

Influence of Crankcase Oil Properties on Low-Speed Pre-Ignition Encountered in a Highly-Boosted Gasoline Direct Injection Engine

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ABSTRACT

This paper reports an experimental investigation on the influence of the crankcase oil properties on the engine combustion in the low-speed pre-ignition (LSPI) zone. The investigation was conducted on a highly boosted 1.5L TGDI engine operated at the low-speed-end maximum torque, at which LSPI events were observed most frequently. Six different engine oils were tested, covering SAE 0W-20, 0W-30, 0W-40, 5W-20, 5W-30 and 5W-40. In order to evaluate the evaporative characteristics of the crankcase oil, for each of the selected engine oils, the tests were conducted at two different coolant temperatures, 90°C and 105°C. Because SAE 5W-30 was the base oil for the engine under study, for this particular oil, the investigation was extended to the impact of different levels of the mixture enrichment. Followings were found: 1) LSPI events were observed when the engine was operated with a stoichiometric mixture for all the oils tested. 2) No clear indication on which SAE oil tested had a stronger influence on LSPI than other oils, either promoting or inhibiting LSPI, because the influences on LSPI of the related oil properties might not be as strong as that of the high gasoline content in the oils, which reached about 6% in the tests. 3) Behavior of LSPI was random in all the tests and a particular LSPI pattern observed in a test was difficult to be reproduced under the same condition. This suggests that LSPI may be triggered at a complicated condition with contributions from many variable parameters. It may be meaningful to characterize the behavior of LSPI with a statistical approach.

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INTRODUCTION

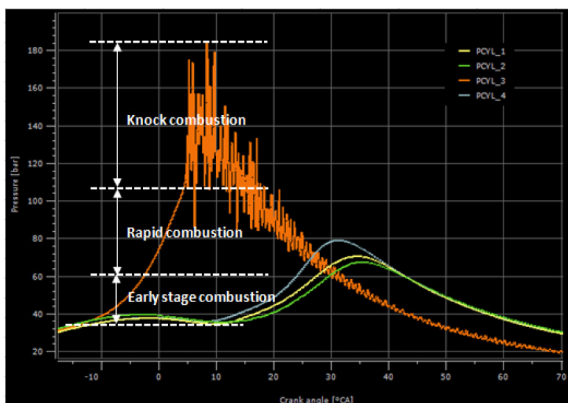


Figure 1. A section of cylinder pressure traces for normal and super-knock combustion for a highly-boosted 1.5L TGDI engine at 1500 rpm.

For turbo-charged gasoline direct injection (TGDI) engines with homogeneous mixture combustion, pre-ignition (PI) is frequently encountered, typically at speeds < 2500 rpm and brake mean effective pressures (BMEP) ≥ 15 bar. This abnormal combustion is known as low-speed pre-ignition (LSPI). Since PI occurs much earlier than the spark timing for normal combustions, it often leads to severe knock combustion. This abnormal combustion may be characterized with three stages: early-stage combustion triggered by PI, rapid combustion, and severe knock combustion with huge pressure

fluctuations as shown in Figure 1. Since the pressure fluctuations during the knock combustion are on the same order of magnitude for the peak firing pressures (PFP) in normal combustions, the PI induced abnormal combustion is also termed as the super knock.

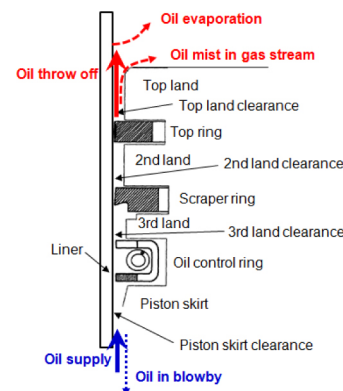


Figure 2. Illustration of oil transport through piston-liner clearance

The cause for LSPI is widely believed to be due to the liquid particles of the crankcase oil entering the engine cylinder [1, 2, 3, 4, 5, 6, 7, 8, 9]. For TGDI engines, the oil enters the cylinder mainly in two ways: as the oil transport through the piston-liner clearance and as the oil loading in the blowby recirculation or the oil carryover. Figure 2 illustrates the oil transport mechanism proposed by Yu and Han [10] for oil entering the engine cylinder through the piston-liner clearance in

three ways, i.e., oil throw-off by the piston motion, the oil mist in the reverse gas flow when the cylinder pressure becomes lower than that in the ring grooves, and evaporation of the oil wetted the cylinder wall. The oil throw off and the oil mist in the reverse gas are related to the piston motion and thus may be combined as the oil transport. According to the test results of Yilmaz, the oil transport increases with the engine speed; at a given engine speed, the oil transport decreases with the engine load as a result of increase in oil evaporation from the cylinder wall [10]. This suggests that the oil transport may not be a unique characteristic for the low-speed and high-load operations where LSPI is encountered.



Figure 3. Hydrocarbon fouling on the back and stem of the intake valves due to liquid oil particles carried by blowby recirculation.

For highly boosted TGDI engines, the blowby recirculation reaches its maximum in the LSPI zone on the engine speed-load map [11]. Due to a high level of fuel dilution of the crankcase oil in the LSPI zone [12], the crankcase oil becomes highly volatile and, as a result, considerable liquid oil particles are carried by the blowby recirculation and burned in the engine cylinder as part of the oil consumption. After being cooled at the intercooler, small liquid oil particles may coalesce and form large and more viscous liquid oil particles. Figure 3 shows a phenomenon of hydrocarbon fouling or carbon deposits on the back and stem of the intake valves due to the liquid oil particles in the blowby recirculation for a 1.5L TGDI engine tested by the present authors. Considerable carbon deposits were built up on the backs and stems of the intake valves after the engine was operated at low speeds and high loads for a certain period of time. As the liquid oil particles landed on the intake valves and intake ports, some large and viscous liquid oil particles in the blowby recirculation could also land on the combustion chamber roof during scavenging, which is used as a method for boosting the low speed torques in almost all TGDI engines for [11,12]. Based on the blowby flow rates in the scavenging zone and the characteristics of the liquid oil particles in the blowby recirculation, the number of liquid oil particles entering the engine cylinder as the oil carryover is estimated on orders of $10^7 \sim 10^8/\text{cycle}$ for each cylinder [11]. Due to the cooling in the intercooler, the liquid oil particles entering the engine cylinder become less volatile and thus more easily land on the combustion chamber roof with an assist of the air short circuiting flow from the intake ports to the exhaust ports during scavenging. If they are not fully vaporized in the compression stroke, then these liquid oil particles could become the triggers for LSPI.

The influence of the additives in the oil has been studied by many investigators [e.g., 13, 14, 15, 16, 17, 18, 19, 20]. Most of these investigations were focused on the oil-soluble metals added into the oil as the detergents. According to these studies, the impacts on LSPI of the oil additives can be classified as promoters, quenchers, or

neutral (no effect). Based on our tests on three different highly boosted TGDI engines (1.5L/1.8L/2.0L) all lubricated with 5W-30 synthetic oil, LSPI is seldom encountered in a new engine with fresh oil, but it is unavoidable for the engines operated for a long period of time, especially with the contaminated crankcase oil and the contaminated intake system. This indicates that the engine condition and the levels of the oil as well as the intake system contaminations have a significant impact on LSPI. In a previous SAE paper [12], we investigated the effect on LSPI of the fuel dilution of the crankcase oil. The aim of this investigation is to understand the influence on LSPI of the crankcase oil with different SAE viscosity grades. Six different market available engine oils were tested with the same engine at the same load point. The oils tested covering SAE 0W-20, 0W-30, 0W-40, 5W-20, 5W-30 and 5W-40 from two different international oil suppliers.

TGDI ENGINE UNDER STUDY

The engine under study is an inline 4-cylinder 1.5L TGDI engine fueled with RON93 gasoline. The basic engine parameters are presented in Table 1. The engine is equipped with a high-efficiency, waste-gated turbo charger and dual cam-phasers allowing both intake and exhaust cams to shift up to 60 deg-CA with respect to their home positions independently. The engine is highly boosted and has a flat torque curve with low-end speed at 1500 rpm and high-end speed at 4600 rpm. Figure 4 shows the engine torque and power curves normalized with their peak values. The side-mounted fuel injector has 6 orifices, with the maximum injection pressure being 150 bar. The fuel spray targets on the piston top are illustrated in Figure 5.

Table 1. Basic parameters for the TGDI engine under study.

Engine configuration	I4
Engine displacement	1.5L
Bore	79 mm
Stroke	76 mm
Compression ratio	9.5:1
Number of valves per cylinder	4
Fuel injection equipment	Direct injection
Max injection pressure	150 bar
Injector mounting	Side mounted
Fuel	RON93 gasoline
Turbo flow control	Waste gate

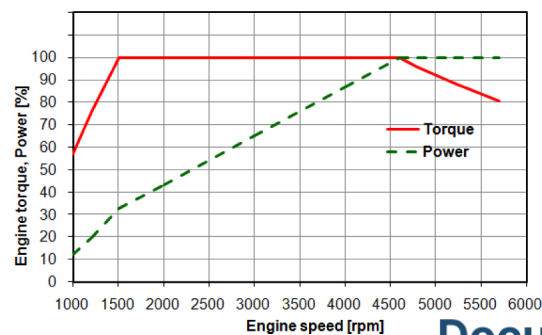


Figure 4. Torque/power curves for TGDI engine under study.

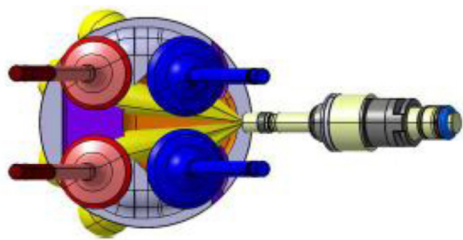


Figure 5. Side-mounted fuel injector and the spray targets.

The base engine oil is SAE 5W-30 synthetic oil with high temperature and high shear performance. Selected physical properties given in the oil specification are presented in Table 2. Figure 6 shows the distillation curve for the RON93 gasoline used in the engine tests. The oil temperature range for the engine operations is shown in the shaded area for a reference. It is seen that for oil temperatures greater than 140 °C, up to 25% of the gasoline entering the oil may remain in the oil in case of fuel dilution, which is unavoidable in TGDI engines.

Table 2. Selected properties of engine crankcase oil.

Oil grade	5W-30
Density @ 15 °C [kg/L]	0.852
Viscosity @ 100 °C [cSt]	11.7
Viscosity @ 40 °C [cSt]	67.5
Total base number TBN [mg-KOH/g]	10
Flash point [°C]	229
Noack volatility @ 250 °C [wt%]	< 10

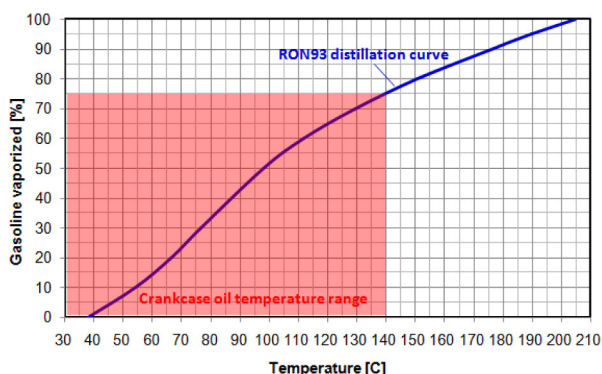


Figure 6. Distillation curve for Chinese RON93 gasoline.

CONDITION FOR LIQUID OIL PARTICLES IN CYLINDER TO BECOME AN IGNITER

Figure 7 illustrates a process for a liquid oil particle in the engine cylinder to ignite the air-fuel mixture. Flash point of the oil is the temperature at which the oil gives off vapors that can be ignited with a flame held over the oil if the oxygen required by the flame is available. Flash point can be used as a measure for the oil volatility [21]. Fire point of the oil is defined as the lowest oil temperature at which the oil vapor produced enables supporting combustion once being ignited. In comparison to gasoline, the engine lubrication oil is a fluid with high boiling point and high auto ignition temperature, with the values for these two characteristic temperatures being very close. Flash point, fire point and boiling point are properties for the

liquid oil, but the auto ignition temperature is a property of a combustible gaseous mixture. Figure 8 shows the values of fire point, flash point and viscosity at 100 °C for different SAE viscosity grade oils reported in the literature. Note that flash point and fire point for the engine oils are their high-temperature properties, and thus for two-grade SAE oils these properties are similar to those of the corresponding summer-grade oils. In general, the higher viscosity grade the SAE oils, the lower the oil volatility, and the higher the flash and fire points.

Figure 9 shows the estimated probability for the auto ignition and mass of evaporation at different temperatures for 5W-30 synthetic engine oil [22], where the red line is the auto ignition and the dotted blue line is the distillation curve for synthetic 5W-30 oil. It is seen that the auto ignition is governed by the most volatile species in the oil, i.e., the species with lower boiling points.

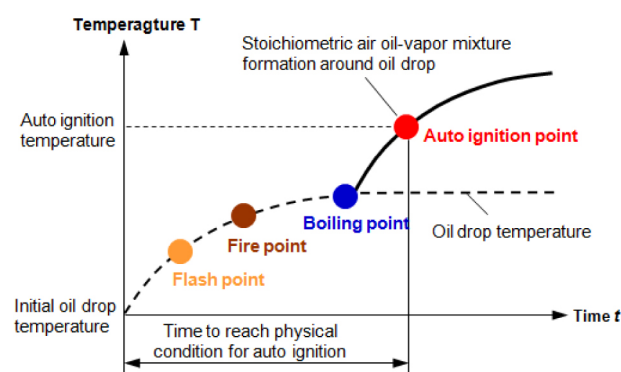


Figure 7. Process for an oil particle in cylinder to be an igniter.

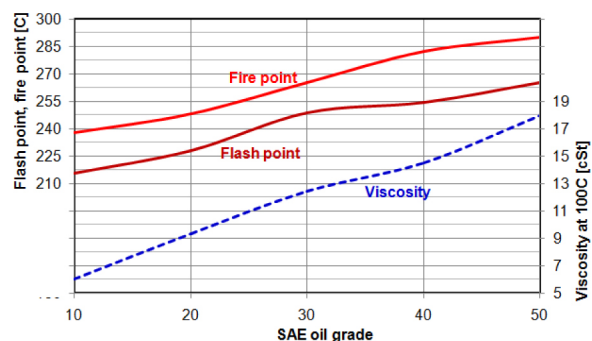


Figure 8. Fire point, flash point, and viscosity for different SAE oils.

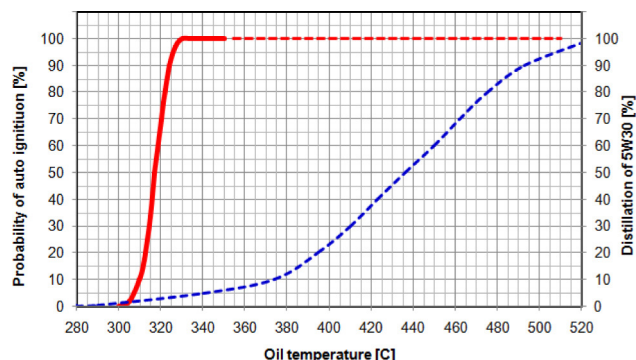


Figure 9. Auto ignition temperature and distillation curve for 5W-30.