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A novel versatile methodology for the assessment of the effects of alternative fuels on engine durability

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Abstract

Since the introduction of first generation biodiesel (Fatty Acid Methyl Esters, FAME) at blending rates in diesel of up to 7% vol., concerns were raised regarding engine component durability. The deposition rate on engine components appears to be related to specific biodiesel characteristics, not included in the EN14214 standard. This paper describes a test method developed that is able to predict the effects of specific fuels on engine components that are not possible to be revealed by initial fuel properties as tested according to fuel standards EN590 and EN14214. The method is able to simulate long engine operation within a feasible test duration with controllable acceleration of involved phenomena and in a cost effective manner including the use of limited amount of fuel and only engine components affected by the fuel degradation. The paper presents the developed method, the experimental setup configuration, fuel treatment, key operating conditions and operating protocol of the main test. Test results are being presented for both current market fuels of different characteristics as regards FAME content and presence of detergent additives as well as for experimental and reference fuel blends developed for the assessment of possible future fuels and fuel injection system configurations. The paper concludes that the specific method is able to provide information on the applicability and possible durability issues associated with the use of alternative fuels and advanced fuel injection system technologies under consideration and is a candidate to be implemented as a future fuel standard.

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1. Introduction

Blending of biodiesel in market diesel fuels beyond a safety rate may have negative effects on engine causing wear of components and formation of deposits in various areas. Engine component wear may be caused by corrosion due to increased water concentration and acidity of the biodiesel. Biodiesel may also be responsible for sludge formation in fuel lines and filters and degradation of sealants and elastomers due to incompatibility with biodiesel (Lopes et al., 2012, Singha et al., 2012).

Engine deposits can be divided into 2 types, cylinder deposits and internal deposits. Cylinder deposits are carbonaceous compounds developing on cylinder and injector nozzles. Deposits on cylinder walls cause piston ring wear. Injector nozzle deposits are referred as “nozzle coking” and are evaluated by tests such as Lubrizol DW10 fouling test Nozzle. Coking affects the formation of fuel spray resulting in poorer combustion. (Caprotti et al., 2010, Amara et al., 2014, Singer et. al., 2014).

With the evolution of FIE system, injection system components such as fuel injectors became more sensitive to fuel quality, particularly due to the formation of Internal Diesel Injector Deposits (IDID). The formation of IDIDs is a complicated mechanism associated with several factors. It is associated with oxidation products caused by FAME degradation resulting in deposit build up on the injector needle and the injector command piston as well as inside the high pressure fuel pump (Yamane et al., 2007, Amano et al., 2014). Internal deposits are also associated with interaction of Poly-isobutene succinimides (PIBSI) additives with FAME components, forming lacquer type polymeric structures (Schwab et al., 2010, Reid et al., 2013). Additionally, soaps or wax type internal deposits may be formed due to Sodium (NaOH is a catalyst for FAME esterification), calcium or other contaminants interacting with fuel additives (Barker et al, 2013). Internal deposits can cause sticking of critical components (injector needle or HP pump flow control valve in the case of pump internal deposit) that affect engine startability and engine operation. (Omori et al, 2011)

The deposition rate on engine components appears to be related to specific biodiesel characteristics, not always possible to predict by fuel properties measured according to EN 590 and EN 14214 standards. Influencing parameters include type and origin of feedstock used for FAME production, addition and composition of used cooking oils (UCO), FAME production methods, FAME storage and transportation, interaction with fuel additives, interaction with fossil diesel etc. The sensitivity of engine components is the result of the complexity and high accuracy of the designs that are required for optimized engine control in order to minimize exhaust emissions and fuel consumption to comply with demanding current and future vehicle emission standards.

This paper describes a test method developed that is able to predict the effects of specific fuels on engine components that are not possible to be revealed by initial fuel properties as tested according to fuel standards EN590 and EN14214. The method is able to simulate long engine operation within a feasible test duration with controllable acceleration of involved phenomena and in a cost effective manner including the use of limited amount of fuel and only engine components affected by the fuel degradation. The paper presents the developed method, the experimental setup configuration, fuel treatment, key operating conditions and operating protocol of the main test. Test results are being presented for both current market fuels of different characteristics as well as for experimental and reference fuel blends developed for the assessment of possible future fuels and fuel injection system configurations. The method and test setup are able to produce an index that indicates the fuel tendency to form deposits and lead to durability problems of vehicles in long term operation. In addition, the method was tested over different FIE system technologies in order to identify common critical components and determine a reference FIE system to be used as the representative of current and immersing FIE technologies. The paper concludes that the specific method is able to provide information on the applicability and possible durability issues associated with the use of alternative fuels and advanced fuel injection system technologies under consideration and a candidate to be implemented as a future fuel standard.

2. Materials and methods

2.1. Test setup

The fuel test rig of this study was built using OEM parts in order to minimize the effect of any design modification or material difference of custom made parts on the result of the measurement. The fuel circuit consists of four solenoid diesel injectors, a common rail, a high (HP) and a low pressure (LP) pump, a fuel filter, a fuel cooler, all OEM connection lines and a generic fuel tank. A detailed sketch of the complete test rig is shown in Figure 1.

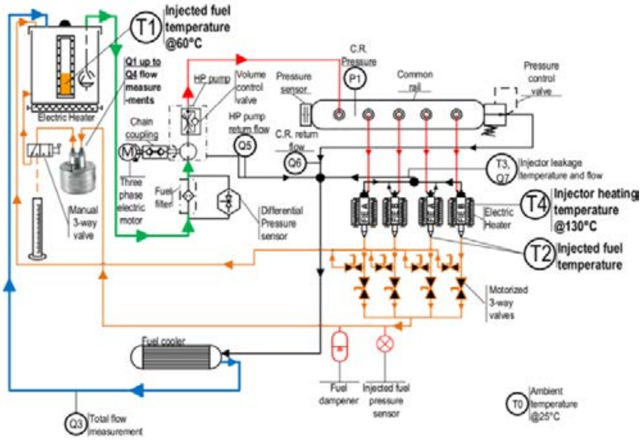

Fig. 1. Test rig layout.

The FIE is driven by an electric motor coupled to a frequency inverter to allow better control of operating speed. Fuel is recirculated within FIE components and not rejected after injection in order to minimize fuel consumption and accelerate ageing at the same time. Injectors are installed in special heated brackets to simulate the thermal conditions and assembly tolerances of the actual cylinder head. Injected fuel is collected in stainless steel receptors installed in the end of the injector brackets and returned to the fuel tank. In the fuel tank temperature is maintained at 60 °C in order to simulate a possible high temperature condition of an actual vehicle fuel tank due to excess fuel return in real world operation. Air is removed from the fuel collection receptors and lines in order to minimize interaction of fuel with air that may accelerate fuel ageing in a non-controllable and non-repeatable manner. The setup presented in this paper consisted of a complete set of FIE type A components (base FIE, supply pump, high pressure pump, common rail and tubing), paired with a set of FIE type A injectors connected on cylinder positions #1 and #4 and FIE type B injectors connected on #2 and #3. Coupling different types of injectors on the same FIE system allowed direct comparison of injectors only, avoiding the effect of different fuel ageing that would by caused by different types of base FIE.

Two different control systems can be used to control the FIE and provide activation current to fuel injectors:

- System 1: Open Electronic Control Unit (ECU) specially programmed to by-pass safety modes and allow injector control together with all necessary wire harnesses and power electronics including the Electronic Drive Unit (EDU).
- System 2: Prototype programmable engine control system (FI2RE, IAV GmbH) with adapted connectors.

The latter allows the operation of the test setup without the support of the OEM. System 2 can be calibrated using measurements performed on a real vehicle.

Injection flow rate is measured sequentially on one injector per period using an automated by-pass valve system which sends flow from one injector at a time to a Coriolis flow meter via a custom designed flow pulsation damper. The period of measurement for each injector is defined by the simulated engine operating point (essentially the injection flow rate) and the time needed for the flow rate to stabilize after valve switching, allowing this way stable and reliable measurement along the test.

Temperatures are being measured at various points of the FIE circuit keeping this way a record this way of the thermal cycle that the fuel undergoes. At the same time this allows another way of diagnosing the status and the stability of the FIE.

2.2. Test procedure and protocol

Fuels and/or FIE systems are comparatively assessed on the FIE test rig with a fixed reference FIE or a fixed reference fuel respectively which have been experimentally defined and consist part of the test specifications. The test protocol includes the simulation of specific engine operation test patterns, timing, pressure and temperature control of critical parts of the fuel circuit. Fuel properties as well as injection flow rate are measured in order to monitor fuel degradation and the effect of deposits. A reduction in injection flow rate indicates a gradual FIE failure. This is due to the development of different failure mechanisms such as the deterioration of injector activation (reduced piston movement) as a result of friction increase due to built-up of deposits. An FIE is considered failed when its injection flow rate drops below the nominal flow rate by 80% and further operation indicates no recovery potential. This percentage was defined as the threshold below which an ECU cannot compensate for the injection flow rate reduction by increasing injection duration. The running time at which total failure is observed consists the index of fuel or FIE endurance. Higher value of failure time corresponds to more durable fuel or FIE.

2.3. Test fuels and handling

Four diesel fuels were tested in order to demonstrate the sensitivity of the methodology in evaluating fuels with different composition and initial properties:

- B0: a neat petroleum diesel with no FAME or other additives was selected as the reference fuel.
- B7-M: a common market B7 diesel fuel without any additives.
- B7-M,A: a premium market B7 diesel fuel with injector detergent additive.
- B20: a test fuel with increased biodiesel content produced by mixing neat B0 biodiesel with 20% v/v FAME.

The properties of test fuels are summarized in Table 1.

Table 1. Fresh properties of test fuel batches.

ID	Description	FAME content [% (V/V] EN 14078	Total Acid Number (TAN) [mgKOH/g] ASTM D664	Oxidation Stability (IP) [h] EN ISO 15751	Water Content [ppm] ASTM D6304	CFPP [°C] EN ISO 116
B0	Neat petroleum diesel with no FAME or additives	0	0.1	35	74	0
B7-M	Common market diesel	7	0.09	7	Not measured	Not measured
B7-M,A	Premium market diesel with detergent additive	7	0.03	30	Not measured	Not measured
B20	Test diesel with increased FAME content	20	0.02	22	167	-1

3. Results and discussion

The evolution of injection flow rate during the tests is shown in Figure 2. It must be noted that although the test is terminated when the critical threshold Q_{80} is reached, the particular tests are continued in order to highlight the impact of deposits beyond critical conditions and confirm that the effect is not reversible. Injector fouling with B20 and B7-M occurred at $Q_{80,t}$ = 133 h and $Q_{80,t}$ = 203 h respectively. The effect of deposits is cumulative and injection flow is completely blocked after 40 h and 50 h of further operation with each fuel respectively. With the additivated B7-M,A and B0, injection flow rate was unaffected within a span of 280 h. In the case of B0, the rig results verify no deposits are formed within a sufficient running period when the fuel contains no FAME. Comparison of B7-M and B7-M,A also verifies that detergents can be effective against the formation of deposits.

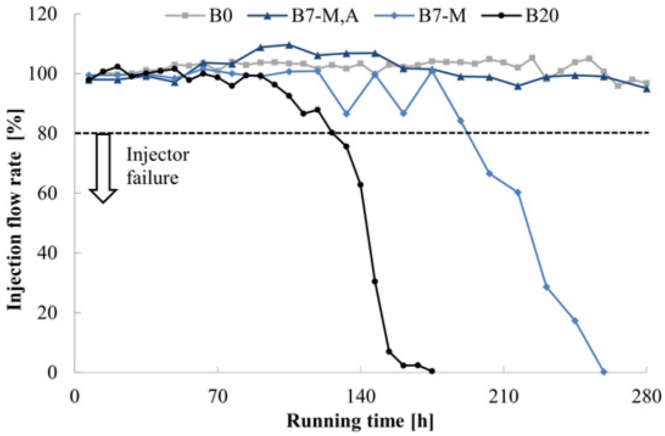

Fig. 2. Fuel injection flow rate during FIE operation.

The effect of FIE operation on oxidation stability is shown in Figure 3. Rancimat analysis is an accelerated oxidation stability screening test measuring the induction period (IP) as an indicator of a fuel's resistance to oxidation. When a value of IP = 0 h is reached, the oxidation rate of the fuel is maximized. As shown in Table 1, the IP values of fresh fuels B7-M,A, B7-M and B20 fuels was measured at 35 h and 22 h respectively. It can be seen that B20 reached an IP value of 0 h faster than B7-M despite having higher initial value (22 h vs 7 h). Fuel B7-M,A showed strong oxidation resistance. Its rate of IP degradation was slower than both B20 and B7-M fuels. The above indicate that the oxidative behavior of a fuel was not possible to be characterized by properties defined in EN590 such as the oxidation stability.

In order to verify that the test method is able to produce deposits similar to ones sampled from in-field failed vehicle parts, after the termination of B20 the injectors were disassembled to sample deposit from their internal components. The chemical composition was analyzed via FTIR. The analysis showed that deposits consisted mainly from FAME oxidation products as indicated by spectrum peaks at around 3400 cm^{-1} and 1735 cm^{-1} which correspond to alcohols and carboxylic acids or esters respectively. These types of deposits were also spotted in the field (Amano et al., 2014) indicating that the test method produced deposits similar to the ones produced under real world operation.

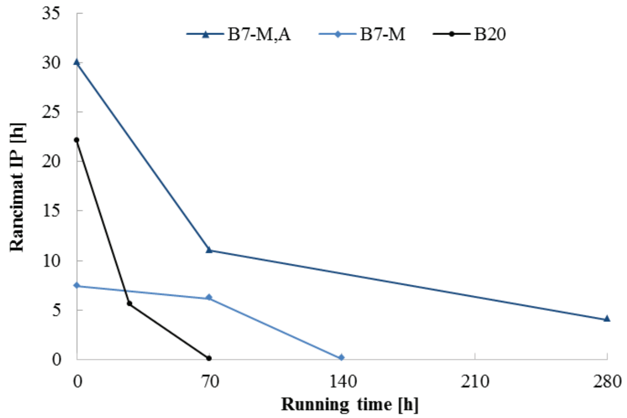

Fig. 3. Degradation of oxidation stability during FIE operation.

Total Acid number (TAN) is a measure of fuel acidity and is used as an indicator of overall fuel degradation during the rig test. As shown in Figure 4, the two market diesel B7 fuels depict considerably different degradation rate despite the fact that they contain the same percentage of FAME. TAN degradation of B7-M,A is negligible whereas for B7-M and B20 it is considerably and beyond the TAN limit set by the EN 14214 protocol for fresh FAME (TAN = 0.5 mgKOH/g). As expected due to the increased FAME content, B20 presents the highest TAN degradation rate, while B0 degradation was minimal.

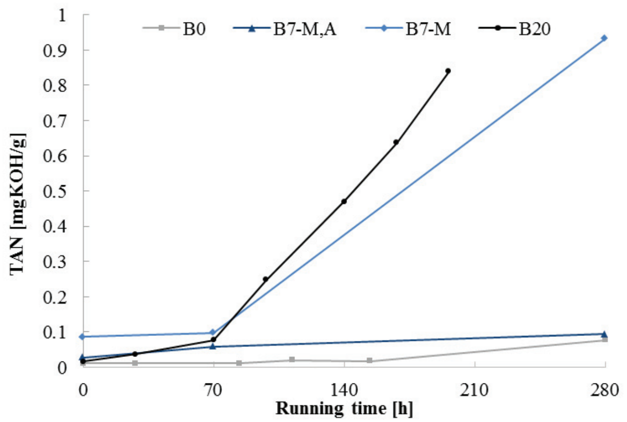

Fig. 4. Overall fuel degradation expressed as TAN increase during FIE operation.

Fuel degradation and tendency to form deposits are closely related. For this reason, TAN is assessed in relation to injection flow rate reduction. Comparison of Figure 2 with Figure 4 confirm that injector fouling potential increases proportionally to fuel degradation when operated on the FIE rig. Moreover oxidation related initial properties such as the oxidation stability IP are not representative of a fuel’s behavior on the FIE and consequently not indicative of its potential to form deposits. The test methodology is able to evidently highlight the impact of two different market B7 fuels on deposit formation potential.

In summary it can be said that:

- The operation of the system with B0 led to no failure, therefore the system is not sensitive to fuels that are expected to have no detrimental effect to the FIE.
- Higher blending ration (B20) was verified to have more detrimental effect on the FIE compared to lower blending ratio (B7).
- The inclusion of additive to a market B7 fuels had a significantly beneficial effect on FIE durability leading to a behavior similar to the one of the B0 reference fuel with no FAME content.
- The proposed methodology was able to assess the differences of fuels as regards their effect on FIE failure although this was not reflected by the initial, fresh fuel properties.
- The method was able to come to a conclusion within 280 h of operation for the worst case fuel which is a reasonable testing time for long durability simulation.
- Therefore, it is proposed to consider the inclusion of the proposed methodology as either a tool or a standard for quick assessment of alternative fuels, fuel qualities and fuel injection system.

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References

Amano, Y. et al., 2014. “Adhesion mechanism of internal diesel injector deposit”, FISITA World Automotive Congress, 2014.

Amara, B., Lecointe, A., Jeuland, B., Takahashi, N., 2014. “Experimental Study of the Impact of Diesel/Biodiesel Blends Oxidation on the Fuel Injection System”, SAE Int. J. Fuels Lubr. 7(3):849–860, 2014, doi:10.4271/2014-01-2767.

Barker, J., Cook, S., and Richards, P., 2013. “Sodium Contamination of Diesel Fuel, its Interaction with Fuel Additives and the Resultant Effects on Filter Plugging and Injector Fouling,” SAE Int. J. Fuels Lubr. 6(3):826–838, 2013, doi:10.4271/2013-01-2687.

Caprotti, R., Bhatti, N., Balfour, G., 2010. “Deposit Control in Modern Diesel Fuel Injection Systems,” SAE Int. J. Fuels Lubr. 3(2):901–915, 2010, doi:10.4271/2010-01-2250.

Lopes, S., Cushing, T., 2012. “The Influence of Biodiesel Fuel Quality on Modern Diesel Vehicle Performance,” SAE Technical Paper 2012-01-0858, 2012, doi:10.4271/2012-01-0858.

Omori, T., Tanaka, A., Yamada, K., Bunne, S., 2011. “Biodiesel deposit formation mechanism and improvement of Fuel Injection Equipment (FIE),” SAE Technical Paper 2011-01-1935, 2011, doi:10.4271/2011-01-1935.

Reid, J. and Barker, J., 2013. “Understanding Polyisobutylene Succinimides (PIBSI) and Internal Diesel Injector Deposits,” SAE Technical Paper 2013-01-2682, 2013, doi:10.4271/2013-01-2682.

Schwab, S., Bennett, J., Dell, S., Galante-Fox, J. et al., 2010. “Internal Injector Deposits in High-Pressure Common Rail Diesel Engines,” SAE Int. J. Fuels Lubr. 3(2):865–878, 2010, doi:10.4271/2010-01-2242.

Singer, P., Ruhe, J., 2014. “On the mechanism of deposit formation during thermal oxidation of mineral diesel and diesel/biodiesel blends under accelerated conditions”, Fuel 10/2014; 133:245–252. DOI: 10.1016/j.fuel.2014.04.041.

Singha, B., Korstadb, J., Sharma, Y., 2012. “A critical review on corrosion of compression ignition (CI) engine parts by biodiesel and biodiesel blends and its inhibition”, Renewable and Sustainable Energy Reviews 06/2012; 16(5):3401–3408. DOI: 10.1016/j.rser.2012.02.042.

Yamane, K. et al., 2007. “Oxidation stability of Biodiesel and its effects on Diesel combustion and emission characteristics”, International Journal of Engine Research, 2007, vol. 8, pp. 307–319, DOI: 10.1243/14680874JER00207.