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FUEL FORMULATION FOR LOW EMISSIONS IN DICI ENGINES

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ABSTRACT

Design of a fuel for premixed charge compression ignition combustion in a direct injection engine has been attempted considering two component normal paraffin fuels. The mixture promoting component, igniting component, and the blending ratio were varied to find out the best combination. The mixture formation behavior was investigated photographically in a constant volume combustion chamber at elevated temperature and pressure. Combustion and exhaust emission behavior were tested in an actual direct injection diesel engine with high-pressure common rail injection system. It was found that inclusion of a short chain n-paraffin as mixture-promoting component and moderately dense n-paraffin as igniting component yields the optimum potential for flash boiling and sufficient fuel evaporation rate. Both the very high and very low potentials for flash boiling are not beneficial for emission reduction. A mixture ratio of about 3:1 between pentane and tridecane was found to be optimum both from the point of view of mixture formation and emission and therefore proposed as a new fuel.

Keywords: Premixed Charge, Compression Ignition, Direct Injection, Paraffin Fuels, Flash Boiling.

1. INTRODUCTION

In diesel engines the long evaporation and mixing time required to achieve a homogeneous charge necessitates either port injection or direct injection near bottom dead center of the compression stroke [1,2]. Flash boiling represents a possible mechanism for more rapidly achieving a uniform mixture at usual injection timings and is possible to get PCCI (premixed charge compression ignition) combustion.

The difficulty in effectively applying PCCI is controlling the ignition timing to maximize the efficiency and extend the operating load range [1]. Early injection can result in the desired uniform mixture; but requires additional control strategies to maintain the ignition timing [2]. Late injection is of course standard diesel operation; the fuel ignites prior to the establishment of a uniform mixture. Flash boiling phenomenon through the mixture of two fuels with widely different boiling points has potential for reducing particulate emissions from CI engines at relatively retarded injection timings [3]. Thus, the motivation of this research is to develop a fuel and it's direct-injection concept to achieve premixed charge in a CI engine with appropriately late injection timing.

Blending of a low boiling point n-alkane with a high boiling point n-alkane at a predetermined ratio was implemented. The low boiling point fuel accelerates the 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. Because of the high cetane number, the kernels of high boiling point fuel ignite easily and act as ignition sources. Utilizing this phenomenon, preparation of approximately lean and homogeneous charge and it's combustion simultaneously from several points is possible, which has potential for reducing PM and NOx emissions [3].

This investigation focuses on the influence of boiling point differences as well as the flash boiling of two-component normal paraffin fuels on the mixture formation, combustion and emissions. The mixture formation behavior was investigated photographically in a CVCC (constant volume combustion chamber) while the combustion and exhaust emission behavior was investigated in an actual DI diesel engine. The results indicated that cases both with very high and very low potentials for flash boiling emit higher PM. A mixture ratio of about 3:1 by volume of n-pentane and n-tridecane showed an advantageous level of potential for flash boiling and yielded the lowest PM emission at all injection timings and load ranges.

2. EXPERIMENTAL SYSTEM AND METHOD

A schematic of the photographic system is shown in Figure 1. Fuel was injected into a CVCC under high pressure and high temperature from a high-pressure common rail injection system. Three electric heaters each of 1 kW capacity were inserted into the chamber from three different sides. Nitrogen gas was introduced into the chamber under high pressure to suppress the combustion. Argon-Ion laser was used as continuous light source while the photographs were taken by a high-speed video camera. A common electrical signal was used to drive both the ECU of injection system and the camera unit. When the required chamber pressure and temperature were achieved, fuel, at an injection pressure of 40 MPa was injected into the chamber via a single hole nozzle of hole diameter 0.18 mm. The time scale of each frame was estimated from the recording frame speed.

Schematic of the combustion and emission analysis system is shown in Figure 2. The experiments were conducted in a Hino single-cylinder engine. The engine used is a 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, power of 6.97 kW (50% of full load) and engine speed of 1000 rpm with no pilot injection and no EGR. However, the operating load, injection timing and injection pressure were varied in some cases.

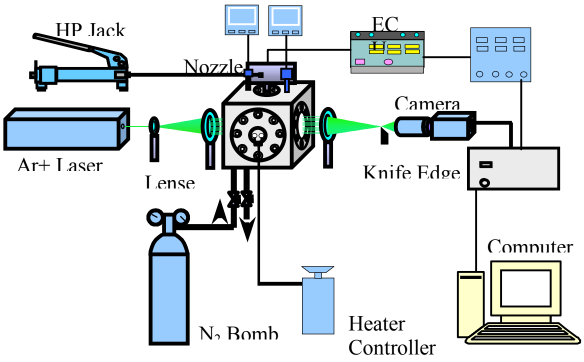


Fig. 1 Schematic of the schlieren system

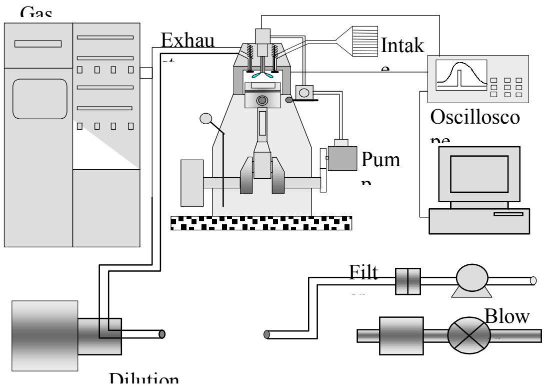


Fig. 2 Schematic of the exhaust analysis system

Table 1: Engine Specifications

Engine	DI Diesel (Hino)
Type	Single cylinder
Cylinder head	4 valve
Bore × Stroke, mm	135 × 150
Displacement	2.15 Liters
Compression ratio	16
Swirl ratio	2.2

Table 2 shows the properties of the fuels tested (NIST Database). 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 Heptane were used as the MPCs with Hexadecane as the IC. In these cases (Fuel through A to E), the overall density and cetane number were kept constant by varying the mixture ratios. But when the carbon number of IC was increased for the same MPC, the viscosity and boiling point difference increased. Similarly, when the carbon number of MPC was increased for the same IC, the boiling point difference decreased. Blending with tridecane when the ratio of pentane increases 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 on combustion and exhaust emission when the blending ratio between pentane and tridecane was changed.

3. RESULTS AND DISCUSSIONS

3.1 Effect of Igniting Component

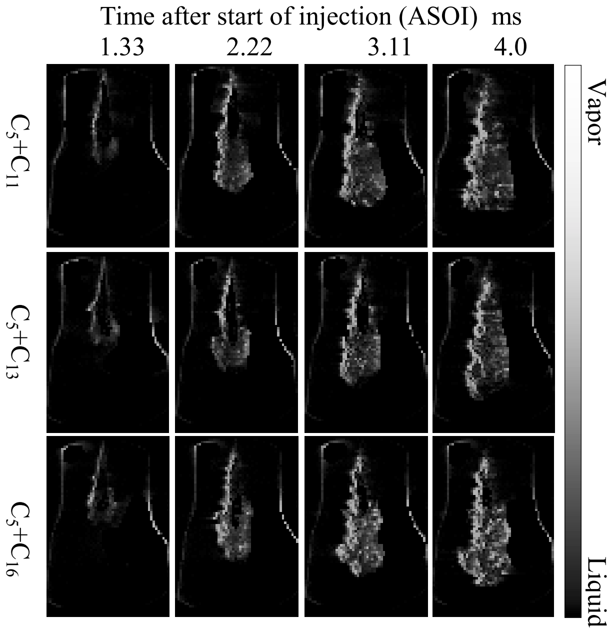
Figure 3 shows the schlieren photographs (monochromatic) of sprays for different igniting components. According to the schlieren principle the white zones in the spray represent the vapor while the black zones represent liquid. The photographs show that at early time after start of injection (ASOI) fuel evaporation starts from the outer periphery of spray with a clear liquid core. At this stage most of the vapors are from light MPC. At 4.0 ms after start of injection the whole spray is broken up due to fully evaporated light MPC but still containing some liquid portions of the dense IC distributed haphazardly in the spray. In most cases the liquid cluster of the dense IC is surrounded by the vapor of light MPC. When the chain length of IC increases the relative volume fraction of the light MPC also increases to keep the overall fuel density constant. As a result the fuel evaporation rate increases. But the overall tip penetration remains almost the same due to the same fuel density as found in the photographs. The spray angle is slightly larger for short chain IC than that of the long chain IC.

Table 2: Properties of test fuels [25°C and 1 atm]

Fuel	Formula	Volume frac.	Density [gm/cc]	CI	Visc. [mm^2/s]	ΔT	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	0723	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 relative vapor fraction (RVF), which is the ratio of the vapor area in the spray at a particular time to the maximum area that the completely evaporated spray can occupy, is shown in Figure 4. The two dimensional free space in the CVCC where the spray is injected is considered as the maximum area. The RVF is defined by the equation [1].

$$RVF(\%) = \frac{Vapor\ area\ in\ the\ spray}{Maximum\ vapor\ area} \times 100 ------[1]$$



(P$_{inj}$=40 MPa P$_{amb}$=1.3 MPa T=523K)
Fig. 3 Effect of igniting component on spray evaporation

Figure 4 shows that there is no significant difference in the relative vapor fraction when the chain length of IC increases. The volume fraction of light MPC increases with increases in the chain length of IC and results higher vapor concentration in the spray due to MPC. But evaporation rate of the long chain (dense) IC decreases. As the result total vapor concentration remains almost the same. However mixture of pentane and undecane shows slightly higher vapor concentration in comparison with the other two fuels. It is thought that the potential for flash boiling increases, but the component boiling point of IC and the average boiling point increase with increases in the chain length of IC, which produces slightly less amount of premixed charge.

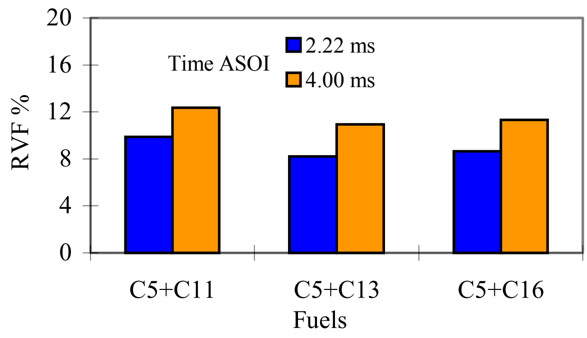


Fig. 4 RVF for different igniting components

The combustion pressure and heat release rate diagrams for different IC are shown in Figure 5. The heat release rates show that the ignition delay becomes shorter as the boiling point difference between MPC and IC increases. The combined effect of flash boiling and component cetane number was thought to be responsible for this early start of ignition. When the chain length of IC increases the potential for flash boiling increases, which reduces the physical delay time. On the other hand component cetane number of IC increases and ignites quickly. Fuel A ignites very late with relatively higher premixed combustion. The average boiling point is low enough for this fuel and produces much premixed charge during the long ignition delay period enhanced by low potential for flash boiling and it burns violently.

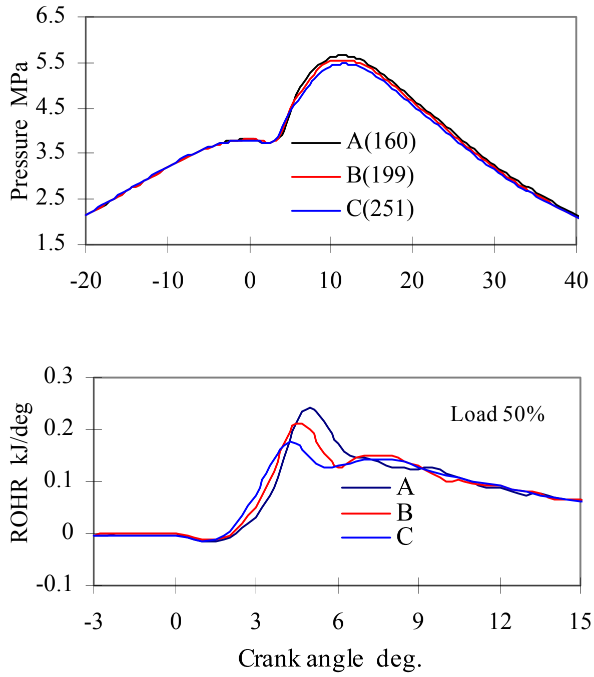


Fig. 5 Combustion behavior for different ICs

The exhaust emission behavior for different ICs is shown in Figure 6. The graph indicates 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. There is no significant difference in NO$_x$ emissions among these fuels. It is reported that the potential for flash boiling increases with increases in the boiling point difference even with the same MPC [1]. Therefore the potential for flash boiling of fuel C is the highest and of fuel A is the lowest. As the result very high and very low potentials for flash boiling result in higher PM emission. Fuel B has an advantageous level of potential for flash boiling and emits minimum PM.

A very light IC with low cetane number ignites very late and during this long delay period much fuel deposits on the chamber and cylinder wall. As a result the amount of soot emission increases. 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 acts as an optimum IC with it's optimum density and cetane number and produces balanced mixture distribution when blended with n-pentane.

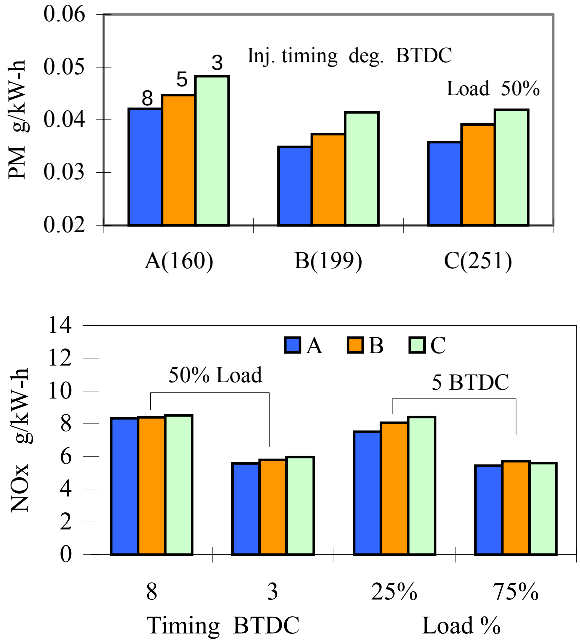


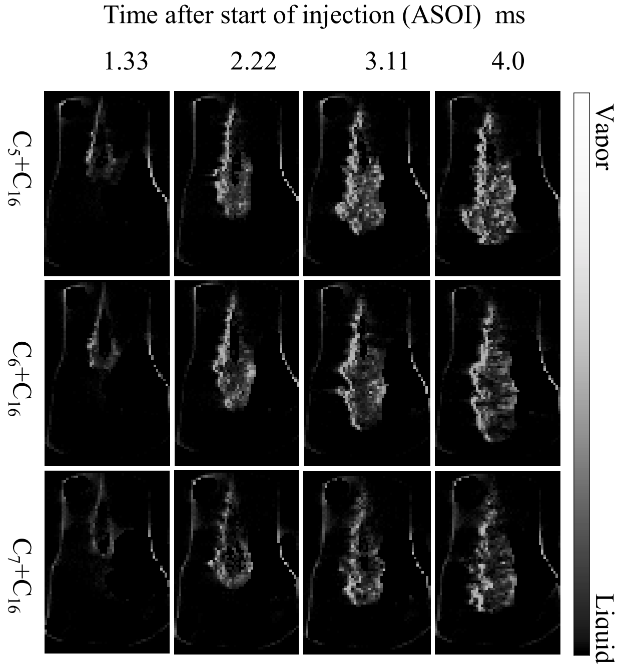
Fig. 6 Effect of igniting component on exhaust emission

3.2 Effect of Mixture Promoting Component

Figure 7 shows the schlieren photographs of sprays for different mixture promoting components. The photographs show that the tip penetrations and spray angles are approximately same due to the similar fuel density. At early time after start of injection there is no significant difference in the relative vapor and liquid concentration in the spray, but at 2.22 ms the liquid core in the spray is longer for the long chain MPC. At the late timings after start of injection the concentration of liquid fuel in the spray increases and the vapor concentration decreases with increases in the chain length of MPC.

Figure 8 shows the variation of the relative vapor fraction for different mixture promoting components. It shows that there are no significant differences, but the vapor concentration in the spray increases for the inclusion of a short chain paraffin as MPC. The average boiling point, and the amount of high boiling point MPC increase with the increases in it's carbon number. But the potential for flash boiling decreases as a result evaporation rate decreases and the total amount of premixed charge decreases.

The combustion pressure and heat release rate graphs for different MPCs are shown in Figure 9. The heat release rate graph shows that there is slight variation in the ignition delays when the carbon number of MPC changes. The start of 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 to some extent. As a result, the start of ignition remains almost the same. The spike of the premixed combustion increases slightly with decreases in the carbon number of MPC. The volume fraction of light MPC increases with the chain length, the amount of premixed charge also increases which causes higher premixed combustion. The combustion characteristics found in Figure 9 is supported by the mixture formation characteristics presented in Figure 7.



(P_{inj}=40 MPa P_{amb}=1.3 MPa T=523K)

Fig. 7 Effect of MPC on spray evaporation

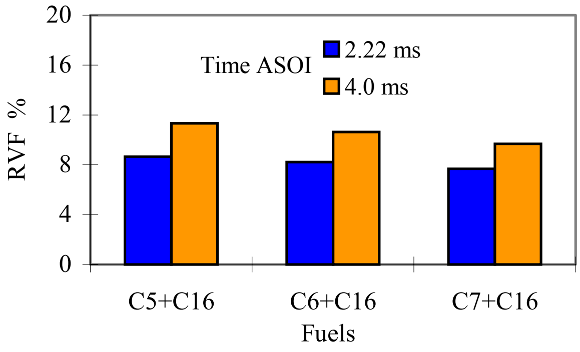


Fig. 8 RVF for different mixture promoting components

The emission behavior for different mixture promoting components is shown in Figure 10. It shows that PM emission increases by about 10 to 20% with increases in the carbon number of the mixture-promoting component from 5 to 7. However the NO_x emission shows no significant differences among the three fuels but maintain the trade off relation as expected. On the other hand the PM emission increases with the retardation of the injection timing and increases in the engine operating load. The exhaust emission behavior is well justified by the mixture formation behavior and the combustion behavior presented in the figures 7 and 9. It is reported that inclusion of a short chain normal paraffin as mixture-promoting component tends to increase the height of the two-phase region and flash boiling is accelerated [4]. As the result the total amount of premixed charge increases which burns violently and the PM emission decreases. On the other hand when the chain length of MPC increases the component boiling point of MPC increases and evaporation rate decreases. As the result amount of premixed charge decreases and PM emission increases.

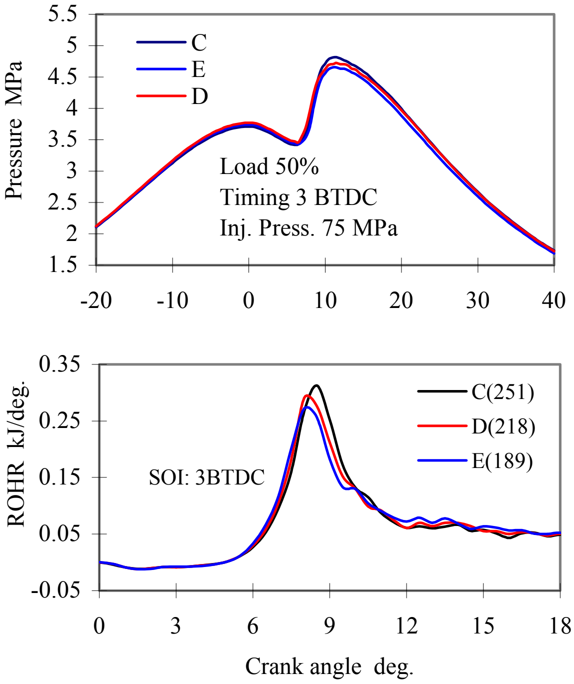


Fig. 9 Combustion behavior for different ICs

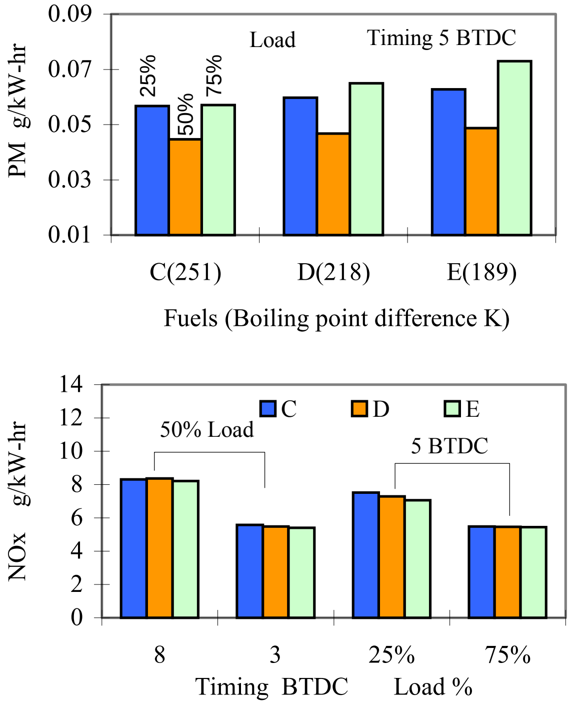
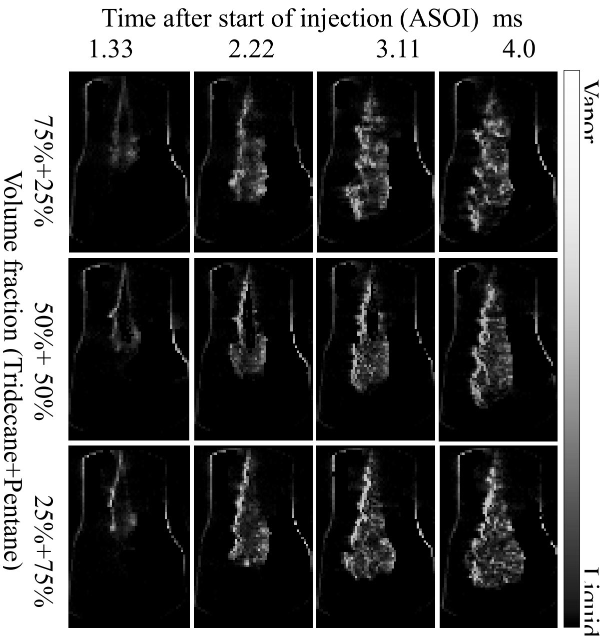


Fig. 10 Effect of MPC on exhaust emission

3.3 Effect of Mixture Ratio

Figure 11 shows the schlieren photographs of sprays for different mixture ratios between pentane and tridecane. Photographs show that with smaller fraction of pentane the spray penetrates longer while with higher fraction of pentane the spray disperses widely. Moreover the number of liquid clusters increases and the size decreases with higher fraction of pentane. When the volume fraction of pentane in the mixture increases the density, boiling point and equivalent carbon number decrease, but the potential for flash boiling increases. It is reported that a mixture ratio of about 3:1 has the highest critical pressure, therefore exhibiting the highest potential for flash boiling [4]. As the result the total amount of premixed charge increases with the increases in the fraction of pentane.



(P_{inj}=40 MPa P_{amb}=1.3 MPa T=523K)
Fig. 11 Effect of mixture ratio on spray evaporation

Figure 12 shows the effect of mixture ratio on relative vapor fraction. It shows that as the fraction of pentane in the mixture increases the RVF increases. About 50% increase in RVF was found when the volume fraction of pentane was increased from 25% to 75%. Therefore the fraction of pentane should be as high as possible. However there may have some problems in the injection system with higher fraction of light component. Due to very low boiling point the light fuel component may evaporate in the fuel line, which may cause vapor lock.

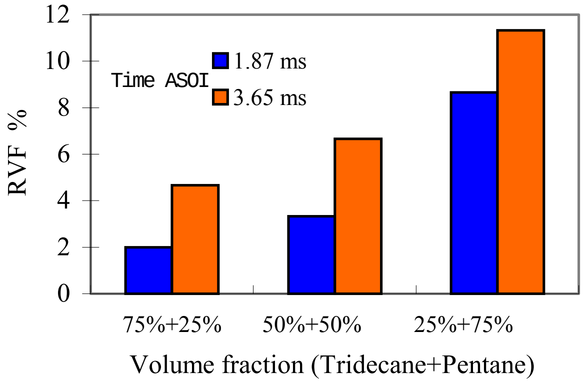


Fig. 12 Effect of mixture ration on relative vapor fraction

The combustion pressure and heat release rate for different mixture ratios are shown in Figure 13. 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 number. The mixture having 25% pentane shows higher diffusion combustion while the mixture having 75% pentane shows higher premixed combustion. These types of combustion phenomena are supported by the mixture formation characteristics shown in Figure 11.

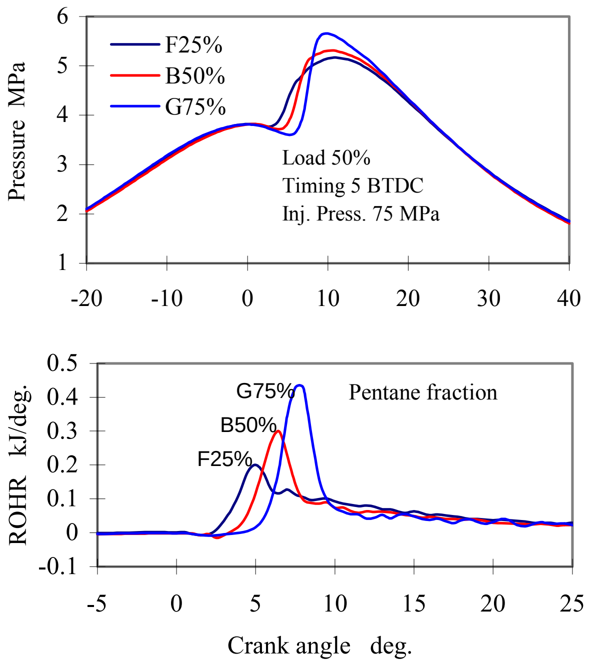


Fig. 13 Combustion behavior for different mixture ratios

The emission characteristics for the different mixture ratios are shown in Figure 14. It shows that at medium load there is no difference in NOx emission among these fuels but at light load fuel G having 75% pentane emits slightly higher NOx than the other two fuels. The PM emission decreases with increases in the proportion of n-pentane. A mixture ratio of 3:1 shows the minimum PM emission. However, it is assumed that for further increases in the fraction of pentane the PM emission might further increase partially due to decreases in the potential for flash boiling and improper combustion. In this study a higher fraction of pentane was attempted but the steady operation of the engine was difficult due to evaporation of the light fuel components in the fuel line even with proper cooling system. Higher amount of diffusion combustion due to much improper mixture causes higher PM emissions. Therefore, an optimum distribution of IC and MPC is necessary. A blending ratio 3:1 between pentane and tridecane is considered to be optimum in this study.

4. CONCLUSIONS

Design of a fuel has been attempted on the basis of mixture formation, combustion and emissions behavior of some two-component normal paraffin fuels. The following results are concluded:

1. A large difference in boiling points between MPC and IC has benefits for fuel evaporation and fuel-air mixing due to high flash boiling. But too low and too high potential for flash boiling do not always offer benefits to the reduction of PM emission.
2. A mixture ratio of about 3:1 by volume of n-pentane and n-tridecane showed an advantageous level of flash boiling, produces higher premixed charges and yield the lowest PM emission at all injection timings and load ranges and is therefore proposed as a low emission fuel.

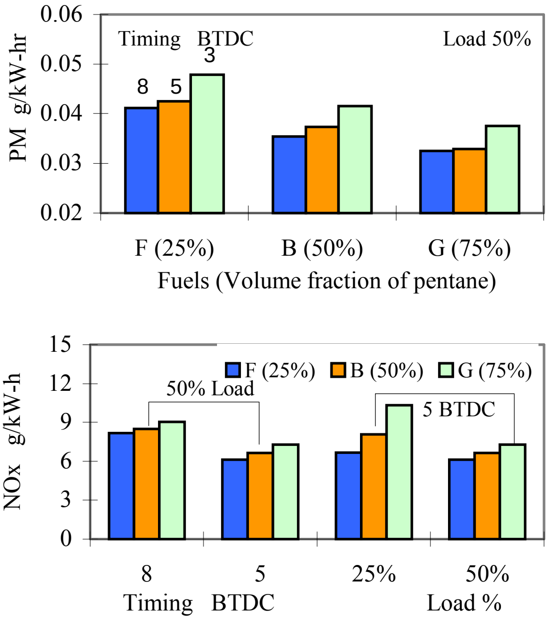


Fig. 14 Effect of mixture ratio on exhaust emission

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