

An Intake Valve Deposit (IVD) Engine Test Development to Investigate Deposit Build-Up Mechanism Using a Real Engine

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ABSTRACT

In emerging markets, Port Fuel Injection (PFI) technology retains a higher market share than Gasoline Direct Injection (GDI) technology. In these markets fuel quality remains a concern even despite an overall improvement in quality. Typical PFI engines are sensitive to fuel quality regardless of brand, engine architecture, or cylinder configuration. One of the well-known impacts of fuel quality on PFI engines is the formation of Intake Valve Deposits (IVD). These deposits steadily accumulate over time and can lead to a deterioration of engine performance. IVD formation mechanisms have been characterized in previous studies. However, no test is available on a state-of-the-art engine to study the impact of fuel components on IVD formation. Therefore, a proprietary engine test was developed to test several chemistries. Sixteen fuel blends were tested. The deposit formation mechanism has been studied and analysed. The results of this study indicate that addition of C6 to C16 olefins did not increase the deposit mass, unless the oxidation stability of the resultant gasoline was impaired. The deposit analyses suggested aromatics (including PAH) with a high boiling point or used at high concentrations tend to remain on the valve surface as a deposit. The engine tests also suggest that a small fraction of the base fuel has a disproportionate impact on deposit weight. A high final boiling point of the fuel does not necessarily make a fuel more prone to IVD formation, but rather it depends on the chemical composition of the high boiling components.

CITATION: Gail, S., Nomura, T., Hayashi, H., Miura, Y. et al., "An Intake Valve Deposit (IVD) Engine Test Development to Investigate Deposit Build-Up Mechanism Using a Real Engine," *SAE Int. J. Fuels Lubr.* 10(3):2017, doi:10.4271/2017-01-2291.

INTRODUCTION

Intake valve deposits (IVD) have been extensively studied over the past 20 years. Many documents published in the literature cover IVD and combustion chamber deposit formation [1,2,3,4,5]. Examples of available literature cover gasoline engine deposits e.g. [6] on deposits present on internal areas in contact with gasoline fuel or [7] where the authors developed a laboratory scale test to evaluate fuel propensity to generate deposit on intake valves. Other studies investigated the macrostructure of IVD [8,9] confirming the "sponge-like" behaviour of IVD linked to adsorption of fuel components in IVD.

Deposit formation mechanisms have been studied to lesser extent. Some interesting papers have been published on formation mechanisms and the composition of IVD. Some of these investigations used well known standard methods like [1] using different fuel compositions on a Ford Ranger 2.3 L four-cylinder engine following the ASTM D6201 test method [10]. In another

investigation [11] the authors followed the CEC F-20-A-98 engine test method [12] using a Mercedes Benz M111 gasoline engine to discriminate between additives reducing deposit amount. In [13] the authors present some results from an IVD test method developed on mass production 2.0L DOHC engine from the South Korean market. The test was designed to evaluate and to screen additives.

In some emerging markets, fuel samples can contain a high content of olefins or aromatics. Such fuel samples could cause poor engine running conditions leading to a poor driving experience for customers. To improve the knowledge on the effect of olefins and aromatics, the authors [14,15] focused on understanding the effect of fluid catalytic cracking (FCC) gasoline and aromatics respectively on IVD formation.

However, some gaps exist between the IVD formation mechanism and the effect of components like aromatics, heavy aromatic hydrocarbons (PAH), olefins and some fuel contaminants.

This paper introduces a newly developed IVD test using a state-of-the-art PFI gasoline engine. Also, it describes the experimental procedure including, the tests, the test cycles and fuels used. The method repeatability and precision are assessed. Deposit composition was also investigated using measurement methods like GC-MS and TGA.

The aim of this test development was to define a robust IVD test procedure to evaluate the influence of specific fuel components sometimes present in gasoline fuels.

EXPERIMENTAL PROCEDURE

For each test, the cleanliness of the inlet system and combustion chamber surfaces were checked and the engine was assembled using new intake valves. The engine oil used in this study was Shell Helix HX-7 0W-20 (SN/GF-5). Fresh engine oil was used for each engine test after flushing. The test engine was carefully controlled under the designated engine operating conditions as shown in Figure 1. The driving cycle was repeated until the total operating time reached 100 hours. The eight intake valves were removed from the engine and the average weight of formed IVD could be calculated for each valve from the difference between valve weights before and after the test. The PCV (Positive Crankcase Ventilation) system was routed as a “foul air system”.

Engine details

The test engine used for this study was a production engine from a Japanese OEM. Table 1 indicates the engine specifications. The engine Electronic Control Unit (ECU) was operated and checked by the Japanese OEM.

Table 1. Engine specifications

Type	In-line 4 cylinders
Displacement	1598 cc
Stroke	78.5 mm
Bore	80.5 mm
Compression ratio	10.2
Valve mechanism	16-valve DOHC, Dual VVT-i
Injection system	PFI
Output	91kW(124PS) at 6,000 rpm
Torque	160Nm at 4,400 rpm

Experimental design

Engine Test Cycle

During the test development phase several test cycles (Figure 1) were evaluated using a dirty-up fuel as indicated in Table 2 and Appendix 1. Several test cycles were evaluated as follows:

- Cycle A and Cycle B were defined respectively as common constant-speed mode (equivalent to a 60 km/h cruising car driving condition) and as low-speed cyclic mode (equivalent to the combination of accelerations to 60 km/h and frequent idling conditions). These cycles were evaluated as low speed driving cycles.

- Cycle C and Cycle D were defined as high-speed cyclic modes. Cycle C was defined as similar to cycle A with a high speed high load component and Cycle D was defined as similar to the CEC F-20-98 test method [12].

Further details on the test cycles and test sequences can be found in the Appendix 2.

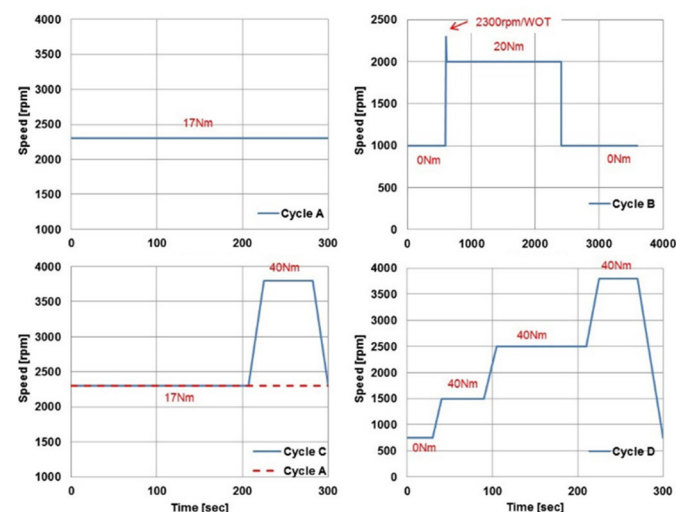


Figure 1. Driving cycles investigated during test method development

Fuel Properties and Additive Chemistries

A fuel matrix was defined to cover a wide range of chemicals. Table 2 describes the different chemistries and additives evaluated in this study. The fuel designated as base RG (Regular Gasoline) is a commonly-available regular grade gasoline in Japan. Base RG is a detergent-free fuel. On the Premium Gasoline (PG) side, Base PG is a marketed premium grade gasoline also detergent-free. All test fuels, from No.2 to 15, were prepared from Base PG using the various chemistries listed in Table 2.

Olefins with different carbon number were used to investigate their effect on IVD formation. All olefin components were obtained from JAPAN CHEMTECH LTD and their properties are listed in Appendix 3.

Aromatics and PAH were used to investigate the effect of aromatic content increase on deposit formation. 1-methylnaphthalene (97%) was purchased from Wako Pure Chemical Industries and the PAH and Aromatics like phenanthrene (98%), pyrene (98%), pentylbenzene (99%), biphenyl (99.5%), and triphenylmethane (99%) were ordered from Sigma Aldrich. A metal candidate (copper) was used to investigate the effect of fuel oxidation on deposit formation. The source of copper was copper (II) acetate monohydrate (98%) purchased from Wako Pure Chemical Industries. 1.25g/L of copper solution was prepared by dissolving copper acetate monohydrate into acetic acid. This copper solution was blended with No.3 test fuel at 18mg/kg. Finally, Diesel fuel was used as a contamination source via distribution channels. Diesel fuel was sourced from standard grade diesel in Japan.

Table 2. Table showing the fuels investigated, the chemicals used and their dosage in base fuel

Fuel type investigated	No	Chemical used	Dosage or content increase	Description
Dirty-up	0	Base RG + Heavy component	0.5%	
Base	1	Base PG	-	DCA-free
Olefin-doped	2	Hexene (C6)	3%	b.p. 63°C
	3	Hexene (C6)	15%	b.p. 63°C
	4	Octene (C8)	3%	b.p. 121°C
	5	Dodecene (C12)	3%	b.p. 214°C
	6	Hexadecene (C16)	3%	b.p. 289°C
PAH-doped	7	1-methylnaphthalene	1000 mg/kg	b.p. 241°C (2-rings)
	8	Phenanthrene	1000 mg/kg	b.p. 340°C (3-rings)
	9	Phenanthrene	2000 mg/kg	b.p. 340°C (3-rings)
	10	Pyrene	1000 mg/kg	b.p. 404°C (4-rings)
Aromatic-doped	11	Pentylbenzene	1000 mg/kg	b.p. 205°C (1-ring)
	12	Biphenyl	1000 mg/kg	b.p. 256°C (2-rings)
	13	Triphenylmethane	1000 mg/kg	b.p. 359°C (3-rings)
Other chemistries	14	Copper (+ No. 3)	18 mg/kg	320min(IP)
	15	JIS#2 Diesel	0.5%	

The dirty-up fuel used in the preliminary study was prepared from heavy components extracted from refinery streams. The main properties of the test fuels are presented in [Appendix 1](#).

Analytical methods

The IVD samples generated during this study were analysed to investigate deposit formation mechanism. A thermogravimetric analyser (RIGAKU CORPORATION, TG-8120) was used to perform continuous recording of property changes of IVD samples as a function of temperature and time. The sample was heated up to 1000°C at a 10°C/min constant rate under air flow. The chemical composition of IVD samples was evaluated via Fourier Transform Infrared spectroscopy (FTIR) and pyrolysis gas chromatography coupled with mass spectrometry (PGC-MS). The FTIR device used was a Thermo Fisher Scientific K.K. Nicolet 6700. The GC-MS equipment was a SHIMADZU CORPORATION GCMS-QP2010.

The induction period was calculated according to JIS-K-2287 method. A 50mL fuel sample was introduced in a chamber then filled with oxygen up to 689-703kPa at 15-20°C, and heated by a thermostatic bath at 100°C. The induction period was defined as the time elapsed as the sample showed a decrease of 13.8kPa in oxygen pressure during a 15min pressure monitoring.

Quantitative elemental analyses of the deposits were carried out using CCD-ICP apparatus (RIGAKU CORPORATION, CIROS Mark II).

RESULTS AND DISCUSSION

Preliminary engine tests

Four engine tests using predefined driving cycles (A, B, C, D) were performed using a dirty-up fuel to develop the method. The initial results are summarized in [Table 3](#) including the ratio IVD mass per valve to litres of fuel consumed and the ratio of IVD mass per valve to running distance. These ratios were defined to select the best driving cycle. Cycle A generated the largest quantity of deposit, while Cycle B generated the smallest quantity among all cycles.

However, IVD formation rates per litre of fuel or per running distance showed a different ranking. Indeed, Cycle B generated deposit efficiently by consuming less fuel and accumulating deposit over a shorter running distance. Cycle C formed lower deposit quantities even though it consumed a substantial amount of fuel and indicated the longest running distance. Cycle D performed in between Cycle A and Cycle C. Cycle B appeared to be the most sensitive cycle to IVD regarding fuel consumption, IVD weight, running distance, IVD/fuel consumption and IVD/running distance ratios. From these observations, it was agreed to select Cycle B as the test cycle for this study.

Table 3. Results of preliminary engine tests

Cycle	Details	Time	Running distance	Fuel Cons.	IVD weight	IVD/fuel	IVD/distance
		[hrs]	(=A) [km]	(=B) [L]	(=C) [mg/valve]	(=C*8/B) [mg/L]	(=C*8/A) [mg/km]
(A)	Constant-speed	100	Ca.6000	274.8	277.4	8.08	0.37
(B)	Cyclic-low	100	Ca.4250	173.1	193.9	8.96	0.36
(C)	Cyclic-high	100	Ca.9000	383.2	229.0	4.78	0.20
(D)	CEC mode	100	Ca.6000	374.9	231.1	4.93	0.31

In parallel, deposit analyses were carried out to compare differences in composition as the engine tests showed different deposit formation tendencies under the different driving conditions.

The visual aspect of the dirty intake valves is shown in Figure 2. The IVD visually exhibit two distinctive structures regardless of driving cycles.

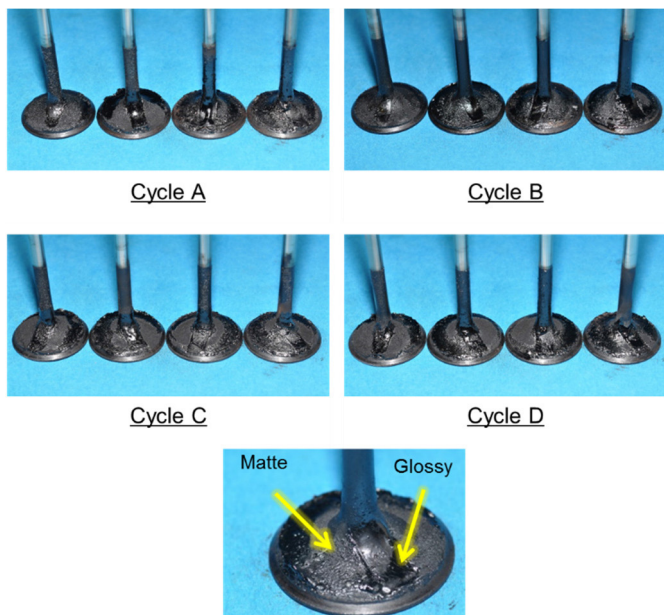


Figure 2. Appearance of deposit samples collected for different driving cycles

The structures were defined as “glossy” and “matte” areas. Glossy deposits were predominantly formed along the intake valve outskirt facing the injector spray compared to the back side of a valve stem. It is assumed the back side of the valve was protected from spray droplets by the valve stem. The OEM confirmed intake valve rotation did not happen under our test conditions based on their experience on several driving cycles. Both glossy and matte deposit samples were subject to PGC-MS and TG analyses. The results are summarized in Figure 3 and Figure 4.

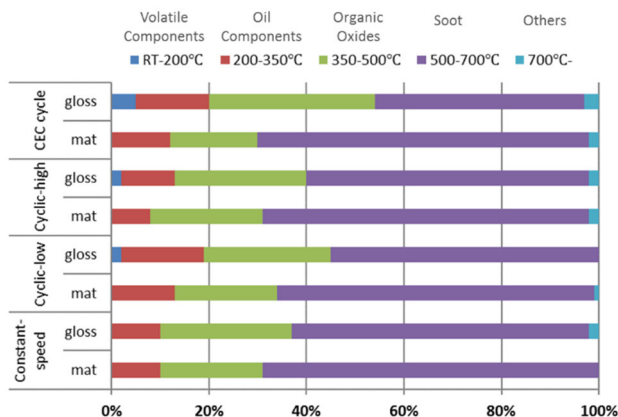


Figure 3. Deposit composition obtained by TG analysis (gloss and mat stand for glossy and matte areas respectively)

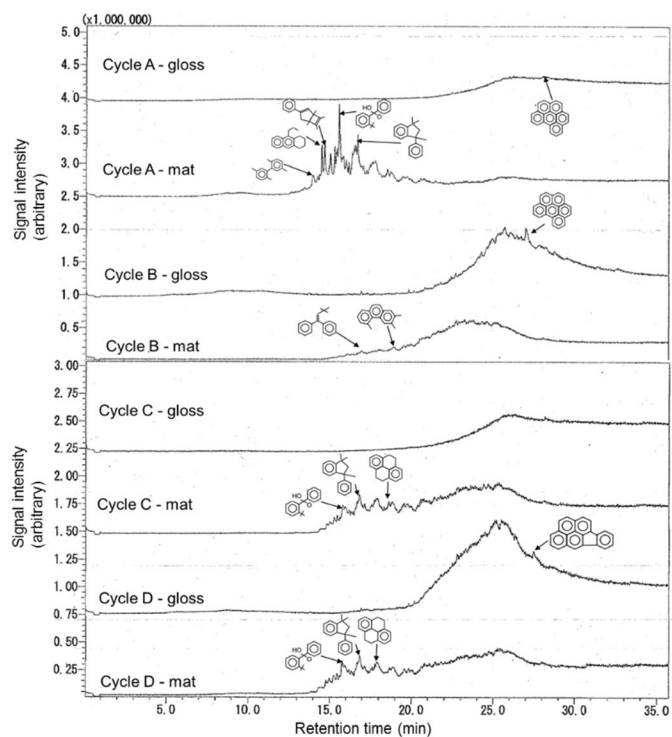


Figure 4. Deposit chromatograms obtained by pyrolysis GC-MS (gloss and mat stand for glossy and matte areas respectively)

The composition of deposit samples analysed by TG analysis was obtained using a method developed by Toyota previously described in [2].

This method categorises the selected deposit sample into five parts against their decomposition temperature:

1. volatiles
2. concentrated engine oil,
3. oxidation products,
4. pre-carbonization products (soot)
5. ash (residue).

The TG analysis results from Figure 3 do not show significant differences among the four deposit samples. However, pyrolysis GC-MS results from Figure 4 indicates three glossy deposits out of four are composed of polymerized substances.

These polymerized substances are assumed to be linked to high temperature seen by the intake valve even if it is difficult to estimate the valve heat distribution. One explanation is derived from the cooling effect generated by the spray droplets evaporation as they touch the surface of the valve. A similar explanation is given in [16] where the author studied combustion chamber deposits and linked the deposit thickness with temperature profiles: cooler surfaces lead to thicker deposits.

A second explanation agrees with the composition of matte deposit as the composition analysis (Figure 4) shows the presence of non-polymerized molecules with three or less aromatic rings. This is mainly because of a lower temperature in this area of the valve which