CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 139

Development and prospect of the ‘stratified injection system’

Fuel Injection & Gas Admission and Engine Components

Koji TAKASAKI, Kyushu Univ./ National Maritime Research Institute, Japan

Tatsuo TAKAISHI, ex-research-manager in Mitsubishi Heavy Industries, Ltd.

ABSTRACT

In this paper, further development of the ‘stratified injection system’, which can be applied to diesel combustion of ammonia, methanol and low-grade fuels is introduced.

The stratified injection system was originally developed at Mitsubishi Heavy Industries, Ltd., as the stratified fuel-water injection system for low-NOx diesel combustion and presented at CIMAC London in 1993.

In that case, fuel, water, and fuel are injected in this order from the same injection nozzle hole during the injection duration of every cycle. Recently, this has been put to the practical use for low-speed two-stroke engines by Japan Engine Corporation (J-ENG) and presented at CIMAC Vancouver in 2019. In the practical system, fuel and water are injected in five layers from the same injection hole.

In the first half of this paper, the authors describe the new stratified fuel-water injection system, and the process by which fuel and water mix well when forming a spray after injection is analyzed. By a simple CFD, the reason why NOx reduction and combustion improvement effects equivalent to those of fuel-water emulsion case is clarified.

Next, the authors introduce the following studies in detail. Experiments using the system has been conducted to apply a low-quality BFO (bunker fuel oil), which has poor ignition and combustion characteristics, to a high-speed diesel engine. In this case, the stratified injection system injects MDO (marine diesel oil) with a good ignition and combustion characteristics like a gas oil, BFO, and MDO in this order from the same injection nozzle hole. Even in the case that a total mass ratio of pilot- and post-MDO is only 10%, 90% of BFO has completed the combustion just as well as the case of 100% MDO, as the pilot-MDO has improved the ignition and the post-MDO has mitigated the after-burning of the BFO.

This system is characterized by its ability to improve the combustion of a main fuel, which has poor ignition and combustion properties, by injecting the pilot-fuel from the same injection nozzle hole as the main fuel. If necessary, post-fuel can also be injected from the same hole.

While the engine that uses a hard-to-self-ignite fuel originally requires two injection systems for main and pilot fuel, and the cylinder head must be equipped with two types of injection nozzles, the stratified injection requires only one injection system and simplifies the engine design.

At the end of this paper, the authors propose a system to apply this concept to diesel combustion of methanol and ammonia. Methanol requires pilot fuel due to poor ignition properties, while combustion characteristics are good and post-injection is not necessary. Therefore, a stratified injection system is proposed to realize pilot injection only. In addition, both methanol and ammonia have a high latent heat of evaporation and may cool the preceding pilot flame. A concept incorporating countermeasures against these problems is also introduced.

1 INTRODUCTION

The 'Stratified Injection System' was initially developed as a stratified fuel and water injection system for NOx control. In that case, fuel, water, and fuel were injected in this order from the same injection nozzle hole during the injection duration of every cycle. Recently, this has been put to practical use for low-speed two-stroke engines in Japan.

Next, the following studies are introduced. Experiments using the stratified injection system was conducted to apply a low-quality residual fuel (BFO: Bunker Fuel Oil) to a high-speed diesel engine. In that case, BFO was sandwiched by pilot- and post-MDO (Marine Diesel Oil with a good ignition and combustion characteristics like a Gas Oil). Even in the case that a total mass ratio of pilot- plus post-MDO was only about 10%, that meant the rest about 90% was BFO, the BFO completed the combustion just as well as 100% MDO, as the pilot-MDO improved the ignition and the post-MDO mitigated the after-burning of the BFO.

In other word, this system is characterized by its ability to improve the combustion of a main fuel, which has poor ignition and combustion properties, by injecting the pilot- and post-fuel from the same injection nozzle hole as the main fuel.

As an example, the effect of sandwiching ammonia with pilot- and post- gas oil has been presented by J-ENG, Japan Engine Corporation and NMRI, National Maritime Research Institute at CIMAC 2023 [1].

On the other hand, the post-fuel is not necessary for fuels with poor ignition properties but good combustion characteristics like methanol [2]. For such a fuel, the stratified injection with pilot-injection but without post-injection is proposed.

If main fuel which has a high latent heat to evaporate like methanol or ammonia is injected after the pilot fuel, it is possible that the main fuel spray may cool and make the pilot flame inactive in the extreme case.

As a countermeasure, a concept is proposed to create an air layer between the pilot spray and the subsequent main fuel spray. This would allow the pilot fuel to form an active flame before the main fuel catches up with it.

While the engine that uses a hard-to-self-ignite fuel originally requires the two injection systems for main and pilot fuel, and the cylinder head must be equipped with two types of injection nozzles, the stratified injection requires only one injection system and simplifies the engine design.

2 STRATIFIED FUEL AND WATER INJECTION SYSTEM

2.1 Fundamental studies on stratified fuel and water injection system’

The 'Stratified Injection System' was initially developed as a stratified fuel and water injection system for NOx control [3]. In that case, fuel, water, and fuel were injected in this order from the same injection nozzle hole during the injection duration of every cycle. Recently, this has been put to practical use for low-speed two-stroke engines by J-ENG [4].

Many researches were carried out in the past on the water injection into cylinder for NOx reduction. Among them, the stratified fuel and water injection system was developed by Mitsubishi Heavy Industries, Ltd. The advantage of this system is that it does not cause a deterioration of ignitability as in the case of fuel-water emulsions. The system is also simpler than the independent water injection system, where the cylinder head is equipped with an independent water injection nozzle.

2.1.1 Working principle of the stratified fuel and water injection

The working principles of the stratified fuel and water injection are explained according to Figure 1 on the basis of the author's previous paper [5].

The whole system consists of a fuel injection pump with 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 Figure 1(a).

During the period of water supply, a certain quantity of fuel pushed by water flows back to the fuel injection pump, passing through the non-return valve (X). But some fuel remains in the nozzle tip as can be seen in Figure 1(a). When injection starts, the non-return valve (Y) blocks the passage of water. Thus, the fuel remaining in the nozzle tip is injected first as shown in Figure 1(b). Then the water in the fuel passage and lastly fuel from the injection pump is injected in this order from the same injection holes.

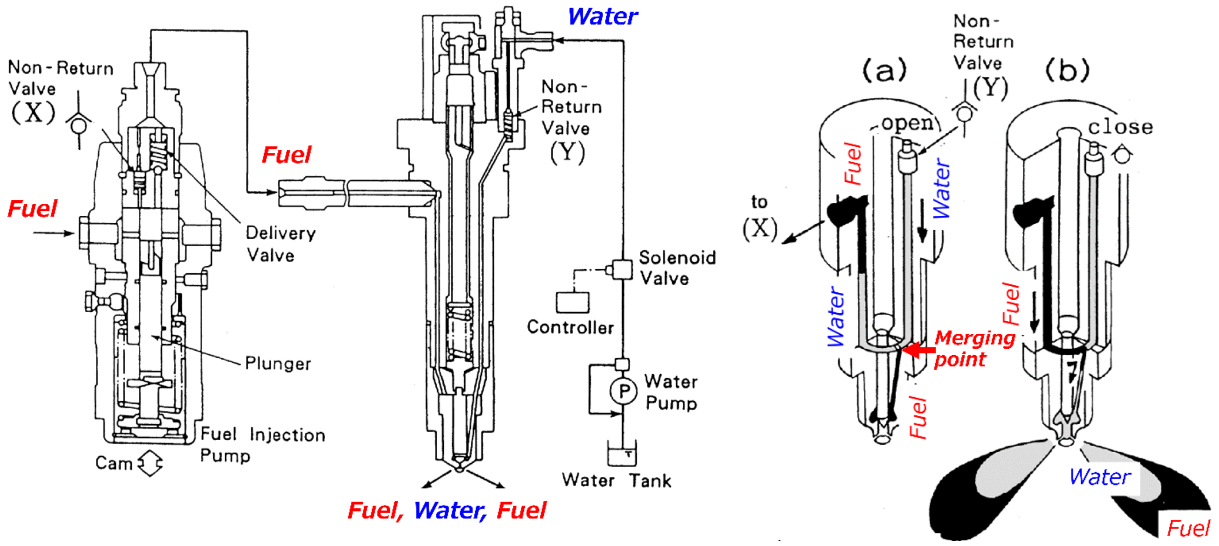


Figure 1 Stratified fuel and water injection system [5]

This method has the following advantages over the fuel-water emulsion.

• The first fuel injected does not contain water, so there is no risk of deteriorated ignitability.

• The main parts of the fuel injection pump, such as the plunger, are not exposed to water.

• The surfactant required for the emulsion is not necessary for this method.

As will be discussed later, even though fuel and water are stratified at the timing of injection, water is distributed in the fuel spray at the stage of spray forming in the air, achieving a NOx reduction effect equivalent to that of the emulsion method.

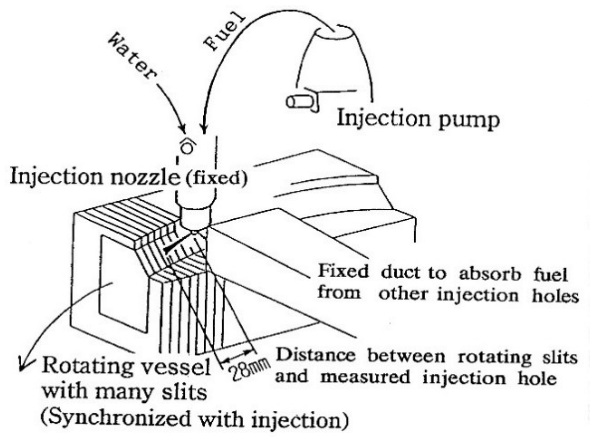


Figure 2 Fuel and water injection rate measuring apparatus [5]

2.1.2 Real injection rate of fuel and water

In order to obtain the real fuel and water injection rate by this system, a rotating slit box shown in Figure 2 was used. For this test, the injection system was removed from the engine and driven by an electric motor. The slit box, a vessel divided into many slits, was fixed to one end of an arm which rotated about its opposite end. The rotation of the slit box and the injection was synchronized. Only the spray of one hole of the injection nozzle was collected in the slit box. The injection rate was then obtained by measuring the height of fuel and water captured in each slit after many rotations.

Figure 3 shows two examples of the measured injection rate of fuel and water, the cases that 100% fuel plus 40% water are injected (left) and 100% fuel plus 50% water (right). Comparing the upper and lower cases of Figure 3, as the amount of fuel injected is set as the same, the lower case has more liquid for the water added to it.

According to the result, actually pure fuel is injected at the beginning of injection, then fuel + water and finally pure fuel again. As mentioned, since the fuel quantity is the same as with the case of fuel only, the total quantity of liquid to be injected is larger when injecting fuel and water and thus the injection duration is also longer.

2.1.3 Combustion with fuel and water injection

The system was tested on the ‘visual test engine’ (Bore: 190 mm) in Kyushu University [5] as follows. Figure 4 shows an example of the photographs of flames by the test engine. As seen in the figure, a pair of four-hole injection nozzles was used simulating a low-speed two-stroke engine. The two photographs show the spray/flame at the end of fuel injection, comparing between (a) 100 % diesel fuel and (b) 100% fuel plus 50% water.

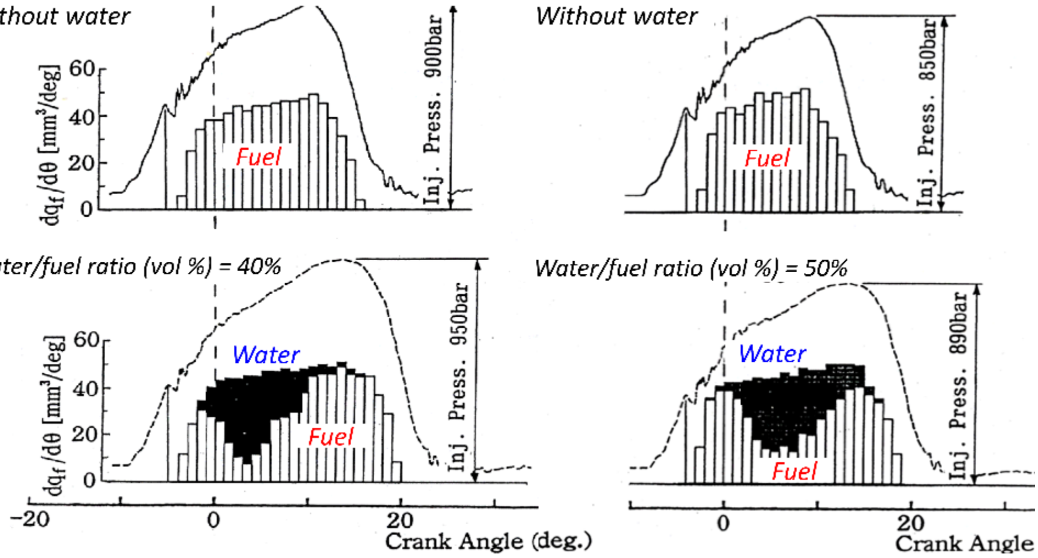


Figure 3 Measured fuel and water injection rate [5]

Although size of the visual test engine is small and it is questionable whether it is representative of the phenomenon for a real engine bore of, for example 500 mm, the photograph shows a shorter spatial burn-up length of the flame with water than without water, that also suggests a good result of shorter after-burning with the effect of added water [5].

Though not illustrated here, despite the longer injection duration in the fuel plus water case compared to the fuel-only case, the duration of combustion determined from the measured heat release rate was remained about the same.

2.1.4 Distribution of water within the spray

Reasons for the expected improvement in combustion with injected water is believed to be the improved air entrainment into the spray. In this section, this phenomenon is discussed using the results of the model calculation.

The distribution of the water (vapor) in the spray was calculated using a CFD software [5]. A model injection rate as shown in the left side of Figure 5 was used as an input of the CFD. Figure 5 also shows one printout of the model calculation. The distribution of fuel is shown by red dots and that of water by green dots.

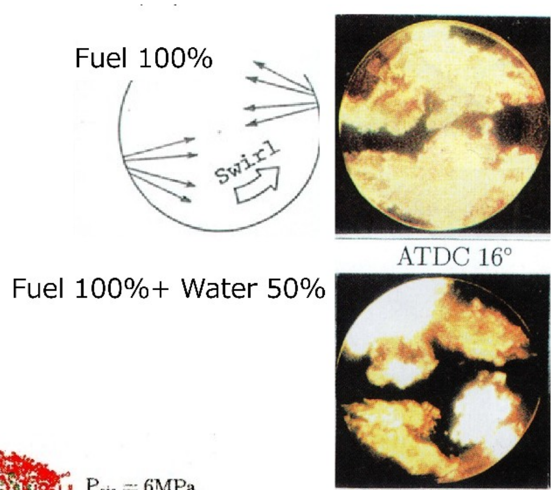


Figure 4 Visualized flame (Fuel: Marine Diesel Oil)

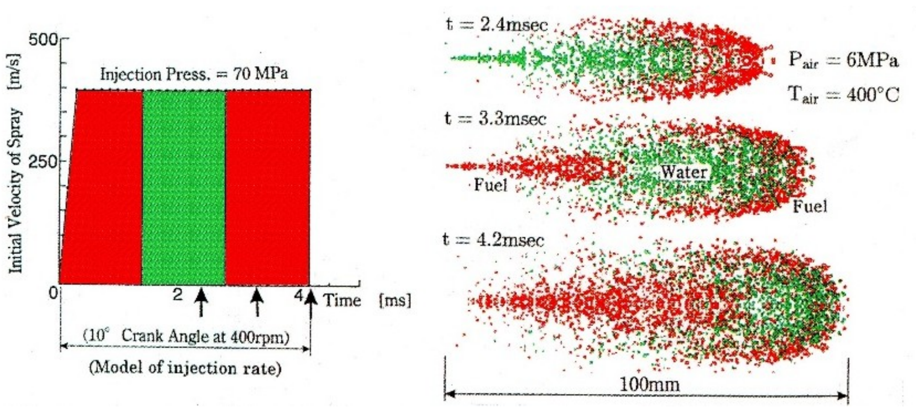


Figure 5 Calculation of fuel and water distribution in spray [5]

At t = 2.4 ms in the figure, the fuel spray front is decelerated by the air drag. Then the water spray penetrates the initially injected fuel spray and push and disperse the high concentration of fuel near the spray axis to the periphery.

It can be seen from the graphs t = 3.3 ms and t = 4.2 ms that fuel is injected after the water again. This second fuel spray pushes the water to the front and to the side.

In any case, it can be seen that the fuel and water are not distributed in clear stratified layers any more in the spray, but are mixed in some degree during forming the spray.

Especially in the case of five-layers system in practical use mentioned below, thanks to this phenomenon, NOx reduction due to a uniform decline in flame temperature similar to that by the fuel-water emulsion can be achieved.

Moreover, a spray with a higher momentum by added water entrains more air into the spray/flame, which may activate the diffusive combustion.

In one example of a commercialised system by J-ENG, water is injected twice during fuel injection in five layers: fuel, water, fuel, water and fuel. The mechanism to realize it is shown in Figure 6 [4]. As mentioned above, this system will provide a more uniform water distribution and greater NOx reduction with less amount of water.

3. STUDIES FOR STRATIFIED LOW-GRADE FUEL INJECTION SYSTEM

With this system, if another fuel is provided instead of above-mentioned water, two different kinds of fuels can be injected without mixing from the same injection nozzle. MHI, Mitsubishi Heavy Industries, Ltd. conducted an experiment using the system to apply a low-grade heavy fuel oil, which has poor ignition and combustion characteristics, to a high-speed diesel engine [6].

For such a small bore (170 mm), high-speed diesel engine used in these experiments, it is usually not possible to burn heavy fuel oil containing petroleum refining residues. Use of the stratified fuel injection system suggested a solution to this issue.

The following studies are introduced. Experiments using the stratified injection system was conducted to apply a low-quality residual fuel (BFO: Bunker Fuel Oil) to a high-speed diesel engine. In this case, BFO was sandwiched by pilot- and post-MDO (Marine Diesel Oil with a good ignition and combustion characteristics like a Gas Oil) and injected from the same injection holes.

Even in the case that a mass ratio of pilot- plus post-MDO was only 10% of total fuel, that meant the rest 90% was BFO, the BFO completed the combustion just as well as 100% MDO, as the pilot-MDO improved the ignition and the post-MDO mitigated the after- burning of the BFO.

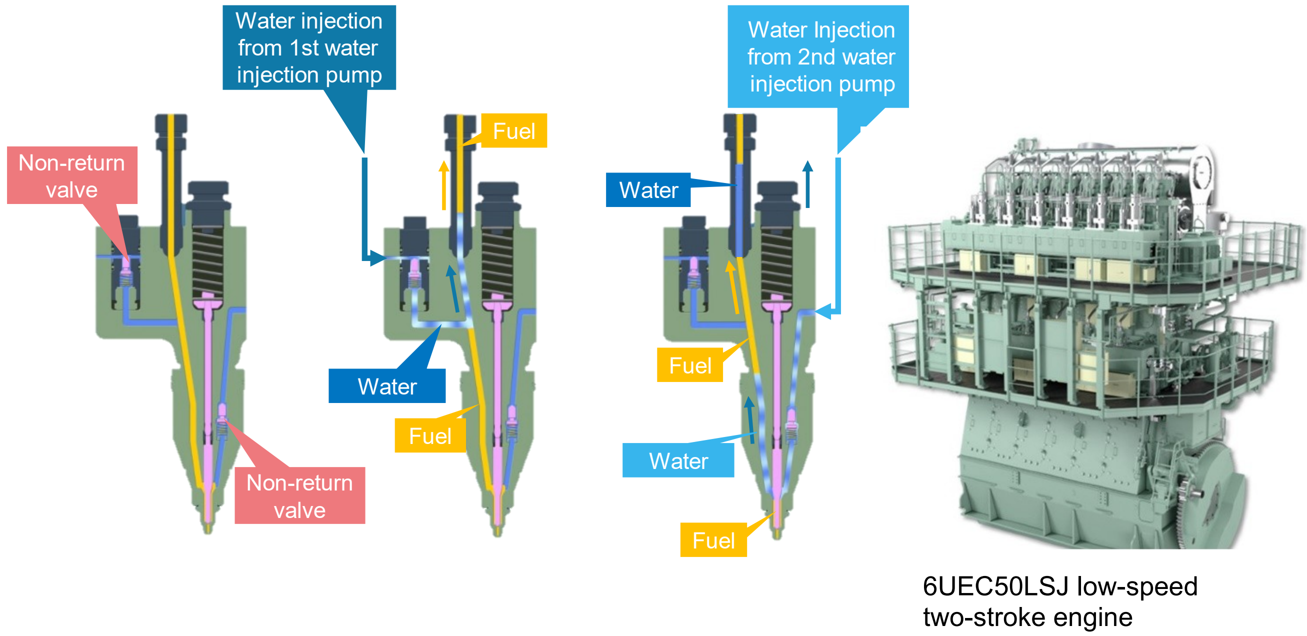


Figure 6 J-ENG’s five layers stratified fuel and water injection system and engine to which it applies [4]

3.1 Test engine and working principle of the stratified fuel injection system

Table 1 Specification of test engine (H-170)

Engine Type	1 Cylinder, 4 Stroke, D.I., Super-charged
Bore × Stroke	170 × 180 mm
Stroke Volume	4086 cm^3
Compression Ratio	16.3
Rated Power	110 kW/1500 rpm
max. Pme	2.15 MPa
Nozzle Holes	ϕ 0.35 mm × 10

A supercharged single-cylinder engine with 170 mm bore was used for the test runs. The specifications of this engine are given in Table 1.

The working principle of the stratified fuel injection system is shown in Figure 7. The whole system consists of a MDO injection pump, a fuel injection nozzle and a BFO supply unit. The MDO injection pump is equipped with the non-return valve (X) and the fuel injection nozzle with the non-return valve (Y).

The fuel injection nozzle has a special BFO passage, which is connected to the MDO passage. The BFO supply unit feeds the required quantity of BFO into the passage of the injection nozzle. In other words, BFO is injected instead of water of Figure 1, and BFO is sandwiched between pilot- and post-MDO.

3.2 Experimental results using the stratified fuel injection system

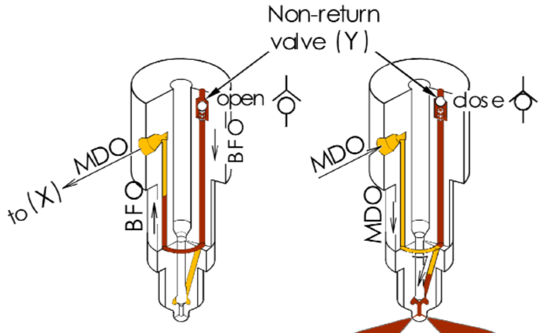
Figure 8 shows the results obtained with the test engine equipped with the stratified fuel injection system at full load. The abscissas in (a)～(c) represent the percentage of MDO added to the BFO. 0% MDO means 100% pure BFO.

In Figure 8, (a) shows that adding even only 10% of MDO to BFO leads to a short ignition delay which is close to that of pure MDO.

(b) shows the measurement of particulate matter (PM) in the exhaust gas. As expected, BFO emits much more PM than MDO. This (b) data means the following. With an addition of total 10% of pilot- and post-MDO using the system, the PM from BFO is reduced to the same value as from pure MDO

(c) shows the change in specific fuel consumption (SFC) with MDO%. Each SFC data is converted to the heat value of MDO. It also shows that 10% addition of MDO improves the SFC drastically.

According to these results, it is concluded that the system is highly effective. Even though the percentage of MDO is relatively low, good combustion characteristics, almost equal to those of pure MDO, can be obtained, as the pilot-MDO improves the ignition and the post-MDO mitigates the after-burning of BFO.



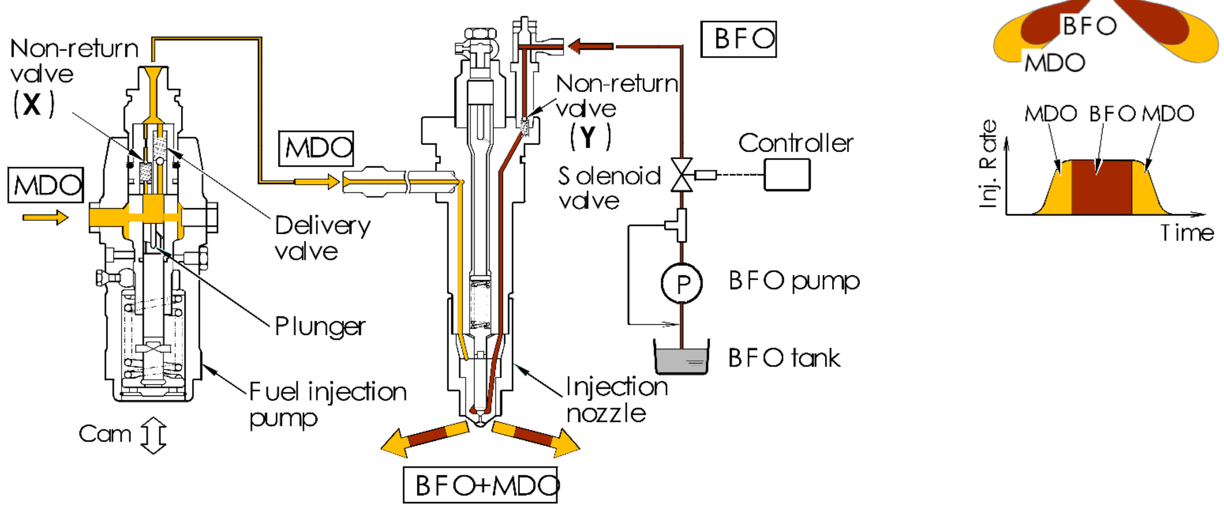


Figure 7 Working principle of stratified fuel injection system

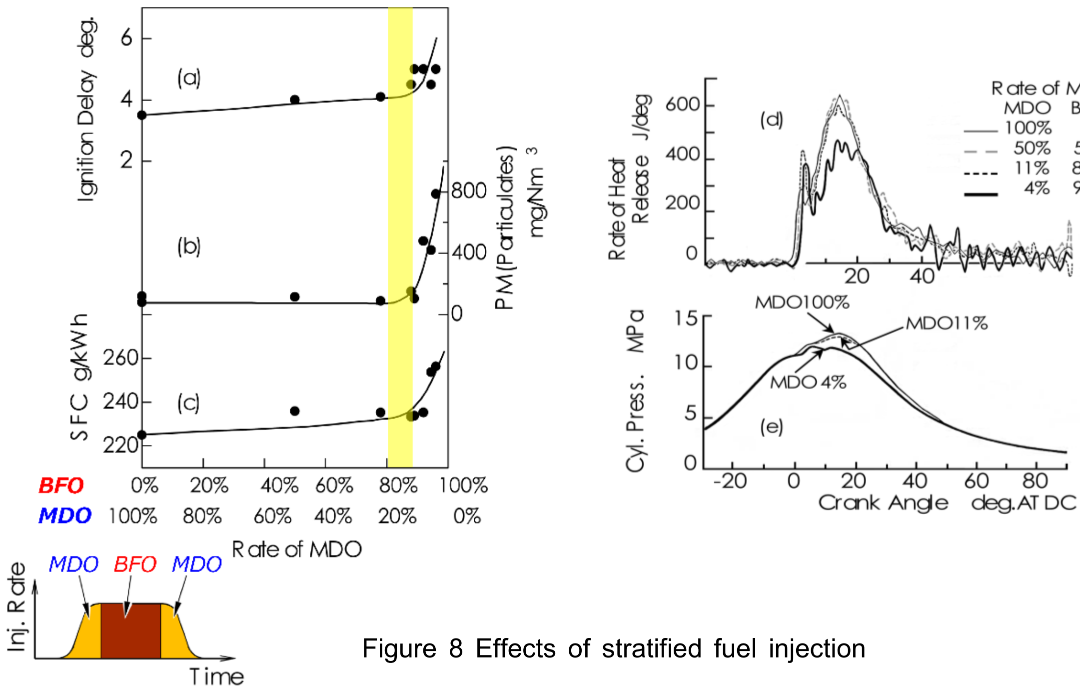


Figure 8 Effects of stratified fuel injection

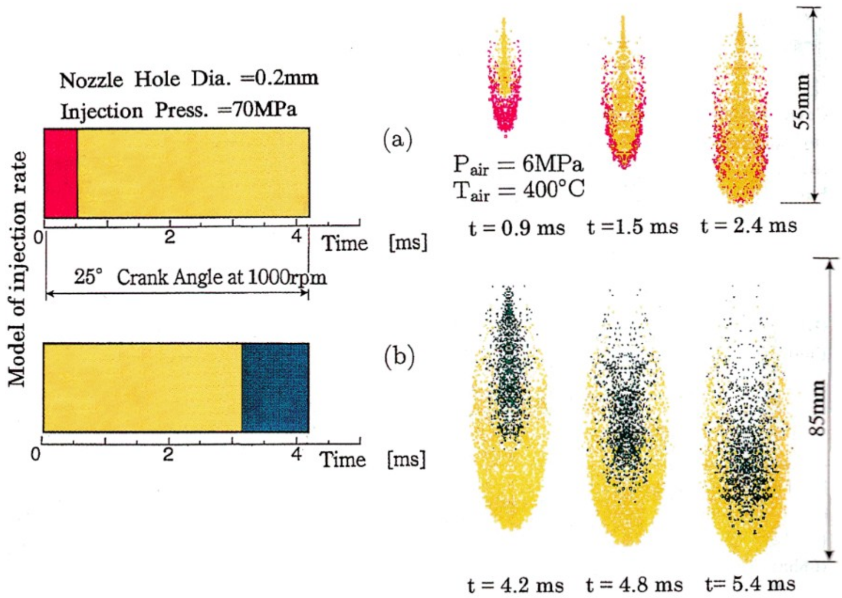


Figure 9 Numerical results of spray characteristics

Figure 8 (d) and (e) show the heat release rate and the cylinder pressure. As a challenge, a further reduction in the amount of MDO to 4% was tried. Comparing the cases in the addition rates of 11% and 4% MDO in the figure, the 11% addition shows almost the same combustion characteristics as pure MDO, whereas the 4% addition shows a much poorer heat release rate during the main combustion duration. The maximum cylinder pressure also becomes much lower. From these results, it is concluded that 4% of MDO is not sufficient to improve the BFO combustion.

3.3 Explanation of the effectiveness of the system through fuel spray simulation

To understand the characteristics of the fuel spray in detail, 2D numerical simulation was performed using a CFD software [6]. The calculation conditions and the results are shown in Figure 9. The purpose of this simulation is to examine the distribution of the fuel particles injected at the beginning and those injected at the end of the injection duration within the spray.

In Figure 9 (a), the distribution of the fuel particles injected at the beginning of the injection duration is examined. On the left, the model injection rate is shown, on the right the resulting distribution of the particles. The red dots of the spray represent the fuel injected at the beginning, first 1/8 of the injection duration marked in red in the model injection rate. The other particles are marked in yellow.

The fuel particles injected at the beginning of the injection duration are first located at the tip of the spray (at t=0.9 ms). These particles are slowed down by the air drag. The later injected yellow particles penetrate the earlier injected red ones at a high velocity and push them to the side (at t=1.5 ms). At t=2.4 ms, all the red particles have been pushed to the side of the spray.

In Figure 9 (b), the distribution of the fuel particles injected at the end of the injection duration is examined; the blue dots represent the fuel particles injected at the end, last 1/4 of the injection duration. Blue dots, in contrast to the red particles in (a), remains in the center of the spray as no more spray to push them out is following.

The results from this calculation explain the high level of effectiveness of the stratified fuel injection system. If the red particles of the spray in Figure 9 (a) represent a good fuel like MDO, then the early igniting MDO flame surrounds the yellow particles representing the low-grade fuel. Then the temperature of the low-grade fuel will soon rise and the evaporation and ignition of the low-grade fuel droplets would be accelerated.

As mentioned above, the fuel injected last in the injection duration remains in the center of the spray, where the air supply is not sufficient. This difficulty would be the reason for the after-burning and the long combustion duration of low-grade fuel. If the fuel injected last is a good fuel like MDO, this problem would be much less severe.

4. FURTHER SUGGESTIONS

4.1 A propose of stratified injection with pilot fuel and main fuel without post-fuel

As mentioned above, the stratified fuel injection system paves the way for the use of fuels with poor ignition or combustion characteristics. As an example, the effect of sandwiching ammonia with pilot- and post-gas oil has been presented at CIMAC 2023 [1].

On the other hand, the post-fuel is not necessary for fuels with poor ignition properties but good combustion characteristics like methanol [2]. For such a fuel, the stratified injection with pilot-injection but without post-injection is proposed as in Figure 10.

In this case, a nozzle tip with two passages is prepared as shown in the figure. The left passage is fed with methanol (yellow) from a methanol injection pump. On the other hand, the right-hand passage is fed with pilot fuel (red) like a diesel oil. A non-return valve is fitted upstream of the right-hand passage. Function is described as (1) to (4) in the figure.

(1) corresponds to the timing of fuel injection start, the main fuel pump is activated and methanol (yellow) is supplied at a high pressure to the left-hand passage. However, the space surrounding the needle (needle chamber) is filled with diesel oil (red) and the needle opens to inject the pilot diesel oil.

(2) shows that the methanol is injected as main fuel following the pilot diesel oil. During this time, the diesel oil in the right-hand passage stays there because the non-return valve is closed.

(3) is the timing at needle valve is just closing. then methanol injection ends without post-injection.

(4) is preparation for the next pilot injection, during which the diesel oil supply system is activated to charge the diesel oil from the right passage until the condition before (1) is reached for the next injection. The methanol equal to that amount of diesel oil is pushed back to the main injection pump.

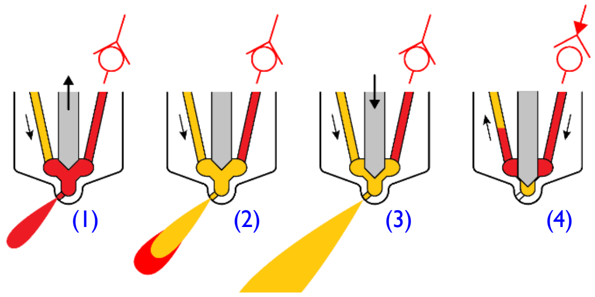


Figure 10 A propose of stratified injection with pilot fuel and main fuel without post-fuel (yellow part: main fuel like methanol, red part: pilot fuel like a diesel oil)

4.2 Stratified injection for fuels with high latent heat of evaporation such as methanol and ammonia

Figure 11 is quoted from the author's CIMAC 2023 paper [2], which calculates the reduction in temperature in the spray due to evaporation when fuels with high latent heat of evaporation, such as methanol and ammonia, are injected into the hot air in the cylinder.

For both methanol and ammonia, even at a stage where the spray has developed to some extent, the temperature in the spray is about 100°C lower than that of the gas oil component according to the figure.

If a main fuel such as methanol or ammonia is injected after the pilot fuel and it catches up with the pilot flame, it may prevent the pilot flame from growing, which in turn may make the main fuel itself even more difficult to ignite.

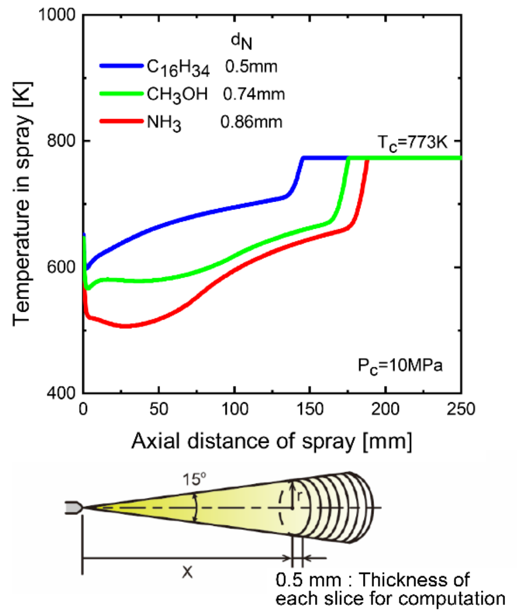


Figure 11 Calculated reduction in temperature in the spray due to evaporation when fuels with high latent heat is injected [2]

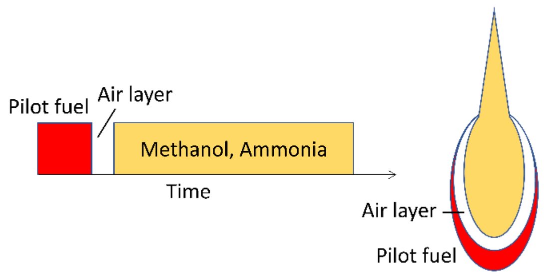


Figure 12 A desirable injection rate and a spray model with air layer

As a countermeasure, a concept could be considered to create an air layer between the pilot spray and the subsequent main fuel spray, as shown in Figure 12, in the other words, to make a time interval between the pilot fuel and the main fuel to create a separation between the two fuels without contact at the first stage.

Even in the case shown in Figure 12, the initial pilot flame would be slowed down by the air drag, as can be imaged from the calculation results in Fig. 9 (a), and is eventually overtaken by the main fuel spray that is injected later, so that the pilot flame can touch the main fuel in the end, even if there is an air layer in between at the first stage.

Effect of the pilot fuel and main fuel being injected in a separated state, with no contact between them, is that the pilot fuel would be less affected at the first stage by the main fuel spray, which has a high latent heat of evaporation. Therefore, the temperature drop of the pilot fuel spray/flame would be suppressed and it could demonstrate its inherent good ignition performance.

5. CONCLUSION

The stratified injection system has been developed on the basis of the philosophy that the fluid supplying the energy for injection and the actual fluid being injected can be different. The following conclusions have been derived from several experiments.

• As a kind of the stratified injection system, the stratified water injection system has been developed for NOx control. The mechanism by which water is sandwiched between fuels and injected from the same injection holes and why NOx reduction and combustion improvement can be achieved simultaneously has been explained.

• With a stratified fuel injection system, which injects a small amount of good fuel before and after the main injection of a low-grade fuel, the whole combustion process can be improved. In other word, this system is characterized by its ability to improve the combustion of a main fuel, which has poor ignition and combustion properties, by injecting the pilot-fuel and post-fuel from the same injection nozzle holes as the main fuel.

• A stratified injection system with pilot-injection but without post-injection has been proposed for the case that the post-fuel is not necessary for fuels with poor ignition properties but good combustion characteristics such as methanol.

• If a main fuel with a high latent heat of evaporation, such as methanol or ammonia, is injected after the pilot fuel and it catches up with the pilot flame, it may prevent the pilot flame from growing, which in turn may make the main fuel itself even more difficult to ignite.

• As a countermeasure, a concept could be considered to create an air layer between the pilot spray and the subsequent main fuel spray, in the other words, to make a time interval between the pilot fuel and the main fuel to create a separation between the two fuels without contact at the first stage.

Literature

[1] Oba, H. et al., Fundamental study of the effect of stratified NH3 injection system for nitrogen compounds reduction, CIMAC 2023, Busan, Paper No. 101 (2023).

[2] Takasaki, K. et al., Progress and prospect of combustion studies on low- and zero-carbon fuels, CIMAC Congress 2023, Busan, Paper No. 103 (2023).

[3] Miyano, H. et al., Development of Stratified Fuel-Water Injection System for Low-NOx Diesel Combustion, CIMAC 1993, London (1993).

[4] Matsuda, Ch., Miyanagi, A. and Edo, K., The Latest Technologies of J-ENG UE Engine, CIMAC Congress 2019, Vancouver, Paper No.137 (2019).

[5] Takasaki, K., Verbesserung der Verbrennung in Dieselmotor durch geschichtete Wassereinspritzung (Improvement of Diesel Combustion with Stratified Fuel/Water Injection System), MTZ (MotorTechnische Zeitschrift) 59. Nr.4, April 1998.

[6] Osafune, S., Takaishi T., Takasaki, K. et al., Study on Stratified Injection System, COMODIA 2001, July 2001.