A Novel Injector Deposit Fuel Test Method: "ENIAK"

H. Hoffmann*[1], W. Koch[1], K. Lucka[1]

[1]OWI Oel-Waerme-Institut GmbH

Abstract

Internal Diesel Injector Deposits (IDID) have been observed in the field around 2008 and investigated since. Testing, however, is difficult, as the engine tests are either outdated or costly. Since the internal parts of the injector are not in direct contact with the combustion, a test method emulating the indirect influences from engine operation, mainly the injection pressure, injection rate and the injector temperature has been developed. This so called "ENIAK"-test tests fuels and injectors outside of an engine. The fuel is re-used during testing in order to provide forced aging thus shorter test times. It furthermore can test conditions which are impossible to be set in an engine, e.g. low injection pressure at high injector temperature.

Introduction

The description of the project and the most of the test results have already been submitted as a paper for the 10th International Colloquium on Fuels in January 2015, which is currently in press and will be published alongside the Colloquium [12]. The present paper is based on and updated from the previous one.

The latest developments in diesel engines aimed to increase power while decrease the formation of pollutants before exhaust gas treatment and furthermore increase the comfort. This has mainly been accomplished by combustion shaping through multiple smaller injections during combustion. High injection pressures of 2,000 bar and more [1] combined with reduced clearings are prerequisite for this kind of operation. This results in sophisticated injectors with reduced clearings compared to older injectors. Such an injector is less resistant to deposit formation inside the injector compared to an older one [1]. In the last few years internal diesel injector deposits (IDID) have been observed and have been investigated since [1, 2, 3]. Quigley et al. suggest, that IDID is not actually a new phenomenon, but became more critical with the newer injection systems [3].

In order to investigate fuel injector deposits, mainly two certified engine tests are used: the XUD9-test (CEC F-23-01) and the DW10-test (CEC DF 98-08). The XUD9 test utilizes a 1.9 l XUD9 engine, which is an indirect injection engine from the late 1980s [6]. It cannot reproduce IDID. However, it is cheap and easy to perform. The DW-10-test (CEC DF 98-08) utilizes the 2.0 l DW10 common rail diesel engine refitted with Euro V piezo injectors. and is operated at up to 1,600 bar. The evaluation criterion is a power loss of the engine. For testing, zinc neodecanoate is added to the test fuel as deposit accelerant [7]. Measurements of Ee et al. [8] show no power loss when the zinc was not added, but almost 10 % power loss for the same base fuel with 1 ppm zinc. The test cycle aims for high load, not for realism. The engine is only 18 % of the test time at speeds below the maximum rated torque speed and idle operation is not present at all [9]. Hawthorne et al. [9] used the data of the test cycle, technical data from a Peugeot 407 and minor assumptions, such as which gear would have been used, to estimate the movement of a real vehicle operated with the cycle. Under these assumptions, the Peugeot 407 would have travelled 6,900 km at an average speed of 143 km/h. Within the 48 h of test time, 1,200 l fuel is consumed, which yields to an average fuel consumption of 17.4 l/100 km (13.5 miles per gallon). This already gives an indication on two major factors contributing to the high costs of the test. The fuel consumption of 1,200 l reference fuel alone is within the magnitude of the costs of a complete XUD9 test. Furthermore, the high load limits the engine life. Hawthorne et al compared the calculated speeds from the DW10 test with data from customer survey and estimated the severeness of the test to correspond to between 165,000 km and 290,000 km of consumer operation, depending on the assumptions applied [8]. Ee et al. reported an engine life time of 600 to 1,100 h of testing [7]. Quigley et al. [10] also reported experience with the severeness of the DW10 test. As further factors contributing to the high test costs, they add the need for a complete set of injectors for each test run (1,200 €), a relatively complicated measurement setup, which has to be applied to every new engine, the need to reference each new engine and premature failures of the turbocharger and/or the oxidation catalysts. As further calamities during testing they point out long delivery times for spare parts, for example 4 months for a new engine and several weeks for injectors and ECUs.

The present work gives a brief introduction into the ENIAK-project with its main goal the development of a non-engine fuel injector deposit test. The development of the ENIAK setup was based on experiences of several different "Hardware-in-the-Loop" (HiL) tests which have been successfully developed and

* Corresponding author: H.Hoffmann@owi-aachen.de

implemented at OWI [11]. A HiL test rig conveys a small amount of fuel in a circle, a.k.a. loop, but still uses all components of the corresponding application, thus putting "the hardware" into "the loop". This small amount of fuel is stressed during testing und therefore ages accordingly, which leads to more severe testing conditions. These more severe testing conditions are inherent to the fuel, unlike the addition of zinc neo-decanoate in the DW10 test. These testing methods have proven to be able to discriminate standard-conform fuels between critical and non-critical fuels. Within the ENIAK project, the HiL-principle is transferred to automotive applications. Hence, a complete set of common rail components is operated without combustion on each of the four test places on the test rig. The advantages of the HiL principle are low requirements on the infrastructure of the test site (e.g. acoustic insulation, vibration dampening and exhaust gas system) and smaller sample volume required for testing, compared to engine tests.

Test rig

The general test setup has already been described in [5], but some minor details have changed since. The test rig utilizes four identical common rail systems. It is currently equipped with a Euro V system with up to 1,800 bar injection pressure. Figure 1 shows the general schematics of the test rig.

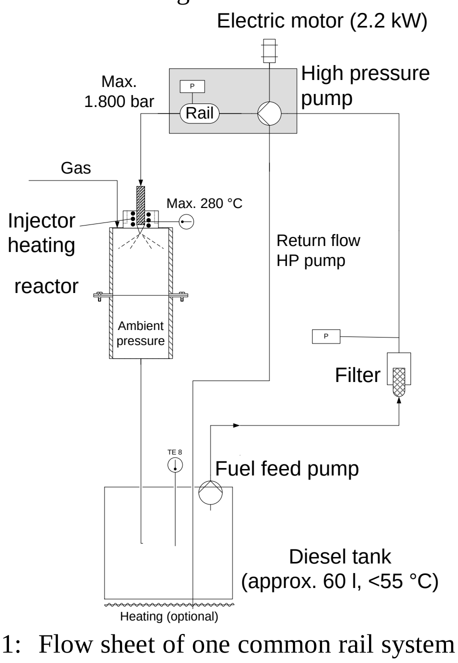

Figure 1: Flow sheet of one common rail system on the test rig.

As suggested in [5], the fuel is fed by an intank fuel feed pump through a filter to the high pressure pump. Since there is no engine operation driving the high pressure pump, it is driven by an electric motor. The high pressure pump feeds the rail. At each rail, only one injector is connected. The injectors can be heated to 370 °C at the needle shaft. In order to simulate the temperatures of engine operation at full load as measured by Tang [4], they are heated up to 230 and/or 280 °C. Tests at 350 °C at the needle shaft have been performed as well. The injector injects at ambient pressure into a vessel, which can be flushed with gas, for example ambient air or nitrogen.

If the amount of external deposits formed within the ENIAK test rig differs between different fuels this test rig could be used to discriminate fuels as being critical or uncritical. However, they will certainly differ morphologically from the ones found in an engine. The assessment of this capability is part of the present project. The main goal, however, is to reproduce the IDID occurring at engine-like conditions. The applied temperature in the present setup is comparable to high load engine operation and is simulated by an external heating. The internal parts of the injector are neither in contact with the peak temperatures of the combustion nor the combustion atmosphere. As the fuel is stressed significantly, it degrades accordingly; hence the test is performed partially with an aged fuel. Polymeric material as ageing product can deposit at the armature/magnet [1]. The injection parameters, such as injection pressure, injector temperature or the injection timing, are not depending on engine operation. This allows an independent and flexible variation of the parameters. This can be used to investigate the influences on deposit formation more thoroughly [5].

Test results

The initial tests were all performed at 1,400 bar injection pressure, 10 Hz injection frequency and 500 µs energizing time. Tang [4] measured maximum temperatures of 350 °C on the nozzle tip and 260 °C on the needle shaft. In order to investigate the influence of the temperature, the needle shaft was heated up to 230 °C, 280 °C and up to 350 °C. At 350 °C, all three injectors tested failed due to deposits blocking the needle completely. They failed after a comparatively short testing time of 70, 76 and 77 h of operation, which points towards a good repeatability. Opening the injectors confirmed IDID to be the cause of the failure. Figure 2 shows a part of the injector needle of one of the injectors.

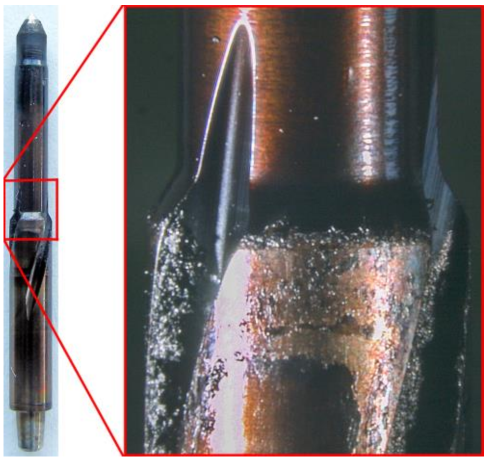

Figure 2: Deposits on the injector needle

One major goal of the project, producing IDID in short time without using an engine, was achieved.

However, at this unrealistically high temperature, the test did not discriminate between different fuels anymore. Two fuels were a B10 (Reference Fuel RF 06-03 + 10 % FAME) with a “critical” additive, which failed to pass the XUD9-test, while the third one was a B0 (mineral diesel without FAME) additised with a commercial performance additive with clean-up capability. The temperature at the needle shaft therefore was reduced to 280 °C, which is still a high temperature, but within the magnitude of 260 °C measured by Tang [4]. At this temperature, two injectors, one with each fuel, passed the 200 h test cycle without failure. These results reveal a strong temperature influence, which also was suggested in previous publications, for example by Hawthorne et al. [9].

Two test runs, each with all four injectors operated with the same fuel, have been conducted with this temperature setting of 280 °C on the needle shaft. In both test runs, two systems were operated at 1,300 bar while the other two were operated at 600 bar. During the first test run, the fuel was additised with the same “critical” additive from the tests before, during the second test, a commercial performance additive with tested and proven keep-clean capabilities was used. During both tests, the flow through the injectors was measured on a regular basis. The accuracy was empirically estimated to be 10 %, if performed by different persons. In both tests, the flow measurements did not show any change in flow during testing. After the tests, the injectors were investigated in an external injector diagnosis device. All eight injectors operated showed disturbed operation due to IDID. At high pressure, the injected amount of fuel was either still at its initial value or showed a decrease of up to 5 %, which corresponds to the flow measurements during the test. However, the timing was off even at high pressure. At low pressure, the amount of fuel flow deviated and some pilot injections did not take place. In an engine, this would have resulted in a very rough operation during idle. All eight injectors showing IDID means, that at 280 °C the test does not discriminate between the two fuels. 280 °C is still slightly above the highest temperatures measured in an engine by Tang [4] of approximately 260 °C. Obviously, this temperature still does not represent real operation conditions. It seems that at these high temperatures the thermal influence supersedes the other influences.

A difference between the two pressure levels regarding the IDID formation was not observed. The rail pressure during testing does not seem to have a significant influence. This is an important update to the empirical observation, that IDID became more important with newer injection systems with increased injection pressures. The most plausible explanation is that the increased injection pressure in modern systems only has an indirect influence by lower clearings within the injector and increased fuel temperatures due to the higher compression. That the smaller clearings might be a major cause for the latest IDID occurrences was already suggested by Quigley [3].

Accordingly, the investigation at different pressure levels was not further investigated and it was decided to decrease the temperature. In the latest test run, a similar B10 fuel was additised with dodecenyl succinic acid (DDSA) and sodium (Na). DDSA is used as corrosion inhibitor in diesel fuel and has been reported to form sodium salts when in contact with sodium, leading to IDID [13]. The intent of this additisation was to test a known critical fuel. The main investigation was now the comparison between 280 °C at needle shaft and 230 °C at the needle shaft. The flow measurements were performed at 400 bar at a low energizing time. The intent was to provide for the best conditions to observe IDID, as a low pressure corresponds to low operating forces on the injector needle while short energizing times highlight the opening and closing of the injector. Nevertheless, a decrease in flow could not be observed, neither when operated at 280 °C, nor when operated at 230 °C. The injector diagnosis for this test run is pending.

The observation that the injectors, although not functioning properly anymore, did not show a reduced flow or another obvious behavior during operation in the test rig underlined the need for an online diagnosis tool during testing. In an engine, injector operation would be verified by measuring the pressure curve in the cylinder. Since in the present setup the injection takes place in a vessel at ambient pressure without combustion, a new method has to be developed. Currently, three concepts are investigated more closely.

All injectors were also investigated with an optical microscope regarding external deposits. It is obvious, that the external deposits found on injectors after ENIAK-testing differ from the ones found during real engine operation. The present amount of deposits is much higher, since the shock waves of combustion can remove bulky deposits. Figure 3 gives an example of deposits found on the injector tip after a test run.

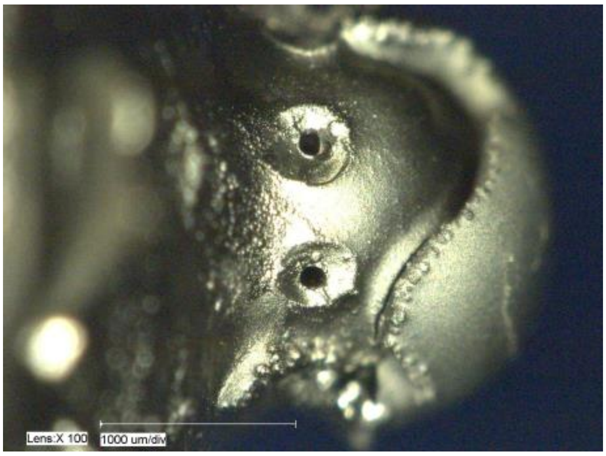

Figure 3: External deposits after test run (1,300 bar, 10 Hz, 500 µs, B10)

On the other hand, the injection against ambient pressure probably leads to more severe cavitation effects near or even inside the spray holes. If this is the case, this would lead to less deposit formation in the critical area. Nevertheless, it might be possible to differentiate fuels regarding their tendency to form external deposits. In this case, a criterion for the assessment would have to be set. However, test results so far indicate, that during testing other influences, have a more significant impact on deposit formation than the fuel.

Conclusion and Outlook

Within the ENIAK project, a non-engine injector deposit formation test rig with four separate common rail systems has been assembled and commissioned. Using this test rig, it was succeeded to form internal diesel injector deposits without engine operation. Operation with all four systems in parallel has been tested.

Initial tests point towards a very good repeatability. However, the repeatability of the test method has yet to be determined statistically.

Compared to the existing engine tests, the test offers low requirements on the infrastructure of the test site, flexible integration of different common rail hardware and a low amount of sample for testing, all leading to low test costs. The ability to test four fuels in parallel allows either rapid screening or multiple testing for statistic verification.

The test rig can also be used to investigate the mechanisms of deposit formation more thoroughly, as the setting of the injection parameters is not depending on engine operation and can therefore be chosen more freely. As it uses all components existing in a real engine, it remains at the same time closer to the application than a pure laboratory method.

The tests showed a very strong influence of the temperature on deposit formation. At high temperatures, deposits inside the injector form within very short test times of less than 200 h.

The tests also indicate that the injection pressure has a minor influence on internal diesel injector deposit formation, if at all. Within two test runs corresponding to eight measurements at the same injector temperature, four tests were conducted at 600 bar injection pressure and four at 1,300 bar injection pressure. While showing signs of IDID for all eight injectors, a difference between the two pressure settings was not observed.

An online diagnosis during testing is desirable and currently under development.

As soon as a capability to differentiate between critical and uncritical fuels has been verified, several topics will be investigated, among them the influence of different bio fuels and different injectors.

Acknowledgements

The Project is funded by the German Federal Ministry of Food, Agriculture and Consumer Protection (BMELV) through the FNR ("Fachagentur Nachwachsende Rohstoffe", Agency for Renewable Resources).

The authors would like to thank Christoph Nailis, Sebastian Deist and Roy Hermanns from OWI for their support within the project.

References

[1] Ullmann, J.; Geduldig, M.; Stutzenberger, H.; Caprotti, R. et al., „Effects of Fuel Impurities and Additive Interactions on the Formation of Internal Diesel Injector Deposits“ in : Bartz, W.J.: Fuels 2009: mineral oil based and alternative fuels; 7th International Colloquium; January 14 - 15, 2009; TAE, Ostfildern, 2009, Seite 377-388, ISBN 3-924813-75-2

[2] Ullmann, J.; Geduldig, M.; Stutzenberger, H.; Caprotti, R. et al., "Investigation into the Formation and Prevention of Internal Diesel Injector Deposits", SAE Technical Paper 2008-01-0926, 2008, DOI:10.4271/2008-01-0

[3] Quigley, R.; Barbour, R.; Fahey, E.; Arters, D., Wetzel, W. and Ray, J., "A Study of Internal Diesel Injector Deposit Phe-nomenon", in : Bartz, W.J.: Fuels: Conventional and Future Energy for Automobiles; 8th Interna-tional Colloquium, January 19 - 20, 2011; TAE, Ostfildern, 2011, p. 565-578, ISBN 3-924813-86-8

[4] Tang, J.: "Belagbildung in Einspritzdüsen direkteinspritzender Dieselmotoren", Dissertation RWTH Aachen, 2010

[5] Hoffmann, H.; vom Schloß, H.: „Development of a Non-Engine Fuel Injector Deposit Test for Alternative Fuels (ENIAK-Project)" in Bartz, W.J.: Fuels: Conventional and Future Energy for Automobiles; 9th International Colloquium, January 15 - 17, 2013; TAE, Ostfildern, 2013, p. 613-615, ISBN 98-3-943563-04-7

[6] Caprotti, R.; Breakspear, A.; Klaua, T.; Weiland, P. et al.: "RME Behaviour in Current and Future Diesel Fuel FIE's", SAE Technical Paper 2007-01-3982, 2007, DOI:10.4271/2007-01-3982

[7] Barbour, R.; Quigley, R.; Browne, D. and Panesar, A.: "A Comparsion of Peugeot DW10 Dynamometer and Vehicle Engine Perfermance" in: Bartz, W.J.: Fuels: Conventional and Future Energy for Automobiles; 8th International Colloquium, January 19 - 20, 2011; [proceedings 2011], TAE, Ostfildern 2011, p. 125-132, ISBN 3-924813-86-8

[8] Ee, J.; Panesar, A. and Barbour, R.: "Operation and Appetite - Our Experience with the CEC F98-08 DW10 Nozzle Coking Test", retrieved on November 1st, 2011, http://www.lubrizol.com/9040Zer0/DW10Nozzle Cokin gTest.pdf

[9] Hawthorne, M.; Roos, J.W.; Openshaw, J.: „Use of fuel additives to maintain modern diesel engine performance with severe test conditions", SAE

technical paper 2008-01-1806, 2008, SAE International

[10] Quigley, R.; Barbour, R.; Panesar, A.; Arters, D.C.: "A review of fuel and additive performance in the new CEC F-98-08 DW10 injector fouling test", 2009, 7th International Colloquium on Fuels (2009), p. 307-314, Ostfildern: Technische Akademie Esslingen (TAE)

[11] Neulen, M.; Hoffmann, H.: “Anwendungseigenschaften flüssiger Brennstoffe mit biogenen Anteilen (DGMK-Projekt 729), 7. Rostocker Bioenergieforum, 20. – 21. Juni 2013, Rostock

[12] Hoffmann, H.; Deist, S.; Koch, W.; Lucka, K.: „Development of a Non-Engine Fuel Injector Deposit Fuel Test: Results”, in Bartz, W.J.: Fuels: Conventional and Future Energy for Automobiles; 10th International Colloquium, January 20 - 22, 2015; TAE, Ostfildern, 2015 (currently in press)

[13] Quigley, R.; Barbour, R.; Fahey, E.; Arters, D., Wetzel, W. and Ray, J., “A Study of Internal Diesel Injector Deposit Phenomenon“, in : Bartz, W.J.: Fuels: Conventional and Future Energy for Automobiles; 8th International Colloquium on fuels, January 19 - 20, 2011; TAE, Ostfildern, Germany, 2011, p. 565-578, ISBN 3-924813-86-8