Visualization of Combustion and CFD Study for NOx Reduction with Water Injection *

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Abstract

The Shipbuilding Research Association of Japan started a project in 2003 to develop a direct water injection (DWI) system to decrease NOx formation through the reduction of flame temperatures at the combustion stage in marine diesel engines. In this project, it was decided that an 80% reduction in NOx emission must be achieved with a less than 3% increase in specific fuel consumption. To evaluate this system, high-speed photography of combustion was carried out using a visual test engine that had the same construction as a low-speed marine engine. Flame temperature decreases were visualized using the two-color method of digital photo data analysis. CFD calculations using KIVA code and StarCD were also made, and the behavior of sprays/flames and the temperature distribution in flames were successfully simulated. Furthermore, experiments to optimize the water injection system design, ensuring NOx reduction, were carried out using a constant volume combustion chamber simulating the engine running conditions.

1. Introduction

NOx regulations for marine engines (MARPOL 73/78 Annex VI) officially started last May. According to these rules, newly built engines running at speeds lower than 130 rpm must keep NOx emissions under 17 g/kWh. It was also decided that the allowable NOx value should be lowered every five years. In order to comply with these tightening regulations, new measures to reduce NOx emission must be developed urgently. The Shipbuilding Research Association of Japan started a project in 2003 to develop a direct water injection (DWI) system to decrease NOx formation at the combustion stage in marine diesel engines. This project involves many members from Japanese marine industries. Fig.1 shows the new NOx regulations. As shown in this figure, the second phase of regulation has already been planned, and a voluntary reduction to 3.5 g/kWh (80% less than the above-mentioned 17 g/kWh) has been proposed in some countries. Considering these circumstances, the target of the Shipbuilding Research Association project was set to clear the voluntary value of 80% below the present level. At the same time, this project also aimed to minimize the sacrifice of specific fuel consumption (SFC) to carry out this NOx reduction. Thus, it was decided that the 80% reduction in NOx emissions must be achieved with a less than 3%

increase in SFC.

The reason that DWI into the combustion chamber was selected for investigation in this project is as follows. It is considered that NOx emissions have their most harmful influence on the land when a ship is running near the coast or is in the harbour. Thus, the measure used for NOx reduction must be effective at low load operations. At such low loads, however, exhaust gas after-treatment using catalysts like SCR will not work well because the exhaust gas temperature is too low for the catalytic reaction. Fortunately, adding water into the combustion chamber is effective in limiting NOx formation throughout the load range, as water or steam injected into the flame always decreases combustion temperatures owing to its high specific heat.

A HAM (Humid Air Motor: Humidification of intake air) system was not proposed in this project. Although this type of system has the merit not requiring modification of the combustion chamber, a huge amount of water would be necessary to carry out an 80% reduction of NOx formation, as only about a half of the added water affects the flame at the combustion stage. Other than the HAM method, the following methods can also be used to inject water into the combustion chamber.

1. Fuel-water emulsion
2. Stratified fuel water injection
3. Direct water injection (DWI) with a "two-needle type"

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fuel and water injection nozzle

4. DWI with a “separate water injection nozzle”

The authors of this paper have closely examined all of the above-mentioned fuel + water injection systems for medium and large sized diesel engines. Accordingly, it was estimated that almost the same volume of water as fuel should be injected to carry out an 80% NO_x reduction with any of these systems. Considering the required volume of water, the fuel-water emulsion and the stratified fuel water injection,

Fig.1 Target of the project

for which fuel and water are injected through the same injection nozzle hole, would be difficult to implement since they would require a much larger injection system to inject double the amount of the liquid.

For the current project, the authors chose to investigate DWI. The main advantage of the DWI method is that water injection timing can be controlled independently of fuel injection. The authors of this paper have already reported some research on the “two-needle type” injection nozzle [1]. Thus, in the current investigation, visual and CFD studies of a DWI system with a “separate water injection nozzle” was examined.

The plan for this project is as follows. This paper describes parts 1 and 2 of this plan.

1. Development of CFD (Computed Fluid Dynamics) simulations to discuss the optimum water injection conditions.
2. Comparison of the CFD results and experimental data from a visual test engine and a constant volume combustion chamber (CVCC) to confirm the validity of CFD.
3. Running test using a single-cylinder 2-stroke test engine (Bore 400 mm) equipped with a DWI system.

Fig.2 Schematics of visual test engine and its combustion chamber layout

2. Experimental Apparatus

2.1 Visual Test Engine

To observe the combustion process, a single cylinder, uni-flow type 2-stroke cycle test engine with a 190 mm bore and a 350 mm stroke was used. This engine was equipped with a transparent piston as illustrated in Fig.2. The fuel used throughout all the experiments was marine diesel oil (MDO) available on the market. The test engine was externally super-charged to 0.28 MPa scavenging air pressure. At the beginning of the experiment, the engine was driven by an electric motor to keep the glass window of the piston clear. After reaching a speed of 360 rpm, fuel was injected for 6 cycles (1 sec) and the flame was photographed by a high-speed video camera. Fuel injection pressure was about 110 MPa. Measured air swirl velocity at the combustion stage was about 12 m/s.

A normal 2-stroke marine diesel engine with a 'side injection system' has at least two fuel injection nozzles (opposite to each other) per one cylinder. Likewise, in the visual test engine two fuel nozzles can be installed and a Pmi of 1.5 MPa is possible when burning the fuel injected from two nozzles. However, when the photos used in this study were taken, only one nozzle was set, so as to observe one flame clearly, avoiding the overlapping of multiple flames. Therefore the quantity of fuel injected was half of what would be injected by two fuel injection nozzles.

The indicated thermal efficiency was measured by analyzing the indicator diagram of the firing cycle, obtained at the same time as the photography was carried out. However, NO_x emissions could not be measured because the 6 firing cycles were too rapid for any kind of NO_x measurement.

Fig.3 Schematics of water injection nozzle

2.2 Water injection system

A high-pressure water injection system was prepared for the test. Water was kept at a maximum pressure of 30 MPa and injected into the combustion chamber using the water injection nozzle shown in Fig.3. At the time of injection, the nozzle needle seen in Fig.3 was opened by the working-oil pressure, controlled electronically, and was closed by the spring force discharging the oil pressure. Thanks to this system, water was injected at a constant injection pressure, ending sharply without lingering leaking.

In this project, three patterns of the water injection, shown in Fig.4, were tested using the visual test engine. In all the cases, the water injection holes were larger in diameter than the fuel injection holes, so as to keep the momentum of the water spray as high as that of the fuel spray, even though the water injection pressure was much lower than the fuel injection pressure. Water injection timing preceded and overlapped fuel injection in all cases, but its detail cannot be open here because of a patent-relating issue.

2.3 Constant volume combustion chamber (CVCC)

As it was impossible to measure NO_x emissions from the visual test engine, a constant volume combustion chamber (CVCC), shown in Fig.5, modeling the combustion chamber of a long stroke engine, like the one that will be used in part 3 of this project, was used to obtain the NO_x reduction data for the DWI system. Air swirl was generated with a rotating vane as seen in the figure. The measured swirl velocities were 10 – 12 m/s, almost same as in the visual test engine.

A fuel injection nozzle and a water injection nozzle were installed on the cover of the CVCC as seen in the figure. Fuel was injected by an electronically controlled, hydraulic-actuated fuel injection system. The water injection system was the same as the one used in the visual test engine.

The test procedure was as follows. Fuel and water were

Fig.4 Water injection patterns in visual engine test

injected into the chamber, which contained air at a pressure of 6 MPa and a temperature of 850 K. The same MDO (Marine diesel oil) as used in the visual test engine was injected for 12 ms with an injection pressure of 65 MPa. Such experimental conditions were equivalent to the half load of the single cylinder engine, which will be used in the running test in part 3 of this project.

After the self-ignition and combustion of the fuel, all of the exhaust gas was discharged from CVCC to a sampling bag. During this process, the sampled gas was mixed well, becoming homogeneous in the bag. Subsequently, the gas was transferred from the bag to a NO_x analyser. In addition to NO_x levels, the oxygen percentage was measured and NO_x data was converted to the state of 13% oxygen.

CVCC test had the following advantages:

1. The influence of engine speed and fuel injection timing on NO_x formation was fully eliminated.
2. It was possible to eliminate the influence of humidity on NO_x formation by charging the chamber with dry air.

3. Analysis and CFD Procedures

3.1 Two-Colour Method

To obtain the flame temperature distribution from the visual test engine using the images taken by the high-speed video

(CMOS) camera, the “two-colour method” explained in detail in the reference [1] was applied. Attention should be paid to ensure that the temperature analysed by this method represented the mean value through the flame thickness.

3.2 Numerical CFD Simulations

KIVA III and StarCD, well-acknowledged codes in the engine simulation field, were used to examine the effect of DWI on NO_x formation. Both were used in a standard configuration except for some slight modification to handle the direct water injection [1]. To detect the distribution of injected water, StarCD code was more convenient than KIVA III. Computational grids used in the KIVA III were 19800 cells and for the StarCD simulations a radial mesh with further refinement in the region of combustion and NO formation was used, resulting in a grid of some 72000 cells. Calculation results on both codes were in good agreement in flame (temperature) distribution and tendency of NO_x formation except for the NO_x level, which was slightly higher in StarCD results because of its finer mesh size.

Fig.5 Schematics of CVCC

4. Results and Discussions

4.1 Experimental visual data and CFD results

According to the established Zeldovich theory for NO_x formation, if the flame combustion temperature is decreased, for example from 2400 K to 2200 K (−200 K), the amount of NO_x formed will be reduced to less than 20%.

Fig.6 shows the comparison of experimental data from the visual test engine and the CFD illustrations derived from KIVA code simulating a combustion state with the same conditions as the visual test engine; this figure shows the case where no water is injected. The upper row (a) shows the experimental data, temperature distribution of the flame, analysed by the two-colour method. The data at 12, 17 and 22 deg. ATDC are demonstrated. As the fuel injection duration is from 4 deg. BTDC to 18 deg. ATDC, the figures at 12 and 17 deg. ATDC represent the flame during the fuel injection, and the after-burning flame can be seen at 22 deg. ATDC.

CFD results, predicted flame temperature distributions and

NO concentrations (g/m^3) at the horizontal plane 5 mm below the cylinder head are illustrated in (b) and (c). Exactly speaking, they cannot be directly compared with the experimental data in (a) that represents the mean temperature through the thickness of the flame as explained in 3.1.

As seen in the measured temperatures presented in (a), almost all of the area of the flame at the three time points is coloured red, indicating temperature in the range of 2250–2400 K. These data agree with the predicted temperature distributions shown in (b), which also have large areas in the range of 2300–2400 K. Furthermore, according to the calculated NO concentrations, illustrated in (c), there are spots where NO is actively formed in the hot areas of the flame, even at the after-burning stage at 22 deg. ATDC.

An example of the result of applying the type B'' fuel injector is shown in Fig.7. As in Fig.6, the measured temperature distributions at three time points are shown in (a), the predicted temperature distributions are illustrated in

Fig.6 Comparison between experimental visual data and CFD results (without water injection)

(b) and the calculated NO concentrations (g/m^3) are demonstrated in (c). In this case, a volume of water equivalent to 50% of the fuel volume was injected at a pressure of 14 MPa.

As depicted in Fig.7 (a), almost all the areas of the flames, at each of the three time points, are successfully cooled down to the range of 2050–2200 K. The predicted temperature distributions, Fig.7 (b), show that, in comparison with the fuel only case in Fig.6 (b), the red spots indicating temperatures hotter than 2300 K has become much smaller at each time point. Furthermore, Fig.7 (c) shows that the calculated NO concentrations following water injection are much smaller than those seen in Fig.6 (c). Moreover the spots where NO is actively formed, seen in Fig.6 (c), have all vanished at each time point. The calculated NO_x values from the end of each cycle showed a 60% reduction in this case of a 50% vol. water injection.

Fig.8 shows the flame temperatures and injected water distributions calculated by StarCD code under the same condition as Fig.7. As explained in 3.3, StarCD code is more

convenient than KIVA code when used to detect the distribution of injected water. According to these figures, at 7 deg. ATDC, it is understood that the injected water spray is transported downstream by the air swirl and entrained into the flame. After that, the water spray extends into the flame, resulting in the successful cooling seen at 12–22 deg. ATDC. Considering the function of the air swirl demonstrated in this figure, it is supposed that extremely strong penetration is not necessary for the water spray.

4.2 NO_x measurement by CVCC test

As it was impossible to measure NO_x emissions from the visual test engine as explained in 2.3, and NO_x values calculated by KIVA and StarCD codes were not perfectly reliable, CVCC, shown in Fig.5, was used to obtain the NO_x reduction data from the application of the DWI system. In this experiment, the effects of the downward direction of the water spray, defined as the depression angle β in Fig.9, on NO_x reduction was specifically examined.

Fig.9 shows the results of this test. According to this figure,

Fig.7 Comparison between experimental visual data and CFD results
(Water injection from upper stream of air swirl)

Fig.8 Distribution of injected water by StarCD code (Oblique sections through spray axis, 50% water injection)

Fig.9 Experimental result using CVCC

the NO_x reduction rate strongly depends on the water injection angle β . A β of 20 deg. showed the poorest results. This is considered to be the result of the water spray being injected too deeply and being distributed under the burning flame in the chamber, resulting in less overlapping with the flame. Similarly, in the case of 6 deg. β , the water spray would be located in the upper part in the chamber, above flame, again resulting in less overlapping.

It is considered that the two-dimensional analysis of the interaction between the flame and the water spray using the visual test engine, as explained in 4.1, is not sufficient to determine the water injection nozzle specifications. Optimisation of the water spray distribution, aiming to cover the whole flame three-dimensionally, is essential for DWI to be applied successfully to relatively high combustion chambers like that of the long stroke engine.

5. Conclusions

In this paper, only a 65% reduction in NO_x formation was confirmed in Fig.9 by the CVCC test. However, the running test using a single-cylinder 2-stroke test engine in part 3 of this project has already been commenced by the engine builder member of this project. Using this engine, the target of this project, an 80% NO_x reduction with a less than 3% increase of SFC, has almost been achieved at a low load

(25% load) thanks to the fundamental research work and CFD methods explained in this paper.

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