

Coking Phenomena in Nozzle Orifices of DI-Diesel Engines

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ABSTRACT

Within a public founded project test cell investigations were undertaken to identify parameters which predominantly influence the development of critical deposits in injection nozzles. A medium-duty diesel engine was operated in two different coking cycles with a zinc-free lubricant. One of the cycles is dominated by rated power, while the second includes a wide area of the operation range. During the experiments the temperatures at the nozzle tip, the geometries of the nozzle orifice and fuel properties were varied. For a detailed analysis of the deposits methods of electron microscopy were deployed. In the course of the project optical access to all areas in the nozzle was achieved. The experiments were evaluated by means of the monitoring of power output and fuel flow at rated power. The usage of a SEM (scanning electron microscope) and a TEM (transmission electron microscope) revealed images of the deposits with a magnification of up to 160 000. The methods EDX (energy dispersive X-ray) and EELS (electron energy loss spectroscopy) delivered spectra of defined elements. The results of the project show enhanced nozzle fouling by increasing the temperature at the nozzle tip. Zinc marks a major parameter affecting the build-up of deposits. Above a critical concentration of zinc in fuel significant coking develops within a relative short period. These deposits are partly reversible by zinc-free operation. Zinc-derived deposits contain an inhomogeneous distribution of the metal. Nozzle coking based on zinc-free operation

displayed morphology with a different texture in comparison to the coking developed in the presence of zinc. Cavitation inside the nozzle posed the major parameter to inhibit the formation of deposits.

INTRODUCTION

The stringent future emission legislation along with the costumer's desire for a steadily improved performance pose a major challenge towards the development of new diesel engines for passenger cars. Pollutant limitations as for example demanded by Tier 2 Bin 5 require in addition to an advanced aftertreatment a robust combustion process minimizing emissions in the process of formation.

An important part in the great improvements so far achieved belongs to the advances in the technology of diesel injection (DI) systems [13]. Particularly the downsizing of nozzle orifice diameters by enhanced flow characteristics in combination with increased injection pressures offered the opportunity to carry out engines featuring high power density along with minimized emissions. However, these modern spray hole geometries suffer more often a reduction of power output during long term operation. Investigations by, for example, Caprotti [1] identify a critical formation of deposits as the main reason of this behavior.

Deposits, in and on nozzles, influence the fuel injection resulting in a different mixture formation and combustion [2]. In indirect injection (IDI) diesel engines this can lead to increased acoustic [3] and pollutant emissions [4], [5]. Since the formation of deposits in these applications could not be prevented, the design of the nozzles included a consideration of the impact of the formed deposits [6], [7], [8]. Various investigations on direct injection (DI) diesel engines observed a deterioration of combustion and mixture formation. The results revealed increased pollutant emissions [9], [10], [11] and slightly increased fuel consumption [12]. The reduction in power output is very characteristic for nozzle fouling [9], [12], [13], [14], [15].

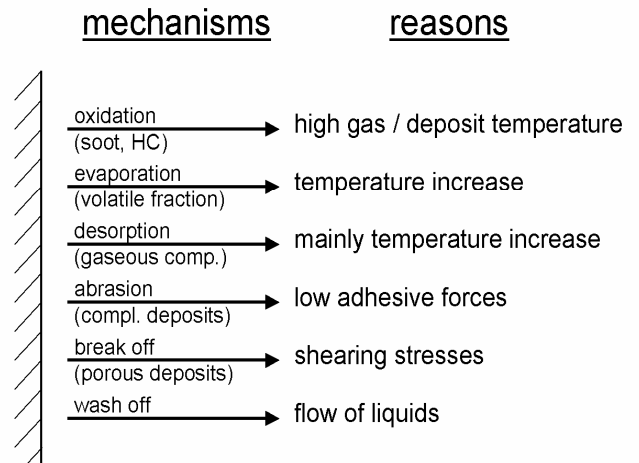
MECHANISMS OF DEPOSIT FORMATION AND REMOVAL

Lepperhoff and Houben [16] explained the formation and removal of deposits in internal combustion engines by means of basic mechanisms. These mechanisms are independent of the location of formed deposits (e.g. injection nozzles, heat changer) of the combustion process (e.g. IDI, DI; diesel or gasoline).

Their model describes the interaction of a wall to the enclosing flow regime. The transport of particles to the wall is mainly based on thermophoresis [17]. This effect causes a force on particles in gases in direction of the temperature depression. It is amplified with an increasing temperature difference between wall (cold) and fluid (hot). The result is an increased concentration of deposit building particles near the wall. High turbulences near the wall may attenuate the aerosol again to a mean value compensating an increased temperature difference. [16]

Deposits are attached particles (solid and liquid) and gas (Figure 1). A condensation [18], [19] and adsorption [20] of gaseous compounds at the cold wall initiates the formation process. The growth is now mainly influenced by the sticking, impaction and incorporation of particles [21], [22], [23], [24]. The adsorption of gaseous components as well as 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 for example in inhomogeneous extensions of 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].

Deposit Removal



Deposit Formation

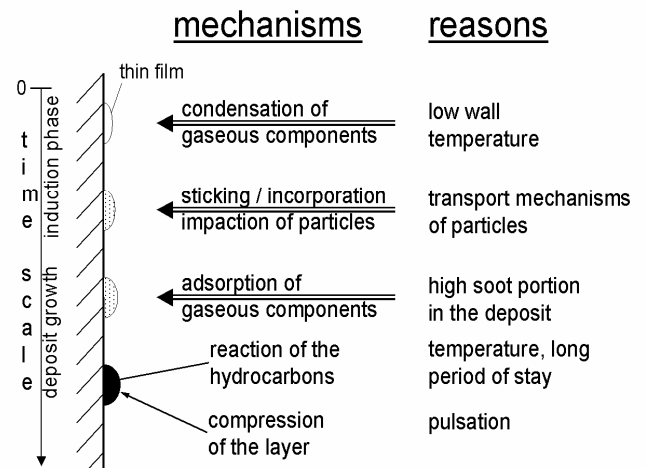


Figure 1: Mechanisms of deposit formation and removal [16]

PROJECT OBJECTIVES

The objectives of this project were to investigate the major causes for the formation of deposits in the spray hole and to figure out the dominant parameters which support the formation and the decay of deposits. The goal is to find measures to decelerate or even inhibit the formation of these deposits. The project was divided into two subprojects. One subproject dealt with experimental investigations including a detailed deposit analysis. The other subproject focused on simulation of the effect of various nozzle types (cylindrical, ks-nozzle) on heat transfer and fluid flow utilizing a coupled CFD- and thermal modeling. A further aspect of the research was the thermal situation of the nozzle including a sensitivity analysis regarding the thermal conditions at the injector tip. Furthermore, the cavitation including thermal effects was investigated. In this paper the experimental results are presented including the deposit analysis. The outcome of the other subproject is partly published [30].

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).

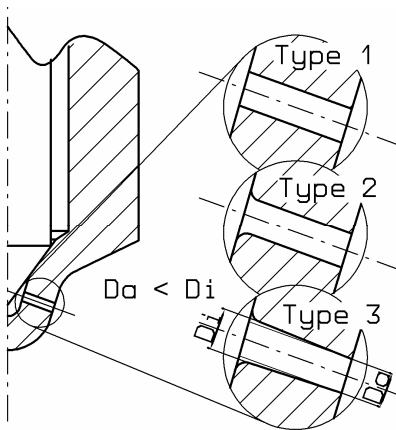


Figure 2: Schematic of utilized nozzle orifice geometries (type 1: cylindrical, no rounding; type 2: cylindrical, high rounding; type 3: conical, high rounding)

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 thermo couples 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).

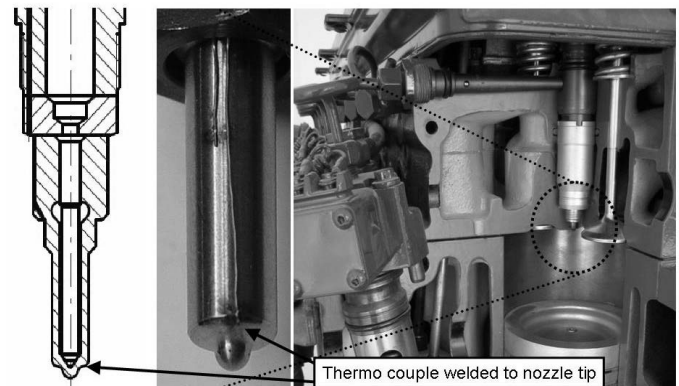


Figure 3: Application of thermocouple at the nozzle tip

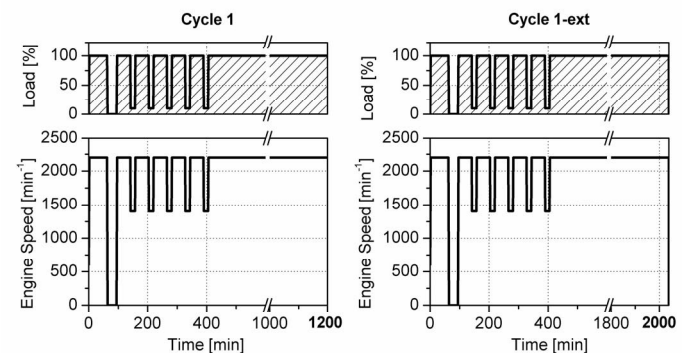


Figure 4: Base coking cycles (Cycle 1 / Cycle 1-ext.) provided by Daimler

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.

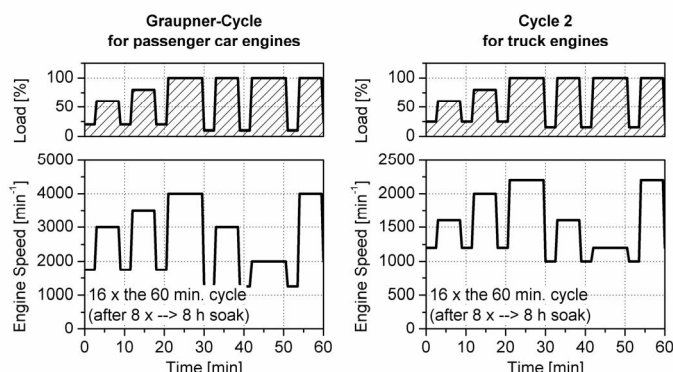


Figure 5: Different coking cycles (Graupner-Cycle [33] / Cycle 2)

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.

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).

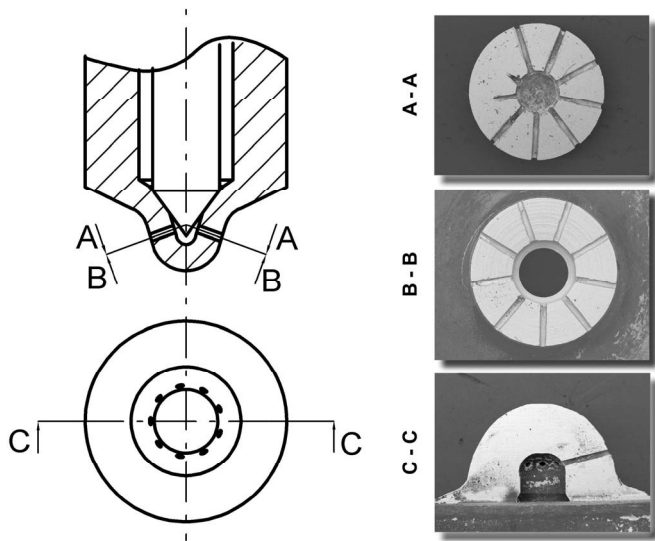


Figure 6: Sample preparations for optical access of deposits in nozzles

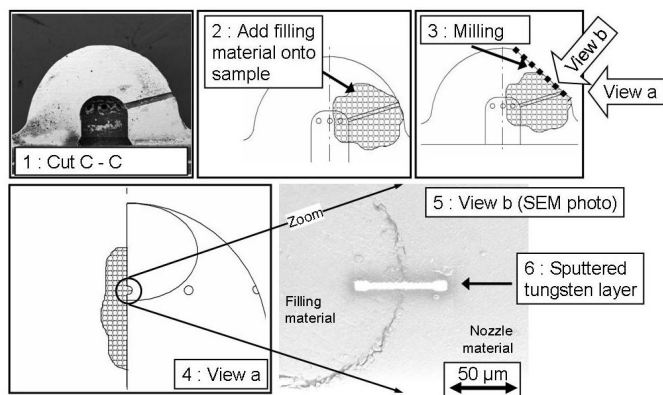


Figure 7: Procedure of preparing a surface in the nozzle normal to the nozzle orifice

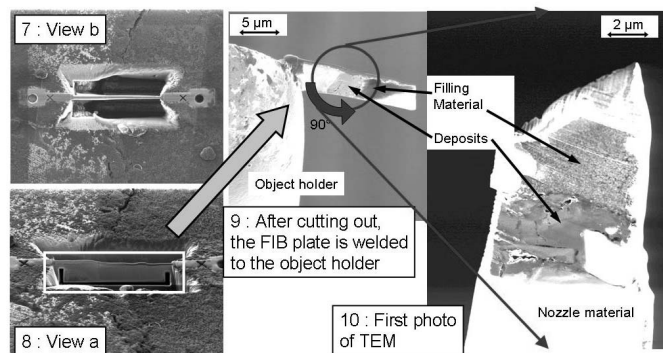


Figure 8: Preparation of FIB plate out of nozzle

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,

various influences were investigated in the following chapters.

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, resulting in degraded performance by more than five percent.

The test run with zinc (TR #09) was a repeat 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.

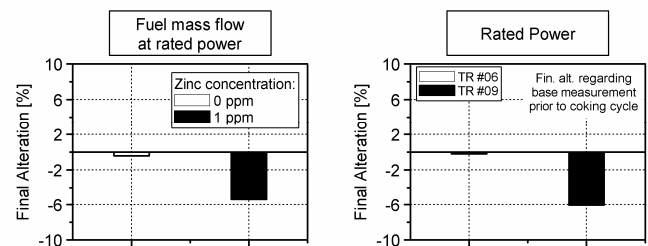


Figure 9: Deposit formation under the influence of zinc within fuel

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). One test (TR #08) featured nozzle geometry type 3 (compare with Figure 2) and a maximum temperature at the nozzle. Fuel and intake manifold temperatures were as high as possible, the heat shield was omitted and the nozzle tip protrusion was increased by 0.5 mm.

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.

Critical zinc concentration

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 (as already discussed during the chapter influence of cavitation). 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