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A fundamental investigation into the relationship between lubricant composition and fuel ignition quality

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ABSTRACT

A fundamental experiment involving the use of an ignition quality tester (IQT) was carried out to elucidate the effects of lubricant oil composition which could lead to low speed pre-ignition (LSPI) processes in direct injection spark ignition (DISI) engines. Prior to the IQT tests, lubricant base oils were analyzed using ultra-high resolution mass spectrometry to reveal their molecular composition. High molecular-weight hydrocarbons such as $nC_{16}H_{34}$, $nC_{17}H_{36}$, and $nC_{18}H_{38}$ were selected as surrogates of lubricant base oil constituents, and then mixed with *iso*-octane (iC_8H_{18}-gasoline surrogate) in proportions of 1 vol.% (iC_8H_{18} = 99 vol.%) and 10 vol.% (iC_8H_{18} = 90 vol.%) for the IQT experiments. In addition, lubricant base oils such as SN100 (Group I) and HC4 and HC6 (Group III) and a fully formulated lubricant (SAE 20W50) were mixed with *iso*-octane in the same proportions. The IQT results were conducted at an ambient pressure of 15 bar and a temperature range of 680–873 K. In the temperature range of 710–850 K, the addition of 10 vol.% base oils surrogates, base oils, and lubricating oil to the 90 vol.% iC_8H_{18} reduces the average total ignition delay time by up to 54% for all mixtures, while the addition of 1 vol.% to 99 vol.% iC_8H_{18} yielded a 7% reduction within the same temperature range. The shorter total ignition delay was attributed to the higher reactivity of the lubricant base oil constituents in the fuel mixtures. A correlation between reactivity of base oils and their molecular composition was tentatively established. These results suggest that the lubricants have the propensity of initiating LSPI in DISI engines. Furthermore, similar results for *n*-alkanes, lubricant base oils, and fully formulated commercial lubricants suggest that it is the hydrocarbon fraction that contributes primarily to enhanced reactivity, and not the inorganic or organometallic additives.

1. Introduction

Downsizing strategies are being employed in direct injection spark ignition (DISI) engines to improve fuel economy and reduce emissions. Reducing engine displacement allows lower part-load operating conditions to shift into positions of the operating map with higher efficiency and lower specific fuel consumption [1]. As a result maximum power in full-load operation decreases, so DISI engines are either supercharged or turbocharged to achieve higher specific loading compared to naturally aspirated engines. This reduces frictional losses, vehicle weight, and pumping losses, leading to an 12–16% improvement in fuel economy compared to naturally aspirated engines [2]. Despite the benefits of downsizing, a major challenge is pre-ignition occurring at low engine speeds (under 3000 rpm) and high loads in the BMEP range of 10–20 bar and above. According to Kalghatgi and Bradley [3], pre-ignition in DISI engines, which could be related to fuel/air autoignition, is an abnormal phenomenon that causes the cylinder pressure to increase above the compression pressure before the spark plug fires. If pre-ignition occurs in the end gas at high pressure and temperature, it can lead to extremely heavy knock and subsequently damage the engine. The causes of pre-ignition are numerous. Earlier studies in the 1950s reported that as a result of improvements in octane numbers and increases in compression ratio, pre-ignition was initiated by hot combustion chamber deposits on the spark plugs and/or valves [3]. Recently, Kalghatgi and Bradley [3] added that pre-ignition could be caused by residual

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Nomenclature

Abbreviations

API	American Petroleum Institute
CN	cetane number
DISI	direct injection spark ignition
FTICR-MS	Fourier transform ion cyclotron resonance mass spectrometer
HP-DSC	high pressure differential scanning calorimetry
IQT	ignition quality tester
LSPI	low speed pre-ignition
SoIgn	start of ignition
SoInj	start of injection
iC_8H_{18}	*iso*-octane
max (dP/dt)	maximum change in pressure with time
m/z	mass to charge ratio
$nC_{16}H_{34}$	*n*-hexadecane
$nC_{17}H_{36}$	*n*-heptadecane
$nC_{18}H_{38}$	*n*-octadecane

gases or particles creating hot spots, higher pressures, and/or higher temperatures. Dahnz and Spicher [4] provided a comprehensive and exhaustive list of the factors that could initiate pre-ignition in DISI engines. Of all the factors, it was reported that the main cause of pre-ignition is the occurrence of highly ignitable droplets of lubricant oil in the combustion chamber, as opposed to only surface ignition (i.e., hot spark plugs and valves). It was further reported that these droplets are released during the deceleration phase before the piston reaches top dead center. Surface tension was found to be the main factor influencing droplet release from the oil wiped off form the crank case liner during the compression stroke. In a further work, using a similar set up as Dahnz and Spicher [4], Palaveev et al. [5] reported that spray/lubricant interactions can lead to pre-ignition. However, it was observed that engine modifications enhancing chemical reactions have little or no influence on pre-ignition. Okada et al. [6] used optical techniques to visualize the in-cylinder state before the start of low speed pre-ignition combustion and observed the behavior of particles, which are thought to be the ignition source. They injected deposit flakes and other combustible particulate substances into the combustion chamber. It was observed that these particles require at least two combustion cycles to reach a glowing state that becomes an ignition source. Furthermore, deposits peeling form combustion chamber walls were identified as a new mechanism leading to pre-ignition. Their experiments further clarify the work done by Dahnz and Spicher [4] in explaining the low speed pre-ignition (LSPI), which could occur by dilution of lubricant oil in the bulk mixture composition in the DISI chamber. Takeuchi et al. [7] observed that engine oil formulations have significant effects on LSPI. It was found that the spontaneous ignition temperature of engine oil, as determined using high pressure differential scanning calorimetry (HP-DSC) correlates with LSPI frequency in a prototype turbocharged DISI engine. It was further observed that the oxidation reactions of the oil are an important factor for LSPI. Amann and Alger [8] performed a fundamental study using an ignition quality tester (IQT) to investigate the reactivity of different types of lubricants. By using an IQT, they observed that unconventional oil formulations and additives lowered the lubricant reactivity while maintaining lubricating properties. They further used a single cylinder variable compression ratio (VCR), naturally aspirated, spark ignition engine to further justify their claims. It was observed that lubricants with low combustion reactivity allowed the engine to be operated with improved combustion phasing and higher geometric compression ratio, and this further enabled the engine to operate at a higher efficiency without LSPI. From these previous findings, it is clear that lubricants play a vital role in the LSPI process in DISI engines. Amman and Alger [8] reported that the main constituents of lubricants are lubricant base stock (about 90 vol.% and above) with various additives to reduce friction wear, decrease oxidation tendencies and modify viscosity. They further grouped lubricant base-stocks using the American Petroleum Institute (API) classification, as shown in Fig. 1.

In order to develop upon previous research, this study involves carrying out fundamental experiments using an IQT to investigate the ignition propensity of selected base oil surrogates, real base oils, and real lubricants. Results from this fundamental research provide information on the effects of lubricant formulation on pre-ignition in DISI engines. To the knowledge of the authors, no systematic work has been done on the effect of the composition of lubricant base oils on pre-ignition, and the present work is intended to fill this gap.

2. Experiment

2.1. Ignition quality tester (IQT)

A fundamental experiment has been performed by using an ignition quality tester (IQT) to investigate the effect of lubricants on ignition propensity of gasoline-like fuels. The IQT machine can reasonably reproduce thermodynamic conditions in production DISI engines. Fig. 2 shows the IQT (Advance Engine Technology Ltd.) used in the present study. Details on the IQT can be found in the American Society for Testing and Materials (ASTM) method D6890-08 [9], and has been reported by Bogin and co-workers [10] as a constant volume combustion system with a fuel injection system designed for the direct measurement of ignition delay of liquid fuel sprays.

The IQT has a volume capacity of 0.21 liters and variable experimental parameters, such as the initial charge air temperature and pressure, chamber wall temperature, and mass of fuel injected. The inner part of the IQT chamber is heated by electrical heaters embedded in the outer wall of the steel combustion chamber. An initial charge temperature of about 818 K close to the nozzle tip and 873 K near the middle of the chamber can be maintained. An ambient pressure of 1.5 MPa was maintained in the IQT, which is similar to the pressure achieved in a typical turbocharged DISI engine. After initial heating, a temperature range of 680–873 K was achieved in the IQT by switching off the electrical heater. This was done in order to obtain ignition delay data over a wider range of temperature. For the fuel injection system, a pneumatically driven mechanical fuel pump and a single-hole S-type delayed inward opening pintle nozzle injector was utilized, which has an orifice diameter of about 700 μm. The fuel was injected by a variable displacement pump, which has a capability of injecting fuel at a wider range of temperatures. A pressure transducer is installed at the end of the combustion chamber to measure the pressure rise during a combustion event. The high speed needle lift and pressure signals were simultaneously measured at a sampling rate of 50 kHz. Three thermocouples were used to measure the skin, air-back, and air-front temperatures inside the IQT chamber.