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Progress and prospect of combustion technologies developed in Japan for zero-carbon fuels

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Abstract

In order to achieve the IMO's 2050 target of net zero GHG emissions from international shipping, the use of zero-carbon fuels such as hydrogen and ammonia is essential. In order to burn these fuels without problems, new technologies on the side of marine engines are required.

In Japan, a national project named "Green Innovation" funded by NEDO (New Energy and Industrial Technology Development Organization) is underway to develop the next generation of ships, which includes the development of technologies to burn hydrogen and ammonia in low-speed two-stroke main engines. This paper introduces the representative technologies that may be applicable to the project.

(1) The first half of the paper describes a fundamental study on the Diesel-cycle type diffusive combustion by high-pressure injection of hydrogen.

A Diesel-cycle type hydrogen-fuelled low-speed two-stroke engine for ocean-going ships is under development at Japan Engine Corporation (J-ENG.). The authors focus on the diffusive combustion by high-pressure hydrogen injection, which realizes high power and high efficiency without worrying about the back-firing, pre-ignition and knocking associated with Otto-cycle type hydrogen combustion.

As a fundamental research work for the development, visual studies on the combustion by high pressure (for example, 30 MPa) hydrogen injection including the case of 100% hydrogen without pilot fuel has been carried out.

(2) In the second half of the paper, development of the 'Stratified Injection System', which can be applied to diesel combustion of ammonia, methanol, low-grade bio-fuels, etc. is introduced.

This system was initially developed as a stratified water injection system for NO_x 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 by J-ENG.

Next, the following studies are introduced. Experiments using the system was conducted to apply a low-quality BFO (Bunker Fuel Oil), which had poor ignition and combustion characteristics, to a high-

speed diesel engine. In that case, MDO (Marine Diesel Oil with a good ignition and combustion characteristics like a Gas Oil), BFO, and MDO were injected in this order. Even in the case that a total mass ratio of pilot- plus post-MDO was only 10%, 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.

In other words, 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 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.

1. Introduction

This paper introduces the two representative technologies that may be applicable to the alternative fuels.

(1) The first half of the paper focuses on the Diesel-cycle type diffusive combustion by high-pressure hydrogen injection, which realizes high power and high efficiency without worrying about the back-firing, pre-ignition and knocking associated with Otto-cycle type hydrogen combustion.

As a fundamental research work for the development, visual studies on the combustion by high pressure (for example, 30 MPa) hydrogen injection including the case of 100% hydrogen without pilot fuel has been carried out.

(2) The second half of the paper introduces the 'Stratified Injection System' technology. This system was initially developed as a stratified water injection system for NO_x 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 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 10%, 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.

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2. Studies on Diesel-cycle type hydrogen diffusive combustion

2.1. A Study for a high-speed 4-stroke hydrogen engine

Research on the diesel-cycle type hydrogen-burning engines in Japan dates back to 2004. MHI: Mitsubishi Heavy Industries, Ltd. conducted operational tests on a high-speed single-cylinder engine with an output of 100 kW [1].

Technical challenge of hydrogen injection engine

Comparison of properties between hydrogen and petroleum is shown in Table 1. Hydrogen has a high self-ignition temperature of over 570 °C despite its extremely high combustion speed, and its application in internal combustion engines usually requires an ignition source such as pilot diesel oil or a spark plug.

The results of this study overturned this forecast. By using a spark plug only at start-up and no ignition source at medium and high loads, and by increasing the compressed air temperature, stable hydrogen jet self-ignition operation was achieved.

The second challenge was to achieve a higher target of thermal efficiency than that of conventional diesel engines. As shown in Table 1, theoretical air quantity per heat value (L_0 /LHV) of hydrogen is smaller than that of petroleum fuels. It means that intake air pressure can be lowered in case of the same excess air ratio of petroleum fuels. Therefore, with a lower intake air pressure and a higher compression ratio, consequently higher cycle efficiency should be realized keeping the Pmax, maximum cylinder pressure constant. Furthermore, the high combustion speed of hydrogen, i.e. the short combustion duration, contributes to improve the thermal efficiency.

Apparatus for testing

The whole tests were conducted using a single cylinder test engine the specification of which was the same as engine planned to produce (Table 2). The ignition and combustion system are shown in Figure 1. For stable starting, a spark plug is set near the injection nozzle so that a hydrogen jet injected from the injector goes directly toward the electrode. Hydrogen gas is compressed to 30 MPa before the engine by a compressor.

The cross-section of a hydrogen injector is shown in Figure 2. It is controlled hydraulically and electrically. Hydrogen gas at 30 MPa is conducted from an accumulator into the needle chamber. At this time, injection does not occur because the working oil pressurized by a pump pushes the top of the needle. When the solenoid is activated, the working oil in the control chamber flows out through a small orifice. After the pressure in the control chamber gets lower and the force under the needle seat by hydrogen is higher than that on the needle, an injection starts.

Table 1: Comparison of properties between hydrogen and petroleum

Items	Hydrogen	Petroleum
Self-ignition temperature*[1] [°C]	571	230
LHV [MJ/kg]	120	42.7
Stoichiometric air L_0 [kg/kg]	34.3	14.3
L_0/LHV [g/kJ]	0.271	0.334
Sonic Velocity [m/s]*[2]	1370	-

*[1] at atmospheric pressure
*[2] expansion from 300 K and 30 MPa

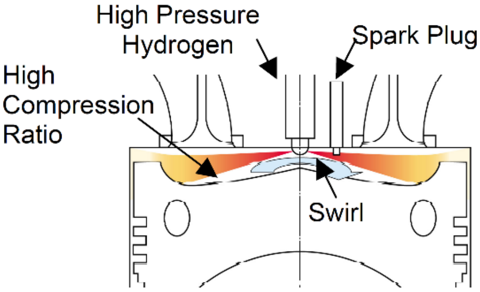


Figure 1: Combustion system of test engine

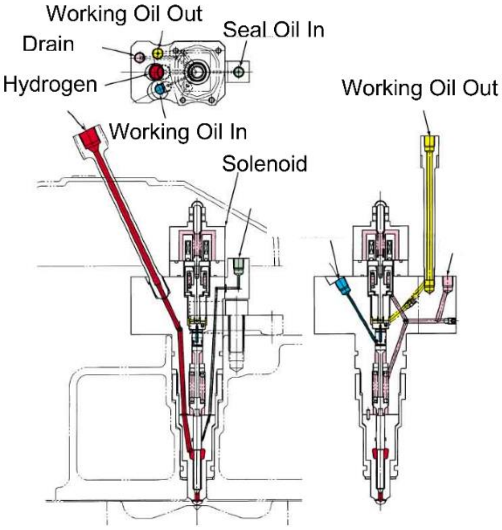


Figure 2: Cross-section of injector

Table 2: Main specifications of product engine

Items	Specifications or Values
Cylinder Bore x Stroke	ϕ170mm x 220 mm
Cylinder Number	6 cylinders
Generating Output	600 kW / 1500 min^{-1}
BMEP	1.69 MPa

*Generator Efficiency 95%

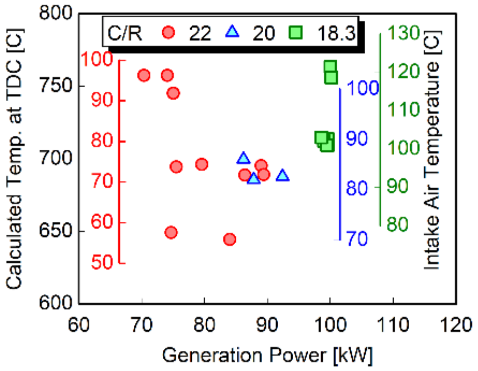


Figure 3: Estimated air temperature at TDC at higher load

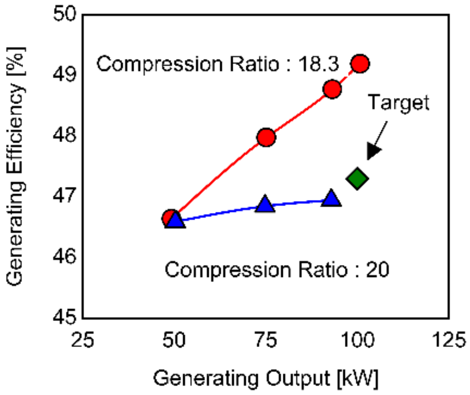


Figure 4: Measured generating efficiency

Self-ignition test at high load

As hydrogen has a higher self-ignition temperature than petroleum, stable self-ignition is supposed to be realized by enhancing the compression ratio. Therefore, tests were done with high compression ratios of 18.3, 20, and 22. At starting, intake air was heated up to the temperature at 180°C in case of 18 of compression ratio and was lowered as increasing engine output. The generated powers, intake air temperatures, and the calculated compression temperatures that were reached at top dead center (TDC) are shown in Figure 3. Although there were some differences depending on the compression ratio, self-ignition of hydrogen was achieved at higher compression temperature than 690°C. As for the intake air temperatures, self-ignition of hydrogen was realized at higher temperature than 100°C even with the lowest compression ratio of 18.3.

As a result, the generating (thermal) efficiency of 49.2% (LHV base) was obtained as shown in Figure 4, with compression ratio of 18.3 and lower intake air pressure than conventional diesel engines, aided by the high-pressure hydrogen injection of 30 MPa.

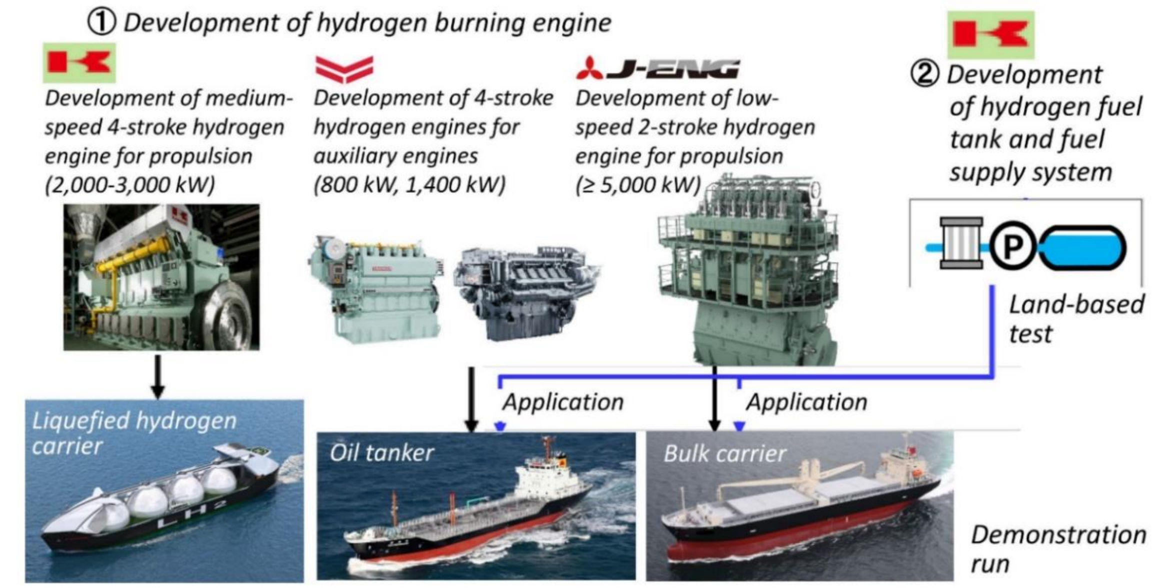
Thermal NO_x was generated as much as that of a conventional diesel engine because of direct injection and diffusive combustion. To reduce NO_x emission, the exhaust gas re-circulation (EGR) could be adopted easily without any risk of reliability because the exhaust gas from a hydrogen engine was free from particulate matters and SO_x. In that case, the EGR gas contained no CO_2 with high specific heat, but NO_x was reduced due to the lower oxygen concentration during combustion. If the effect of EGR would be insufficient, NO_x should be deoxidized by the after-treatment apparatus. As an example, the NO emission was reduced to 835 ppm (as converted into O_2 of 0%) by EGR. Furthermore, it could be possible to be decreased to 100 ppm (likewise) by the catalytic reduction.

Reliability test

The running test for more than 50 hours was carried out to investigate the fluctuation of the engine performance and the surface condition of the fuel injection system. It was found that the movement of the parts of the fuel injection system and the engine performance did not change. After the test, the parts of fuel injection system were disassembled and it was confirmed that there was no trouble of the surface of sliding parts and gas seal parts.

As a result of measuring test of the surface temperature of combustion chamber, the temperature of burning side of piston and cylinder liner at the first ring position at TDC were similar to those of a conventional diesel engine. Therefore, it was possible that the reliability of parts composing combustion chamber for thermal load would be equivalent to that of a conventional diesel engine.

2.2. A fundamental study for a low-speed two-stroke hydrogen engine



Project Period: FY 2021 – FY 2030 (10 years)
Source: Kawasaki Heavy Industries, Ltd., YANMAR POWER TECHNOLOGY CO., LTD. and Japan Engine Corporatio

Figure 5: Green Innovation Fund project, Development of marine hydrogen engines and MHFS (Marine Hydrogen Fuel System) [2]

In Japan, the development of ocean-going vessels fuelled by green or blue hydrogen has started in 2021 under the "Green Innovation" fund by NEDO (New Energy and Industrial Technology Development Organization). An overview is given in Figure 5. As shown in this figure, three types of hydrogen engines are developed, with the low-speed, two-stroke hydrogen engine for bulk carriers on the right being a diesel cycle.

This part presents a fundamental study of high-pressure injection and diffusive combustion of hydrogen for the Diesel-cycle type hydrogen burning engine development, which has not been studied extensively compared to the premixed lean-burn (Otto-cycle) type.

Fundamental studies by Kyushu University and NMRI: National Maritime Research Institute

The properties of hydrogen are shown in Table 3 in comparison with those of methane. Based on the ratio of molecular weights of hydrogen and methane (2:16), the density of hydrogen is 1/8 of that of methane. The (lower) Calorific Value of hydrogen per mass in Table 3 is 2.4 times that of methane, but when considered per volume, hydrogen must be injected about three times the volume of methane to gain the same amount of heat.

However, the sonic velocity of hydrogen is about three times higher than that of methane, and in the case of high-pressure injection, where the initial speed of gas jet is the sonic velocity, a sufficient volume of hydrogen can be injected without extreme enlargement of injection nozzle hole.

As seen in Table 3, although hydrogen has a lower minimum ignition energy, its self-ignition temperature is much higher than that of diesel fuel oil, as already mentioned in the previous section. Therefore, at beginning of this study, pilot injection of gas oil (5% heat base) is tried to ignite the hydrogen jet. Shadowgraphs of ignited hydrogen jet taken from the side window of the RCEM (Rapid Compression and Expansion Machine) are shown in Figure 6. As hydrogen flame cannot be visualized by the direct photography because it does not emit a luminous flame, the shadowgraph technique is applied. The white flame in the image in Figure 6 is the pilot gas oil flame and the black area is the hydrogen flame.

Figure 7 shows a comparison of heat release rate by a single spray between of methane and of hydrogen injected into the RCEM. Both sprays are ignited by a gas oil pilot injection. While both fuels are injected during almost the same injection duration and at the same injection pressure (at 30MPa into 8 MPa air), hydrogen shows the higher heat release rate and shorter combustion duration. As the injection-end timing is almost the same for the two fuels, the shorter combustion duration of hydrogen represents a faster burn-up after the end of injection, i.e., a shorter after-burning.

In this experiment, a hydrogen jet is also tried to self-ignite by further increasing the air temperature. The air temperature at hydrogen injection is raised to a higher level (estimated to be around 700°C, although unable to be measured) than normal case of diesel engines, and that allows the hydrogen to self-ignite.

From the photograph in Figure 8, it appears that the jet is self-ignited before 5.5° after the start of injection, after that the flame develops almost in proportion to the square root of the elapsed time. The penetration of flame front would be based on the momentum theory [3], just like a normal diesel fuel spray flame. This result will lead to the development of absolute zero-GHG hydrogen burning engine without any pilot fuel.

Table 3: Comparison of physical properties between hydrogen and methane

	Hydrogen	Methane
Calorific Value [kJ/g]	119.9	50.2
Maximum Adiabatic Flame Temperature [℃]	2124 (φ=1.07)	1967 (φ=1.05)
Flammable Range : vol.%	2.0-75	5.0-15.0
Equivalence Ratio (φ)	0.1-7.1	0.5-1.68
Maximum Burning Velocity[cm/s]	350 (φ=1.45)	45 (φ=1.07)
Self-Ignition Temperature [℃]	576	635
Minimum Ignition Energy [mJ]	0.015	0.29
Minimum Quenching Distance [mm]	0.51	2.03
Diffusion Coefficient [cm²/s]	0.82	0.23
Methane Number	0	100

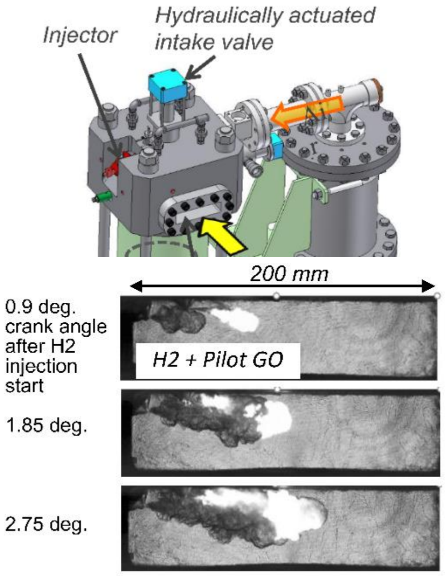


Figure 6: Upper: Side-view style RCEM, Rapid Compression and Expansion Machine

Lower: Hydrogen flame injected at 30 MPa and ignited by pilot Gas Oil

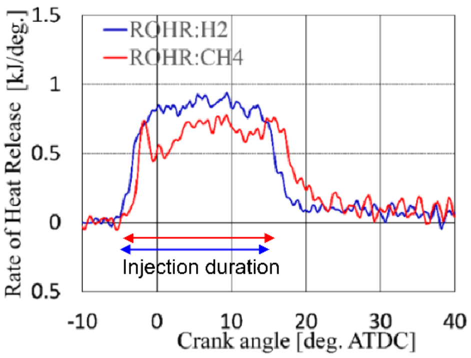


Figure 7: Comparison of heat release rate by single spray between of methane and of hydrogen, injected at 30 MPa and ignited by pilot GO. Air condition: (8 MPa, 550 ℃)

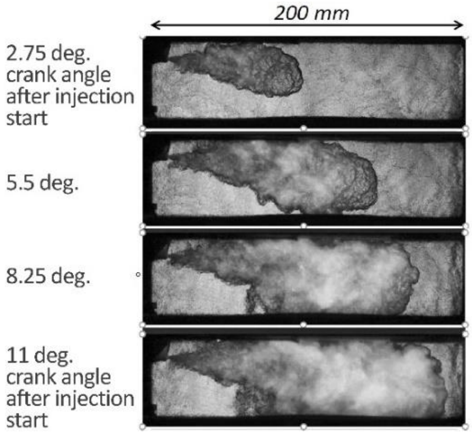


Figure 8: Hydrogen flame injected at 30 MPa and self-ignited by a higher air temperature than for Figure 6

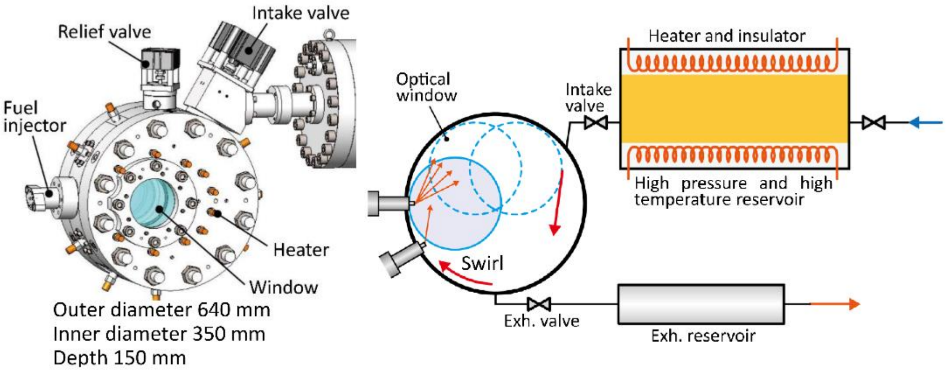


Figure 9: New visual combustion chamber for NMRI (National Maritime Research Institute in National Institute of Maritime, Port and Aviation Technology (MPAT), Japan)

Although the observation of a single flame as described above can provide some information, it is important to create the conditions close to those of the actual engine. The NMRI is currently building a visual combustion chamber as shown in Figure 9 simulating the engine to be developed. On the day of the Symposium, data taken with this equipment will be presented. CFD calculations based on this data will also be introduced.

Schedule for real engine development

As shown in Figure 5, J-ENG is developing a diesel-cycle, low-speed, two-stroke hydrogen engine with a cylinder diameter of 350 mm (UEC35LSGH). Figure 10 shows the development schedule for this engine. ClassNK has issued an Approval in Principle (AiP) for a parcel layout concept for a hydrogen-fuelled multi-purpose vessel [4]. This is the world's first AiP certification for the ship equipped with a low-speed two-stroke hydrogen-fueled engine as a main propulsion machine.

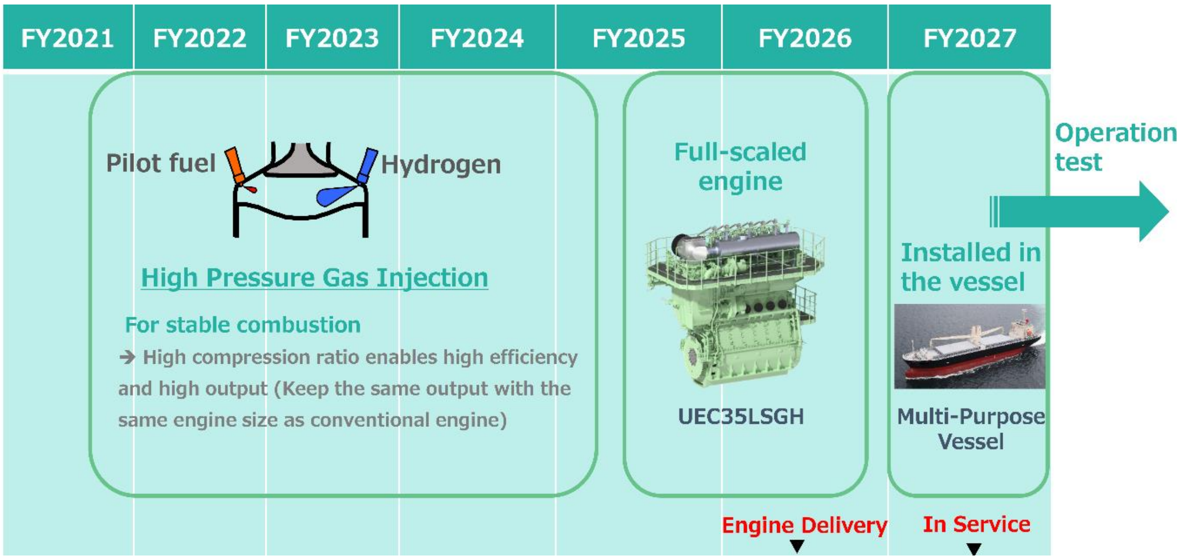


Figure 10: Schedule of hydrogen fuelled engine development by J-ENG

3. Fundamental studies on ‘Stratified Injection System’

3.1. A study for a stratified fuel-water injection system

The second half of the paper introduces the 'Stratified Injection System' technology. It was initially developed as a stratified water injection system for NO_x control [5]. 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 [6].

Many researches were carried out in the past on the water injection into cylinder for NO_x reduction. Among them, the stratified 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, where the cylinder head is equipped with an independent water injection nozzle.

Working principle of the stratified fuel and water injection

The first author analyzed the real injection rate of fuel and water injected by this system and simulated the distribution of water (water vapor) in the fuel spray [7]. As mentioned above, this system has been put into the practical use by J-ENG and its mechanism has been refined, but the function is explained at first according to Figure 11, the system used in the past study.

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 11(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 11(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 11(b). Then the water in the fuel passage and lastly fuel from the injection pump is injected.

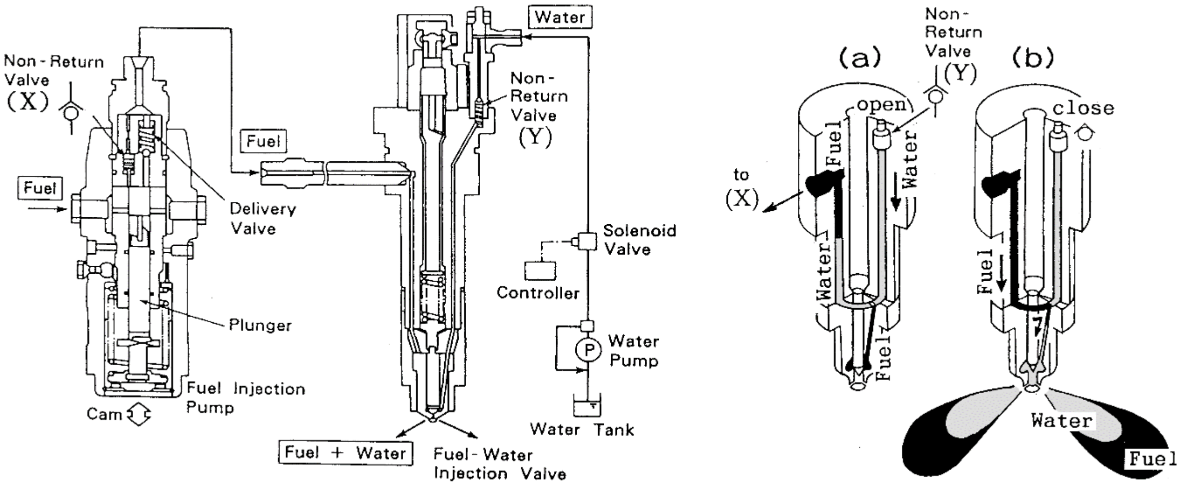


Figure 11: Stratified fuel-water injection system used in experiments by the author [7]

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 NO_x reduction effect equivalent to that of the emulsion method.

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, Figure 12 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 in each slit after many rotations.

Figure 13 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). According to the result, actually pure fuel is injected at the beginning of injection, then fuel + water and finally pure fuel again. 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.

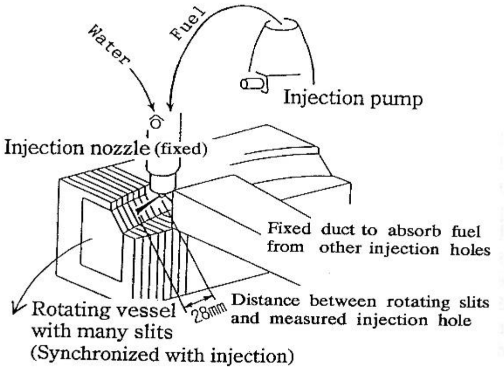


Figure 12: Fuel and water injection rate measuring apparatus

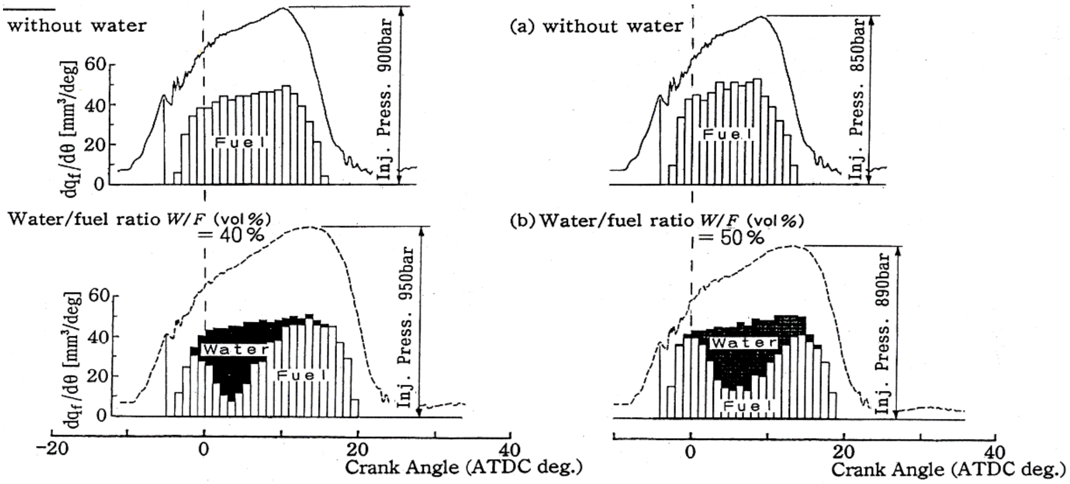


Figure 13: Measured fuel and water injection rate

Combustion with fuel/water injection

The system was tested on the 'visual test engine' in Kyushu University as follows. Figure 14 shows an example of the photographs of flames by the test engine. As can be 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.

Although size of the visual test engine is small (bore: 190 mm) and it is questionable whether it is representative of the phenomenon for a real engine bore of 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 water. 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.

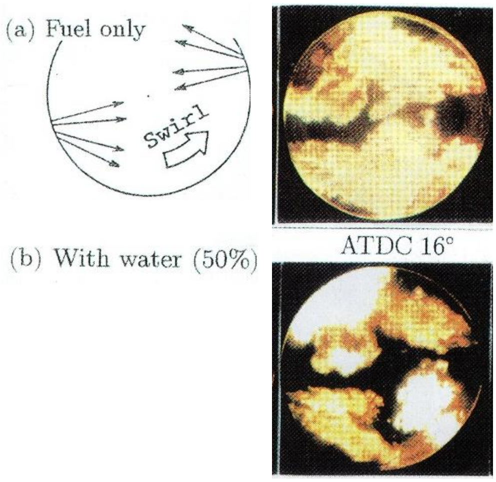


Figure 14: Visualized flame (Fuel: Marine Diesel Oil)

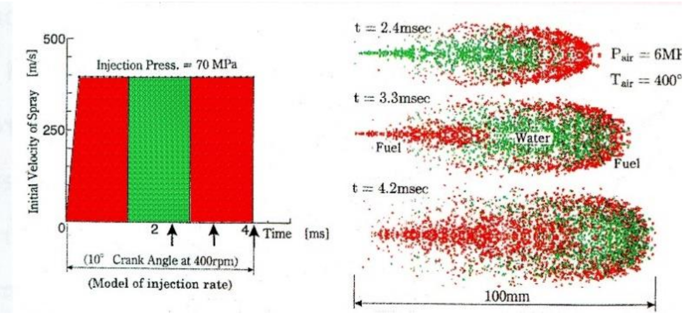


Figure 15: Calculation of fuel/water distribution in spray

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 [7]. A model injection rate as shown in the left side of Figure 15 was used as an input of the CFD. Figure 15 also shows one printout of the model calculation. The distribution of fuel is shown by red dots and that of water by green dots.

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. As imaged by the photographs in Figure 14, the red dots of the initial fuel spray are 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 = 4.2 ms). This effect prevents the second fuel spray from entraining burnt gas, which usually happens when using fuel alone.

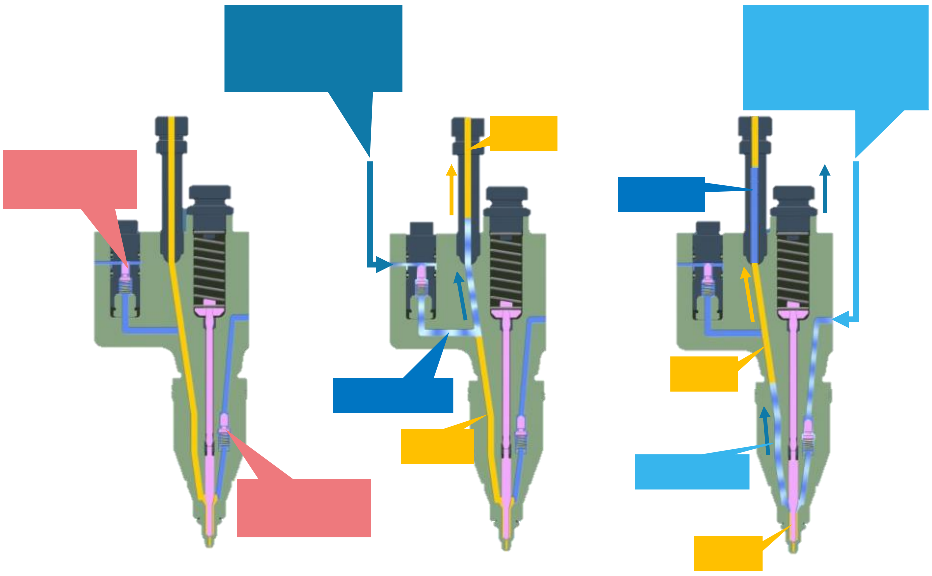


Figure 16: J-ENG's five layers stratified fuel and water injection system [6]

In any case, it can be seen that the fuel and water are not distributed in clear stratified layers in the spray, but are mixed close to homogeneously during forming the spray. Thanks to this phenomenon, NO_x 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 entarains more air into the spray/flame, which may activate the diffusive combustion.

In the practical system by J-ENG, water is injected twice during fuel injection, in five layers: fuel, water, fuel, water and fuel. The mechanism is shown in Figure 16 [6]. This system will provide a more uniform water distribution and greater NO_x reduction with less amount of water.

3.2. A study for a 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 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 [8]. 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 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. Even in the case that a total mass ratio of pilot- plus post-MDO was only 10%, 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.

Test engine and working principle of the stratified fuel injection system

A supercharged single-cylinder engine with 170 mm bore (H-170 engine) was used for the test runs. The specifications of this engine are given in Table 4. The working principle of the stratified fuel injection system is shown in Figure 17. 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 the previous section and BFO is sandwiched between MDO.

Experimental results using the stratified fuel injection system

Figure 18 shows the results obtained with the H-170 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.

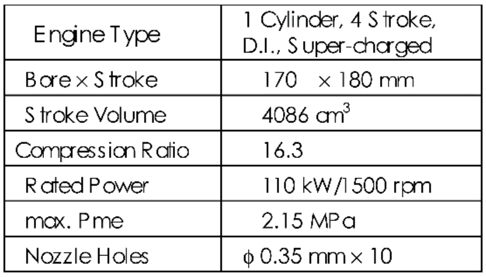
(a) shows that adding even only 10% of MDO leads to an ignition delay which is close to that of pure MDO.

(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.

Table 4: 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

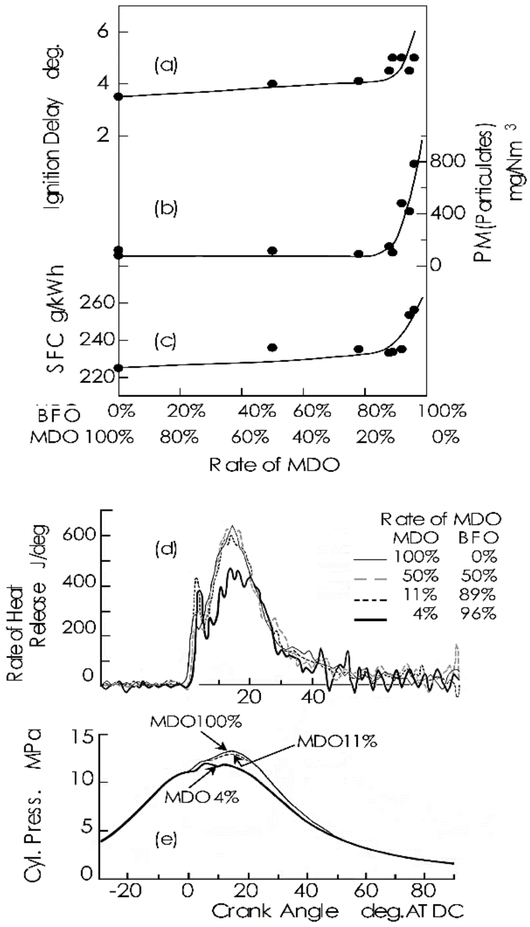


Figure 18: Effects of stratified fuel injection system

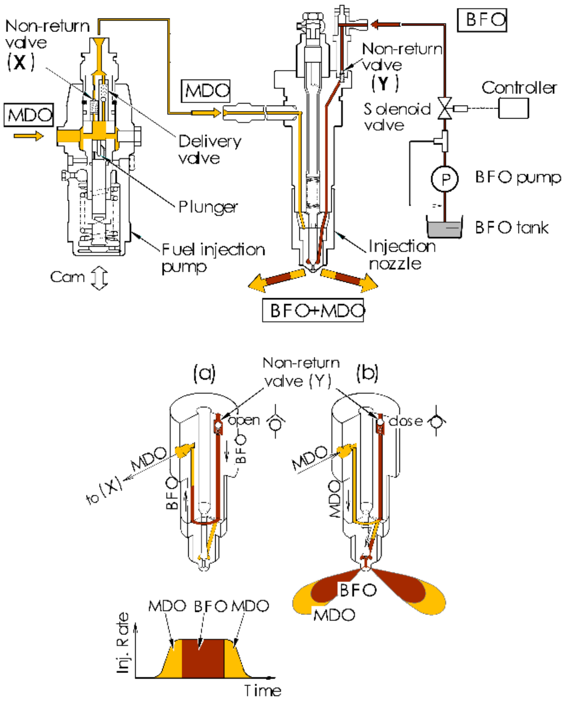


Figure 17: Working principle of stratified fuel injection system

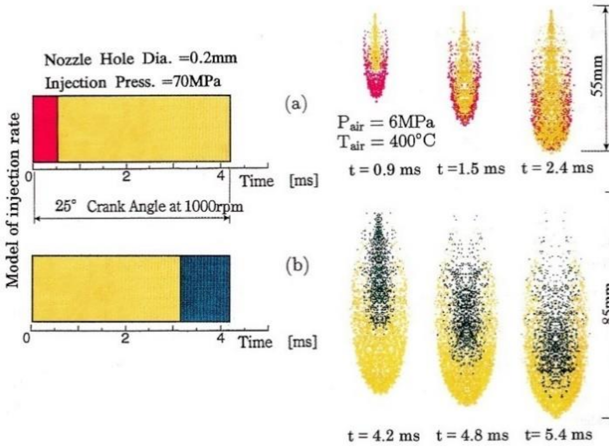


Figure 19: Numerical results of spray characteristics

Figure 18 (d) and (e) show the heat release rate and the cylinder pressure. With regard to the cost of the fuel, a smaller percentage of MDO is desirable. Therefore, a further reduction in the amount of MDO to 4% was examined. Comparing the addition rates of 11% and 4% MDO, the 11% addition shows almost the same combustion characteristics as pure MDO, whereas the 4% addition shows a much lower heat release rate during the main combustion duration. The maximum cylinder pressure becomes much lower. It is concluded that 4% of MDO is not sufficient.

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 [8]. The calculation conditions and the results are shown in Figure 19. 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 19 (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). They are 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 (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 (t=1.5 ms). At t=2.4 ms, all the red particles have been pushed to the side of the spray.

In Figure 19 (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 (t=4.2 ms to t=5.4 ms), because no spray is following to push it to the side.

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 19 (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 is accelerated.

As mentioned above, the fuel particles injected last remain 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.

3.3. Further Suggestions

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 by J-ENG and NMRI, National Maritime Research Institute at CIMAC 2023 [9]. 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 20.

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 diesel oil. A non-return valve is fitted upstream of the right-hand passage.

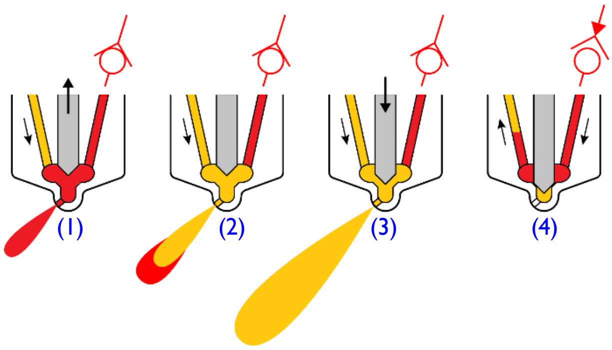


Figure 20: A propose of stratified injection with pilot injection and main injection (without post-injection)

The function is described as (1) to (4) in Figure 20.

(1) corresponds to the timing of the start of fuel injection, 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.

4. Conclusion

This paper has introduced the two representative technologies that may be applicable to the alternative fuels and the following conclusions have been confirmed.

The first half of the paper has explained on the diffusive combustion by high-pressure hydrogen injection quoting the following studies, which realize high power and high efficiency without worrying about the back-firing, pre-ignition and knocking associated with Otto-cycle type hydrogen combustion.

- Research on the diesel-cycle type hydrogen-burning engines through the operational tests of a high-speed single-cylinder engine with an output of 100 kW has been successfully conducted by MHI: Mitsubishi Heavy Industries, Ltd.
- As a fundamental research work for the development, visual studies on the combustion by high pressure (for example, 30 MPa) hydrogen injection including the case of 100% hydrogen without pilot fuel has been conducted by Kyushu University and the National Maritime Research Institute, Japan.
- The second half of the paper has introduced the 'Stratified Injection System' technology.
- As a kind of the stratified injection system, the stratified water injection system has been developed for NO_x control. The mechanism by which water is sandwiched between fuels and injected from the same injection hole and why NO_x 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. The effectiveness of stratified injection has been explained with the help of fuel spray simulation. 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 hole 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.

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