Combustion and PM Emission Behavior of 2-Component n-Paraffin Fuels under Flash Boiling

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1. Introduction

Preparation of homogeneous charge in HCCI engine necessitates either port injection or direct injection near bottom dead center [1,2]. But the controlling of ignition timing to maximize the efficiency and extend the operating load range is difficult. Early injection results in uniform mixture; but requires additional control strategies to maintain the ignition timing [2]. Late injection causes ignition of fuels prior to the establishment of a uniform mixture. Flash boiling represents a possible mechanism for more rapidly achieving a uniform mixture at usual injection timings. Mixtures of two fuels with widely different boiling points have potential for flash boiling and reduce particulate emissions from CI engines at relatively retarded injection timing [3].

The motivation of this research is to develop a fuel to achieve premixed homogeneous charge with appropriately late injection timing for simultaneously reduction of PM and NOx. As a part of this blending of a low boiling point n-alkane (MPC) with a high boiling point n-alkane (IC) was implemented. The low boiling point fuel accelerates mixing and evaporation through the flash-boiling phenomena. The high boiling point fuel mixed with the low boiling point fuel quickly disperses throughout the combustion chamber and ignites easily. To obtain the optimum potential for flash boiling, both the MPC and IC and their mixture ratios were varied.

The combustion and emissions tests performed in a DI diesel engine with different fuel combinations. The results indicate that a mixture ratio of about 3:1 by volume of n-pentane and n-tridecane showed an optimum potential for flash boiling and yielded the lowest PM emission at all injection timings and load ranges. Therefore proposed as a low emission fuel in this study.

2. Experimental System and Method

The schematic of the experimental system is shown in Fig. 1. The in-cylinder combustion analysis and emissions measurements were conducted in a Hino single-cylinder engine. The engine used is a medium sized direct injection diesel engine with a high-pressure common-rail injection system. The engine specifications are shown in Table 1. The standard test condition included injection timing of 5° BTDC, injection pressure of 75 MPa and load of 50%. To investigate the effect of flash boiling the operating load, injection timing and injection pressure were varied. The details of the test conditions are shown in Table 2.

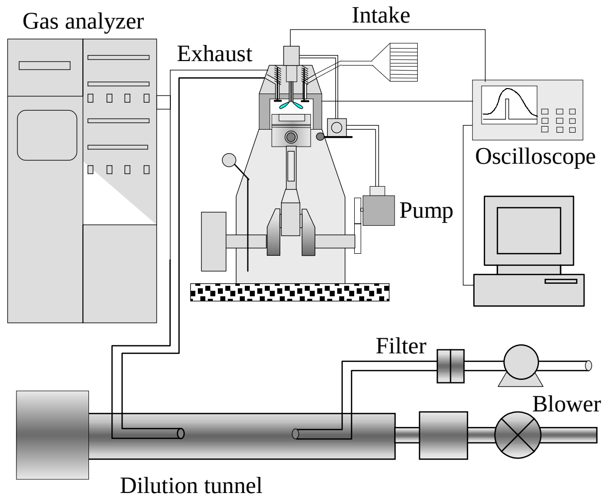

Fig. 1 Schematic of the experimental system

Table 1: Engine Specifications

Engine Type	Single cylinder 4V DI Diesel
Bore × Stroke	135 × 150 mm
Displacement	2.15 L
Comp. ratio	16
Swirl ratio	2.2
Injection system	Common rail

Table 2: Test conditions

Injection pressure	35, 50, 75 MPa
Speed	1000 RPM
Load	25%, 50%, 75% of full load
Injection timing	10, 8, 5, 3 °BTDC
Water Temperature	80°C

Simultaneous measurements of NO_x, CO, CO_2, HC were performed by an exhaust gas analyzer while the PM was measured gravimetrically in a full dilution tunnel with the engine operated at a steady state condition allowing a sufficient warm-up time. However, only the PM emission behavior was presented in this study. The in-cylinder combustion pressure was measured by a piezoelectric transducer mounted on the cylinder head.

3. Fuel Properties

Table 3 shows the properties of the fuels tested. Normal alkanes; Undecane, Tridecane and Hexadecane were used as the igniting components (IC) with Pentane as the mixture-promoting component (MPC). Similarly, Pentane, Hexane and Nonane 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. Additionally, for the various mixture ratios between pentane and tridecane the density and cetane number were not constant.

The table also shows that when the carbon number of IC was increased for the same MPC (Fuels A, B and C), the viscosity increased while the H/C remained almost the same. Similarly, when the carbon number of MPC was increased for the same IC (Fuels C, D and E), the boiling point difference decreased and the H/C ratio was changed very. Blending with tridecane when the ratio of pentane increases (Fuels F, B and G), the density, viscosity and cetane number all decrease but the H/C ratio increases. Therefore, it is very difficult to distinguish the respective 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 2 shows the P-T diagram for different ICs. The two-component fuels have two-phase regions separating the liquid phase on the left from the gas phase on the right. Within the two-phase region, liquid and vapor stages are in thermodynamic equilibrium with the proportions of each component in each phase. The horizontal line in this figure indicates the cylinder pressure at the start of injection for engine tests in this study. It shows that for injected fuel being heated and evaporated, the quasi-equilibrium pathway passes through the two-phase region.

Flash boiling occurs when the ambient pressure is lower than the saturated pressure at a particular temperature [5]. The potential for flash boiling increases with the increases in the pressure difference with sufficient heat addition rate. Therefore, it can be concluded that the potential for flash boiling increases with increases in boiling point difference even with the same MPC.

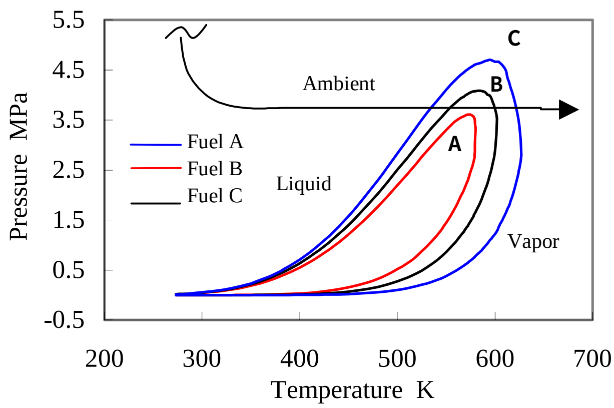

Fig. 2 P-T Diagram for different ICs

Table: Properties of test fuels

Fuel	Formula	Mixture ratio	Density [g/cc]	CI	K Visc. [mm^2/s]	T_{50} [K]	T_{90} [K]	ΔT_b [K]	LHV [kJ/g]	H/C
A	C_5H_{12}+$C_{11}H_{24}$	0.437:0.563	0.690	55	0.752	370.0	430.5	160	44.94	2.267
B	C_5H_{12}+$C_{13}H_{28}$	0.500:0.500	0.695	55	0.791	347.7	455.0	199	45.02	2.264
C	C_5H_{12}+$C_{16}H_{34}$	0.555:0.445	0.700	55	0.868	335.5	487.0	251	45.09	2.261
D	C_6H_{14}+$C_{16}H_{34}$	0.592:0.408	0.705	55	0.9768	369.7	486.5	218	44.81	2.239
E	C_7H_{16}+$C_{16}H_{34}$	0.725:0.275	0.705	55	0.944	388.0	468.0	189	44.54	2.237
F	C_5H_{12}+$C_{13}H_{28}$	0.250:0.750	0723	73	1.249	451.0	482.2	160	44.81	2.206
G	C_5H_{12}+$C_{13}H_{28}$	0.750:0.250	0.655	37	0.502	322.2	420.0	160	45.23	2.319

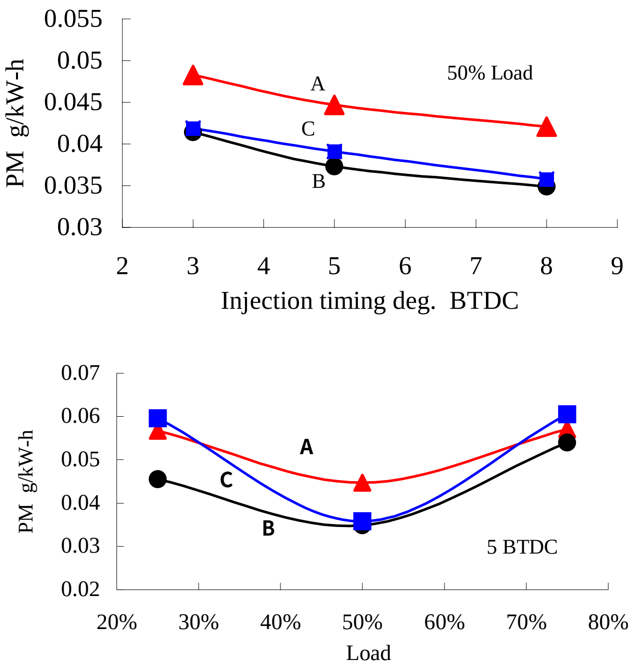

Fig. 3 Exhaust emission for different ICs

The exhaust emission behavior for different ICs is shown in Fig. 3. The graph shows that Fuel B emits the least PM at all loads and injection timings though the difference between Fuel B and C is small at 50% load. Increases or decreases in the potential for flash boiling result in higher PM emission. There is no significant difference in NO_x emissions among these fuels even when the injection timing and load are changed.

The combustion pressure, heat release rate and needle lift diagram of the above fuels are shown in Fig. 4. The needle lift graph supports that the injection mass and the operating load were well adjusted. The heat release rates show that the ignition delay becomes shorter as the potential for flash boiling increases. However, the combined effect of flash boiling and component cetane number was thought to be responsible for this early start of ignition. 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 potential for flash boiling.

As shown in the figure in every cases ignition starts before all the fuel is injected and sufficient premixed charge is prepared. It is assumed that all the MPC evaporates immediately after injection due to flash boiling whatever the amount is. However, with higher potential for flash boiling, as the ignition delay becomes very short the amount of premixed charge due to IC decreases and the amount of inhomogeneous and locally rich mixture increases. The diffusion combustion of the inhomogeneous and locally rich mixture causes higher PM emission. With low potential for flash boiling, the ignition delay is very long and produces much premixed charges. In addition, the density and the size of the kernels of IC increase with increases in chain length. Even the kernels of high density IC act as ignition sources but themselves produce rich zones those are responsible for higher PM emission.

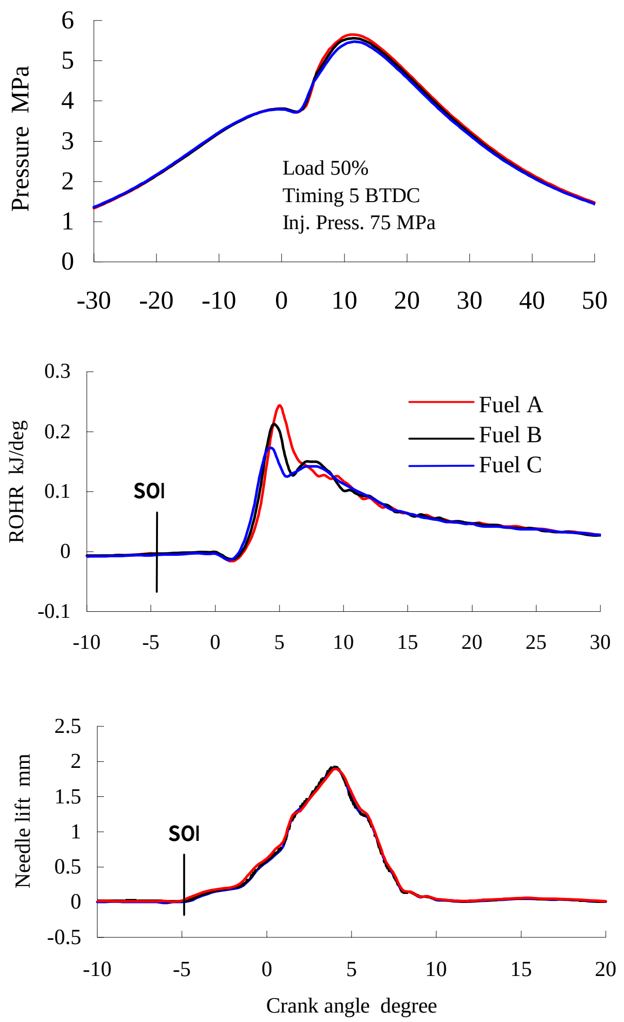

Fig. 4 Combustion behavior for different ICs

A very light IC with low cetane number ignites very lately and during this long delay period much fuel deposits on the chamber and cylinder wall and forms soot particles. On the other hand a dense IC with high cetane number ignites very quickly therefore, the amount of rich mixture including the kernels of IC is high which is responsible for higher PM emission. Normal tridecane has optimum density and cetane number and producing balanced mixture distribution between MPC and IC.

Figure 5 shows the distillation curves for the above fuels. The two-component fuels have step-like shapes due to the large difference in boiling points between MPC and IC. It shows that the low temperature evaporation is almost entirely from the MPC. In fact, at the 70% evaporation point only 1% of the vapor is IC [3]. Beyond the 70% distillation point the evaporation temperature increases with the increases in the boiling point difference between components.

On the other hand T_{50} decreases but T_{90} increases as the carbon number of IC increases. Therefore, the PM emission behavior is correlated with T_{50} and T_{90} depending on the relative amount of MPC and IC. For the same MPC, PM emission depends on T_{50} with light IC while it depends on T_{90} with dense IC.

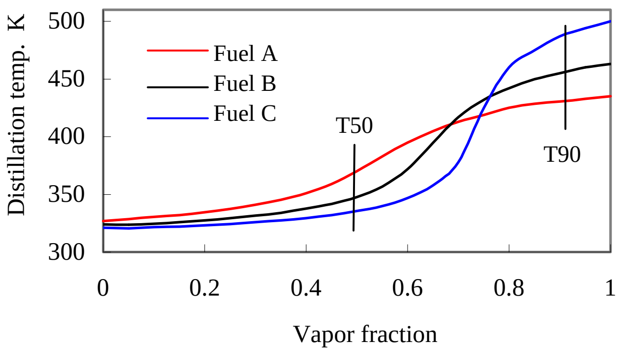

Fig.5 Distillation curves for different ICs

4.2 Effect of Mixture-promoting Component

Figure 6 shows the P-T diagram for different MPCs. The light n-paraffin shows the higher critical pressure so that the inclusion of short chain normal paraffin as MPC tends to increase the height of the two-phase region and flash boiling occurs more violently.

The emission behavior for different MPCs is shown in Fig. 7. It shows that PM emission increases by about 10 to 20% with increases in the carbon number of MPC from 5 to 7 while the NO_x emission shows no significant differences but maintains the trade off relation as expected. The PM emission increases with the retardation of the injection timing and increases in the operating load.

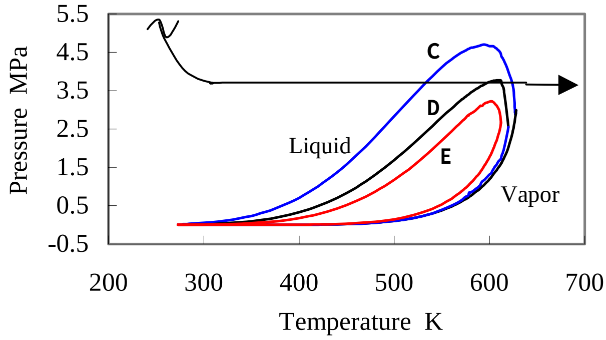

Fig. 6 P-T Diagram for different MPCs

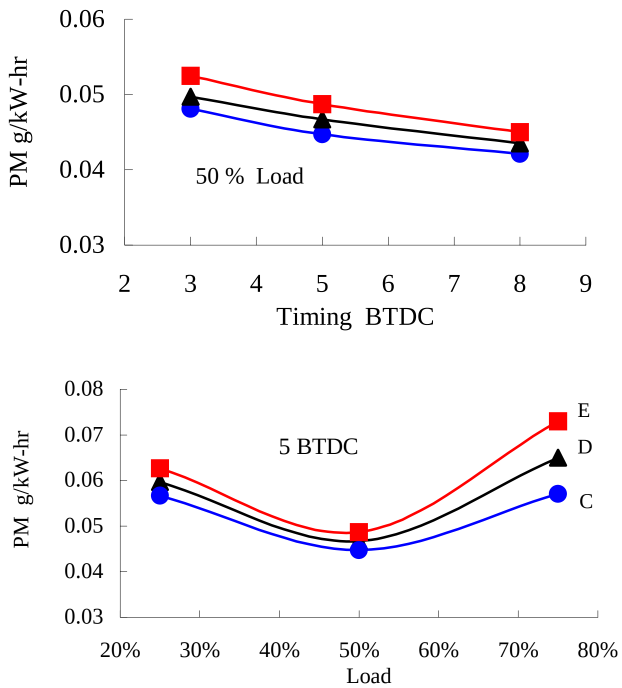

Fig. 7 Emission behavior for different MPC

The combustion pressure and heat release rate graphs for different MPCs are shown in Fig. 8. The heat release rate graph shows that there is very slight variation in the ignition delays when the carbon number of MPC changes. 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, the start of ignition remains almost the same. 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 it’s carbon number, the total amount of premixed charge decreases which reduces the amount of premixed combustion.

Figure 9 shows the distillation curves for different MPCs. It shows that until 70% distillation point the evaporation temperature increases with the increases in the carbon number of MPC and becomes insignificant after this point. On the other hand T_{50} increases but T_{90} remains almost the same as the carbon number of MPC increases. Therefore, for the same IC the PM emission is correlated with the T_{50} rather than to T_{90}.

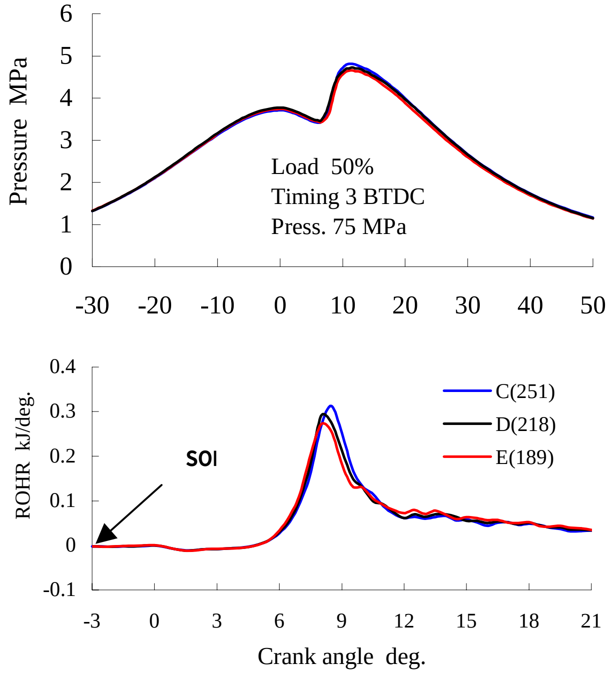

Fig. 8 Combustion behavior for different MPC

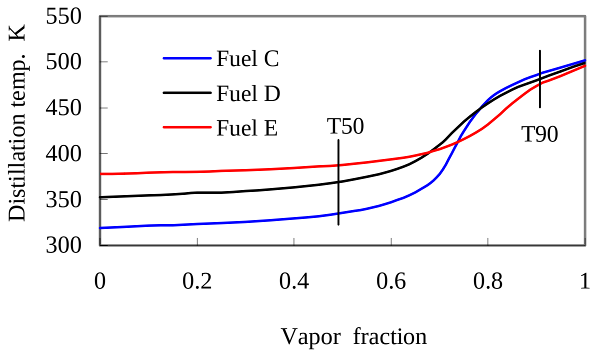

Fig. 9 Distillation curves for different MPC

4.3 Effect of mixture ratio

The P-T diagram for different mixture ratios of pentane and tridecane is shown in Fig. 10. It shows that a smaller fraction of n-pentane in the mixture has a lower critical pressure and a mixture ratio of about 3:1 has the highest critical pressure, therefore exhibiting the highest potential for flash boiling with respect to the low ambient pressure in this study.

The emission characteristics for the above mixture ratios are shown in Fig. 11. It shows that the PM emission decreases with increases in the proportion of n-pentane. A mixture ratio of 3:1 shows the minimum PM emission. The steady operation of engine beyond this mixture ratio was very difficult due to evaporation of the light fuels in the fuel lines even with a proper cooling system.

The combustion pressure and heat release rate graphs for different mixture ratios are shown in Fig. 12. The heat release rate graph 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

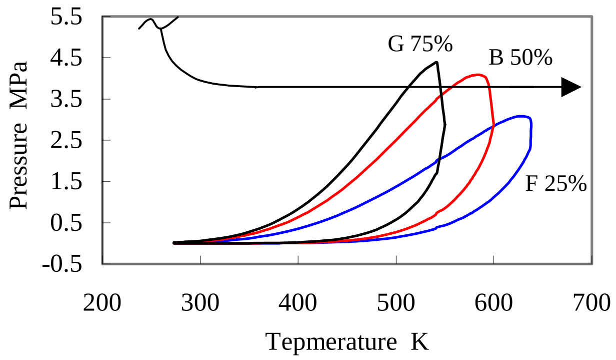

Fig. 10 P-T Diagram for different mixture ratios

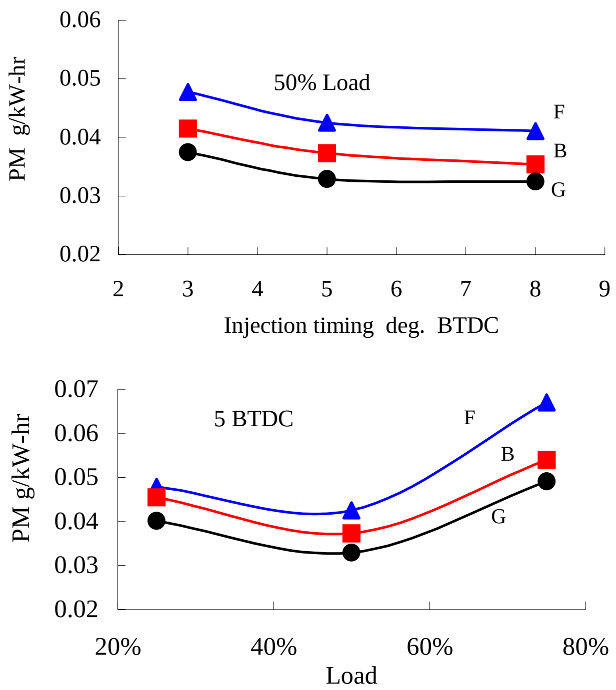

Fig. 11 Emission behavior for different mixture ratios

number. However, it is very difficult to distinguish the effect of flash boiling due to the variation in cetane number. The mixture having 25% pentane shows higher diffusion combustion while the mixture having 75% pentane shows higher premixed combustion those correspond to the respective PM emissions.

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 PM emission and a very small number of ignition sources cause incomplete combustion. Therefore, an optimum distribution of IC and MPC is very necessary.

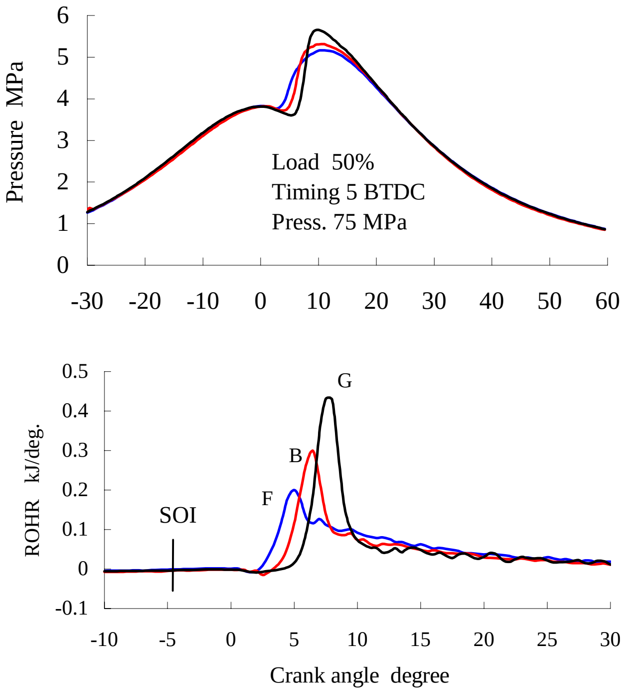

Fig. 12 Combustion behavior for different mixture ratios

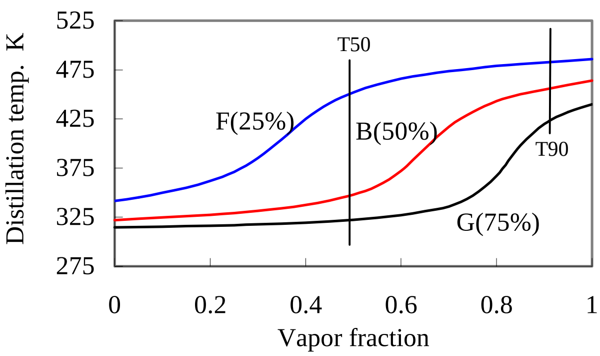

Fig. 13 Distillation curves for different mixture ratios

Figure 13 shows the distillation curves for different ratios of pentane. It shows that the overall distillation temperature decreases with increases in the proportion of pentane. On the other hand both T_{50} and T_{90} decrease as the ratio of n-pentane increases. Therefore, for the same MPC and IC, PM emission behavior is correlated with both T_{90} and T_{50} even with different mixture ratios.

5. Conclusions

Both too low and high potentials for flash boiling are not beneficial. A mixture ratio of about 3:1 by volume of n-pentane and n-tridecane showed an advantageous level of flash boiling and yielded the lowest emission at all injection timings and load ranges. For the same IC, the PM emission is well correlated with the T_{50} while for the same MPC, PM emission depends on T_{50} with light IC and depends on T_{90} with dense IC. For the same MPC and IC, PM emission behavior is correlated with both T_{90} and T_{50} irrespective to the mixture ratio.

References

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