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Fuel properties effects on wall-wetting and fuel-in-lube dilution under stochastic pre ignition prone conditions

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Abstract: Fuel-engine interactions have been shown to influence stochastic pre-ignition (SPI), however there is uncertainty on the root causes, participially if effects are primarily physical or chemical in nature. To better delineate the physical and chemical dependencies of fuel properties on SPI, this work studies interactions between aromatics, distillation, and particle matter index on SPI with a laser induced fluorescence (LIF) diagnostic to observe wall wetting. Fuels with high aromatic components or higher distillation temperatures tend to increase SPI events, but it is not well understood if the increased fuel dilution or a chemical aspect of this process is the primary mechanism for SPI. By employing the novel LIF in this work we measure fuel dilution in real-time in a running single cylinder research engine operated at SPI conditions. Three fuels were used in the present work, with the LIF diagnostic. Each fuel was operated at two injection timings, generating fuel specific effects on wall wetting. The LIF measurements are coupled with engine combustion measurements and SPI event counts. Results enable a deconvolution of fuel physical and chemical properties on SPI propensity, providing unique and novel insights into the dominant fuel effects affecting SPI. [1]

Keywords: Low Speed Preignition, Abnormal Combustion, Fuel Properties, Laser Induced Florence

1. Introduction [12pt]

Fuel-in-oil (FiO) dilution is hypothesized as one of the most relevant underlying mechanisms that promotes stochastic pre-ignition when operating the engine at high-load conditions in spark-ignition (SI) engines [1-6]. Although hypothesized, little direct measurement of FiO has been achieved under SPI conditions as its acquisition is complex and cumbersome from the top ring zone (TRZ) in a running engine.

Studies by Saville et al., [7] and Watson [8] in diesel engines both showed that the TRZ lubricant undergoes more aggressive oxidation and degradation processes than lubricant sampled from the oil sump. Second,

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relative to the sump the TRZ processes occur quickly, requiring short runtimes to initiate lubricant degradation, as evidenced by in-situ spectral diagnostic measurements by Nattrass et al. [9]. In spark ignited gasoline engines it has been found that even more complex chemistry may be occurring. Specifically work by Lee, et al. [10], Frottier et al. [11] highlighted that unique carbonyl chemistry is occurring in the TRZ, where operating conditions could affect the TRZ liquid. More recently Splitter et al. [12] also showed through direct sampling that much of the fuel retained in the TRZ is of elevated boiling point, dominated by aromatics in the fuel used in that study.

It is known that gasoline direct injection (GDI) systems can exhibit wall-wetting effect due to the in-cylinder fuel delivery, however wall wetting is not unique to GDI engines. When wall wetting occurs, fuel interacts with the linear and associated lubricant though piston motion and is retained in the oil at the wall and mixed within the TRZ. Of critical importance to SPI is that the resultant mixture might be able to react when given pressure and temperature conditions are reached during the compression stroke according to the literature [9-14]. This is of critical importance to understanding SPI as ejected TRZ liquid is thought to be a leading theory of an ignition source for SPI [15]. Despite it is known that fuel dilution plays a key role on the onset of SPI, there is not a robust technique when it comes to measuring fuel retention while the engine is being operated.

These studies highlight the importance of the fuel, lubricant, and associated TRZ liquid in influencing SPI and the associated potential of transition from deflagration to a detonation which can result in engine damage. Consequently, to avoid SPI engine calibration must reduce the downspeeding and downsizing potential of boosted SI engines [16] and limiting fuel economy improvement potential. To reduce SPI it is thought that fuel-linear impingement must be known as a function of operating condition and correspondingly reduced though calibration, design, and or fuel property changes. The present work shows the potential of a novel LIF optical diagnostic tool using the latest chemometrics based approach applied to a single-cylinder engine (SCE) to explore the fuel retention under a broad range of engine load and injection timings. The novelty of this work is that the fuel-in-lube dilution measurements can be performed in a minute-time scale with an excellent accuracy and precision. The laser-induced fluorescence (LIF) optical diagnostic tool has been developed by Neupane et al. [17-19] at Oak Ridge National Laboratory (ORNL) for real-minute fuel-in-oil (FiO) dilution on-engine measurements. The FiO instrument has been used in the present work to evaluate the impact of fuel-wall interactions at SPI prone conditions [20]. FiO instrument measures dye not fuel. Measurements in [20] highlight that that dye is transported with the fuel to the linear, where the dye remains but it is possible that fuel or fuel species could evaporate or partially evaporate from the wall.

The present work couples the LIF diagnostic with dedicated engine tests to evaluate the fuel retention rate in a light-duty SI engine with three fuels of varying distillation and chemical composition. Tow injection timings are explored one that targets the piston and one that targets the linear. The engine is operated at SPI prone conditions, and the effects of FiO, and SPI rate for the various fuels are analyzed to indicate fundamental processes underlying SPI propensity. The results highlight that fuel properties and in-cylinder fuel delivery are critical factors affecting SPI rates.

2. Methods / Experimental

Fuel in Oil Diagnostic

An schematic and details of the FiO instrument can be found in Sneha et al. [17-20]. the FiO technique uses a dye (Model TP-3400, Tracerline) which has fluorescence properties observable independent of fuel and lubricant composition, where the dye is a hydrocarbon mix that is miscible in both fuel and lubricant. It has been widely used by the industry in internal combustion engines for leak detection, not being potentially harmful for the hardware. In addition, internal measurements have verified that the dye has no measurable effect on the fuel properties (within uncertainty of ASTM standards) when using a range of dye between 50-500ppm on mass. In particular, 75ppm concentration has been used and added to the fuels in the present investigation.

Engine

A single cylinder engine (SCE) was used in the present work to carry out the experimental campaign. The SCE has derived from a light-duty production engine GM 2.0L ECOTEC LNF. Significant detail on the setup is provided in [20], where the transformation is possible through the deactivation of three of the four cylinders of the engine. In all experiments in the present work, the engine was operated at 2000 r/min with a 35°C intake temperature with lambda 1 exhaust conditions (ECM EGR 5220). The lambda provided to the engine was also calculated simultaneously by using the air mass flow of the air aforementioned and the Coriolis-based fuel flowmeter (Micro Motion ELITE CMF010P), and intake mass flow controller (ALICAT2000 SLPM) using a carbon balance-based approach. Exhaust backpressure is controlled by a backpressure valve (Flowserve Series 75) installed downstream the surge tank, maintaining constant positive ΔP of 15kPa between intake and exhaust pressure when running SPI conditions (intake pressure maintained higher than exhaust). This replicates boundary conditions relevant to the turbocharging system of the production engine with a combined turbocharger efficiency of 35% during the set of experiments [21].

Fuel supply was performed by using a low-pressure pump to supply the production GDI fuel pump in the SCE with a low-pressure lift pump suppling the fuel to the stock GDI pump. The SCE was cooled from an external coolant pump and maintained at 90°C during the experimental campaign. The SCE lubrication system has been heavily modified form stock by employing a dry sump oiling system. The retrofit system maintained the stock oil pump, but the oil sump was moved external to the engine and the volume was increased to 3 gallons capacity the system pumps crankcase oil from the engine to the external reservoir via a 2-stage scavenge pump driven by the engine crankshaft. The dry-sump system was used to increase the FiO sensitivity of the equipment. Moreover, this system enables the use of two FiO probes simultaneously to access to the oil flow that comes and goes from the engine, as it is observed in the layout of the engine set up which can be found with greater detail and schematics in [20]. In the scavenged oil from the engine a 2-satage deaeration process was used by installing 2 centrifuges (Spintric III) in series. Deaeration of the oil flow becomes critical for the FiO instrument since the excess of air in the oil flow affects the signal. Hence, the probe for the instrument was installed after the second deaeration stage (lube returning from the engine) and between the reservoir and the oil pan (oil flowing towards the engine) as it can be observed in the layout.

All pertinent control of the engine was conducted by National Instruments (NI) software. The software has the engine control package with the associated Combustion Analysis Toolkit (DCAT) tool. Data was acquired by using the DAQ from the same NI software supplier. Pressure traces were measured by a Kistler

6125C pressure transducer, engine speed was acquired by an AVL encoder (365C01) with a crank resolution of 0.2°CA.

Fuels and Lubricant

The experimental campaign conducted in this investigation used Mobil 1 5W30 SN grade lubricant. To ensure the quality of the FiO signal when running the experiments, the oil and filters were changed for every set of segments performed. This procedure will guarantee starting with fresh fuel for every case run, without fuel and dye traces from previous operating conditions. Three fuels have been used in the present investigation. The fuels used are low Aromatic – Low Distillation, Low Aromatic – High Distillation and High Aromatic – High Distillation hereafter referred as LALD, LAHD and HAHD respectively. Most relevant fuel properties are shown in Table 1. Note, an additional property that is subject of study in the present work is the particulate matter index (PMI). The fuels selected present a wide range of PMI ranging from 0.6 to 2.2. The fuels were each doped with 75ppm by mass with dye (Tracerline TP-3400), specially designed and marketed for engine leak detection and used as the tracer for the FiO diagnostic.

Table 1. Fuel properties

	Low Aromatic-Low Distillation (LALD)	Low Aromatic-High Distillation (LAHD)	High Aromatic-High Distillation (HAHD)
RON [-] (ASTM D2699)	89.7	90	89.6
MON [-] (ASTM D2700)	85.1	85.4	83.5
S [-] (RON – MON)	4.6	4.6	6.1
IBP [°C (°F)] (ASTM D86)	33.4(92)	31.8 (89.2)	34.3(93.7)
T10 [°C (°F)] (ASTM D86)	56.3(133.3)	68.7(155.7)	71.8(161.3)
T50 [°C (°F)] (ASTM D86)	87.3(189.2)	118.7(245.7)	129.2(264.5)
T90 [°C (°F)] (ASTM D86)	122.9(253.3)	172.7(342.8)	172.4(342.4)
FBP [°C (°F)] (ASTM D86)	160.7(321.2)	198.4(389.1)	194.3(381.8)
C [wt%]	84.9	85.18	86.13
H [wt%]	15.1	14.82	13.87
O [wt%]	0	0	0
LHV [MJ/kg]	44.170	43.920	43.220
Aromatics [%]	6.9	8.1	26.3
Saturates [%]	87.1	86.7	67.8
Olefins [%]	6	5.2	5.9
Ethanol [%]	0	0	0
Particle Matter Index (PMI)	0.6	1.3	2.2

Combustion Analysis

Combustion analysis was carried out by using an in-house made MATLAB routine. The routine calculation is in-cylinder pressure based and resolves the calculation after applying a zero-phase filtering and a phasing against the crank position every cycle. The stock cam profile is used to resolve the trapped residuals following the approach proposed by Cavina et al. [22] on a cycle-to-cycle basis. This approach enables to consider the effects of using EGR, however, EGR was not used in this study. In-cylinder losses were calculated by using two models. Thermal losses were accounted following the approach proposed by Woschni et al. [23] and the losses coming from the crevices volume were accounted by using the approach proposed by Gatowsky et al. [24]. Finally, it is worth to note that these subroutines were applied in series to resolve the heat release rate. Top dead center (TDC) is based on the shape of the heat release rate when motoring the engine and was estimated by using the approach proposed by Tunestål et al. [25]. Heat loss power through the walls is assumed constant during motoring at the vicinities of the TDC, and it was verified to work excellent by using a magnetic proximity probe (AVL OT-SENSOR 428) and showing good level of agreement.

SPI Characterization

The combustion analysis was updated with a dedicated subroutine for SPI events identification, resolving all the metrics and statistics required for such study. In this subroutine, potential SPI cycles were identified analyzing every cycle by using the approach proposed by Mansfield et al. [26], using a threshold for statistical significance of at least 4 standard deviations from the mean in onset of crank angle of 2 percent mass fraction burned (CA02). The total number of SPI events also includes those that happened in a cluster, being defined as SPI events that occur by no more separation than 3 cycles.

Operating conditions

All experiments were performed at 2000r/min and at 185kPa of boost pressure. ΔP of the intake and exhaust surge tank pressures was maintained constant at 15kPa between intake and exhaust, with the intake higher than the exhaust. Two different start of injection (SoI) timings were used in this study, 310°CA bTDC and 220°CA bTDC.(wall wetting) 310°CA bTDC (piston wetting/smoke) [20,27]. Regardless of the SoI timing explored, the combustion CA50 was held constant at 33°CA aTDC for all the operating conditions by adjusting spark as needed. The SPI experiments were run using a set of 10 square-waved segments in automated operation. Each segment consisted of 5 minutes at low-load (5bar IMEPg) operation and 25 minutes at high-load (18.5bar IMEPg) operation. During high-load operation, first 5000 cycles were discarded from the analysis due to the transient behavior. Recording such a high number of cycles (20,000 cycles per segment) is made to ensure enough data for accurate statistical analysis.

3. Results and Discussion

Results in Figure 1 clearly illustrate that SPI dependency on FiO rate is injection timing dependent. Primarily when fuel injection timings are at the 310 SOI conditions, both FiO rate and SPI activity are simultaneously reduced. Moreover, there appears to be no appreciable trend in SPI with FiO rate at this injection timing. Note that as shown in [20] this injection timing results in the spray targeting the piston and not the cylinder wall. This results in reduced FiO measured. Therefore, the results in Figure 1 highlight that SPI has little to no activity or dependency on FiO rates when the spray is not targeting the wall.

Conversely, the results in Figure 1 highlight that when the fuel targes the wall, at the 220 SOI conditions, SPI has a dependency on FiO rates. Interestingly the confidence on the linear trendlines for both the 310 and 220 SOI conditions are nearly identical suggesting that the observations are of near equal merit.

Interestingly the although the SPI rates of the 310 SOI condition were dramatically reduced, the SPI magnitudes and activity on a per-event basis were relatively similar. That is, the events were not smaller in magnitude overall regardless of there being reduced FiO rates and wall wetting. Figure 2 shows the maximum peak cylinder pressure (PCP) and the maximum peak-to-peak measured knock intensity (KI) of the accounted SPI events for all 200,000 cycles per fuel/condition. The solid line in Figure 2 represents the mean value of condition and the symbols show each respective measurement. Except for the HAHD 310 case, the PCP is above 225bar for each fuel/condition. It is worthy to note that the maximum PCP was limited to 300 bar because of the charge amp settings used in the experiment causing saturation at 300 bar. The KI show high values for almost every case run. The reason for such higher values of PCP and KI is not a dependency on the ignition source of the fuel as much as it appears to be on the relatively low RON of these fuels and reduced knock resistance and large end-gas ignition in SPI events. These results align with literature as stated Kalghatgi et al. [15,28].

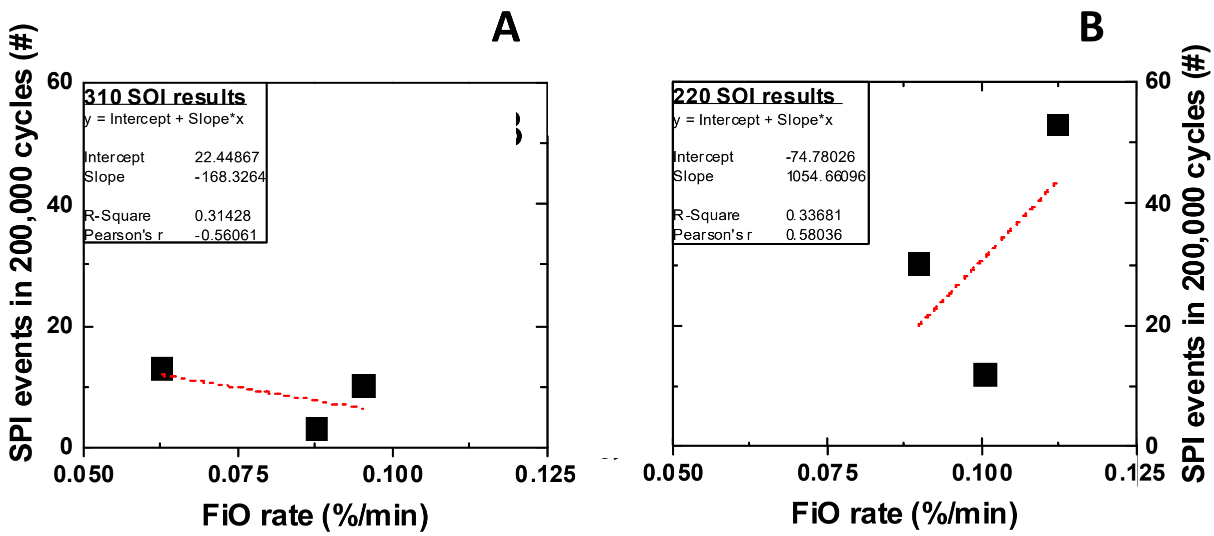

Figure 1. SPI event count as a function of FiO rate for 310 SOI injection (A) and 220 SOI injection (B), linear trendlines added in dashed red.

Clearly the trends in Figure 2 illustrate that the magnitude of the events has no observable direct correlation on the fuel composition and could be more related to the RON of the fuels being identical. However, the dwell of SPI events developing in Figure 3 does show a potential dependency on fuel properties. Specifically, the higher distillation, LAHD fuel and higher aromatic content fuel, HAHD fuels show increased CA5 to CA50 times. It is well known that this portion of combustion is well correlated with flame speed, as shown in [29] on the same engine configuration as the present work. Moreover, the effect of fuel distillation on mixing is possible in the 220 SOI conditions as the heavier fuels appear to have increased combustion durations suggesting that there could be reduced mixing at that condition and potentially increased inhomogeneity in the charge.

The resulting observations on SPI highlight that conditions with reduced flame speed and increased inhomogeneity tended to have increased dwell times, that is longer durations form the onset of SPI to maximum cylinder pressure. This result complements previous work by Jatana et al. [30] that showed the potential for flame speed dependency on SPI, while the current results also highlight the potential for fuel dependent mixing differences and charge inhomogeneity playing another critical role.

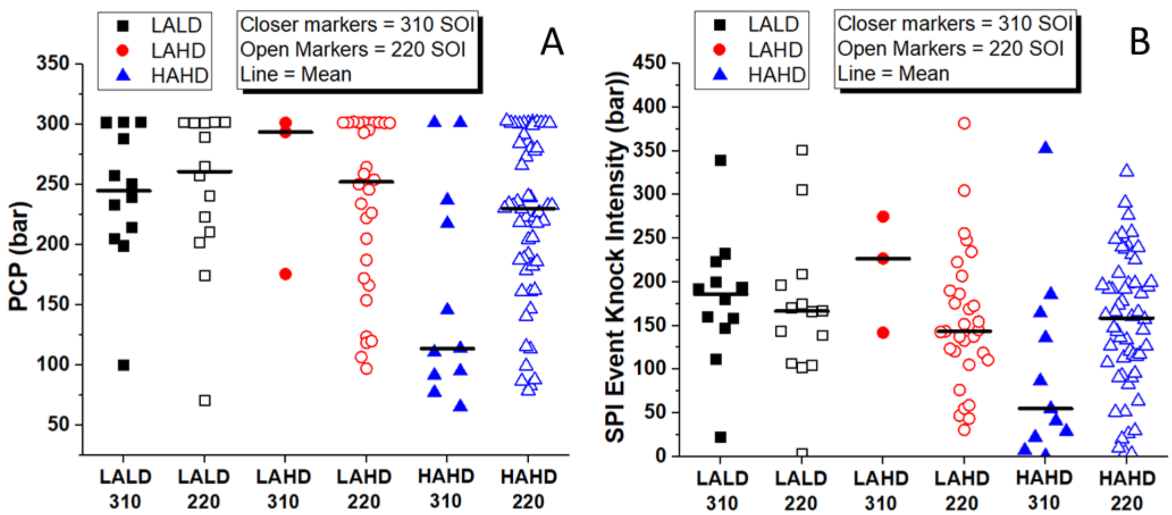

Figure 2. Peak cylinder pressure of the cycles identified as SPI events (A) and knock intensity of the cycles identified as SPI events (B).

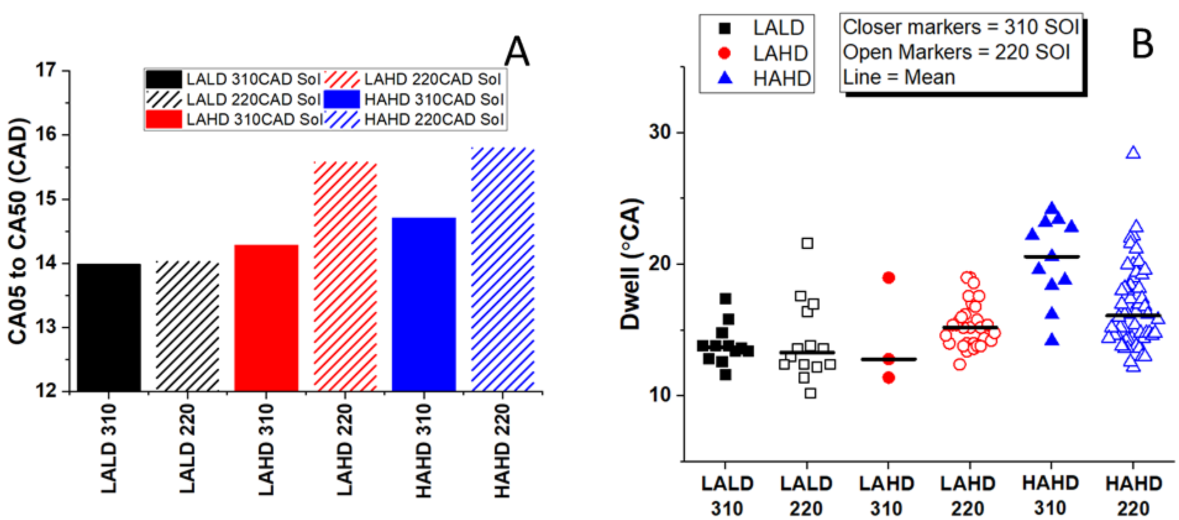

Figure 3. Peak cylinder pressure location (A) and dwell of the SPI events identified at each of the cases studied(B).

Discussion

The effects of mixing and fuel distillation on SPI are directly evident in Figure 4A where FiO and the measured lambda provided to the engine are compared with the SPI rates. The measured lambda (λ_{mass}) is the lambda value calculated from the measured fuel flow and airflow rates. Note that in all experiments the engine is operated with a constant exhaust lambda of 1.00±0.01; therefore, any difference in fueling required form "lost" fuel to the crankcase or elsewhere will be evident in the λ_{mass} value being less than 1.

Clearly in Figure 4A for injections that target the wall (220 SOI), there is a trend in λ_{mass} decreasing when fuel distillation, while when the fuel injection targets the piston (310 SOI) there is no appreciable trend in

λ_{mass} with fuel distillation. Upon first inspection, this result seems almost counter intuitive as the FiO measurements of the 310 SoI condition show stronger correlation with distillation temperature than the 220 SOI results. The reason for this apparent anomaly is believed to be complex. Specifically, at the 220 SOI condition results in Splitter et al. [20] showed that for volatile fuels there is a stronger possibility of retarded injection timing resulting in increased FiO rates, a result of spray collapse and fuel vapor pressure effects. In the present work this is thought to also be observed in the LALD fuel as it shows strong injection timing dependency on FiO rates, where retarded injection timing increases FiO rates. However, there is no correction with this increased FiO rate and an increase in SPI rates, in fact the for the LALD fuel with increased FiO rate the SPI rate decreased by 1 event. Also, note for the LALD fuel regardless of the SoI timing or FiO rate the λ_{mass} value is constant. This suggests that the LALD fuel is sufficiency volatile to evaporate off the wall and mix when it impinges. This results in reduced fuel lost to the crankcase and improved homogeneity of the charge. This observation is critical to understanding the sources of SPI. Note, that the FiO measured dye and not the fuel itself. Thus, interpreting the FiO measurement as crankcase fuel is not entirely accurate.

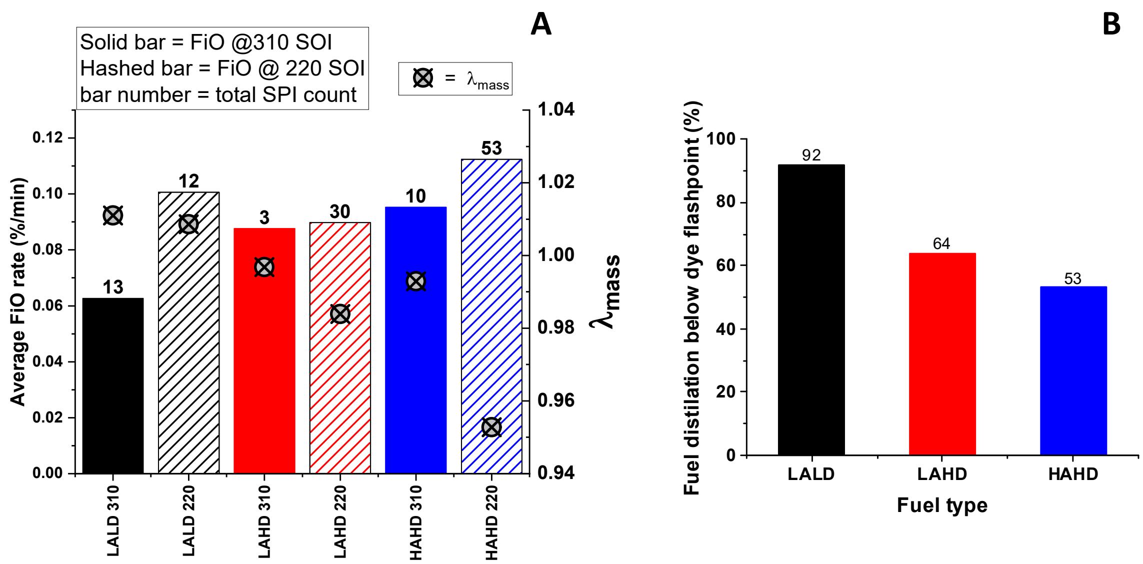

Figure 4. FiO rate, λ_{mass} and SPI event count for all conditions (A) and integrated fuel distillation relative to the dye flash point (B), results highlight fuel flash and dye retention differences that correlate with SPI rates and injection timing

This hypothesis and observation are directly applicable to the LAHD and HAHD fuels as they have increased distillations and clearly show that the FiO rate is less dependent (due to reduced spray collapse effects) on but that the λ_{mass} are directly dependent on SOI timing, where retarded injection timings increase crankcase fuel dilution. Thus, for the more volatile LALD fuel, if fuel impinges on the linear or piston it at 220 or 310 SOI respectively the fuel could evaporate more fully and mix resulting in reduced sources of SPI, while the dye was unable to (dye flashpoint is 135°C). However, for the LAHD and HAHD fuels the increased distillation of these fuels reduced the ability for the fuel to flash off the engine surfaces, especially at the retarded 220SOI timing, resulting in increased inhomogeneity, increased fuel dilution, and thus increased sources for SPI to occur for top ring zone liquid at the 220 SOI timing.

Lastly, the observed effect of volatility on SPI and deconvolving dye evaporation for fuel evaporation is evident from Figure 4B, which shows the percentage of fuel evaporated at the flash point of the dye. Clearly the LALD fuel is nearly fully evaporated by the dye flash point (92% of the fuel is evaporated), where the LAHD and HAHD fuels have much less fuel evaporated at the dye flashpoint, 64% and 53% respectively, highlighting that the FIO rates are more closely indicative of fuel retention in the higher distillation fuels.

4. Conclusions

The present work has indicated that fuel wall impingement and fuel volatility are critical factors influencing SPI rates. Specifically fuel retention, inhomogeneity, and fuel injection timing. The major findings of the present work are as follows:

- The FiO diagnostic was able to illustrate when fuel impacted the wall and there could eb associated fuel effects on SPI.
- FiO and SPI only seemed to be correlated when the fuel spray was targeting the linear and not the piston.
- The difference between FiO and λ_{mass} indicated if impinged fuel was able to evaporate from impinged surfaces.
- When impingement and fuel retention was the highest the combustion inhomogeneity was the highest and there was increased combustion duration and SPI dwell times.
- The magnitude of SPI events in both KI and PCP had no correlation with the fuel composition.
- Cases with the highest impingement and strongest λ_{mass} effects had the highest SPI rates, this corresponded with the highest fuel distillation and aromatic contents.
- Fuel injection timings has a strong influence FiO more volatile fuels.

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