Improvement of Diesel Combustion with Stratified Fuel/Water Injection System

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ABSTRACT

This paper describes the application of a stratified fuel/water injection system for diesel engines. This system makes it possible to inject water during fuel injection from the same nozzle hole without mixing the liquids. First, it was confirmed that NOx reduction and improvement of thermal efficiency and smoke density could be achieved using this system. The reason for such improvement of combustion with water was investigated in detail using a special test engine with which burning flames could be visualised by taking high speed photographs. Moreover, the distribution of the water vapour in the fuel spray was estimated through calculations using the software KIVA.

I. INTRODUCTION

Already many research has been done in order to reduce the NOx emission of automobile diesel engines. In the field of stationary and marine diesel engines, however, research is needed in order to develop measures to reduce NOx emission without reducing efficiency or reliability. Recently stratified fuel/water injection system has been developed as a measure to achieve that purpose [1].

As published in Tayama’s paper [2], in which he compares several methods of water injection as a measure to reduce NOx emission, stratified fuel/water injection has many merits.

- Fuel and water are injected through the same nozzle, i.e. a second nozzle for water injection is not needed.
- The water does not flow through the fuel injection pump. Therefore no corrosion of the fuel injection pump and thus less decrease in reliability.
- During the period of ignition delay only fuel is injected. This avoids the difficulty of self ignition as caused by fuel-water emulsion.

The application of stratified fuel/water injection on high speed test engine has shown that NOx reduction and improvement of combustion can be achieved at the same time [1]. Also an engine maker in Europe is testing stratified fuel/water injection on high speed stationary or marine diesel engine [3]. Even the application of stratified fuel/water injection on automobile diesel engines is under discussion [4]. However, the reasons for above mentioned effects of stratified fuel/water injection are still not known.

It is the purpose of this study to clarify these reasons. For this the following experiments and simulations are conducted:

1. Measurement of the injection rate of fuel and water.
2. Observation of the combustion process using a specially prepared test engine.
4. Cycle simulation to examine the best timing of water injection.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

The working principle of stratified fuel/water injection is shown in Fig. 1. The whole system consists of a fuel injection pump with a non-return valve X, a fuel injection nozzle with a special water passage (including another non-return valve Y) connected to the fuel passage and a water supply unit, which feeds an exact quantity of water into the passage of the injection nozzle.

The working principle is as follows. Before the injection starts water is fed into the injection nozzle with a pressure higher than the opening pressure of the non-return valve X (in the injection pump), but lower than the opening pressure of the needle (in the injection nozzle), as shown in Fig. 1a). During the period of water supply some quantity of fuel flows back to the fuel injection pump passing through the non-return valve X. But there remains some fuel in the nozzle tip as can be seen in Fig. 1a). When injection starts the non-return valve Y blocks the water passage. Thus first the fuel remaining in the nozzle tip is injected. Then the water in the fuel passage and last fuel from the injection pump is injected (Fig. 1b)).

For the observation of the combustion process a single cylinder, 2-stroke cycle test engine with 190mm bore is used [5].
The engine is equipped with a transparent piston, as shown in Fig. 2. The fuel used throughout all experiments is gas oil.

The test engine is externally supercharged to 2.6bar scavenging air pressure. In the beginning of the experiment the engine is driven by external power to keep clear the glass window of the piston. After reaching a speed of 400rpm, fuel is injected and the flame is photographed by a high speed camera (5000 frames per second). The fuel quantity injected is equal to $P_{in} = 15$ bar.

In order to obtain the fuel-water injection rate of this engine a rotating slit box is used (Fig. 3). For this test the injection system is removed from the engine and connected to an electric motor. The slit box, a vessel divided into many slits, is fixed to one end of an arm, which rotates about its opposite end. The rotation of the slit box and the injection must be synchronised. Only the spray of one hole of the injection nozzle is collected in the slit box, the other ones being absorbed by a duct. The injection rate can then be obtained by measuring the height of fuel and water in each slit after many rotations, as shown in Fig. 5. The injection nozzle is placed as close as possible to the slit box, but only approximately 90% of the injected liquid can be collected, the rest being reflected as mist.

3. EXPERIMENTAL RESULTS

Some results of engine test runs with stratified fuel/water injection system [1] are shown in Fig. 4. Here a high speed diesel engine with 160mm bore was used. In this Figure the water quantity injected is defined as follows:

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\text{water \%} = \frac{\text{volume of water}}{\text{volume of fuel}}
\]

Further, since the fuel quantity is kept constant, the higher the water/fuel ratio is the larger is the total quantity of liquid injected. This definition of the water/fuel ratio is the same throughout the whole paper.

As can be seen in Fig. 4, for a water/fuel ratio of 40% the NOx emission is approx. half compared with fuel only injection (0% water). Further more smoke emission is considerably reduced and also specific fuel consumption is improved. All these effects are comparable to fuel-water emulsion [6].
It is the purpose of this research to clarify the phenomena concerning stratified fuel/water injection from the stage of injection to combustion. The influence of water on NOx emission is examined using model calculation and is discussed in detail in section 4. In this section the influence of stratified fuel/water injection on injection rate and state of spray combustion in the test engine is discussed.

Fig. 5 shows the injection rate of fuel/water and heat release rate, while in Fig. 6 the series of photographs of flames are shown. As can be seen in the photographs of Fig. 6, an eight-hole injection nozzle is used. In both Figures (a) stands for fuel only injection and (b) for fuel/water injection with 40% water.

Pure fuel is injected at the beginning of one injection cycle, then fuel/water and at the end again pure fuel, according to the injection rate of Fig. 5. Since the fuel quantity is the same as with (a) fuel only, the total quantity of liquid to be injected is larger when injecting fuel/water and thus the injection duration is also longer.

In the flame photographs (Fig. 6) the soot formed on the piston surface can be clearly seen as a black part in the flame. In case of (a) fuel only, the fuel spray/flame impinges on the piston throughout the whole injection duration (until ATDC 17°). However, in case of (b) fuel/water injection the flame is once apart from the injection nozzle and the unevaporated spray can be seen between flame and nozzle, at ATDC 6° (10° from injection start).

The reason for this is that the flame can not reach the nozzle, because much water is injected at this moment, according to the injection rate of (b) in Fig. 5. At ATDC 11° the initial pure fuel spray is almost burned up and, for a moment almost no luminous flame can be observed. Then, when again pure fuel is injected, it ignites again and a second flame starts to spread out, as can be observed at ATDC 15°. From then on the flame burns very well. Compared with the series of photographs in Fig. 6(a) when fuel only is injected, we can see that during the whole combustion duration in (b) much less soot is formed at the point of impingement.

Soot at the point of impingement is usually formed when fuel rich spray is cooled down on the piston. The reduced formation of soot is usually obtained by the improvement of air entrainment into the spray, i.e. by a reduction of the fuel rich region. The effects of stratified fuel/water injection on the reduction of soot formation will be discussed in section 4, using the model calculation. Here the heat release rate shall be discussed, in order to obtain a clear understanding of the whole combustion.

The comparison of heat release rate between (a) fuel only and (b) fuel/water injection for central injection system is shown in Fig. 5. It can be seen that for (b) the duration from 5° to 15° ATDC (just after the pre-mixed combustion) is restrained and the main part of diffusive combustion is delayed compared to (a). However, the duration of combustion is approx. the same.

The value \( \int \frac{dQ}{dq} \cdot H_r \) in Fig. 5 represents the ratio of the heat release (heat transferred to the cylinder wall is not included) integrated up to a certain crank angle divided by the heat energy of the fuel injected up to that crank angle. From this value we can see that the combustion speed after injection end is faster in case (b) than in case (a). (For instance, for an increase of the ratio from 0.5 to 0.85 a duration of 15° is needed for fuel/water injection in case (b), while 18° for case (a) are needed.) That is the reason why the duration for the whole combustion is not longer for case (b) than for (a), though the injection duration is longer and the main part of diffusive combustion is delayed.

![Graph showing injection rate and heat release rate at visualisation test](image-url)
Central Injection System \( (\text{injection nozzle} = 0.23\text{mm} \times 8\text{ holes}) \)

(a) Fuel only

(b) With water (40%)

Flame
Soot
Liquid Spray

ATDC 6° (10° from injection start)  ATDC 11°  ATDC 13°  ATDC 17°

Fig. 6 Photographs of burning flames

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Fig. 7 Calculation of fuel/water distribution in spray

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Fig. 8 Penetration and excess air ratio \( (\lambda) \) in spray at the end of injection
4. RESULTS OBTAINED USING MODEL CALCULATION

Distribution of the water within the spray

As discussed in section 3, injection of water improves the combustion even before and after the water injection. The reason for this is believed to be the improved air entrainment of the spray. In this section the reasons for improved air entrainment are discussed using the results of the model calculation.

The distribution of the water (vapour) fuel spray is calculated using the software package KIVA [7]. A model injection rate as shown in Fig. 7 is used as input of the software. Fig. 7 also shows one result output of the model calculation. The distribution of fuel is shown by red dots and the one of water by green dots.

At t = 2.4ms in Fig. 7, the fuel spray front is slowed down by the drag. Then the water spray penetrates the initially injected fuel spray and causes the usually high concentration of fuel near the spray axes to be further distributed.

This effect can be confirmed by observing the series of photographs in Fig. 6, central injection system. The flame in direction 3 o'clock in photograph 6′ ATDC is penetrated by the water spray, which is the same condition as obtained by the model calculation of graph t = 2.4ms in Fig. 7. This is the reason for the better combustion of initial fuel spray of stratified fuel/water injection system.

It can be seen from the graphs t = 3.3ms and t = 4.2ms in Fig. 7 that after the water fuel is injected again. This second fuel spray pushes the water to the front and side. The red dots of the initial fuel spray are, according to the photographs, already burnt and the water acts as a shield between the burnt gas of the initial fuel spray and the second fuel spray (at t = 4.2ms). This effect prevents the second fuel spray from inducing burnt gas, which usually happens when using fuel only.

The water being pushed to the side might cause an inhomogeneous distribution of the fuel. This in turn might cause thin flame stripes, which can be seen between adjacent main flames in the photograph of Fig. 6 central injection system (b), ATDC 15°. Though the effect of this phenomena on spray combustion improvement is not completely clear yet, it is possible that it decreases the gas temperature surrounding the flame, which would improve air entrainment of the spray.

It is possible that there is a further reason for the improved combustion of the second flame, beside the ones mentioned above. The moment without luminous flames mentioned in section 3 (Fig. 6 (b), ATDC 11°) can be considered like an ignition delay for the second flame. Thus the second flame can to some extent benefit from a condition similar to premixed combustion.

The improvement of combustion after the end of fuel injection can be estimated by the value of the excess air ratio in the spray calculated using the momentum theory [8]. The results of these calculations are shown in Fig. 8. Here penetration length of spray and excess air ratio, both at injection end, are shown for two cases, 0% and 50% water injection. As air entrainment after the end of fuel injection is impossible, excess air ratio at injection end has a great effect on combustion after fuel injection. The higher excess air ratio caused by the increased momentum due to water injection might be the reason for the faster combustion after injection end mentioned in section 3.

![Graphs showing heat release rate and water injection rate](image)

**Fig. 9** Calculation results using two-zone cycle simulation
(a) NOx reduction rate and (b) combustion temperature curve, both depending on water injection timing.
Calculation of NOx reduction using two zone cycle simulation

The higher specific heat of the working gas caused by the larger quantity of H2O is the main reason for the reduction in NOx emission. In this section the best timing for water injection shall be examined using two zone cycle simulation [9, 10].

The results of the simulation are shown in Fig. 9(a), in which the unit of the abscissa is the same as in Fig. 4, section 3. Four curves are shown, each representing the effects of water injection at a different point of time during the combustion. It can be seen that the earlier the water is injected, the larger is the reduction in NOx emission.

The reason for this effect can be explained by the temperature $T_b$ in the combustion zone, as shown in Fig. 9(b). If water is injected early then the increase of temperature $T_b$ is restrained at an early stage of combustion. So the earlier the water is injected, the lower the maximum temperature will be.

Of these four cases, d) corresponds almost exactly with the conditions of our experiment shown in Fig. 5, in which injecting 40-50% water results in a NOx reduction of more than 50%.

5. CONCLUSIONS

In order to reduce the NOx emission from diesel engines and simultaneously improve the combustion, the application of stratified fuel/water injection was examined by observation of the combustion and by using model calculations. The following was concluded.

1. Observation of the combustion shows that both flames, before (initial flame) and after water injection (second flame), form less soot at the point of impingement.

2. The reason why the initial flame forms less soot seems to be that the water spray penetrates the fuel spray and causes the usually high concentration of fuel near the spray axis to be further distributed.

3. There are three possible reasons why the second flame forms less soot.

   • The water injected acts like a shield between the burnt gas of the initial fuel spray and the second fuel spray.

   • The ignition delay for the second flame caused by the water injection creates a condition similar to premixed combustion.

   • Improvement of the air entrainment, caused by the increased momentum due to water injection, results in a faster combustion after injection end.

4. Combustion temperature reduction caused by an increase of the specific heat of the working gas is the main cause for the reduction in NOx emission. If combustion once started, the water should be injected as early as possible to achieve a maximum reduction in NOx emission, because then the maximum combustion temperature can be kept at a minimum level.

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REFERENCES


