Combustion Stratification for Naphtha from CI Combustion to PPC

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Abstract

This study demonstrates the combustion stratification from conventional compression ignition (CI) combustion to partially premixed combustion (PPC). Experiments are performed in an optical CI engine at a speed of 1200 rpm for diesel and naphtha (RON = 46). The motored pressure at TDC is maintained at 35 bar and fuelMEP is kept constant at 5.1 bar to account for the difference in fuel properties between naphtha and diesel. Single injection strategy is employed and the fuel is injected at a pressure of 800 bar. Photron FASTCAM SA4 that captures in-cylinder combustion at the rate of 10000 frames per second is employed. The captured high speed video is processed to study the combustion homogeneity based on an algorithm reported in previous studies.

Starting from late fuel injection timings, combustion stratification is investigated by advancing the fuel injection timings. For late start of injection (SOI), a direct link between SOI and combustion phasing is noticed. At early SOI, combustion phasing depends on both intake air temperature and SOI. In order to match the combustion phasing (CA50) of diesel, the intake air temperature is increased to 90°C for naphtha. The combustion stratification from CI to PPC is also investigated for various level of dilution by displacing oxygen with nitrogen in the intake. The start of combustion (SOC) was delayed with the increase in dilution and to compensate for this, the intake air temperature is increased. The mixture homogeneity is enhanced for higher dilution due to longer ignition delay. The results show that high speed image is initially blue and then turned yellow, indicating soot formation and oxidation. The luminosity of combustion images decreases with early SOI and increased dilution. The images are processed to generate the level of stratification based on the image intensity. The level of stratification is same for diesel and naphtha at various SOI. When O₂ concentration in the intake is decreased to 17.7% and 14.7%, stratification level is decreased. NO_x emission for both diesel and naphtha show a decreasing trend from CI to PPC.

Comparing diesel and naphtha, the soot emission is lower for naphtha. NO_x and soot emissions at various SOI are correlated with high speed images of combustion to explain the combustion stratification.

Keywords

Naphtha, stratification, combustion homogeneity, PPC, optical CI engine

Introduction

Partially premixed combustion (PPC) is intermediate between compression ignition (CI) and homogeneous charge compression ignition (HCCI) that offers a better control of combustion due to increased stratification [1, 2, 3, 4], compared to HCCI. In conception, increasing the delay time between start of ignition (SOI) and start of combustion (SOC) make the combustion homogenous [5]. While combustion phasing is sensitive to SOI in CI combustion, it is dependent on intake air temperature for HCCI. Since PPC is in between HCCI and CI combustion concepts, combustion phasing is expected to be governed by both intake air temperature and SOI. Therefore, it is worth of an investigation to study the transition from CI to PPC by varying the intake air temperature and SOI to gain more insights on combustion homogeneity and stratification.

Many studies report the transition to PPC and HCCI from CI combustion in metal CI engine [6, 7]. Recently, in-cylinder diagnostics of combustion homogeneity and stratification of air/fuel mixture are studied in an optical CI engine. A study reports achieving PPC by advancing SOI and increasing the dilution level and intake temperature [8]. High speed image of the combustion process was studied for PRF70 and the work elucidated the combustion homogeneity based on image luminosity. Another study concedes that high level of dilution, pilot injections and increased fuel injection pressure influences PPC in an optical CI engine [9]. With dilution, the radial flame distribution was promoted and C₂ imaging indicated that

higher level of dilution enhance premixing so that combustion homogeneity is improved. A recent study varied the oxygen concentration in the intake and fuel composition is changed to analyze the effect of ignition delay on PPC [10]. High speed imaging of chemiluminescence from OH^* identified the edge of flame and a correlation between ignition delay and flame positioning is reported.

Chemiluminescence gives a holistic view on the combustion stratification inside the combustion chamber [11]. Based on Chemiluminescence and high speed imaging, the effect of fuel injection strategies on combustion stratification was investigated for PRF55 [9]. Implementing negative value overlap (NVO) strategy that retains residual gases in the combustion chamber, combustion stability was maintained. The study concluded that degree of stratification decreased with the advancement in fuel injection timing and combustion is more homogenous for triple injection when compared to single or double injection. In an advanced study, the ignition sensitivity of PPC to SOI at different fuel injection pressures was studied [12]. This study proposed a method to estimate combustion stratification wherein the image intensity is averaged both radially and angularly. The OH^* Chemiluminescence images showed more homogenous combustion for early SOI. The study concludes that combustion stratification was lower for early SOI and higher for late SOI, identifying SOI as crucial factor for controlling stratification. Also, lower fuel injection pressure lead to more stratified combustion, while higher injection pressure resulted in more homogenous combustion.

The above literature study shows that PPC can be achieved by advancing the SOI, increasing the dilution in intake and decreasing the compression ratio. Combustion becomes homogenous with advanced SOI and increased dilution levels, whereas increasing the intake air temperature supports auto-ignition. While SOI is a decisive factor that affects combustion phasing, fuel octane number also proves crucial [13, 14]. The use of gasoline like fuels in CI engine enables in achieving PPC or HCCI and reduces the emissions [15]. While gasoline and PRF's were tested, naphtha is also considered for PPC studies in CI engine. Given the lower cetane number (CN) of naphtha, operation of naphtha in CI engine requires modifications with engine to support its auto ignition. A recent study reports optimization of combustion bowl geometry and nozzle hole geometry to adapt naphtha in CI engine [16, 17]. Similarly, to achieve combustion stability with naphtha, fuel injection strategy is also a viable technique [18]. Double injection strategy with single and two stage heat release reportedly increased the efficiency and reduced the emissions for naphtha.

In this research work, combustion stratification from conventional CI combustion to PPC is studied. The SOI is swept from late (-10 CAD aTDC) to early (-30 CAD aTDC) fuel injection timings and the point where SOI decouples with combustion phasing is identified. The experiment is performed in a single cylinder optical CI engine for diesel and naphtha. Most of the studies on naphtha are reported in metal engine; combustion process of naphtha using high-speed imaging is rarely investigated thus far. Therefore, it is noteworthy to study the combustion stratification for naphtha in an optical CI

engine. The experiments are also performed at various levels of dilution and increased intake air temperature. A high speed video of the combustion process is recorded through an optical piston from the bottom and the images are correlated with in-cylinder pressure and rate of heat release. Also, the combustion images are compared between diesel and naphtha at various levels of dilution and SOI's. The stratification analysis is performed based on the image intensity to determine the stratification levels for diesel and naphtha at various operating conditions.

Methodology

Fuel Characterization

Diesel (supplied by Coryton) and naphtha (supplied by Saudi Aramco) are considered for the current study. Naphtha is a less processed fuel in refinery i.e less refining cost and has fuel properties closer to gasoline [19]. The physical and thermal properties of naphtha are compared with diesel and shown in Table 1. When compared to diesel, viscosity of naphtha is lower and this is expected to improve the fuel atomization and air/fuel mixing process. The lower carbon number with decreased boiling point for naphtha than diesel is believed to improve the fuel evaporation and premixing in engines.

Table 1. Fuel Properties of diesel and naphtha

Property	Diesel	Naphtha
Density (kg/m^3)	835	760
Heat of combustion (kJ/kg)	43200	44600
Viscosity ($\times 10^{-6} \text{ m}^2/\text{s}$)	2.43	0.4
Final boiling point ($^{\circ}\text{C}$)	360	180
RON	-	46
H/C ratio	1.79	2.15
Derived cetane number	54	41

The ignition measurements of diesel and naphtha are conducted in an ignition quality tester (IQT) as per ASTM D6890. The specifications of IQT setup and the method involved in estimating ignition delay time (IDT) are detailed in [20]. The experiments are done at IQT standard condition (Temperature = 853K and Pressure = 21 bar) at which IDT of n-heptane is 3.8 ms. Figure 1 shows the IQT chamber pressure for diesel and naphtha. The initial chamber pressure for test fuels is lower than the initial pressure due to evaporative cooling. The measured IDT of naphtha is longer (5.3 ms) and seems to be less reactive than diesel. Though the boiling point of naphtha is lower than diesel, chemical effects predominate the combustion process and thus, IDT is longer for naphtha. Derived cetane number (DCN) of naphtha is 41, which is lower than diesel (DCN = 54).

Figure 1. Ignition study of diesel and naphtha in IQT

Experimental Set Up

A single cylinder AVL optical CI engine with a capacity of 511 cc was used for the current experimentation. The detailed specifications of the engine are shown in Table 2. The engine schematic with other accessories is shown in Figure 2. The piston bowl is made of quartz and combustion is visualized from the bottom of the piston. A metal liner surrounds the piston and a pump aids in moving the metal portion below the cylinder head to facilitate cleaning of glass in the piston. A vacuum cleaner creates a negative pressure of 100 mbar in the crankcase that ably prevents oil squirts on the optical components. A jet of air cools the piston from the bottom. The photographic view of the optical piston with a pip in the center of the combustion chamber is shown in Figure 3. Distortions due to the pip in the bowl is shown in the millimeter paper and marked for reference. A high speed video of the combustion process is recorded from the bottom of optical piston by Photron FASTCAM SA4 color camera. For all operating condition, 150 cycles are recorded with the trigger set at -10 CAD (aTDC) to capture the combustion process. 100 images are recorded for each cycle and the crank angle interval between images is 0.72 CAD. The high speed video is captured at the rate of 10,000 frames per second with a pixel resolution of 768×512 and the aperture for lens is kept at 1.4.

The SOI, fuel injection pressure, mass of fuel injected and valve timing are controlled through engine control unit (ECU) known as AVL FI²RE. A Piezo electric pressure transducer mounted over the cylinder head measures the in-cylinder pressure with a sensitivity of 20 pC/bar. The pressure data were recorded in an interval of 0.2 CAD by AVL indicom software version 2.4. The recorded pressure data was then analyzed using a heat release code and the combustion parameters such as rate of heat release, indicated mean effective pressure (IMEP), CA50 (combustion phasing) and other parameters are determined. The heat release computation entails wall heat model, heat transfer losses, blow by and crevice effects. Initially, rate of heat release is estimated from motored pressure trace and it was deduced to be zero. This gives an indication that the heat release analysis is appropriate; given no heat should be released during motoring condition. Subsequently, rate of heat release is calculated from the pressure traces for fired cases.

Table 2. Specifications of Single cylinder optical CI engine

Bore	85 mm	
Stroke	90 mm	
Compression ratio	9.5:1	
Swept volume	511 cc	
Engine speed	1200 rpm	
Fuel injection pressure	800 bar	
Fuel injection timing	-10 to -30 CAD aTDC	
Intake Valve	Open	30 CAD bTDC
	Close	45 CAD aBDC
Exhaust Valve	Open	50 CAD bBDC
	Close	25 CAD aTDC
Inlet air pressure	1.55 to 1.65 bar	
Inlet air temperature	35 to 160° C	
Coolant temperature	80° C	
Lubrication oil temperature	80° C

Figure 2. Schematic of optical CI engine

AVL PUMA controls the measurement of torque, intake air and exhaust gas pressure and temperature, coolant and lubricant temperature and engine speed. To facilitate the measurement of all gases in intake, a separate emission channel is incorporated and the emission values are measured using AVL AMA i60 test bench in both intake and exhaust. While NO_x emission is measured using an FTIR (Fourier transform infra red analyzer) in the range of 0 to 10000 ppm, soot concentration is measured using AVL micro soot sensor.

Figure 3. Optical piston (top) and distortions captured in millimeter paper (bottom)

Operating Conditions and Test Procedure

The engine runs at a speed of 1200 rpm and fuel is injected at a pressure of 800 bar by a common rail fuel injection system. FuelMEP for both diesel and naphtha is calculated as follows,

$$\text{FuelMEP} = \frac{m_f * Q_{LHV}}{V_d} \quad (1)$$

Where, M_f – Mass of fuel supplied (g), Q_{LHV} – lower heating value (kJ/kg) and V_d – displacement volume (m^3). For the reported calorific value of diesel and naphtha (Table 1), mass of fuel injected is varied to maintain a constant fuelMEP of 5.1 bar. Since IMEP is lower (low load condition), the quantity of fuel injected per cycle is lower. The SOI is swept from –10 CAD (aTDC) to - 30 CAD (aTDC) i.e., from CI to PPC condition. The intake air pressure is boosted (1.55 bar to 1.65 bar absolute pressure) and the motored pressure at TDC is kept at 35 bar. In the current study, oxygen (O_2) concentration in the intake is displaced by nitrogen (N_2) through a mass flow meter to have various levels of dilution at 20.7%, 17.7% and 14.7%. The intake air is heated using an inline heater (from 35°C to 160°C) to facilitate control of combustion during PPC. Since the lubrication quality is low for naphtha, 500ppm of lubricating additive from infenium was added to prevent the failure of fuel pump.

Image Processing and Stratification Analysis

The recorded high speed video is converted into images and each cycle with 100 images is analyzed separately. The natural luminosity of the images are inferred and the color camera that was used showed blue and yellow images. It is interesting to analyze the color images of combustion and investigate the stratification levels. The stratification analysis is based on the methodology from Tu/e Eindhoven University of Technology [12]. The images are examined

in a cylindrical coordinate system and the 7 clouds of combustion, representative of 7-hole nozzle spray, are considered. Stratification analysis was limited by optical distortions in the piston bowl and thus, only angular stratification was analyzed. The angular stratification is determined by selecting a band in radial direction of cylindrical coordinate system. The intensity of images is averaged in the radial direction with respect to polar angle (θ) [12]. The difference between maximum and minimum angular signal is normalized by the sum of intensities to explore the stratification levels between 0 and 1 at various operating conditions.

The estimation of angular stratification is based on the below formulation,

$$\text{Str}_\theta = \frac{1}{n} \sum_{i=1}^n \frac{(I_{\max} - I_{\min})_i}{(I_{\max} + I_{\min})_i} \quad (2)$$

Where Str_θ = Angular stratification, n - number of injection holes, $I_{\max}$ - Maximum angular intensity in i^{th} combustion cloud, $I_{\min}$ - Minimum angular intensity in i^{th} combustion cloud and θ - Polar angle. More detailed information on stratification analysis can be found in the previously published papers [9, 12]. For the stratification analysis, 30 cycles is considered. In total, the images for 150 cycles are recorded and separated into 5 cases, each case with 30 cycles. The level of stratification for each set is same. In the present study, a full optical piston is not used and combustion at advanced SOI could not be captured properly with the glass piston bowl. Combustion visualization is not proper at SOI before –20 CAD (aTDC) as full view of combustion chamber is not obtained. Because of this limitation, stratification analysis at early SOI is not appropriate.

Results and Discussion

Combustion Phasing

Combustion phasing (crank angle at which 50% of fuel is burnt – CA50) for diesel at $T=35^\circ\text{C}$ and $\text{O}_2=20.7\%$ is plotted against SOI (figure 4). From the plot, it is clear to note the transition from CI to PPC when the SOI is swept from late to early injections. For late injections (–10 CAD aTDC), there is a link between combustion phasing and SOI, and this is regarded as CI combustion. At around SOI of –20 CAD (aTDC), PPC is inferred for diesel. At advanced injections, the combustion phasing starts to decouple from SOI. The trend in CA50 decreases from CI and then takes a hook, before starting to decouple from SOI. These findings are in consonance with the past reports wherein the same effect of SOI on combustion phasing is elucidated [21, 22]. When SOI is advanced, the mixing time for air and fuel is increased and the mixture become more homogenous. As premixing is improved due to fuel evaporation, the local equivalence ratio decreases (lean burning) and this prolongs the ignition delay: the start of combustion (CA05) plot with respect to SOI confirms this, as shown in figure 5.

When naphtha is tested in optical CI engine, air/fuel mixture doesn't ignite at an intake air temperature of 35°C due to its lower reactivity. However, when the intake air temperature is increased, auto ignition of naphtha is supported and stable combustion is attained. At an

intake air temperature of 90°C, CA50 for naphtha is closer to diesel and so does is the SOC (figure 4 and 5). The trend of CA50 for naphtha is comparable to diesel, while only the intake air temperature is different. For high octane fuels, SOI is advanced for achieving same CA50 as that of standard fuel [23]. Here, from -10 CAD (aTDC) to -17 CAD (aTDC), CA50 of naphtha is comparable to diesel. Before -17 CAD (aTDC), CA50 is lower for naphtha than diesel due to the combined effect of early SOI and increased intake air temperature.

Figure 4. CA50 plot for diesel and naphtha with respect to SOI

Figure 5. SOC plot for diesel and naphtha with respect to SOI

Effect of Dilution on Combustion Phasing

In an attempt to improve premixing and homogeneity of air/fuel mixture, intake air is diluted by N_2 . The effect of dilution on combustion phasing is studied for naphtha (figure 6). When O_2 in the intake is reduced from 20.7% to 17.7%, combustion phasing is retarded. Dilution by N_2 reduces the reactivity of the mixture and this prolongs the combustion process with increased ignition delay. The intake air temperature is increased from 90°C to 105°C to improve the combustion process and combustion phasing was advanced. CA50 for naphtha at $T_{in} = 105^\circ\text{C}$ and $O_2 = 17.7\%$ is comparable to CA50 for naphtha at $T_{in} = 90^\circ\text{C}$ and $O_2 = 20.7\%$, showing that combustion phasing is recovered with the increase in intake air temperature. When O_2 in the intake is reduced to 14.7%, combustion

is further retarded and to compensate this, intake air temperature is increased to 160°C. At this condition, CA50 for naphtha is matched with the baseline CA50. Thus, dilution is effected to improve the combustion homogeneity and intake air temperature is increased to match the combustion phasing for naphtha.

Figure 6. Combustion phasing for naphtha with respect to SOI at various levels of dilution and intake air temperature

In-Cylinder Pressure and Rate of Heat Release

The in-cylinder pressure and rate of heat release are compared for naphtha and diesel at SOI = -10 CAD (aTDC), -15 CAD (aTDC) and -20 CAD (aTDC) and shown in figure 7. Peak in-cylinder pressure for naphtha is comparable to diesel; however the intake air temperature is increased to 90°C for matching diesel combustion. For the same fuelMEP, diesel and naphtha produces an IMEP of 2.55 and 2.46 bar, respectively, when SOI is -10 CAD (aTDC). For both diesel and naphtha, IMEP is higher for SOI in the range -10 CAD (aTDC) to -20 CAD (aTDC) and it starts to decrease when SOI is advanced further.

Figure 7. In-cylinder pressure and rate of heat release for diesel and naphtha at a) SOI = -10 CAD (aTDC), b) SOI = -15 CAD (aTDC), c) SOI = -20 CAD (aTDC) with inlet O_2 concentration of 20.7%.

b.

c.

Figure 7. (cont.) In-cylinder pressure and rate of heat release for diesel and naphtha at a) SOI = -10 CAD (aTDC), b) SOI = -15 CAD (aTDC), c) SOI = -20 CAD (aTDC) with inlet O_2 concentration of 20.7%.

When comparing the rate of heat release for diesel and naphtha, it is noticed that peak heat release rate is slightly higher for naphtha. The rate of heat release rises sharply for naphtha, while it increases gradually for diesel. Since the properties and reactivity of naphtha are different from diesel, intake air temperature is raised to 90°C . The increased temperature in the intake attributes to slightly higher heat release rate for naphtha than diesel. Interestingly, there is an initial bump in the rate of heat release curve for diesel and naphtha and this is cool flame region. Low temperature reaction phase depends mainly on chemical properties (fuel composition and fuel structure) and in-cylinder conditions (in-cylinder temperature and pressure) [24].

The rate of heat release at different SOI for naphtha at $T_{in} = 90^{\circ}\text{C}$ and $\text{O}_2 = 20.7\%$ and diesel at $T_{in} = 35^{\circ}\text{C}$ and $\text{O}_2 = 20.7\%$ is shown in figure 8. At this condition, combustion phasing of naphtha is comparable to diesel and it is rational to compare the in-cylinder pressure and heat release rate. For late SOI (-10 CAD aTDC), combustion occurs late after TDC for diesel. Both diesel and naphtha

shows a lump in heat release rate and this is an evidence of low temperature combustion as explained above. At early injection, the peak heat release rate of diesel is much lower. The mass of fuel injected is less and the fact that more time is available for premixing at early SOI makes the mixture lean, which affect the combustion. Naphtha shows a pronounced premixed combustion until -25 CAD (aTDC) and the peak heat release rate decreases after that. While diffusion combustion phase is evident for diesel and naphtha at late SOI, it turns predominantly premixed when SOI is advanced. The plot of rate of heat release for naphtha at various intake O_2 concentrations and temperature for SOI = -10 CAD (aTDC) is shown in figure 9. As O_2 concentration in the intake is decreased to 17.7% from 20.7%, ignition delay is prolonged, and the peak heat release rate is decreased. Reduction in intake O_2 concentration has a reflection on in-cylinder temperature and mixture homogeneity [25]. If combustion phasing is advanced, diffusion controlled combustion shifts towards modulated kinetic controlled combustion [26]. To attain stable combustion with dilution, intake temperature is increased to 105°C and rate of heat release is comparable with naphtha at $T_{in} = 90^{\circ}\text{C}$ and $\text{O}_2 = 20.7\%$. Similarly, when O_2 concentration is 14.7%, the intake temperature is increased to 160°C to match the combustion phasing for base line naphtha.

a.

b.

Figure 8. Rate of heat release for diesel and naphtha at various SOI

Figure 9. Rate of heat release for naphtha at various levels of dilution and intake temperature at SOI = -10 CAD aTDC

Combustion Visualization

The in-cylinder pressure and rate of heat release are correlated with the high-speed images and better understanding of the combustion process is obtained (figure 10). The color of the flame changes from blue to yellow during combustion. Blue color signifies the initial low temperature combustion before the diffusion dominant phase of combustion. The dark yellow spots at latter stages of combustion are due to injector dribbling. Combustion clouds representing sprays are evident in the images and soot flames are visible after 13 CAD aTDC when SOI is -10 CAD aTDC.

The difference between combustion phasing is quite obvious from this study based on the color and intensity of high speed images. The first image of combustion is observed at 7.2 CAD (aTDC) for SOI = -10 CAD (aTDC) and intensity of image as well as the flame area increases as the flame starts to propagate towards the outer ring of combustion chamber. While CA10 occurred at 3.7 CAD (aTDC) and maximum intense image is seen at 11 CAD (aTDC). The percentage of heat released at respective crank angle degrees is shown with the images at the top. Moving from left, the percentage of heat released increases and mixing controlled combustion is certain for diesel. All these images are shown at low load condition when IMEP is in the range of 2 to 2.5 bar. Diesel PPC is studied at low load, given the ignition delay is short and enables only low stratified mixture before ignition [27].

The images of combustion for naphtha at SOI = -10 CAD (aTDC) are shown in figure 11, synchronized with in-cylinder pressure and heat release data. When compared to diesel, the percentage of heat released is slightly higher for naphtha. It is worth reiterating that the intake temperature is increased for naphtha to match the combustion phasing of diesel. At this condition, the combustion images of naphtha, compared with diesel at same SOI, elucidate that combustion is similar to diesel. Combustion is stratified for naphtha as SOI is swept from early to late injection. This is in parallel with the results of the previous study for PRF 70 wherein combustion is more stratified for late injections than advanced injections [12]. As

SOI is advanced to -20 CAD aTDC, the diffusion flames become less evident for diesel and naphtha (figure 12). For early injection, combustion is predominantly premixed and diffusion combustion is more pronounced for late injections.

Figure 10. In-cylinder pressure and rate of heat release for diesel at SOI = -10 CAD. Top: high speed images of combustion at various crank angle with respective percentage of heat released.

Figure 11. In-cylinder pressure and rate of heat release for naphtha at SOI = -10 CAD. Top: high speed images of combustion at various crank angle with respective percentage of heat released.

Figure 12. Images of combustion for diesel and naphtha compared at various SOI with intake O_2 concentration of 20.7%

The decrease in luminosity is noticed when SOI is swept from late to early SOI. The luminosity of combustion is low when there is no diffusion combustion and soot formation [8]. However, when $SOI = -10$ CAD (aTDC), intensity of the both blue and yellow flames is higher when compared to the intensity of image at SOI of -15 CAD (aTDC) and -20 CAD (aTDC). The combustion image at various levels of dilution is shown in Figure 13. With dilution premixing is increased (decreased luminosity) and when intake air temperature is increased, the luminosity of images is higher.

Figure 13. Images of combustion for naphtha with various dilution level and intake air temperature at SOI of -10 CAD aTDC

Combustion Stratification

The effect of advancement in fuel injection timing, intake air dilution and increase in intake air temperature on combustion stratification is studied for diesel and naphtha. The angular stratification for diesel and naphtha at an intake temperature of 35°C and 90°C , respectively,

is shown in figure 14 at various SOI. When fuel is injected early into the compressed air, temperature is high enough to evaporate the fuel and time is also sufficient to make the mixture homogeneous. However, for late injections, fuel impinges on the piston bowl, which has a lower surface temperature when compared to the temperature of the compressed air. The evaporation of the fuel is affected and this together with the reduced time available for air/fuel mixing increases the stratification. For late SOI, stratification level is higher for both diesel and naphtha as there is less time available for premixing. However, when SOI is advanced, stratification level is decreased. For early SOI of -30 CAD (aTDC), level of stratification for both diesel and naphtha is 0.1. It is useful to link the level of stratification with flame intensity and analyze the relation between them. The plot of mean intensity as a function of SOI for diesel and naphtha (figure 15) show the same trend as the maximum stratification. The maximum stratification depends on the luminosity of images and when mean intensity decreases, stratification level decreases.

a.

b.

Figure 14. Level of stratification for diesel and naphtha at various SOI

To examine the level of stratification for naphtha and diesel more clearly, maximum value of angular stratification is plotted with respect to SOI and shown in Figure 15. This plot shows that the maximum stratification for naphtha and diesel are comparable. For

both the fuels, maximum stratification decreased from 0.8 to 0.1 as SOI is advanced from -10 CAD (aTDC) to -30 CAD (aTDC). Since intake air temperature is increased to compensate for the lower reactivity of naphtha, combustion is matched with diesel and the degree of stratification is also similar. Thus, naphtha behaves similar to diesel despite its distinct fuel properties at various SOI, signifying that the shift in combustion homogeneity from CI to PPC is similar for both these fuels.

a.

b.

Figure 15. Maximum stratification and mean intensity with respect to SOI for diesel and naphtha

The effect of dilution on angular stratification is studied for naphtha at $\text{SOI} = -10$ CAD (aTDC), shown in Figure 16. The decrease in O_2 concentration from 20.7% to 17.7% improves air/fuel mixing. Dilution turns the mixture leaner and increases the ignition delay, which actually prolongs the combustion to improve premixing. The level of stratification further decreased drastically by 0.5 when O_2 in the intake is reduced to 14.7%. However, increased intake air temperature improves the combustion and stratification level is increased. The objective to move towards PPC from CI combustion mode is met by increasing the dilution level in the intake. Increase in intake air temperature helps to attain stable combustion and thereby, combustion becomes stratified.

Figure 16. Effect of dilution and intake air temperature on level of stratification for naphtha

NO_x and Soot Emission

In the previous studies in optical CI engine that investigates combustion stratification, emission results are rarely reported. To make the analysis comprehensive, we have coupled NO_x and soot emission with the high speed images of combustion from optical engine and some inferences are drawn. NO_x and soot emission for diesel at $T_{\text{in}} = 35^\circ\text{C}$ and $\text{O}_2 = 20.7\%$ and naphtha at $T_{\text{in}} = 90^\circ\text{C}$ and $\text{O}_2 = 20.7\%$ are shown in Figure 17. From the results, it is certain to note that NO_x and soot emission in general are lower in a CI engine for both diesel and naphtha, which could be due to the operation of engine at low load (IMEP in the range 2 to 2.5 bar). NO_x emission is higher for both diesel and naphtha at late injections in the range -10 CAD aTDC to -15 CAD aTDC i.e. during CI combustion. However, when moving from CI to PPC condition, NO_x emission decreases and attains a lower value. This is attributed to increased premixing when SOI is advanced that lowers the local equivalence ratio (lean burning) to decrease NO_x emission. While diesel attains a constant lower value of NO_x emission at -20 CAD (aTDC), it happens late for naphtha after -25 CAD (aTDC). With early SOI, combustion becomes too lean due to premixing to the extent that it extinguishes combustion and increases the soot emission for diesel.

The observed trend in NO_x and soot emissions can be understood by correlating with high speed combustion images, shown in figure 12. While combustion images with high luminosity at late injection correspond to increased NO_x emission and lower soot concentration, images with low luminosity are related to decreased NO_x emission and increased soot emission. NO_x emission for naphtha is slightly higher than diesel, given that the peak in-cylinder temperature is expected to be higher for naphtha. For naphtha, intake air temperature is increased to 90°C to match the CA50 with diesel. Thus, it is certain that the temperature is high enough for naphtha in the intake and this increases NO_x formation. Furthermore, the increased in-cylinder temperature also promotes soot oxidation to decrease soot concentration. The decreased soot concentration for naphtha could also be attributed to lower aromatics present in it compared to diesel. It is noteworthy to point out that the total aromatics content in naphtha is 11.2% (v/v), while for diesel it is 28.7% (v/v). While aromatics are precursors to soot formation during combustion process [28, 29, 30], the amount of olefins present in naphtha is also lower (1.8% v/v), which reduces the soot concentration.

Figure 17. NO_x emission and Soot concentration for diesel and naphtha

Conclusions

Combustion stratification is studied for naphtha in an optical CI engine and the results are compared with diesel. When SOI is swept from late to early injection, combustion is drifted from CI to PPC for both naphtha and diesel. Combustion phasing of naphtha is made comparable to diesel by increasing the intake air temperature from 35°C to 90°C. The shift towards PPC condition occurs at SOI of -20 CAD (aTDC) and -25 CAD (aTDC) for diesel and naphtha, while a better CI combustion is attained at -10 CAD (aTDC). The in-cylinder pressure and rate of heat release are synchronized with the high speed images of combustion for diesel and naphtha when SOI = -10 CAD (aTDC). Diesel and naphtha shows cool flame region due to low temperature reaction phase. When SOI is advanced, premixing is improved for both these fuels and intensity of combustion images diminishes. The peak heat release rate is slightly higher for naphtha; while IMEP for diesel and naphtha are comparable.

In an attempt to study the combustion stratification, the O₂ concentration in intake is reduced to 17.7% and 14.7%. With the increase in dilution, combustion phasing is advanced. With dilution the intensity of images decreases due to increased premixing. For O₂ concentration of 17.7% and 14.7%, intake air temperature is increased and combustion phasing is brought closer to the baseline

combustion phasing. For this, the natural luminosity of the combustion images is increased and the combustion clouds are clearly visible. The level of stratification is determined based on the intensity of images in cylindrical coordinate system. The angular stratification for naphtha and diesel at various SOI is comparable. For early injections, the level of stratification is lower and higher for late injection. Thus, when SOI is swept from advanced to late injection timing, combustion is shifted from PPC to CI. When the intake air is diluted with N₂, premixing is further improved and increasing the intake temperature improves the combustion stratification. This study summarizes that for late injections, combustion phasing is directly linked with SOI, while it starts to decouple when SOI is advanced. Besides SOI, intake oxygen concentration and temperature plays a prominent role in improving the combustion stratification. In future, combustion stratification at higher loads and different operating condition would be explored. Furthermore, a full optical piston would be used so that the combustion images could be captured at early SOI to facilitate comprehensive stratification analysis.

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