power. Water injection was helpful for improving anti-detonation properties of
fuel and achieving higher performance in the form of higher compression ratio. It also permits use of fuel with lower octane ratings.

3. Experimental Setup

![Figure 1: Arrangement of Test Facility](image)

Experimental test facility is as shown in Figure 1. A single cylinder water cooled four stroke diesel engine is used in this work and the details of the engine are given in Table-1. A brake drum dynamometer is used for loading the engine. While diesel injection is done using the standard diesel injector of the engine, water injection is achieved by using a separate injector which is connected to the water pump which is powered by a drive connected to the engine. This separate water injector is placed in the cylinder head by drilling a 20 mm hole at the top with an offset of 37 mm between the tips of the fuel injector and the water injector. To control the timing of water injection, a separate gear box is designed and fabricated which allows varying the injection timing of water with a resolution of 1 degree of crank rotation. A heater with a temperature controller is also installed in the water line to study the effect of injection of water at higher temperatures. Control valves are used to regulate the flow of diesel oil as well as water. Facility for analyzing exhaust gases is also made available.

| **Table-1. Specification of diesel engine used** |
| **Particulars** | **Specifications** |
| Make | Kirloskar Oil Engines, India |
| Type | Naturally aspirated, water cooled, direct injection, Class “A2/B1” governor controlled, and four stroke compression ignition. |
| No. of cylinders | One |
| Bore x Stroke | 80 x 110 mm |
| Cubic Capacity | 0.553 lit |
| Compression Ratio | 16.5: 1 |
| Rated Output as per BS5514/ISO 3046 | 3.7 kW (5.0 hp) at 1500 rpm. |
| SFC at rated/1500 rpm | 245 g/kWh (180g /bhp.hr) |
### Fuel Injection pressure
200 bar

### Fuel Injection timing
23\(^\circ\) BTDC (Standard)

### Engine Weight (dry)
114 kg

### Weight of flywheel
33 kg – Standard

### 3.1 Water injection measurement
Diesel to water ratio is a parameter used to measure quantity of water injected which is defined as follows.

\[
\text{Diesel: Water} = \frac{\text{Volume flow rate of diesel at full load}}{\text{Volume flow rate of water}}
\]

Flow rate of water is controlled using the push rod of the water pump and measured with the help of a burette and stop watch arrangement. At full load, diesel flow rate was found to be 20 cc/min. At 1:1 diesel water ratio, volume flow rate of water is same as that of diesel and at 1:3, volume flow rate of water is regulated to three times that of diesel flow rate. Since rate of water injection is independent of diesel injection, greater flexibility is available for controlling the flow rate of water which is limited in the case in emulsion and fumigation techniques. Since water injection is done after the start of combustion process, a large scope of work is also available to study in detail the effect of injecting larger quantity of water into the combustion chamber at different crank angles across prior and post combustion process in a diesel engine. Hence injecting water more than diesel by volume (diesel to water ratios ranging from 1:1 to 1:4) is tried.

### 4. Results and Discussions

Extensive study has been made in regard to injecting water in various proportions ranging from 1:1 to 1:4 (diesel: water). For each ratio of diesel to water, the injection timing of diesel oil is held constant at 23 degrees BTDC while for water the injection timing is varied from 24 degrees BTDC to 16 degrees ATDC, in steps of 8 degrees (-24\(^\circ\), -16\(^\circ\), -8\(^\circ\), 0\(^\circ\), +8\(^\circ\) and +16\(^\circ\)). The engine performance considering the brake power (BP), brake specific fuel consumption (BSFC), brake thermal efficiency, exhaust gas emissions such as; NOx, hydrocarbon (HC) and carbon monoxide (CO) are measured. Following are the observations.

#### 4.1 Brake Power

![Fig.2. Variation of brake power with water injection quantity and water injection timing](image-url)
The brake power measured is shown in Fig.2. It is observed that the brake power decreases as the quantity of water injected increases. This is mainly due to decrease in cylinder temperature owing to heat absorbed by injected water which may reduce the peak cylinder pressure resulting in lowering the BP. This is evident with the increase in water injection quantity also. BP is maximum when water is injected at TDC for all the water ratios when compared to other crank angles. Also it can be observed that water injection before TDC is better than after TDC. It is also interesting to note that, maximum loss in BP, even at 1:4 ratio, is about 1.7 percent.

4.2 Brake specific fuel consumption:

![BSFC Graph](image_url)

Consumption of diesel oil is found to be increasing in the range of 12% to 20% with the increase of quantity of water injected compared to neat diesel. This may be due to the fact that water absorbs part of the heat energy available and this also affects the speed of the engine due to lower BP produced. Since the engine speed is monitored by the governor, in order to maintain constant speed more fuel is injected. Thus BSFC increases with the increase of quantity of water injection. Here also, injection at TDC and 8 deg before TDC showed consistent fuel consumption readings compared to injection of water after TDC except at 1:3 ratio.

4.3 Brake thermal efficiency
Fig. 4. Variation of brake thermal efficiency with water injection quantity and water injection timing

Fig. 4 illustrates very clearly that with the increase of quantity of water injected the brake thermal efficiency reduces continuously. This is due to the increase in BSFC as observed earlier. However, maximum efficiency is achieved at TDC for diesel to water ratio of 1:4 and at 160 BTDC for 1:1 water ratio. Except at 1:3 water ratio, injecting water before TDC is better than after TDC. At 1:2 water ratio, no significant effect of injection angle on brake thermal efficiency is observed. A loss of 7% to 15% in efficiency is observed for water injection at BTDC.

4.4 Emission of NOx

Referring to figure 5, NOx emission drops as water injection quantity is increased. At 1:4 ratio, NOx is decreased by 65% to 80% at various injection angles considered in the study. It is also observed that injecting water before or at TDC is better than after TDC. For example, at 1:2 ratio the reduction of NOx observed is 34% at water injection at 160 deg ATDC while it is 44% at 160 deg BTDC. It is seen that maximum reduction in NOx is 84% for water injection at 240 deg BTDC at 1:4 ratio. Also, at 240 BTDC the NOx emission is found to be the minimum for all water ratios. This is mainly because at this timing the water that is injected absorbs the heat of the walls of the combustion chamber and becomes steam which will lower the temperature of the gases formed out of combustion. This will reduce the cylinder temperature after combustion and inhibits the formation of NOx.
4.5 Emission of HC:
As seen in Fig.6, the HC emission is lower while injecting water at ATDC than at BTDC. HC emission of the lowest level of 40% is measured at 1:1 and 1:2 diesel to water ratios at 16° degree ATDC. Interestingly, it is seen that HC is low at 1:1 and 1:2 water ratio in the range of 8% to 40%. Further investigation is required in this direction to justify reasons for the decrease in HC. One reason could be, when water is injected at 16° after TDC the combustion process will be nearing to end. Therefore HC released during after burning stage may combine with oxygen content in the water and contribute in reducing HC.

4.6 Emission of Carbon Monoxide (CO):
Another important component of emissions is CO, which is also found to be increasing with the increase in water injection quantity compared to neat diesel as shown in figure 7. At 1:1 ratio, there is no much change in CO emission at all the crank angles considered in this study. Nevertheless, for water injection at 24 degrees BTDC, the CO measured remains higher for all diesel to water ratios
considered. Comparatively CO is less for water injection after TDC than before TDC, a trend similar to that followed by HC emission. At 1:4 ratio the CO is minimum for 8\(^{0}\) ATDC and 16\(^{0}\) ATDC compared to injecting water before TDC.

![Graph](image)

**Fig.7.** Variation of CO emissions with water injection quantity and timing of water injection

5. **Conclusion**

The very objective of studying the effect of water injection on the performance and emission characteristics of diesel engine has been nearly successful. The diesel to water ratios and also the injection timings considered has yielded interesting results. The results of the experiment conducted show that direct water injection at the end of compression stroke is very helpful in reducing NOx emission. Compared to other methods like fumigation and water emulsion, the reduction of NOx is much higher and the percentage decrease is up to 85\% at 1:4 diesel to water ratio. The versatility of direct water injection is it gives freedom to vary the quantity of water.

Referring to the engine performance, as the water quantity is increased from 1:1 to 1:4, the brake power and brake thermal efficiency decrease marginally by about 0.5 to 2.2\% and 7\% to 20\% respectively and BSFC increases by about 7\% to 25\%. But at 1:1 and 1:2 water ratio, the loss in performance is not considerable. (Maximum losses observed are 1.5\% for BP, 11.5\% for brake thermal efficiency and 12.8\% increase in BSFC). With respect to injection timing of water, the results indicate that injecting water at TDC and before TDC is found to be better. Further, these results have shown that a detailed study has to be carried out limiting water injection timing in the range of 8 degree before and after TDC. As seen, the loss in performance is lower in the range of injecting water at TDC and at 8 degrees before TDC.

Considering the aspects of emissions, the results analyzed indicate that NOx decreases drastically whereas CO and HC increase with the increase in the quantity of water injected. Nonetheless, NOx emission is found to be the lowest at 24\(^{0}\) BTDC for all water ratios considered in the study. Also, injecting water at or before TDC is better than injecting water after TDC to reduce NOx emission. Interestingly, HC emission found to be less for 1:1, 1:2 and 1:3 water ratio than neat diesel. The decrease in HC is nearly 40\% for 1:1 and 1:2 water ratio at 16 degree ATDC. In contrast to the results of NOx, HC and CO are found to be less when water is injected after TDC than before TDC which requires further investigation.
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