

Residual Fuel Sprays - Evaporation, Dispersion and Combustion Characteristics

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ABSTRACT

To improve the burning condition of the residual fuel in the combustion chamber of diesel engine, visualization and diagnosis on the residual fuel spray have been carried out.

Firstly, effects of some physical means as impingement of spray onto the combustion chamber wall and air-swirl have been verified. Secondly, effects of increase in air temperature in combustion chamber on the ignition delay and combustion state have been examined.

As results, it has become clear that some means to improve the evaporation rate should be necessary for the residual fuel spray. As it would have much difficulty to improve the evaporation rate of residual components themselves, it is considered as a realistic means to accelerate the evaporation of distillate components in the residual fuel and promote the combustion of residual components.

INTRODUCTION

To improve the burning condition of the residual fuel in the combustion chamber of diesel engine is still one of the problems difficult to be solved.

The authors reported at the 16th CIMAC Congress (1985, in Oslo), on the differences of the combustion performances between a residual fuel oil (a marketed bunker fuel oil) and a marine diesel oil in the engine operation tests⁽¹⁾.

In the present studies, to get more informations regarding the change in fuel-spray combustion characteristics with fuel properties, the authors have tried the photographic visualization of fuel sprays using two apparatuses. Firstly, high-speed photos of burning sprays have been taken in the same engine as above-mentioned operation tests and compared with the operation data. Secondly, the detailed characteristics of evaporation, dispersion and combustion of sprays of many kinds of fuel have been observed in a specially designed single compression machine.

EXPERIMENTAL APPARATUS AND PROCEDURE

Test Engine⁽²⁾

Two experimental apparatuses, the test engine for both the normal operation and the visualization of burning sprays and the single

compression machine for the visualization of a single spray have been prepared.

A sectional view and specifications of the test engine are shown in Fig.1. Alterations of swirl intensity have been made by the variable angle swirler installed around the scavenging ports as shown in Fig.1. The swirl intensities at the beginning of compression stroke are represented with the sine of swirl inflow angle, $\sin\theta$.

In the visualization test, the engine is driven by the auxiliary external power and fuel is injected only during photos are taken to preserve the transparent piston. Cross sections of combustion chambers for operation test and visualization test are also shown in Fig.1. As recent uni-flow scavenging two-stroke-cycle engines, the side-injection system where two injection nozzle holders with three nozzle holes each are installed in the side of combustion chamber, has been adopted.

Single Compression Machine⁽³⁾

The scheme and specification of the single compression machine are shown in Fig.2. A crank mechanism driven by an electric motor is used for the reciprocation of the piston. At first, the piston is steadily reciprocated without compression with valve ③ between the cylinder and large air tank ⑤ open. The single compression is made by closing valve ③ by a hydraulic power. Air pressure and temperature at the beginning of compression can be set exactly by adjusting the air conditions in tank ⑤. A swirling flow can be caused into the cylinder when valve ③ is set to the circumferential direction.

Pyrex-glasses are fitted in both the cylinder head and top of the piston. Two photographic techniques, "back diffused light" and "shadowgraph" have been applied to the visualization tests. Only the liquid part of the spray can be observed before ignition with the former technique and outline of the spray including the gaseous part can be photographed with the latter technique. The scheme of fuel injection system installed in the single compression machine is shown in Fig.3. This system has a plunger actuated by the hydraulic power, and high injection pressure (100MPa) can be achieved with relatively low hydraulic pressure (40MPa) owing to the difference of area between the plunger and the hydraulic piston. In the case with heated fuel, the fuel has been

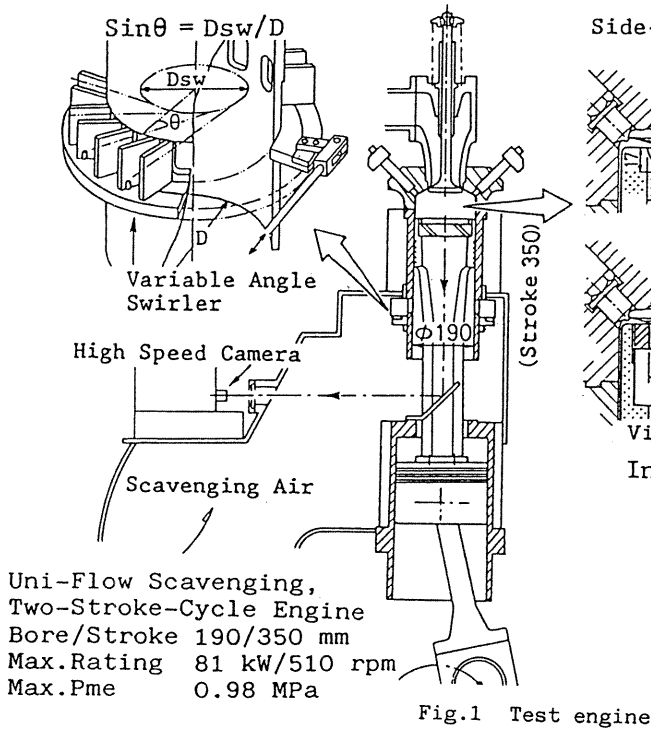
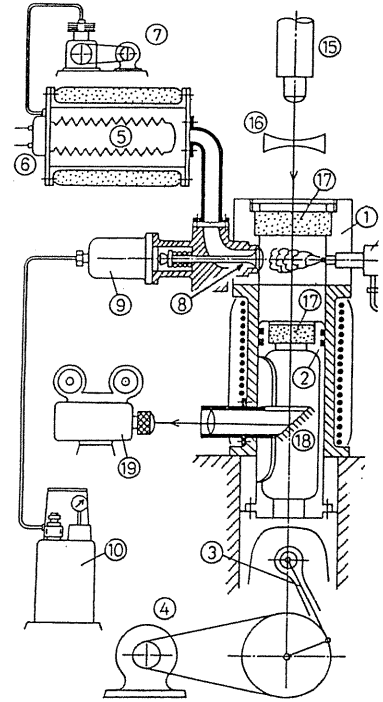
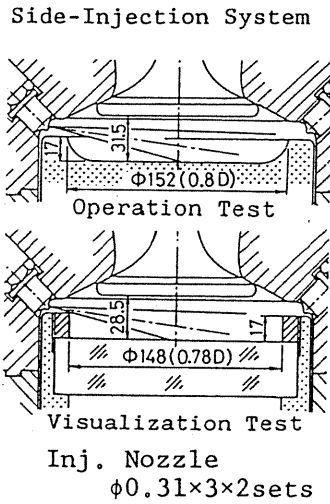


Fig.1 Test engine



Bore 135mm
Stroke 280mm
Machine speed 200rpm
Compression ratio 11
Fuel inj. press. ~ 100 MPa

Fig.2 Single compression machine

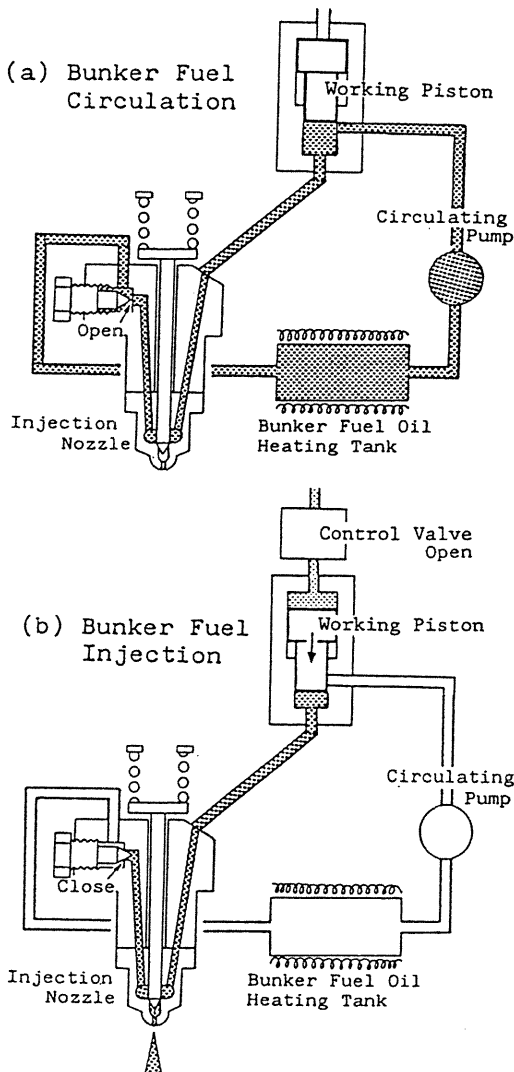


Fig.3 Fuel injection system

circulated in advance through the tip of injection nozzle as shown in Fig.3(a). Just before the injection, the circulating line has been closed as shown in Fig.3(b). Fuel temperature in the nozzle tip has been monitored with inserted thermo-couple even during the injection.

Test fuels

Six fuels whose properties are summarized in Table 1 have been prepared for the study. Distributions of distillate components for each fuel are shown in Fig.4. The marine diesel oil and the bunker fuel oil have been applied to both the test engine and the single compression machine. The marine diesel oil has been injected without heating. The bunker fuel oil has been heated to 80°C to lower the viscosity to 45mm²/s. Other four fuels are specially blended fuels applied to the single compression machine. These have been injected with the same viscosity of 20mm²/s.

Table 1 Fuel Properties

| | Marine Diesel Oil | Bunker Fuel Oil | Sample Fuel | | | |
|---|-------------------|-----------------|-------------|-------|-------|-------|
| | | | (1) | (2) | (3) | (4) |
| Density (15°C) kg/m ³ | 843 | 974 | 867 | 935 | 931 | 930 |
| Kinematic Viscosity (50°C) mm ² /s | 2.5 | 165.5 | 18.5 | 74.6 | 66.9 | 68.9 |
| Flash Point °C | 72 | 92 | 212 | 68 | 40 | 42 |
| Wt% C | 86.1 | 85.5 | 87 | 85.3 | 85.1 | 85.7 |
| Wt% H | 13.0 | 11.0 | 12.9 | 11.6 | 11.6 | 11.7 |
| Wt% S | 0.84 | 3.3 | 0.10 | 2.8 | 3.0 | 2.5 |
| Residual Carbon Wt% | 0.07 | 13.7 | 0.0 | 12.2 | 14.2 | 13.9 |
| Lower Calorific Value KJ/kg | 42500 | 40530 | 42790 | 41030 | 41030 | 41240 |

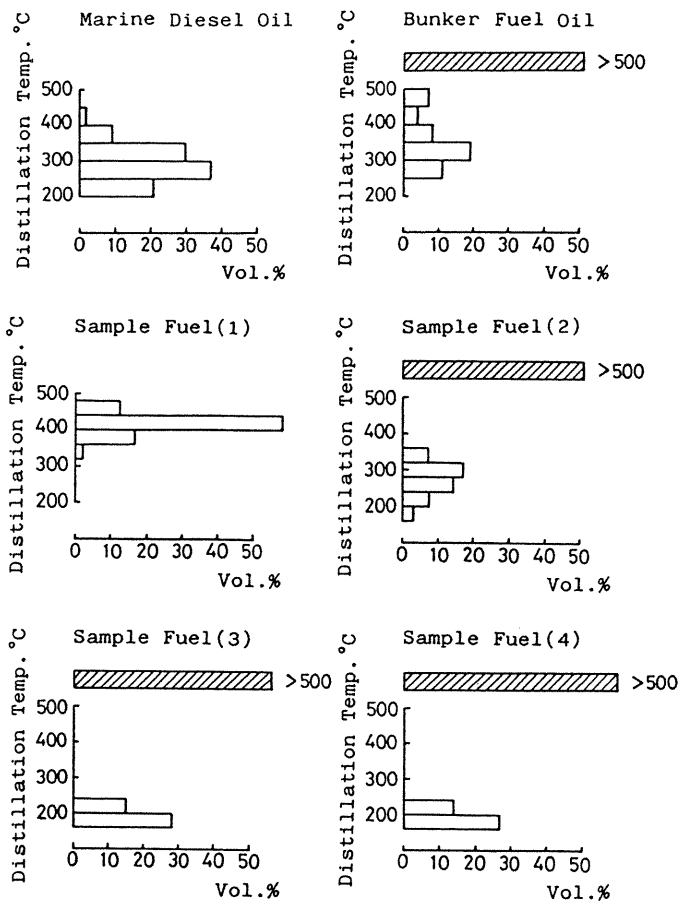


Fig.4 Distributions of distillates in test fuels

CHANGE IN COMBUSTION CHARACTERISTICS WITH FUEL PROPERTIES IN TEST ENGINE

The operation and visualization tests have been carried out under the same conditions of the test engine using the marine diesel oil and the bunker fuel oil. The differences in the engine operation data between two fuels are seen in Fig.5, where the changes in specific fuel consumption (SFC) and smoke density in Bosch scale with swirl intensity are plotted.

In this figure, the bunker fuel oil shows inferior combustion to the marine diesel oil, especially relatively large gap is seen in SFC. Moreover, the optimum swirl intensity for the bunker fuel oil seems to shift to higher intensity than that for the marine diesel oil. According to the comparison of heat release rates shown as Fig.6, the bunker fuel oil shows lower heat release than the marine diesel oil especially during ATDC 5° ~ 15° . In this figure, $Q/Gf \cdot Hu$ (Q :net released heat excluding unburnt portion and heat loss, Gf :quantity of the fuel injected per cycle, Hu :lower calorific value) means the ratio of the net released heat to the energy of the fuel injected per cycle. The bunker fuel oil shows also lower $Q/Gf \cdot Hu$ in whole combustion duration.

Fig.7 shows the comparison of direct photographs of burning sprays of two fuels under the swirl intensity of $\text{Sin}\theta = 0.5$. The profile of swirl velocities is shown in the figure. The clear difference can be seen at ATDC 7.5° , just after the impingement of fuel sprays onto the bottom of combustion chamber. The sprays of bunker fuel oil are less dispersed to the circumferential direction by air swirl than the marine diesel oil.

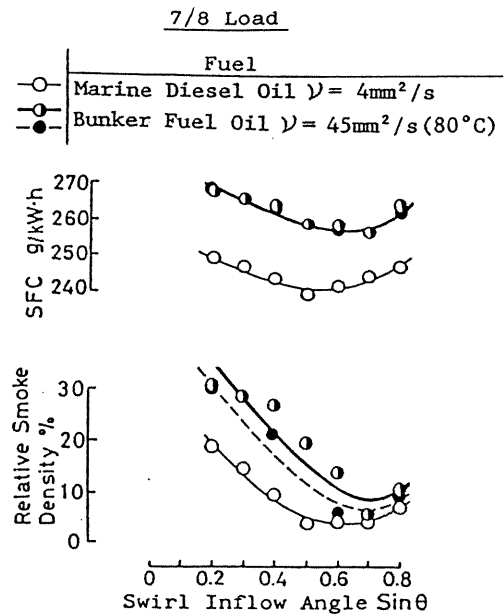


Fig.5 Results of engine operation tests

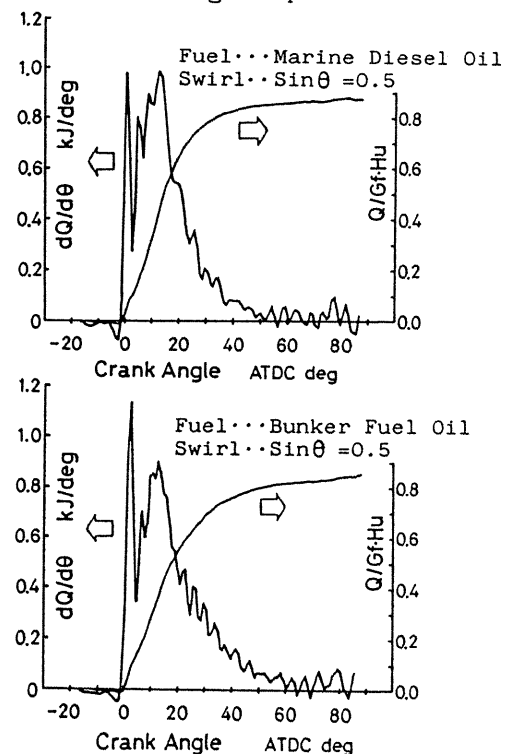


Fig.6 Change in heat release rate with fuel properties

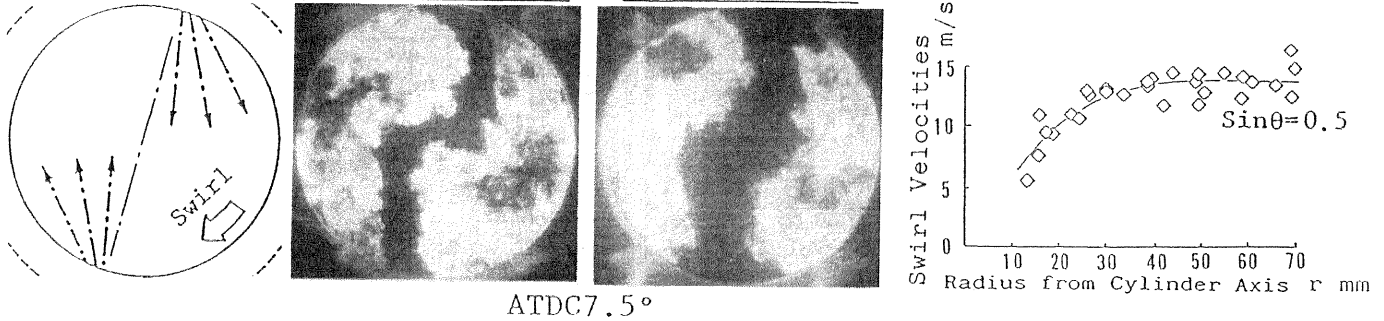
It is considered that such a poor dispersion by air swirl should be one of the reasons of lower heat release of the bunker fuel sprays seen in Fig.6. For that reason, the bunker fuel oil would need higher swirl intensity for the optimum combustion than the marine diesel oil as seen in Fig.5.

CHARACTERISTICS OF EVAPORATION, DISPERSION AND COMBUSTION OF FUEL SPRAY IN THE SINGLE COMPRESSION MACHINE

Combustion Characteristics of Marine Diesel Oil and Bunker Fuel Oil

To clarify the reason of less dispersion in case of the bunker fuel sprays, a single spray has been observed in detail in the single compression

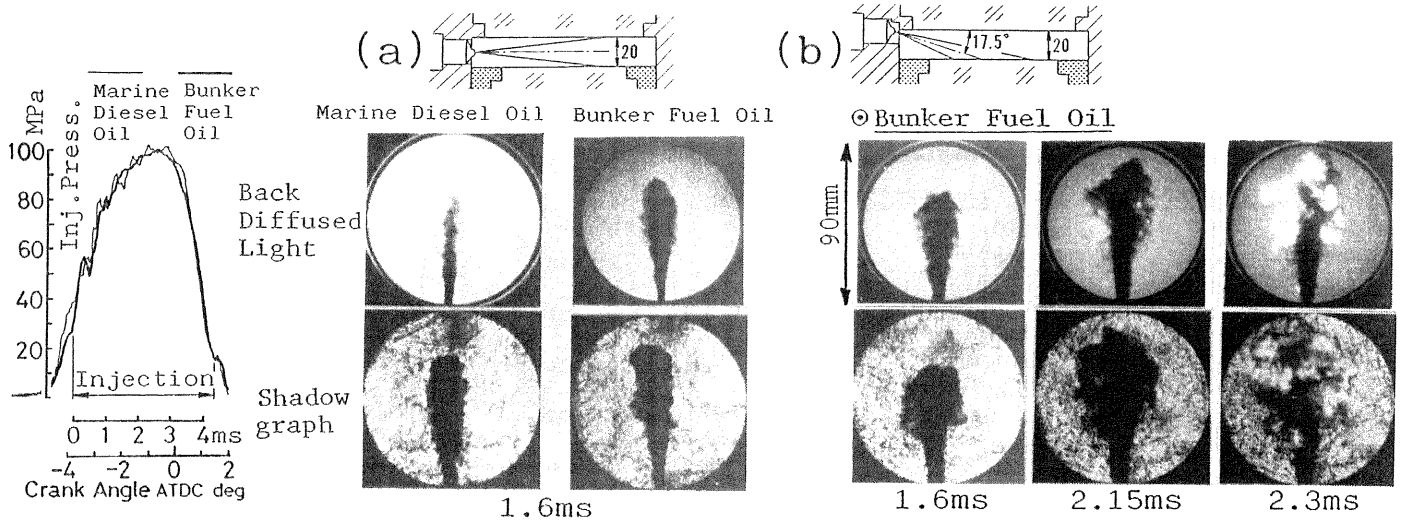
⊙ Marine Diesel Oil ⊙ Bunker Fuel Oil



ATDC7.5°

Fig.7 Visualized flames in the test engine

Inj.Nozzle Hole Dia. 0.3mm
 (Pc=4.9MPa, Tc=470°C)



(c)

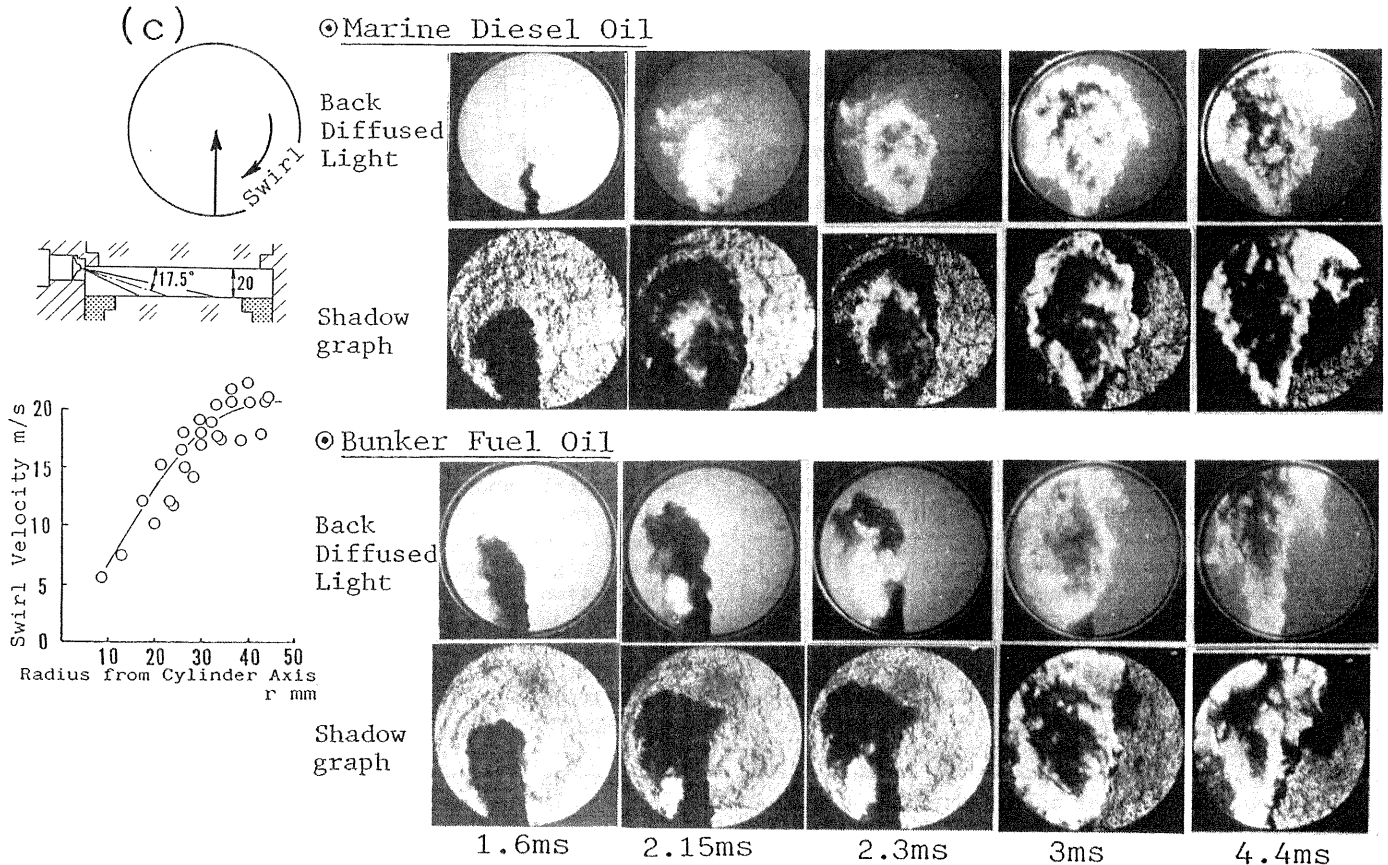


Fig.8 Visualized sprays in the single compression machine

machine under the conditions simulating the test engine. Figure 8 shows the visualized fuel sprays of the marine diesel oil and the bunker fuel oil. Injection nozzle hole diameter and injection pressure have been set at 0.3mm and 100MPa respectively. Injection pressure curves for both the fuels are also shown in the figure. Figure 8(a) is the case that the sprays have been injected in the horizontal direction, and Fig.8(b) is the case injected in the downward direction to impinge onto the bottom of combustion chamber (Pyrex-glass) as shown in the figure. Figure 8(c) shows the sprays injected in the same direction as (b) in the swirling air, whose profile of velocities is also shown in the figure.

Comparing the two fuels before ignition, at 1.6ms from the start of injection in Fig.8(a) and (c), a clear difference can be recognized especially with the back diffused light technique. The liquid part of the bunker fuel spray is much larger than that of the marine diesel oil.

On the other hand, comparing the photos of the bunker fuel spray at 1.6ms in Fig.8(b) with Fig.8(a), while the penetration of the impinging spray is reduced probably because the liquid core clings to the glass surface, some of the liquid part is scattered by impingement. And, ignitions of the bunker fuel spray occur in that scattered part at 2.15ms in Fig.8(b).

In Fig.8(c), in case of the bunker fuel oil, it is observed that the liquid core is bent and some of the liquid part is dispersed downstream by the swirl at 1.6ms. Ignitions occur in that dispersed region, rather near to the injection nozzle at 2.15ms. At 4.4ms, while the bunker fuel spray looks less dispersed by the swirl with the back diffused light technique, a black part that is maybe a burnt gas region is seen in the downstream beside the flame in the shadowgraph of the bunker fuel oil.

According to such results, combination of impingement of spray and swirl is effective means to take off the gaseous part and the small droplets part from the liquid core and supply the spray with fresh air, at the same time to sweep off the burnt gas from the flame area. However, as it is considered that the less dispersion of bunker fuel spray are caused by less evaporation, some means to improve the evaporation rate should be necessary for the bunker fuel spray.

Influences of Air Temperature and Distribution of Distillate Components

As it would have much difficulty to improve the evaporation rate of residual components themselves, it is considered as a realistic means to accelerate the evaporation of distillate components in the residual fuel and promote the combustion of residual components. In this study, influences of air temperature in the combustion chamber and distribution of distillate components on the fuel spray combustion have been investigated with four kinds of sample fuels shown in Table 1 and Fig.4. In the experiments, four fuels have been injected in the single compression machine with all the same viscosity of $20\text{mm}^2/\text{s}$. Air temperature in the combustion chamber has been changed with air pressure keeping the air density constant.

Firstly, ignition delays of four fuels have been examined as shown in Fig.9. According to the figure, sample fuel(1), whose distillation temperature is limited in the range of 320-480°C,

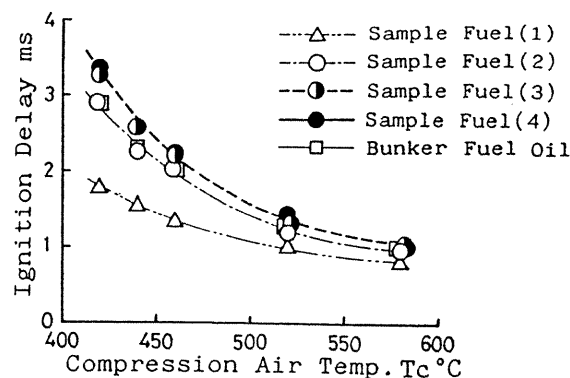


Fig.9 Ignition delays of sample fuels

shows the shortest ignition delay. And, sample fuel(3) and (4), composed of residual components and distillate components of lower temperature than 240°C, show the longest. However, in the range over 550°C of air temperature, ignition delays of all fuels concentrate on about 1ms.

Combustion characteristics of the sample fuels have been examined with curves of the heat release rate and $Q/Gf \cdot Hu$ whose meaning has been explained before. Figure 10(a)~(c) show changes in $Q/Gf \cdot Hu$ curves with air temperature for sample fuel (1)~(3). In this figure, increase of $Q/Gf \cdot Hu$ with raising up of the air temperature is the largest in case of sample fuel(3) and the smallest in case of (1). It is clearer in Fig.11, change in maximum value of $Q/Gf \cdot Hu$ for each fuel with air temperature. Sample fuel (3) shows at last the highest $Q_{max}/Gf \cdot Hu$ in the range of higher air temperature, and sample fuel (1) is the lowest in that range, though it doesn't include any residual components.

According to the results, it is considered that the components of lower distillation temperature have been accelerated to evaporate with higher air temperature and have promoted to burn the residual components. Figure 12 shows change in burning state of sample fuel (4) with air temperature. With increase in air temperature of 40°C, as flame has come up to the part near the injection nozzle, it is considered that the evaporation of the fuel in this part would be improved.

CONCLUSIONS

By the visualizations and diagnoses on the residual fuel sprays mentioned so far, following conclusions have been derived.

- (1) Residual fuel spray is more difficult to be dispersed by air swirl and need higher swirl intensity for the optimum combustion than marine diesel oil.
- (2) Combination of impingement of spray and swirl is effective means to improve the combustion of residual fuel spray to take off the gaseous part and the small droplet part from the liquid core and supply the spray with fresh air.
- (3) Increase of air temperature in the combustion chamber improves the combustion of residual fuel spray by accelerating the evaporation of distillate components.

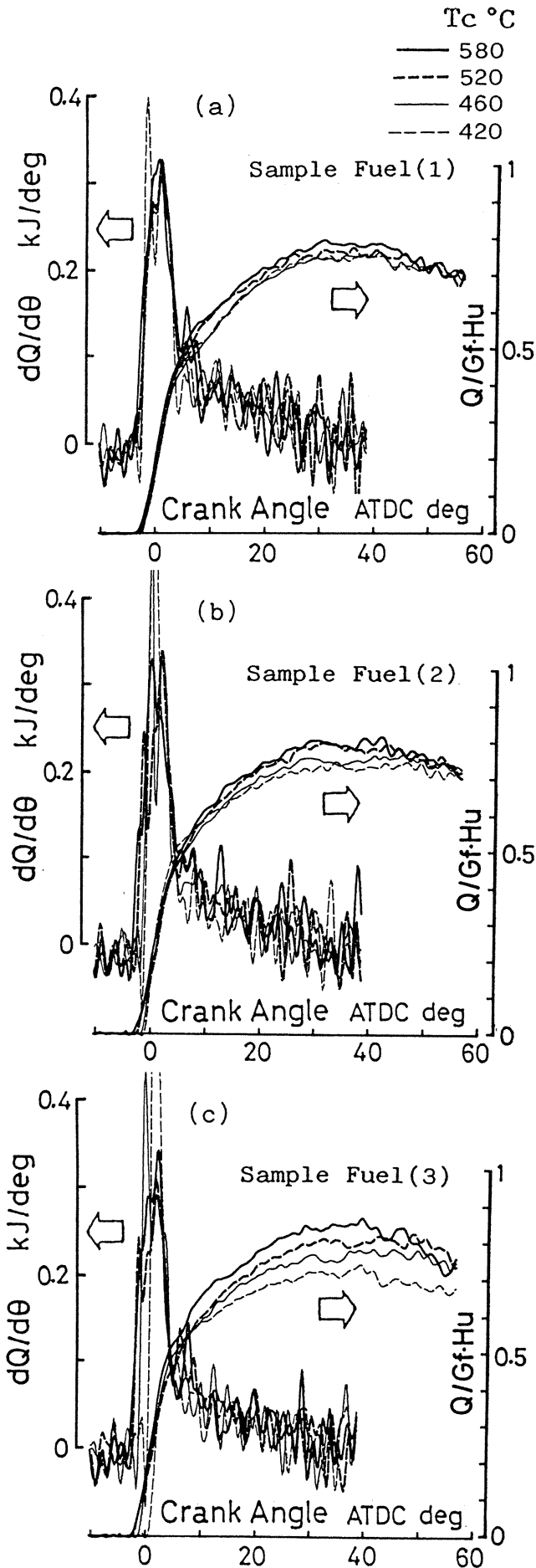


Fig.10 Heat release rates of sample fuels

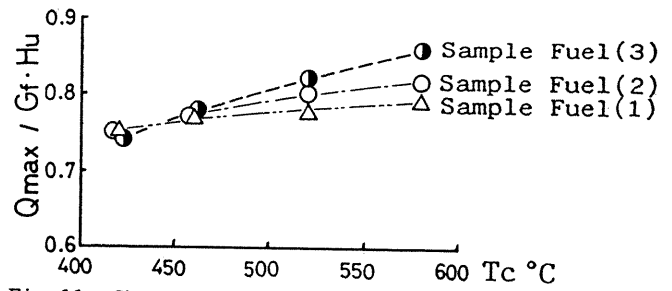


Fig.11 Change in maximum $Q/Gf \cdot Hu$ with air temperature

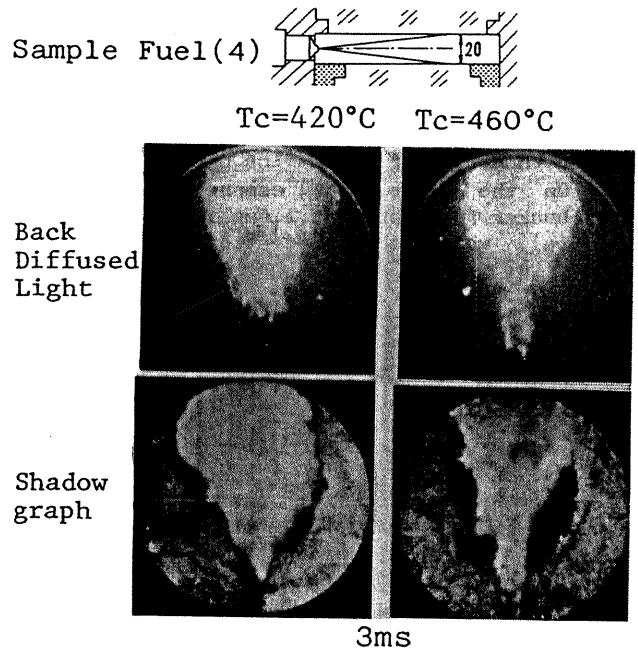


Fig.12 Change in burning state of fuel spray with air temperature

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