

# 14 Spray and Combustion Visualization of Two-Component Normal Paraffin Fuels

Environment Research Department

Rahman M. Montajir, Hisakazu Suzuki, Terunao Kawai, Hajime Ishii, Yuichi Goto, Matsuo Odaka

## 1. Introduction

Two component normal paraffin fuels with widely different component boiling points have potential for flash boiling and reduce particulate emissions from CI engines at relatively retarded injection timing [1]. In the previous study design of such bi-component normal paraffin fuel was attempted considering the mixture-promoting component, igniting component, and the blending ratio. In this study visualization of the physical behavior of spray formation and combustion phenomena of the designed bi-component normal paraffin fuels has been attempted. To understand the physical differences high-speed photography was performed in an optically accessible engine with bottom view piston. In addition thermodynamic analysis of combustion has been performed in an actual DI diesel engine with common rail injection system.

The results indicate that for a constant mixture-promoting component the first visible flame appears very early and the main combustion duration becomes short when the carbon chain length of igniting component molecule increases. On the other hand appearance of first visible flame remains constant but the duration of combustion elongates with much luminous flames for long chain mixture promoting component. For the mixture of pentane and tridecane, a higher ratio of pentane produces much homogeneous charge and combustion duration becomes short with less luminous flames.

## 2. Experimental System and Method

In-cylinder visualization of spray and combustion with the designed fuels was performed in an AVL bottom-view engine. The visualization experiments included laser-illuminated photography of fuel injection phase and combustion phase to investigate the physical differences. Photography was performed with a high-speed video camera operated at a speed of 10,000 frames per second and laser illumination for the fuel injection visualization was supplied by an Ar-ion laser capable of producing 4 watts of power at 488 nm wavelengths. Thermodynamic analysis of combustion was performed in a Hino DI diesel engine with common rail injection system.

The schematic of the photographic engine is shown in Fig. 1. Extended cylinder and piston were mounted on the base cylinder and piston in order to make the engine optically

accessible. The extender piston is hollow type and has a quartz window at the upper side. The specifications of engines for photographic and thermodynamic analysis are shown in Table 1. The test condition included injection timing of 10° BTDC, injection pressure of 20 MPa, engine speed of 700 rpm and load of 40% including engine friction. The water temperature was kept constant at 60°C in all tests.

A common electrical signal was used to operate both the camera and the ECU of the injection system. A function generator was used to control the injection duration and rate. Therefore it was possible to inject a same quantity of fuel in a same duration. Injection was continued for a total time of 5 seconds while the last two cycles with completely matured injection was considered for analysis. At least four tests were performed at each condition.

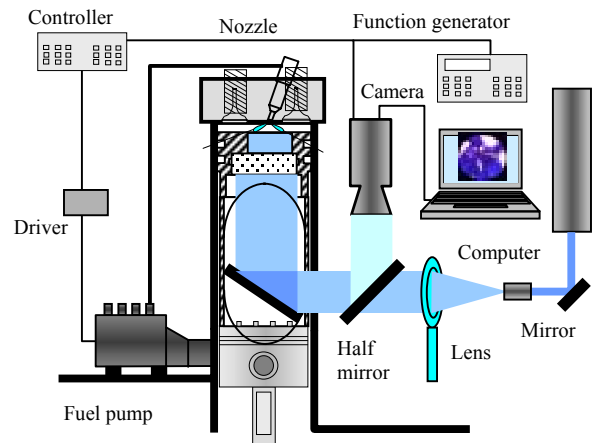


Fig. 1 Schematic of the photographic system

Table. 1 Engine specification

Engine	Hino	AVL
Type	4 V, DI Diesel	2V, DI Diesel
Bore x Stroke	135 x 150 mm	85 x 92 mm
Swept volume	2.15 Liters	0.528 Liters
Compress. ratio	16	16
Nozzle	6 x 0.26 mm	4 x 0.18 mm
Swirl ratio	2.2	1.6

The visible portion of the combustion chamber is represented schematically in Fig. 2. It shows that an equally spaced four-hole nozzle with an injection angle of 150° was used. Sprays issuing from four holes are numbered by 1, 2, 3,

and 4 respectively. The nozzle inclination angle is about  $16^\circ$ . The nozzle centerline is projected from the chamber centerline by 5 mm. As the result the number “3” spray impinges on the quartz window slightly at TDC crank position.

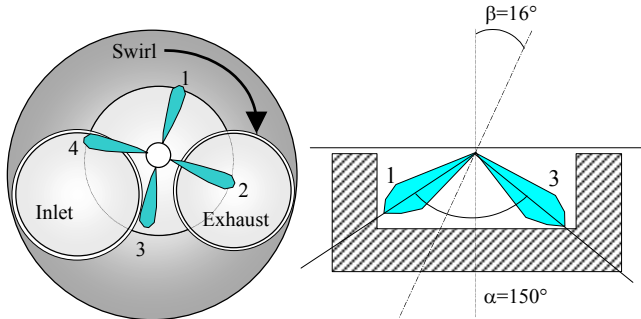


Fig. 2 Schematic of visible portion of chamber

### 3. Fuel Properties

Table 2 shows the properties of the fuels tested [2]. Undecane, Tridecane and Hexadecane were used as the igniting components (IC) with Pentane as the mixture-promoting component (MPC). Similarly, Pentane, Hexane and Heptane were used as the MPCs with Hexadecane as IC. In these cases, the overall density and cetane number were kept constant by varying the mixture ratios. But, for the various mixture ratios between pentane and tridecane the density and cetane number were not constant.

Table. 2 Properties of test fuels

Fuel	Formula	Volume frac.	Density [gm/cc]	CI	Visc. [mm <sup>2</sup> /s]	$\Delta T$	$T_{90}$ [K]
A	$C_5H_{12}+C_{11}H_{24}$	0.437:0.563	0.690	55	0.752	160	430.5
B	$C_5H_{12}+C_{13}H_{28}$	0.500:0.500	0.695	55	0.791	199	455.0
C	$C_5H_{12}+C_{16}H_{34}$	0.555:0.445	0.700	55	0.868	251	487.0
D	$C_6H_{14}+C_{16}H_{34}$	0.592:0.408	0.705	55	0.976	218	486.5
E	$C_7H_{16}+C_{16}H_{34}$	0.725:0.275	0.705	55	0.944	189	468.0
F	$C_5H_{12}+C_{13}H_{28}$	0.250:0.750	0.723	73	1.249	160	482.2
G	$C_5H_{12}+C_{13}H_{28}$	0.750:0.250	0.655	37	0.502	160	420.0

The table also shows that when the carbon number of IC was increased for the same MPC (Fuels A, B, C), the viscosity increased. Similarly, when the carbon number of MPC was increased for the same IC (Fuels C, D, E), the boiling point difference decreased. Blending with tridecane when the ratio of pentane increases (Fuels F, B, G), the density, viscosity and cetane number all decrease. Therefore, it is very difficult to distinguish the in-cylinder effects of density, viscosity and cetane number for fuels F, B and G.

## 4. Results and Discussion

### 4.1 Effect of igniting component (IC)

Figure 3 shows the in-cylinder photographs of spray and combustion for 2-component normal paraffin fuels with different igniting components. The photographs led to the

conclusion that the spray developments are not notably distinguishable for these three fuels. Some difference in the four spray plumes due to inclination of the injector was found. The bottom spray plume (No. 3) does not impinge on the cavity wall while the other plumes narrowly strike the cavity wall. In all cases the sprays evaporate completely at about 1.1 ms after start of injection. But the start of auto-ignition differs from each other. It is said that there is some cool and invisible flame at the early stage of combustion. However the visible flame appears consequently with the formation of cool and invisible flame depending on the mixture quality. Therefore appearance of FVF can be used to compare the auto-ignition among the fuels.

The photographs show that the FVF appears very early for fuels with a very long chain IC. Though the difference between fuel B and C is small but the differences between A and B and between A and C are very clear. FVF appears at 1.7 ms after of injection for fuel A. In this case the combustion duration is very long and visible flame remains till 8.5 ms after start of injection. It is thought that the main combustion may continue little more. Therefore the rate of diffusion combustion is higher in this case. In case of fuel B, FVF appears at 1.4 ms after start of injection and the duration of combustion is relatively shorter than fuel A. FVF appears more early at about 1.3 ms after start of injection in case of fuel C.

The combustion duration is very short in this case in comparison with the other two fuels. Therefore it can be concluded that the amount of premixed combustion increases with increases in the chain length of IC. It is reported that for the same MPC when the chain length of the IC increases the potential for flash boiling increases. For these three fuels the overall density and cetane number are constant due to adjusted blending ratio, but the component cetane number of IC increases with increases in the chain length of IC. Therefore ignition starts shortly after injection for long chain IC.

Usually images of KL factor are used for qualitative visualization of soot. The images having wider luminous region (orange flames) have higher KL factor which represents the higher soot concentration. Though such images

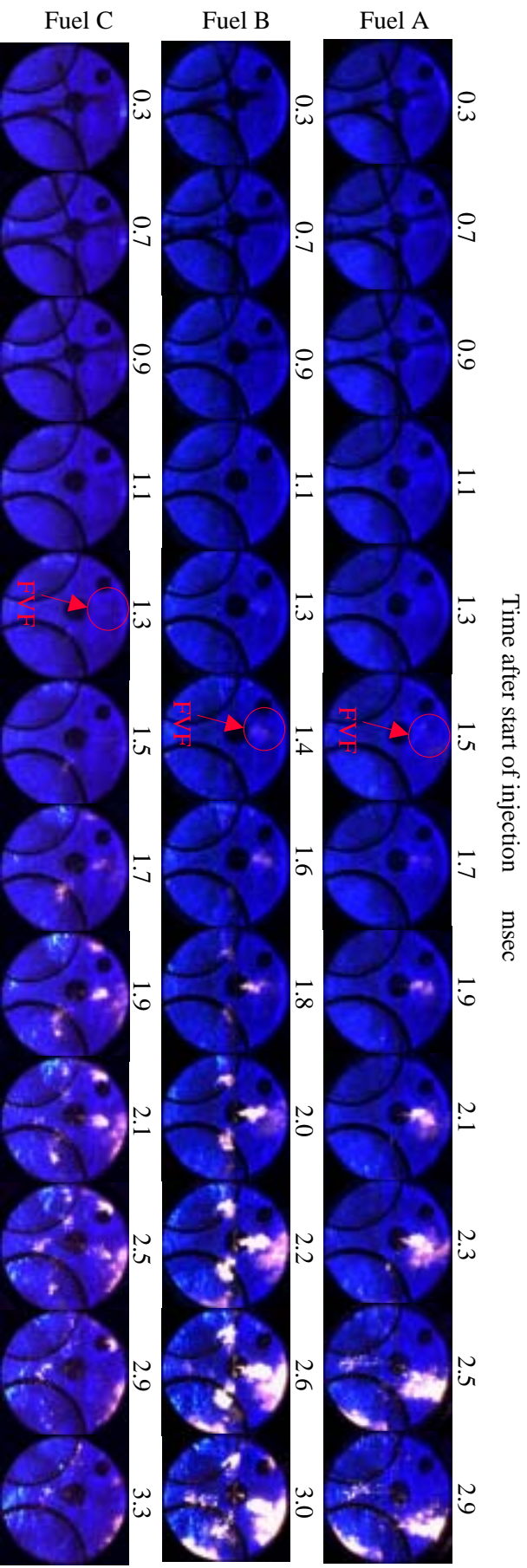


Fig. 3 Effect of igniting component on spray and combustion

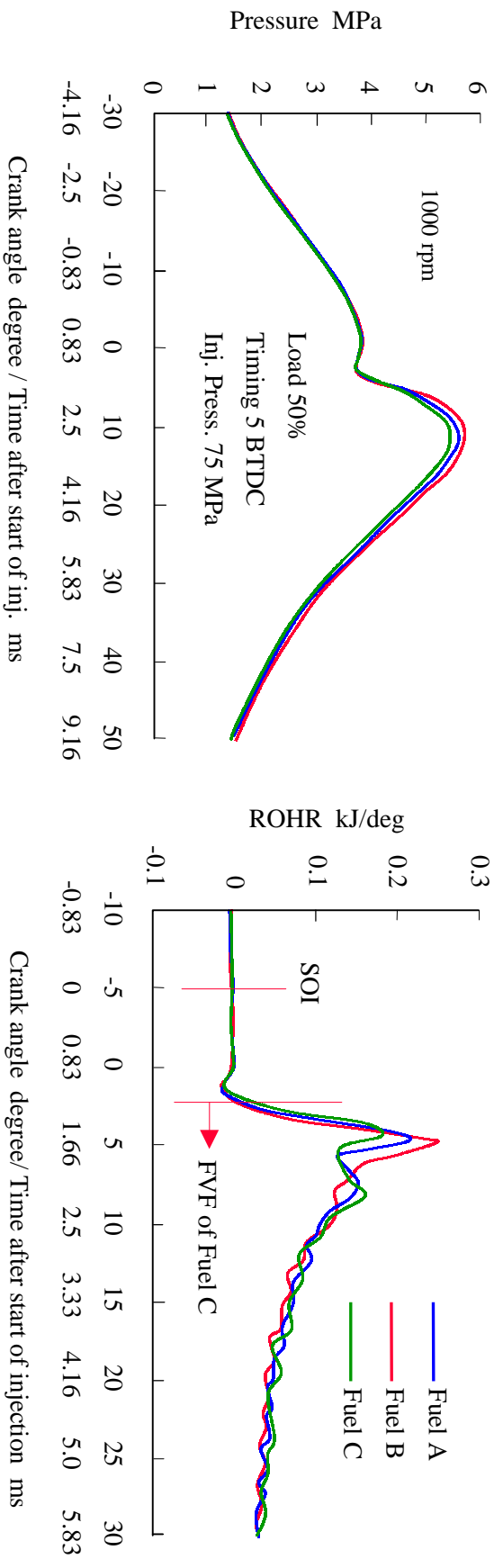


Fig. 4 Effect of igniting component on combustion

are not presented in this study, it is possible to have an overall idea about the soot concentration from Fig. 3. The figure shows that the area of the luminous flames (orange flames due to soot) is relatively higher in case of fuel A and B than fuel C. Therefore from the photograph it can be concluded that fuel C forms much homogeneous charge and emits less soot, while fuel A produces much rich mixtures those are responsible for emitting much soot [1].

The combustion pressure and heat release rate diagram of the above fuels are shown in Fig. 4. These graphs are not the exact thermodynamic representation of the photographs shown in Fig. 3. But the relationship between physical and thermodynamic behavior can be understood. The heat release rates show that the ignition delay becomes shorter as the chain length of IC increases. For the same MPC both the flash boiling and component cetane number of IC increase with the increases in the chain length of IC even at a same equivalent cetane number. The spike of the premixed combustion gradually increases with the decreases in the chain length of IC.

#### 4.2 Effect of Mixture-promoting Component

Figure 5 shows the effect of mixture promoting component on spray development and combustion phenomena. The spray developments are not notably distinguishable. The appearance of FVF as well as the start of ignition remains almost the same even the chain length of mixture promoting component changes. The reasons can be explained by the combustion pressure and heat release rate diagrams.

The area of the luminous flame increases and the duration of combustion prolongs with the increases in the chain length of MPC. In case of fuel C visible flame disappears at 4.9 ms after start of injection while it remains till 6.5 ms in case of fuel E. It is thought that the amount of rich mixture increases with increases in the chain length of MPC, which prolongs the combustion, and the area of luminous flame increases.

The combustion pressure and heat release rate graphs for different MPCs are shown in Fig. 6. The heat release rate graph shows that there is slight variation in the ignition delays when the carbon number of MPC changes. It is reported that fuels with same igniting component when the chain length of MPC increases the critical pressure decreases. Therefore inclusion of short chain normal paraffin as MPC tends to increase the height of the two-phase region and flash boiling occurs more violently [1]. Ignition is delayed due to decreases in the potential for flash boiling with increases in carbon number of MPC. However, the component cetane number of MPC increases which shortens the ignition delay. As a result, start of ignition remains almost the same [1].

The spike of the premixed combustion increases with decreases in the carbon number of MPC. Both the density and the amount of MPC increase with the increases in its carbon

number, the total amount of premixed charge decreases which reduces the amount of premixed combustion.

#### 4.3 Effect of mixture ratio

Figure 7 shows the spray development and combustion phenomena for different mixture ratio between pentane and tridecane. With higher fraction of pentane in the mixture the spray disperses widely and fuel evaporation rate increases while with lower fraction of pentane the spray penetrates longer. But the first visible flame appears very late with higher fraction of pentane. FVF appears respectively at 1.2 ms and 1.6 ms after start of injection when the mixture ratio between pentane and tridecane is 1:3 and 3:1. It is true that the overall cetane number decreases with increases in the fraction of low cetane number pentane. As the result start of ignition is delayed. During this long delay period much homogenous charge is prepared. The photographs also show that the combustion duration and the area of the luminous flame decrease with increases in the fraction of pentane.

The combustion pressure and heat release rate graphs for different mixture ratios are shown in Fig. 8. It shows that the fuel having 25% pentane ignites early due to its higher cetane number and the fuel having 75% pentane ignites at the last due to lowest cetane. As the ratio of n-pentane increases the total amount of premixed charge increases but the number of ignition sources decreases. A very high number of rich ignition sources cause higher luminous flame and a very small number of ignition sources cause incomplete combustion. Therefore, an optimum distribution of IC and MPC is necessary.

### 5. Conclusions

Two component fuels show very similar spray development pattern. But when the fraction of pentane in the mixture with tridecane increases the spray penetration decreases. For a same MPC the first visible flame appears very early and the main combustion duration becomes short when the chain length of IC increases. Oppositely appearance of FVF remains constant but the duration of combustion elongates with much luminous flames when the chain length of MPC increases for a same IC. For the mixture of pentane and tridecane, a higher ratio of pentane produces much homogeneous charge and combustion duration becomes short with less luminous flames.

### 6. References

1. Thermo physical Properties of Hydrocarbon Mixtures Database, National Institute of Standards and Technology.
2. R. M. Montajir et al., "Effect of Boiling Point Difference of Two-Component N-Paraffin Fuels on Combustion and Emission in CI Engines", SAE Paper No. 2003-01-0757.

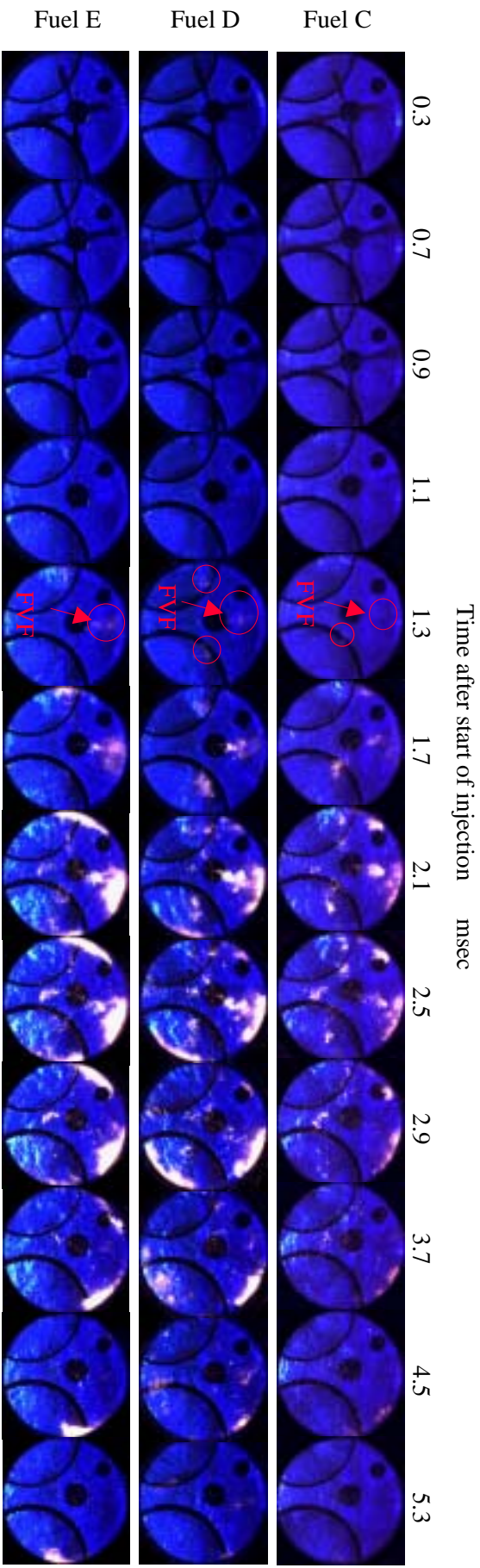


Fig. 5 Effect of mixture promoting component on spray and combustion

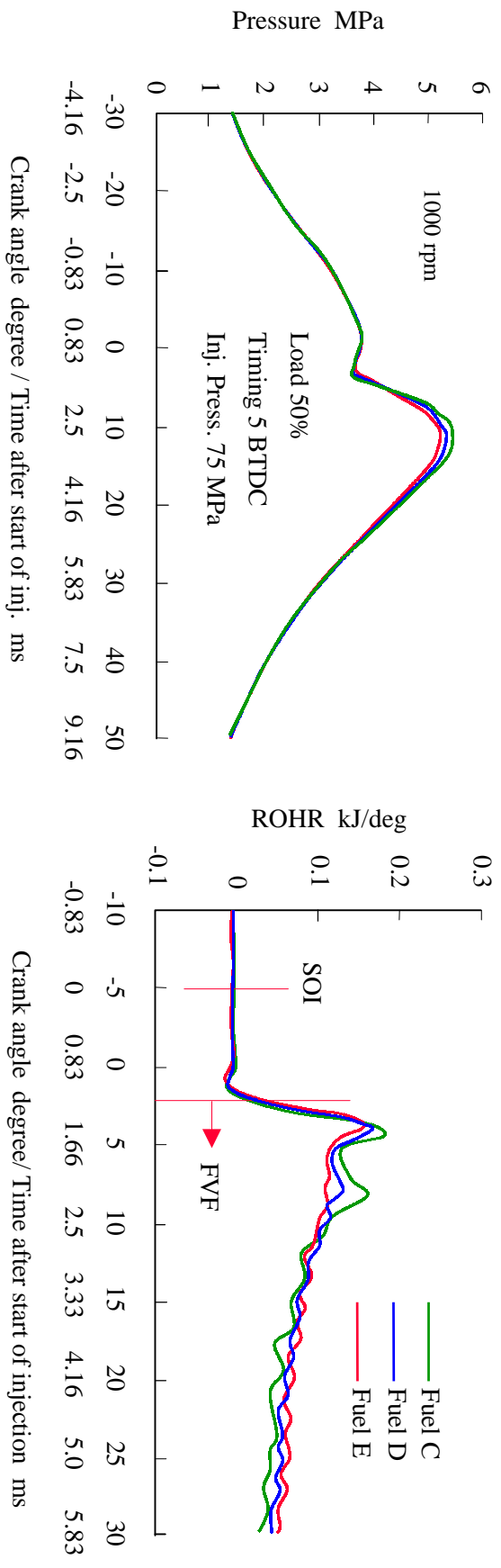


Fig. 6 Effect of mixture promoting component on combustion

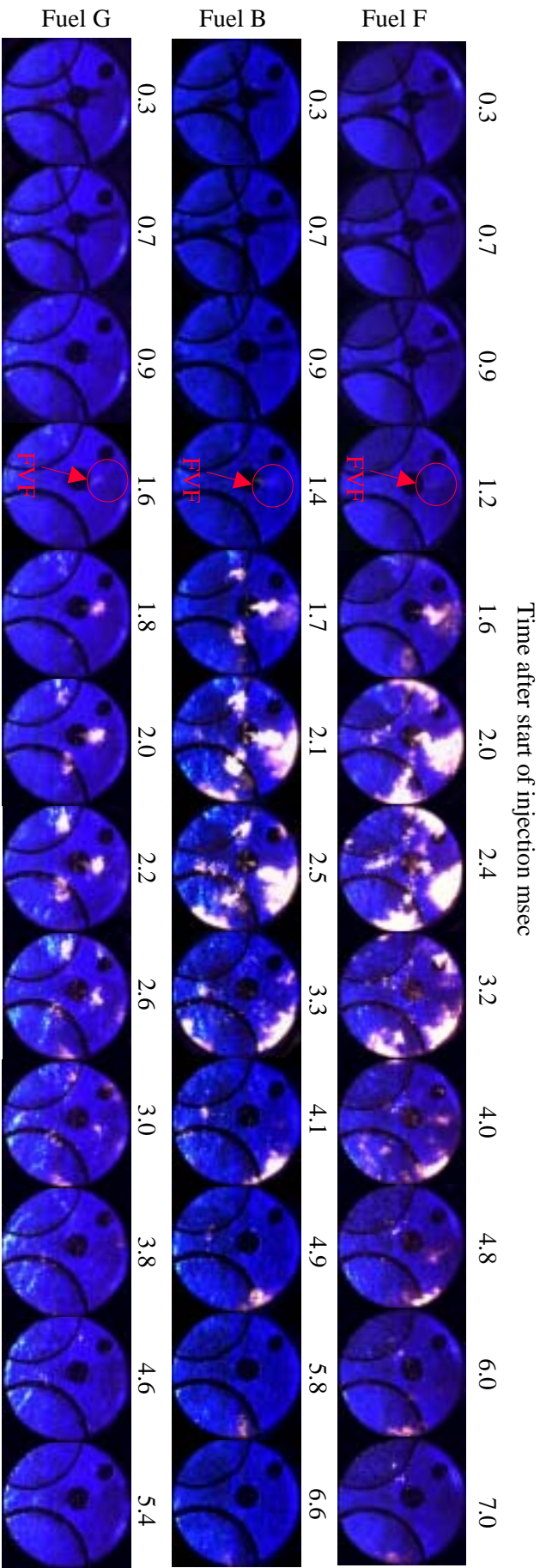


Fig. 7 Effect of mixture ratio on spray and combustion

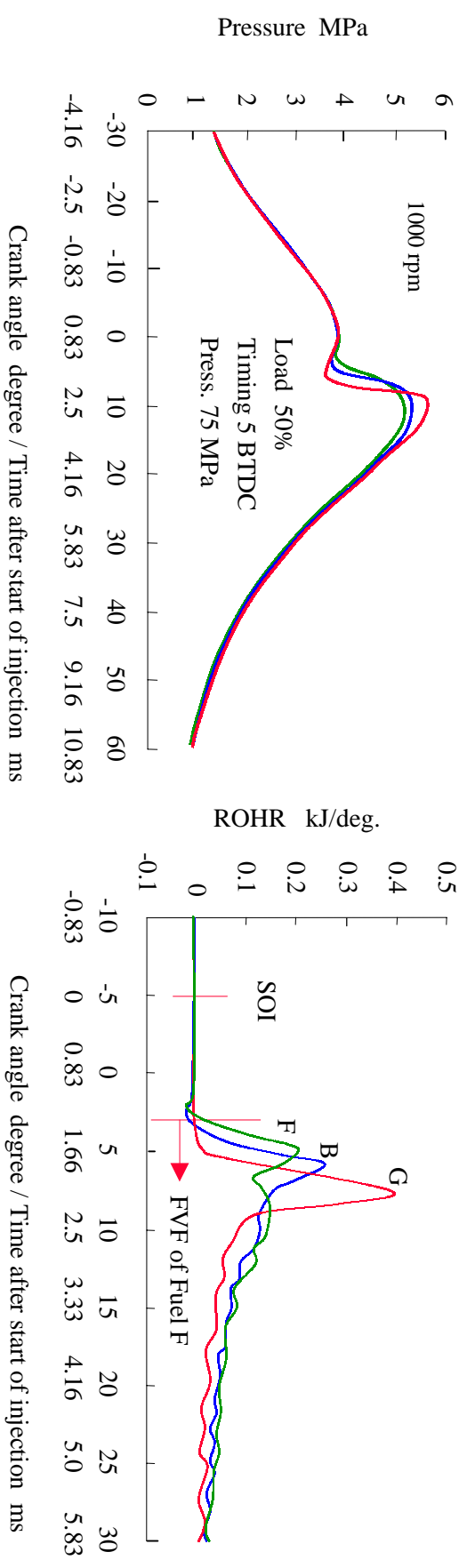


Fig. 8 Effect of mixture ratio on combustion