DI-Diesel Engine - Injection Nozzle Coking

ABSTRACT

A research program was created to perform test cell analyses identify parameters that predominantly influence the development of critical deposits in injection nozzles. The tests were conducted using a medium-duty diesel engine, which was operated under two different coking cycles with a zinc-free lubricant. One cycle is predominately conducted under rated power, while the second operates over a broad area of the engine's operating range. While the experiments were being conducted, the temperatures at the nozzle tip, the geometries of the nozzle orifice and fuel properties were varied. An electron microscope was utilized to provide a detailed analysis of the injection deposits. Optical access to the entire nozzle was gained during this project. The results of the experiments were determined by monitoring the power output and fuel flow at rated power. Two electron microscopes (SEM Scanning Electron Microscope and a TEM Transmission Electron Microscope) were utilized to illustrate images of the deposits with a magnification of up to 160 000. A spectrum of the defined elements was provided by employing the EDX (Energy Dispersive X-ray) and EELS (Electron Energy Loss Spectroscopy) methods. Increased injection nozzle fouling occurs, according to the results of the study, when the temperature at the nozzle tip rises. It was also noted that zinc is a major parameter contributing to the build-up of deposits. When the zinc levels reach a critical concentration in the fuel, significant coking occurs within a relatively short period. Running the engine with zinc-free fuel will partially reverse the nozzle deposition. The deposits resulting from fuel containing zinc have an inhomogeneous distribution of the metal. Operating the engine on zinc-free fuel produced nozzle coking that displayed morphology with a different texture as compared to the coking developed when using fuel containing zinc. The formation of deposits can be inhibited through cavitation inside the nozzle.

INTRODUCTION

The primary challenges towards developing new diesel engines for passenger cars lie in the strict future emission legislation in combination with the customer's demands for steadily improving performance. For example, the emission limitations of Tier 2 Bin 5 requires an advanced aftertreatment system and a robust combustion process that minimizes emissions in the process of them being formed.

Advancements in the technology of Diesel Injection (DI) systems have played in important role in the improvements that have been made up to this point [13]. Combining the reduction in nozzle orifice diameters through enhanced flow characteristics with increased injection pressures provides an opportunity to develop engines featuring high power density and reduced emissions. The primary drawback to these modern spray hole geometries is that they often suffer a reduction of power output during long term operation. Other studies have identified these critical formations of deposits as the main reason for this behavior.

INJECTION NOZZLE DEPOSITS INFLUENCE ON ENGINE BEHAVIOR

Internal and external deposits on fuel injection nozzles impact engine behavior through different mixture formations and changes in combustion [2]. This can produce increased acoustic [3] and pollutant emissions [4], [5] in diesel engines with Indirect Injection (IDI). In these applications, the formation of injection nozzle deposits could not be prevented; therefore, in those designs the impact of the deposits were considered [6], [7], [8]. A variety of studies involving Direct Injection (DI) diesel engines illustrated a deterioration of combustion and mixture formation. The also showed an increase in emissions [9], [10], [11] along with a slight increase in fuel consumption [12]. A decline in power output is quite typical for nozzle fouling [9], [12], [13], [14], [15].

MECHANISMS OF DEPOSIT FORMATION AND REMOVAL

Basic mechanisms can be used to explain the formation and removal of deposits in internal combustion engines [16]. These mechanisms act independently of the location of formed deposits (e.g. injection nozzles, heat changer) and of the combustion process (e.g. IDI, DI; diesel or gasoline).

The model described in the study illustrates the interaction of a wall with the enclosing flow regime. The transport of particles to the wall is based on the process of thermophoresis [17]. This process results in the force of gas particles in the direction of the temperature depression. It is amplified with an increasing temperature differential between wall (cold) and fluid (hot). This process results is an increasing concentration of deposit-building particles near the wall. High turbulence near the wall may reduce the force of the aerosol again to a mean value, compensating for an increased temperature difference. [16]

The deposits are composed of attached particles (solid and liquid) and gas (Figure 1). Condensation [18] [19] and adsorption [20] of gaseous compounds at the cold wall promotes the formation process. At this point, the growth of the deposits is now mainly influenced by the sticking, impaction and incorporation of particles [21], [22], [23], [24]. The adsorption of gaseous components and the chemical reactions (as pyrolysis, dehydration and polymerization, etc.), lead to the compaction of the deposits [25], [26], [27]. The removal of deposits has analogous physical mechanisms. The chemical mechanism is oxidation destroying the organic compounds in the coating [27]. Evaporation and desorption reduce the gaseous fraction dissolved in the deposits. Abrasion is caused by strong aerodynamic forces and breaking-off, due to high temperature changes, resulting in inhomogeneous extensions of the wall and deposit layer. The corresponding shearing stresses initiate the breaking-off process [29]. The soluble fraction of the deposits is washed off by solvents (e.g. water as solvent for salt compounds) [28] [16].

PROJECT OBJECTIVES

The primary goals of this study were to investigate the major causes of the formation of deposits in the spray hole and to establish the leading parameters that promote the formation and the decay of deposits. The following step was to find measures that would slow down or even inhibit the formation of these deposits. It was decided to divide the study into two sub-projects. The first sub-project handled the experimental investigations, including a detailed deposit analysis. The focal point of the other sub-project was on simulating the effects of various nozzle types (cylindrical, ks-nozzle) on heat transfer and fluid flow, utilizing coupled CFD- and thermal modeling. In addition, research was conducted on the thermal situation of the nozzle, which included a sensitivity analysis regarding the thermal conditions at the injector tip. Cavitation and thermal effects were also included as a part of the investigation. This document highlights the experimental results, including the deposit analysis. The results of the other sub-project are partially published [30].

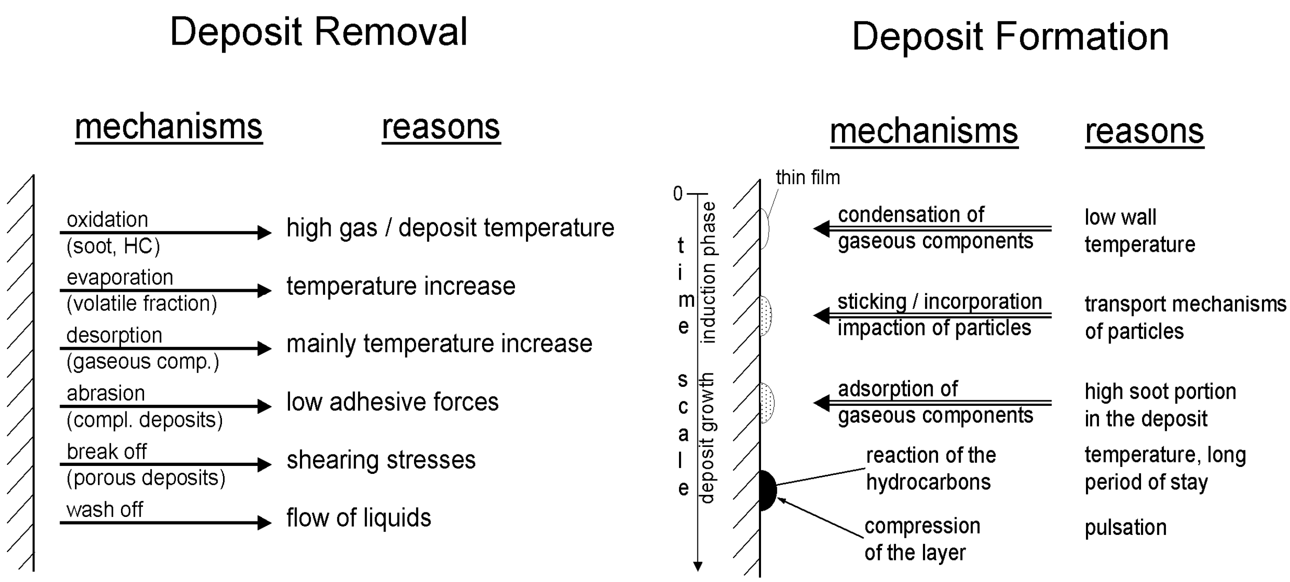

Figure 1: Mechanisms of Deposit Formation and Removal [16]

EXPERIMENTAL PROCEDURES AND TEST ENGINE

TEST ENGINE

Tests were conducted with the medium-duty truck engine OM 906. It has a maximum power output of 210 kW at 2200 min^{-1}. The engine is EURO IV certified and uses a SCR aftertreatment system. The Direct Injection (DI) diesel engine features a Unit Pump (UP) system. Specific for this system is the injection synchronous high-pressure generation. The maximum fuel pressure is higher than 1800 bar. The high-pressure system in the OM 906 has no leakage. The high-pressure pump is lubricated by engine oil. Therefore, in principal traces of lubricant can enter the fuel system. During the testing three different sac-hole nozzles were applied to the engine (Figure 2).

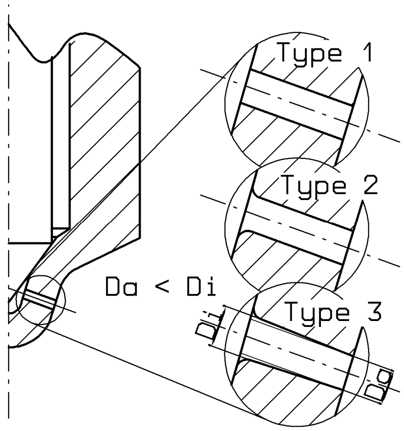

Figure 2: Nozzle Orifice Geometries (Type 1: Cylindrical, no rounding; Type 2: Cylindrical, high rounding; Type 3: Conical, high rounding)

Type 1: Cylindrical spray hole geometry including a non rounded orifice inlet

Type 2: The standard nozzle for this engine features hydro-erosive rounding of the spray holes to improve the flow regime at the inlet of the nozzle orifice and, thus, to reduce cavitation [31], [32]. The cavitation is reduced in comparison to type 1.

Type 3: The also called ks nozzles feature a high level of rounding at the orifice inlet in combination with a conical spray hole geometry to prevent cavitation.

The nozzles are protected during engine braking mode and motoring through a heat shield (see Appendix).

APPLICATION OF A THERMOCOUPLE AT THE NOZZLE TIP

Initial test cell investigations measured nozzle tip temperatures during operation. Production parts were adapted during the project with thermocouples. The concept implied the ability to run the engine at rated power and to avoid any influence on the combustion process. Thus, the requirements led to a design, where the thermocouples are integrated inside the body of the nozzle holder. The thermocouple was then located between nozzle and heat shield. The tip of the thermocouple was welded to the tip of the nozzle (detailed image of welded thermocouple in Figure 3).

COKING CYCLES

Various coking cycles were utilized to accelerate deposit formation. Daimler provided a base cycle which was already in use (Cycle 1, Figure 4 on the left hand side). During the first tests, no significant deposit formation occurred, but results showed a higher tendency towards deposit formation in combination with higher power output. So, the duration of the last rated power period of the Cycle 1 was extended by 14 hours to overall 34 hours to enhance the potential of significant nozzle fouling (DC-ext., Figure 4 on the right hand side).

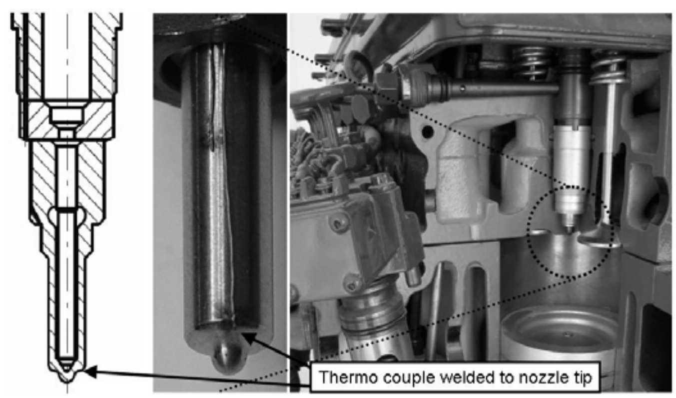

Figure 3: Application of Thermocouple at the Nozzle Tip

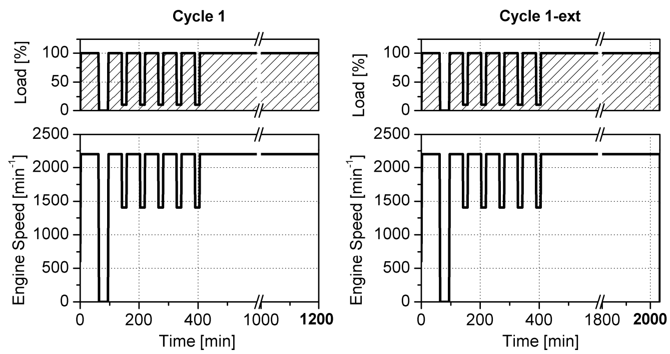

Figure 4: Base Coking Cycles (Cycle 1 / Cycle 1-ext.) Provided by Daimler

A further coking cycle (Cycle 2) was created by using a publication of Graupner et al. [33]. They proposed a coking cycle for passenger car applications, which was altered for operation of a truck engine. Figure 5 displays, on the left hand side, their cycle (rated power at 4000 rpm) used for the small engine and on the right, the version altered for the truck engine. In comparison to the Cycle 1 the duration of engine operation is shorter and, additionally, the soak time prolonged.

MONITORING AND DEFINITION OF COKING LEVEL

A direct rating of the developed deposits was done through the final alteration of power output and fuel flow at rated power with a fuel temperature of 40°C. Reductions of higher than two percent were defined as significant respectively critical, taking into account the repeatability of the boundary conditions and the duration of the coking cycles. The coking level is explicitly not time specific, since the monitored formation rates indicated a declining behavior and the time length of the coking cycles varied. Thus, the coking level is dependent on the boundary conditions. During all tests, insignificant coking cycles were only observed in combination with stabilized rated power. Therefore, the tests are sufficient to decide, whether certain boundary conditions are critical or not. But a comparison of different significant coking levels is only allowed for identical coking cycles.

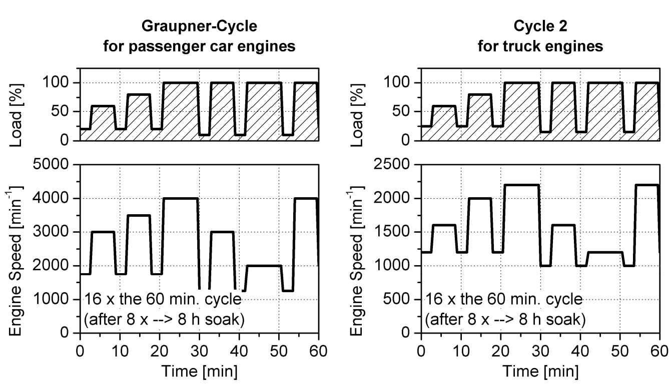

Figure 5: Different Coking Cycles (Graupner-Cycle [33] / Cycle 2)

FUEL AND LUBRICANT

In order to ensure safe engine operation, the fuel complied with standard EN 590. Therefore, a mineral oil-based fuel from an independent refinery (MIRO, Karlsruhe) was chosen with an additional bio diesel share of five percent. Latter fraction is required by legislation [34]. On the other hand, the fuel was required not to possess characteristics, specific to a certain oil company, so the diesel contained no additives. The intended investigation on the chemical parameter zinc necessitated zinc-free oil (comparable to FUCHS TITAN CARGO MAXX 5W-30), since the quantity of oil flowing into or through the spray holes could not be determined.

DEPOSIT ANALYSIS METHODS

Next to the evaluation of the test runs the formed deposits in the nozzle were investigated by electron microscopy with low magnification methods. Afterwards characteristic deposits were analyzed in detail.

ELECTRON MICROSCOPY

The analysis focused on electron microscopy. The following methods were employed:

SEM (Scanning electron microscope): The sample is scanned with an electron beam. The interaction of surface and electron beam is measured. The measurements are used to build an image of the surface [36].

EDX (Energy-dispersive X-ray spectroscopy): The interaction of the electron beam and the atoms is dependent on the element being measured. Elements with a very low atomic number are not or hardly detectable [37].

TEM (Transmission electron microscopy): Similar to the SEM an optical image of the sample is created, but in contrast to it the electron beam is transmitted through the sample. Therefore, the sample thickness is about 0.1 to 0.2 µm [38].

EELS (Electron energy-loss spectroscopy): The method is sometimes called complementary to EDX, because it also delivers information about the chemical elements present in the sample. The range of detectable elements is different to EDX. Furthermore, the technique is known to be more difficult [39] to bring to application.

SAD (Selected Area Diffraction): The wave-like character of electrons is adopted. Crystalline structures larger than 2 nm affect the electron beam significantly, creating an interference pattern downstream of the sample. Amorphous samples will not result in any visible pattern [40].

NOZZLE PREPARATION

Three different views were enabled giving access to any position inside the nozzle (Figure 6). The nozzle material out of view for each preparation was removed and cannot be used for investigation.

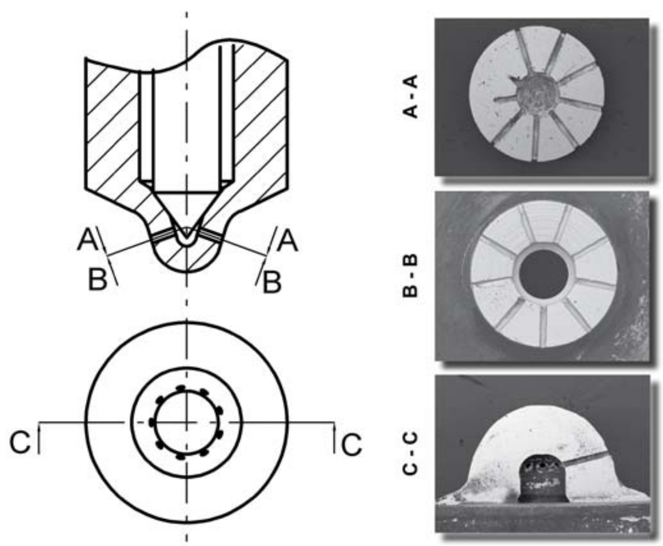

Figure 6: Sample Preparations for Optical Access of Deposits in Nozzles

In order to enable the TEM analysis a further preparation step was necessary. The resulting sample of the spray hole is called a FIB plate (Focused Ion Beam) and is created by a special method which is typical in the field of tribology [35]. It includes nozzle material as well as deposits. The most promising nozzle was primarily prepared for the C-C view. The FIB plate should not be taken directly of the spray hole outlet, but from an area of the inner hole. A FIB plate originates always out of a plain surface. Therefore, this surface had to be machined first, as depicted in Figure 7. Before the sample sheet was cut out of the nozzle by a gallium ion beam, a tungsten layer was sputtered on the surface to protect the sample below. After the surrounding material was destroyed by the gallium ion beam the sample was welded to an object holder and transferred to the TEM (Figure 8).

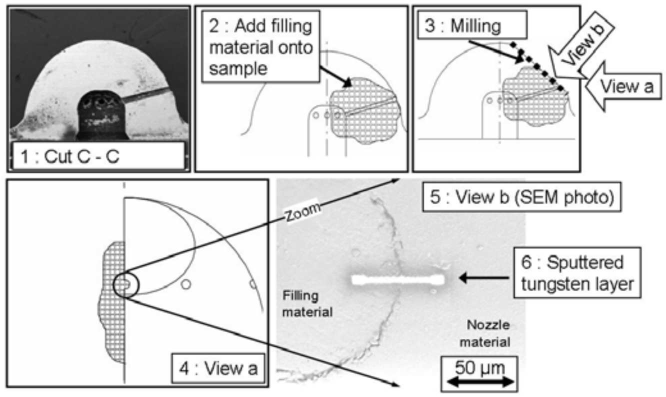

Figure 7: Procedure of Preparing a Surface in the Nozzle Normal to the Nozzle Orifice

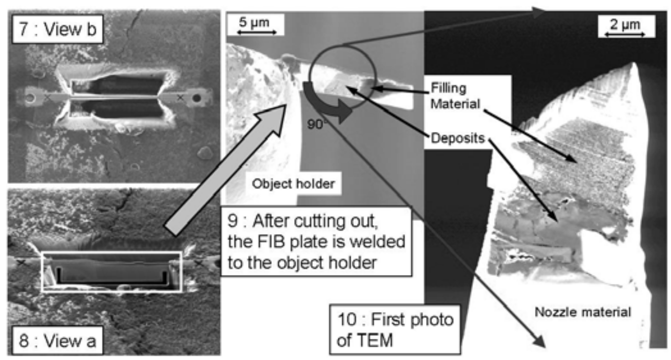

Figure 8: Preparation of FIB Plate Out of Nozzle

EXPERIMENTAL RESULTS

ZINC AS VERY IMPORTANT FACTOR FOR THE BUILD-UP OF CRITICAL DEPOSIT MASSES

Zinc was identified as the main parameter affecting a critical deposit formation in injection nozzles. Therefore, a variety of influences were investigated in this study.

Figure 9 displays a comparison of a test conducted with fuel having 1 ppm zinc concentration, with a test operated with zinc-free fuel. All other boundary conditions were identical. While TR #06 indicated no critical impact on power output and fuel flow, the test run with zinc developed strong deposits, degrading performance by more than five percent.

The test run with zinc (TR #09) was a repeating of TR #07 with the identical nozzles. An ultrasonic bath ensured the complete cleaning of the nozzles, which was validated by reaching the initial power output and fuel flow of TR #07 having identical calibration and boundary conditions.

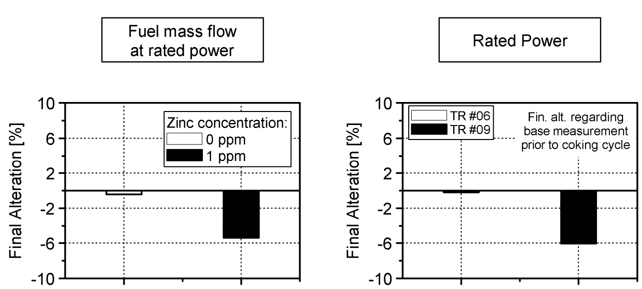

Figure 9: Deposit Formation under the Influence of Zinc within Fuel

Comparison of different parameters on deposit formation

Tests were conducted to evaluate the potential of the parameters temperature and nozzle geometry in comparison to the parameter zinc (Figure 10).

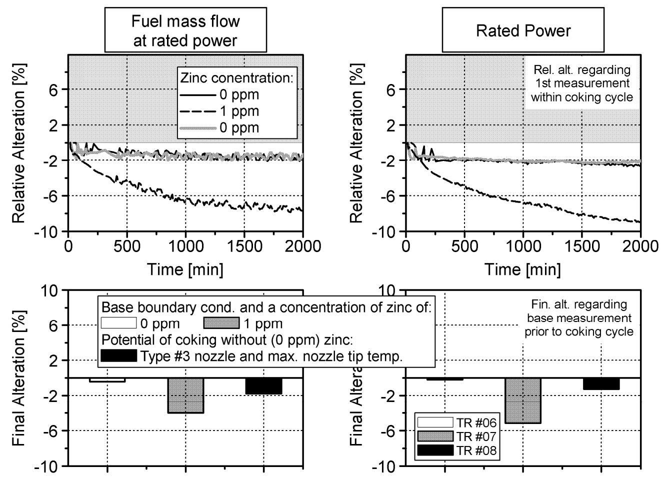

Figure 10: Impact of Zinc as Impact Factor on Formation of Deposits in Comparison to other Parameters

The results marked the large influence of zinc in correlation to the other investigated parameters (Figure 10). During the whole project, no critical nozzle fouling developed without the presence of zinc. Regarding robustness, the worst case conditions demonstrate an acceptable repeatability with TR #06.

<u>Critical zinc concentration</u>

The test with the nozzles with enhanced cavitation resulted in a relatively low coking level during the operation in the presence of 1 ppm zinc, while the type 2 nozzle geometry suffered a high deterioration of power output and fuel flow with these boundary conditions. One conclusion out of the tests is that a critical zinc concentration is existing dependent on the engine hardware configuration. Above this concentration a significant deposit formation occurs. For the base engine configuration, a comparison of three tests displayed the validation of that threshold (Figure 11). The test run (TR #11) with a reduced quantity of zinc in the fuel (0.6 ppm) presented a very similar outcome as the test without zinc. Therefore it can be concluded that the threshold for a critical concentration is in between 0.6 ppm and 1 ppm for this engine configuration.

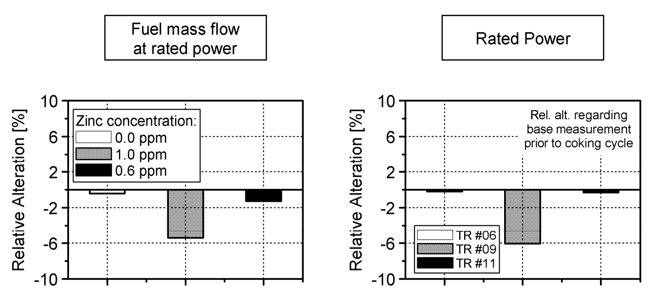

Figure 11: Delimitation of Critical Zinc Concentration within Fuel Regarding Deposit Formation

<u>Reversibility of zinc-derived nozzle fouling</u>

The potential of reversibility of zinc-derived deposits was determined by conducting two subsequent tests with one set of nozzles without any modification during both tests. In the first test run, the diesel fuel contained 1 ppm zinc. The adjacent coking cycle was operated with identical boundary conditions except for zinc content in the fuel. The fuel now was zinc-free. The nozzle fouling created in the presence of zinc diminished during the second test run. It is concluded that at least partially zinc-derived deposits are reversible during zinc-free operation.

INFLUENCE OF TEMPERATURE

During the investigations, the boundary conditions for nozzle tip temperatures were varied. Figure 12 depicts as an example of the results the variation of the operating point. Principally the temperature increases with rising power output. Exceptions are high load points at low engine speed (1000 min-1). The calibration of the engine leads only in this operating area to high particle emissions. It is assumed that the exceptional temperature increase is caused by the glowing soot particles during combustion, leading to an amplified radiation based heat transfer (up to 30 % of heat transfer in diesel engines belongs to the heat radiation of glowing soot particles [41]).

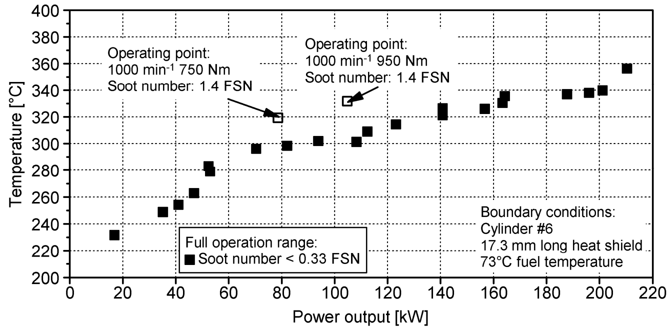

Figure 12: Correlation of Engine Power Output and Nozzle Tip Temperature

Relevant literature indicates that an increased temperature tends to increase the development of deposits in the nozzle orifice. Two variations regarding nozzle tip temperature were investigated. Referring to Figure 12, the Cycle 1 leads to a higher temperature level at the nozzle tip in comparison to the Cycle 2 due to the longer duration of rated power operation.

When basic boundary conditions were applied, both cycles revealed comparable results. The level of coking remained very low for both variants. A different behavior was visible with fuel including a zinc concentration of 1 ppm (the effect of zinc is described in detail below). The presence of zinc led to extensive deposit formation during the operation with the Cycle 1. The Cycle 2, operated under the same boundary conditions, led to no significant coking. Generally, differences in the degradation of fuel mass flow and rated power are considered to be based on error in measurement and changes in combustion during the deposit build-up. The Cycle 2 did not reach degradations greater than two per cent, which was earlier defined as insignificant. The coking level stabilized after about 200 minutes.

Analogue trends were observed with the variation of fuel temperature while operating the engine in the Cycle 1. A lower fuel temperature of fuel having 1 ppm zinc concentration showed a reduced deposit formation, but the reduction of power output did not stabilize.

INFLUENCE OF CAVITATION

The impact of enhanced cavitation on the formation of deposits was investigated, since literature refers to a high influence of the inner spray hole flow regime on the resulting deposit mass. Therefore, two tests were conducted with identical boundary conditions except for the applied nozzles. The geometry of the spray holes varied and, thus, the cavitation tendency. All other parameters such as hydraulic flow rate HFR, cone angle remained identical for both types (for reference see Figure 2). The type 2 nozzle utilizes a hydro-grinded (respectively rounded) spray hole inlet to reduce cavitation in the nozzle orifice. Thus, the test fuel for both tests was doped with zinc to a concentration of 1 ppm. After operating both tests with the Cycle 1, a substantial difference in the results was observed (Figure 13). While type 2 geometry reduced in power output by more than six per cent, type 1 nozzles indicated apparently no significant coking level. The monitoring showed a slowing reduction of power output for the test with type 2 nozzles.

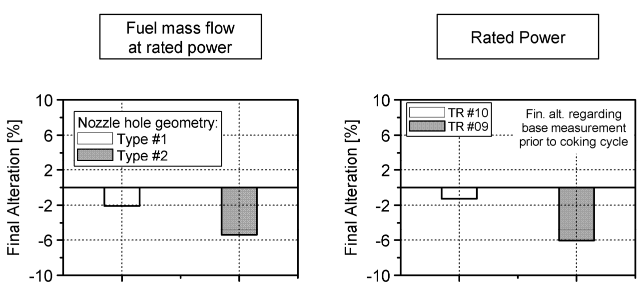

Figure 13: Comparison of Coking Tendencies between Two Different Nozzle Orifice Geometries

CONSEQUENCES OF DIFFERENT BIO DIESEL SHARES

European legislation pushes the part substitution of mineral diesel by bio diesel (for example RME). Since in media the discussion of bio diesel on the behavior of engines is an important issue, the influence on the formation of deposits was investigated. In the near future, values of up to ten percent of RME are realistic. Thus, this concentration is compared to the base bio diesel share of five percent. Two comparisons were investigated. One variation of RME share was conducted without zinc in the fuel and one with 1 ppm. The results display no significant influence of RME on the formation of deposits. The RME for the tests was pure, so side-effects caused by ingredients such as inorganic components often found in bio diesel, were not evaluated.

DEPOSIT ANALYSIS

ELEMENTARY COMPONENTS OF DEPOSITS

The received EDX-spectra display qualitative information about the present elements. The values of y-axis correlate are a function of the element-specific response to the primary electron beam and the concentration of this element in the area under observation.

EDX-images were measured during the low magnification investigation with constant boundary conditions (Figure 14). The figure is an example and the reference. On the right, the EDX-spectrum of location #5, indicated in the SEM image, is shown. This refers to the base material of the nozzle without deposits. The nozzle material contains iron, chromium and nickel. For all following images, the changes of peaks of other elements by varied position or sample are correlated with this basis. The locations indicated in the figure correlate with the area in which the EDX-spectra are taken (surface rectangle for low magnifications always 90 x 112 µm). The size of the rectangle was varied in the range down to 1 x 1 µm for SEM analysis. For TEM analysis even smaller areas were possible.

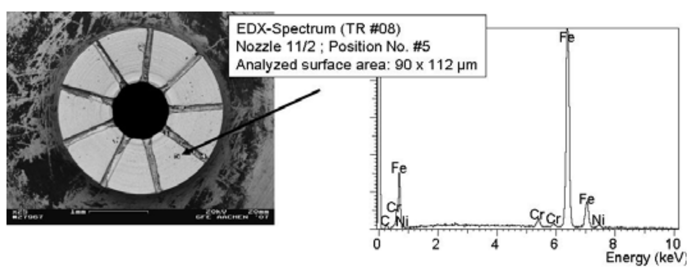

Figure 14: EDX-Spectroscopy of Base Material of Nozzles (Nozzle 11/2)

Deposits in spray holes originated in the investigations out of fuel and lubricant. As described earlier, the iron and chromium peak of the nozzle material were taken as reference to compare the relative concentrations of each detected element in both nozzles. The analysis of nozzle 4/1 showed nearly clean orifices. The elements carbon, oxygen and copper were detected. Copper was at the lower limit of detection. In comparison of both nozzles the number of detected elements varied. Especially elements originating out of lubricant were present in the spectrum of nozzle 5/3. These were calcium, sulfur and phosphor. A possible source of the lubricant was the transport of traces into the fuel in the high-pressure pump. However, the backflow of burned gas including engine oil from the cylinder into the spray hole was more probable, since the analysis of the EDX in flow direction in the spray hole revealed an increasing concentration of these elements. Copper and zinc was observed in the limit of detection. Both nozzles were operated with zinc-free lubricant and fuel. Therefore, the zinc in nozzle 5/3 had to be derived from the engine fuel system hardware. The origin of potassium and sodium could not be clarified. Both elements were not included in the fuel.

Deposits formed in the presence of zinc (usually a mass concentration of 1 ppm zinc within fuel) had also the typical elements derived from the lubricant (Figure 15). But the concentration within the deposits seemed reduced, because the peaks of the elements in nozzle 10/6 were smaller in comparison to the iron peak the corresponding proportion in the EDX-spectrum of nozzle 5/3. On the other hand, the zinc concentration in nozzle 10/6 is highly increased in comparison to nozzle 5/3. It is concluded that the zinc in the deposits originated mainly from the fuel. Since nozzle 10/6 revealed a thick deposit layer, it was used for further analyses.

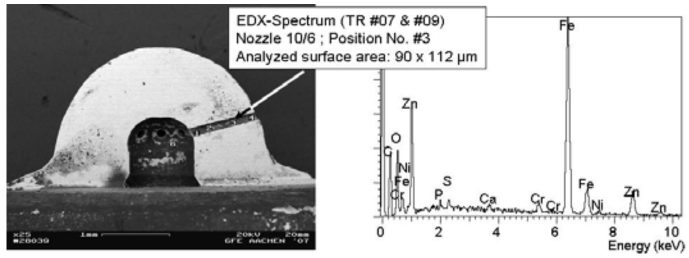

Figure 15: Characteristic EDX-spectra of Spray Holes after Operation with 1 ppm Zinc within Fuel and Zinc-free Lubricant

DEPOSIT MORPHOLOGY

The morphologies of deposits varied strongly during the investigations. There was an obvious correlation of morphology and the rate of deposit formation. A comparison is displayed in Figure 16. The deposits of nozzle 9/3 showed the typical morphology of deposits with a slow growth rate (gradient of power reduction is small). The surface looked crusted. Fine structures were visible without great changes in the morphology dependent on the location. In contrast, nozzle 10/6 displays a smooth base deposit layer, which enclosed fine crusty structures and sharp edged grains with different properties. Various deposit layers with sharp edged grains, respectively, particles are characteristic for fast growing deposits. EDX investigations supposed an increased zinc concentration within the grains in comparison to the enclosing smooth deposit layer.

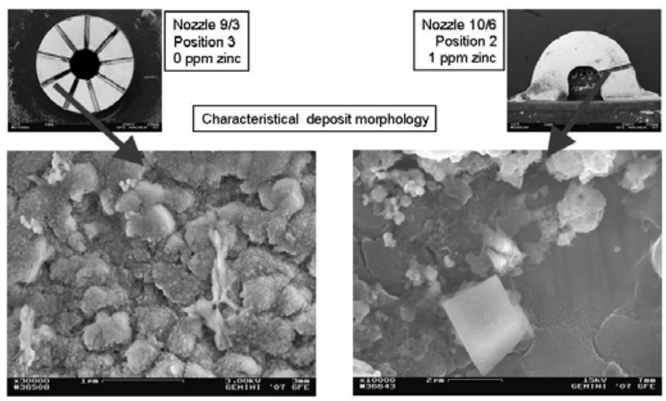

Figure 16: Impact of Zinc-doped Fuel on the Morphology of Deposits

The size of these particles correlated with the position in the nozzle orifice (Figure 17). The nearer the spray hole outlet was, the smaller were the grains. This phenomenon was apparent for the two investigated nozzles. There were two assumptions on the cause of this correlation. First, the concentration of zinc in fuel might reduce in flow direction, since the zinc of the fuel is stored in the deposits. The second assumption includes the temperature distribution in the spray hole. Leuthel and Pfitzner (responsible for the sub project regarding simulation) proclaim an increasing temperature in flow direction in the nozzle orifice [30]. Thus the mechanisms of agglomerating the compounds of the grains might be influenced. The evaluation of the results did not reveal, which assumption is the cause of the different particle size. Finally, a combination of both assumptions is also possible.

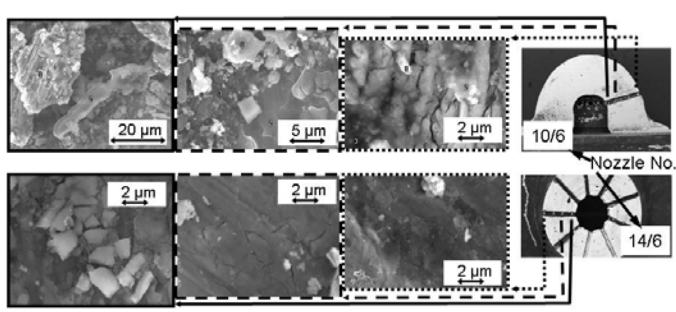

Figure 17: Reduction of Size of Zinc Agglomerates in Direction of the Fuel Flow in the Nozzle Orifice

Another parameter strongly influencing morphology is the flow regime. In Figure 18 nozzle 10/6 was investigated. The morphology of the deposits, especially at inlet and outlet, is compared to optical investigations of a transparent nozzle by Blessing [32] (the image of Blessing is adapted to be more comparable with nozzle 10/6). The visualization of cavitation bubbles in the lower right image at 800 bar fuel pressure and 1500µs after start of injection shows a contradiction at the inlet of the spray hole. The comparison of this view with view II in the lower left corner of the figure led to the conclusion that the particles are grinded by cavitation bubbles. The size of the grains is greater in zone where the flow is not disturbed by cavitation.

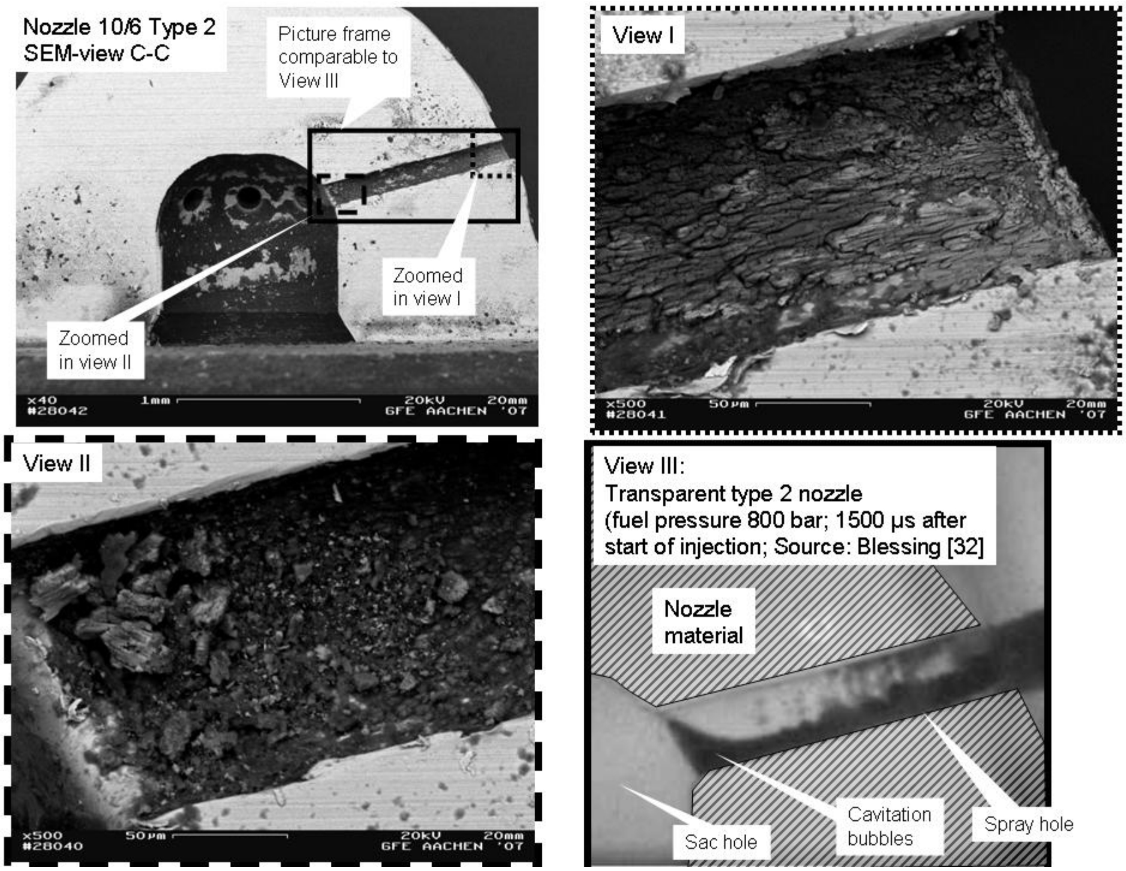

Figure 18: Correlation between Deposit Morphology and Cavitation

DEPOSIT STRUCTURE

A FIB plate was prepared, as described in chapter nozzle preparation, and examined with the TEM microscope for a deeper understanding of the fast growing deposit layers. Goal of the TEM analysis was the validation of different deposit layers and the inhomogeneous distribution of zinc in the deposits. The sample (FIB plate) was taken from near the hole outlet. Its sample view was normal to the nozzle hole surface. Figure19 displays on the right hand side an overview image of the sample taken with the TEM microscope. The nozzle material is visible at the bottom of the image. The filling material marks the upper area of the sample and reveals a homogeneous, grainy structure. The deposit layers are between filling material and nozzle material. The right photo displays various deposit layers having different constitutions. Also small areas were visible, where the deposits are partly destroyed. These areas developed during the preparation due to the gallium ion beam. On the right hand side of the image is a silicon grain. The silicon grain had a size of less than two microns in length and width. It was supposed that the grain joined the sample during the preparation procedure.

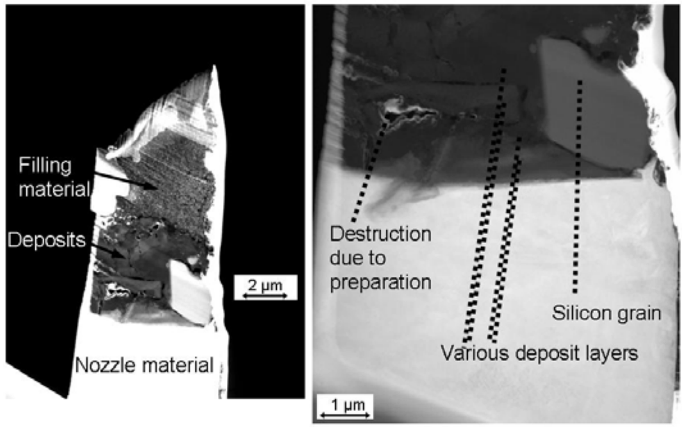

Figure 19: Prepared FIB Plate of Nozzle 10/6

In addition, a method was used to investigate a rectangular area near the nozzle surface. Maps of concentration for each of the elements carbon, oxygen and zinc were produced.

Oxygen had a distribution very comparable to zinc, with one difference, which is at the contact zone of the deposits and the silicon grain. It was concluded that the grain entered the sample during the preparation. The increased oxygen concentration was caused by the previous exposition of deposits to air. Carbon is detected throughout the complete deposit coating. The concentration remains relatively constant. The occurrences of a depression correspond with a peak concentration of the metal zinc. It is assumed that both shares provide the major part of the material and also have a similar magnitude in these locations. Zinc displays a layer of enhanced concentration covering the complete visible surface of the nozzle material. Therefore, it seems characteristic for zinc-derived nozzle fouling, that the initial deposit formation develops under strong interaction with zinc.

The investigation with SAD revealed that no crystalline structures were detected. Therefore, the deposits are most probably amorphous.

SUMMARY

The primary purpose of this study was to conduct test cell investigations, which outlined important parameters in the formation of deposits on the injector nozzles and their removal. Under specific boundary conditions, the acceleration retardation and prevention of the formation of critical deposits in nozzles were intended to increase the knowledge of the formation and removal mechanisms for the deposits.

A medium-duty truck engine with a unit pump fuel system was utilized for this study. A variety of cavitations levels were needed inside the spray hole, which was achieved by using three different nozzle types. To evaluate the impact of the components, the RME share and that concentration of zinc in the fuel were varied. A zinc-free engine lubricant was used to reduce side-effects due to oil consumption. Two coking cycles and a variety of fuel temperatures were included to indirectly alter the temperature at the nozzle.

Evaluation of the severity of the deposit formation was first evaluated by the reduction in power output and fuel mass flow at the rated power conditions. An electron microscope was used to provide a detailed analysis of the deposits in the nozzles. Optical access provided a view of all locations inside the nozzle.

The following results were observed:

- Components within the fuel and engine lubricant provide the source of the deposits in the nozzle spray holes. Two common elements found in the deposits were carbon and oxygen. The engine lubricant supplied calcium, sulfur and phosphor as a part of the material deposited. However, zinc was a crucial element found in the deposit analysis.

- The morphology of deposits changed significantly with the rate of formation. When the low formation rates existed, fine structures with a crusted surface were observed. When the formation rates rose, a base deposit layer was visible with a smooth surface enclosing particles with a different composition and sharp edges appeared. In that instance, the size of the particles was reduced in the direction of the flow within the spray hole. The flow pattern, especially when cavitation is present, had a measurable effect on morphology of the deposits.

- The zinc in the deposits displayed an inhomogeneous distribution with the particles having an increased concentration of zinc.

- Increased power output and high soot emissions cause the temperature at the nozzle tip rise.

- Increased temperature at the nozzle accelerates the formation of deposits.

- Cavitation was identified as a major parameter that inhibits the formation of deposits.

- Increasing the RME share in the fuel had no influence of the formation of deposits.

- The study indicated that zinc was the primary factor in the formation of injection nozzle deposits. A concentration of above a specific threshold of zinc caused a significant formation in deposits within a relative short period of time. The zinc threshold is dependent on how the engine is configured. The study also showed that the zinc-derived deposits could be at least partially reversed by operating the engine under zinc-free conditions.

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REFERENCES

1. Caprotti, R., Breakspear, A., Graupner, O., Klaua, T., Kohnen, O.: Diesel Injector Deposits Potential in Future Fueling Systems. Technical Report 2006-01-3359, SAE, 2006
2. Hage, F.: Experimentelle Untersuchung der Einspritzdüsenverkokung an einem PKW-Dieselmotor – Ursachen und Verbesserungsmöglichkeiten, Dissertation Hannover, 1985.
3. Olsen, R. E., Ingham, M. C., Parsons, G.M.: A Fuel Additive Concentrate for Removal of Injector Deposits in Light-Duty Diesels, SAE 841349, 1984.
4. Hage, F.: Untersuchung der Einspritzdüsenverkokung an einem PKW-Dieselmotor, MTZ, 47(Nr. 7/8), 1986.
5. Herbstman, S., Virk, K.: Use of dispersants/detergents in diesel injector keep clean and clean up studies, Technical Report 912330, SP 797, SAE, 1991.
6. Montagne, X., Herrier, D., Guibet, J.C.: Fouling of automotive diesel injectors-test procedure, in influence of composition of diesel oil and additives, Technical Report 872118, SAE, 1987.
7. Reading, K., Roberts, D. D., Evans, T. M.: The effects of fuel detergents on nozzle fouling and emissions in IDI-diesel engines, Technical Report 912328, SAE, 1991.
8. Panesar, A., Martens, A., Jansen, L. et al.: Development of a new Peugeot XUD9 10 hour cyclic test to evaluate the nozzle coking propensity of diesel fuels, Technical Report 2000-01-1921, SAE, 2000.
9. Claar, K. G., Blythe, G. H., Pocinki, S.: Diesel fuel properties and additive effects on DI-injector deposit formation, Technical Report 932738, SAE, 1993.
10. Winterbone, D. E., Clough, E., Rao, K. K.: Effect of DI-nozzle fouling on fuel spray characteristics, Technical Report 922232, SAE, 1992.
11. Caprotti, R., Bovington, C., Fowler, W. J. et al.: Additive technology as a way to improve diesel fuel quality, Technical Report 922183, SAE, 1992.
12. Pundir, B. P., Singal, S. K., Gondal, A. K.: Diesel Fuel Quality: Engine Performance and Emissions, SAE 942020, 1994.
13. Bonse, B., Dittus, B., Giersch, J.: Innovationen Dieseleinspritzdüse - Chancen für Emissionen, Verbrauch und Geräusch, 5. Internationales Stuttgarter-Symposium, Kraftfahrwesen und Verbrennungsmotoren, Februar 2003, 2003.
14. Caprotti, R., Breakspear, A., Graupner, O. et al.: Detergency requirements of future diesel injection systems, Technical Report 2005-01-3901, SAE, 2005.
15. McMillian, M. L., Halsall, R.: Fuel effects on combustion and emissions in a direct injection diesel engine, Technical report, SAE, 1988.
16. Lepperhoff, G., Houben, M.: Mechanisms of deposit formation in internal combustion engines and heat exchangers, Technical Report 931032, SAE, 1993.

17. Stratmann, F.: Partikeltransport in einer gekühlten laminaren Rohrströmung durch gleichzeitige Konvektion, Diffusion und Thermophorese, Dissertation RWTH Aachen, 1992.
18. Amelin, A. G.: Theory of Fog Condensation, 2nd Edition, augmented and revised, edited by Derygagin, B.V., 1967.
19. Rosner, D. E., Seshadri, K.: Experimental and theoretical studies of the laws governing condensate deposition from combustion gases, 18th symposium on combustion, Waterloo, Canada, 1990.
20. Reichel, S.: Beeinflussung der Partikeln im Dieselabgas bei Abkühlung und Vermi-schung mit Umgebungsluft, Dissertation RWTH Aachen, 1983.
21. N. N.: A Pocket Guide to Crankcase Engine Lubricants Additive Division, Shell International Company Ltd., Shell Center London SE1 7NA.
22. Rüdinger, V.: Ein Modell der Ablagerungsbildung am Dieselmotorkolben, Erdöl und Kohle, EP 27, pages 353-358, 1974.
23. Meyers, P. S., Uyehara, O. A., DeYoung, R.: Fuel Composition and Vaporization Effects on Combustion Chamber Deposits, U.S. Dept. of Energy, DOE/CS/50020, 12/1981.
24. Davis, J. T.: A New Theory of Aerosol Deposition From Turbulent Fluids, Chemical Engineering Science, Tg. 38 (1), 1983.
25. Minh, T. B.: Kokstrompetenbildung an Einspritzdüsen von Schiffsdieselmotoren, Dissertation, Wilhelm-Pieck-Universität Rostock, 1976.
26. Lepperhoff, G., Weber, O.: Ventilverkokung, Teil 1, Ursachen der Koksbildung an Ein-lassventilen von Verbrennungsmotoren, FVV-Nr. 365.
27. Fabri, J.: Ventilverkokung, Teil 2, Ursachen der Koksbildung an Einlassventilen von Verbrennungsmotoren, FVV-Nr. 365.
28. Schommers, J.: Ursachen der Ablagerungsbildung auf Einlassventilen von Verbren-nungsmotoren, Dissertation RWTH Aachen, 1986.
29. Lepperhoff, G.: Deposit Formation on Inlet Valves: The Influence of Mixture Formation as well as the Interaction between Oil, Fuel and Exhaust Gas, 10th European Automotive Symposium, AGELFI, 10/1990.
30. Leuthel, R., Pfitzner, M.: Coupled Thermal-CFD-Modelling of a Diesel fuel injector, 8. Internationales Symposium für Verbrennungsdiagnostik, 10. / 11. Juni 2008, Kurhaus Baden-Baden, ISBN 978-3-00-022057-9
31. N. N.: Bosch Dieselmotor-Management, 4. Auflage, ISBN 3-528-23873-9, Vieweg, 2004.
32. Blessing, M.: Untersuchung und Charakterisierung von Zerstäubung, Strahlausbreitung und Gemischbildung aktueller Dieseldirekteinspritzsysteme, Dissertation, Universität Stuttgart, 2004.
33. Graupner, O., Klaua, T., Caprotti, R. et al.: Injector deposit test for modern diesel engines, TAE Int. Coll. Fuels 2005, 2005.
34. N.N.: § 37a Abs. 3 BlmSchG, referred to in url: http://www.mittlerer-niederrhein.ihk.de/download/merkblaetter/recht_fair_play/biodiesel.pdf, download am 13.03.2008.
35. Bückins, M., Harscheidt, R., Keil, M., Rehbach, W.P., REM-EDX-Analysen mit hoher Ortsauflösung unter Verwendung von FIB-Schnitten, DGM, 38. Metallographie-Tagung mit Ausstellung, Bochum, 2004
36. Flegler, S., Heckmann, J., Klomparens, K., Elektronenmikroskopie Grundlagen, Methoden, Anwendungen, Spektrum, ISBN 3-86025-341-7, 1995
37. Hahn-Weinheimer, P., Hirner, A., Weber-Diefenbach, K., Grundlagen und praktische Anwendung der Röntgenfluoreszenzanalyse, Vieweg-Verlag, Braunschweig/Wiesbaden, 1984
38. Williams, D.B., Carter, C.B., Transmission Electron Microscopy. A Textbook for Materials Science. Plenum Press, New York, ISBN 0-306-45247-2, 1996
39. Brydson, R., Electron energy loss spectroscopy. Garland/BIOS Scientific Publishers, Oxford, ISBN 1-859-96134-7, 2001
40. Randle, V., Engler, O., Introduction to Texture Analysis - Macrotexture, Microtexture & Orientation Mapping. CRC Press, ISBN 90-5699-224-4, 2000
41. Pischinger, S., Verbrennungskraftmaschinen I, 26. Auflage, RWTH, Aachen, 2007