

Injection Nozzle Coking Mechanism in Common-rail Diesel Engine

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ABSTRACT

The hole diameter of injection nozzles in diesel engines has become smaller and the nozzle coking could potentially cause injection characteristics and emissions to deteriorate. In this research, engine tests with zinc added fuels, deposit analyses, laboratory tests and numerical calculations were carried out to clarify the deposit formation mechanisms. In the initial phase of deposit formation, lower zinc carboxylate formed close to the nozzle hole outlet by reactions between zinc in the fuel and lower carboxylic acid in the combustion gas. In the subsequent growth phase, the main component changed to zinc carbonate close to nozzle hole inlet by reactions with CO_2 in the combustion gas. Metal components and combustion gases are essential elements in the composition of these deposits. One way of removing these deposits is to utilize cavitations inside the nozzle holes.

INTRODUCTION

Diesel engines are an effective way of reducing CO_2 emissions and fuel injection equipment is continually being improved to increase thermal efficiency and satisfy ever more stringent emissions regulations. In recent years, common rail fuel injection systems for passenger vehicles have been developed that inject fuel at high pressures up to 200 MPa. High performance injectors that use highly accurate and fast-response piezo devices have also found widespread use [1]-[4]. At the same time, nozzle hole diameter is being designed smaller to create better fuel spray atomization that improves the emissions performance. Holes with a diameter of 100 μm or less have already been developed [4][5].

Growing numbers of diesel vehicles are being exported to emerging markets, and it is necessary to develop measures for fuels in these regions that have uncertain properties. Small nozzle holes and uncertain fuel quality may result in the formation of deposits inside the nozzle hole, thereby causing injection characteristics to deteriorate. Several cases of research have already been published, which have highlighted typical characteristics related to nozzle hole deposits [6]-[14]. For example, it has been reported that deposits are not formed when the fuel contains no metal components, but that substantial deposits are formed when zinc is present in the fuel and deposits have also been shown to increase in accordance with higher zinc contents [9][12]. In contrast, the nozzle hole geometry has a major influence on deposit formation, and it was found that deposits can be removed by increasing cavitations in the nozzle hole [8][13]. Although a wide variety of information about nozzle coking has been obtained in this way, the deposit formation mechanism has yet to be clarified in sufficient detail to control its occurrence, and further research is required.

In this research, the following evaluations and analyses were carried out. This paper reports these results and describes the estimated nozzle coking mechanism in a diesel fuel injection system.

- Deposit formation by engine test due to the use of zinc added fuel was analyzed to identify the specific components, locations, and amounts of the deposits.
- Laboratory tests were carried out to verify the reaction paths and conditions required to reproduce the detected deposit components.

- The factors thought to influence deposit formation and removal were investigated.
- The influence of nozzle hole geometry on deposit formation and removal were considered.
- The nozzle coking mechanism was estimated based on the obtained results.

EXPERIMENTAL AND ANALYSIS METHODS

ENGINE SETUP

The influence of the nozzle hole geometry, engine operating conditions, and the fuel zinc concentration on deposit formation were evaluated by engine tests. Since the formation of deposits in the nozzle hole decreases the injection quantity, the fuel flow loss calculated in accordance with Equation 1 was used as an index for the amount of deposits. During the engine operations, the commanded injection quantity was set constant to evaluate the fuel flow loss caused by deposit formation.

Fuel flow loss ΔQ_v [%]

$$\Delta Q_v = \frac{Q_v(0) - Q_v(t)}{Q_v(0)} \times 100 \quad (1)$$

$Q_v(0)$ Injection quantity at initial time [mm³/st]

$Q_v(t)$ Injection quantity at elapsed time [mm³/st]

Test engine

Table 1 lists the specifications of the engine used in this research. The engine equips a Denso common rail fuel injection system with a maximum injection pressure of 200 MPa and piezo-driven injectors.

Table 1 Test engine specifications

Type	In-line four
Bore x Stroke	φ86.0 mm x 96.0 mm
Displacement	2,231 cm ³
Compression ratio	15.8
Injection system	Common-rail (Denso)
Injector type	Piezo (G3P)
Boosting system	Inter cooled turbocharger

Test fuel

Zinc neodecanoate was added to EU-certified diesel oil to adjust the zinc concentration to an arbitrary level and accelerate deposit formation. The maximum sulfur concentration in the fuel was 5 ppm.

Injection nozzle

Table 2 lists the specifications of the nozzle used in the engine test. The bold figures in the table show the main changes from the base specifications. The detailed nozzle geometry is described below.

Table 2 Nozzle specifications for engine test

	Type	Cd [-]	L [mm]	Cf [%]
Base	MS	0.86	0.8	1.5
A	VCO	0.83	1.05	1.5
B	MS	0.79	0.8	1.5
	MS	0.89	0.8	1.5
C	MS	0.84	0.5	1.5
	MS	0.86	0.8	2.5

MS: mini sac

VCO: valve covered orifice

Nozzle type

Figure 1 shows the geometry of the evaluated nozzles. A mini-sac (MS) nozzle was used mainly. In addition, two types of valve covered orifice (VCO) nozzle were used to evaluate the influence of the combustion gas on deposit formation. In the first, the needle valve blocks the nozzle hole when the valve is closed to prevent combustion gas. In the second, a groove was provided around the whole circumference of the needle valve (i.e., a radial groove) so that the

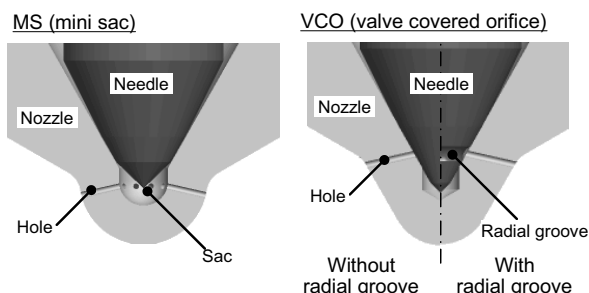


Figure 1 Schematic diagrams of test nozzle types

combustion gas can enter the nozzle.

Nozzle hole geometry

Figure 2 shows the design parameters of the nozzle hole. The discharge coefficient of the nozzle hole (defined by Equation 2) was varied to evaluate the influence of cavitation in the nozzle hole on the deposit removal in the MS nozzle. To achieve this variation in discharge coefficient, the nozzle hole radius at the hole inlet edge was controlled by hydraulic grinding rate.

Discharge coefficient Cd [-]

$$Cd = \frac{q_v}{A \sqrt{2 \cdot \Delta P \cdot \rho}} \quad (2)$$

q_v Injection rate [m³/s]

A Nozzle hole suction area [m²]

ρ Fuel density [kg/m³]

ΔP Fuel differential pressure at 9.8 MPa [MPa]

In addition, since it is possible that factors other than the cavitation inside the nozzle may have an influence on deposit formation, the hole length and conicity factor (defined by Equation 3 as the angle θ at the inlet)

the difference between the hole inlet and outlet) were also varied.

Conicity factor Cf [%]

$$Cf = \frac{d_{in} - d_{out}}{L} \times 100 \quad (3)$$

d_{in} Hole inlet diameter [mm]
 d_{out} Hole outlet diameter [mm]
 L Hole length [mm]

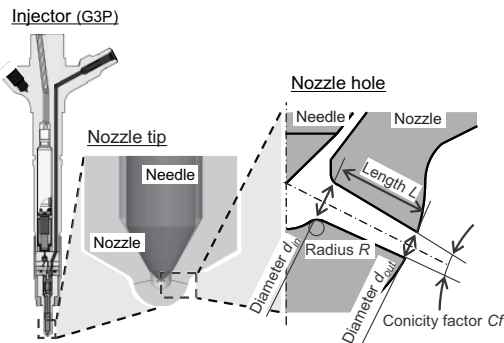


Figure 2 Schematics diagrams of hole geometry

Engine operating conditions

Figure 3 shows the operating conditions of the evaluated engine. Previous research indicated that temperature has a major influence on deposit formation, and that formation is accelerated at higher temperatures [13]. This research also evaluated a wide temperature range from idling to the maximum power point to analyze the influence of temperature. Though various cases of research have described cycles for evaluating nozzle coking [11], the evaluation was performed in a constant load and speed for all conditions to clarify the influence of the temperature on deposit formation. The nozzle tip temperature was measured using an injector with a thermocouple installed.

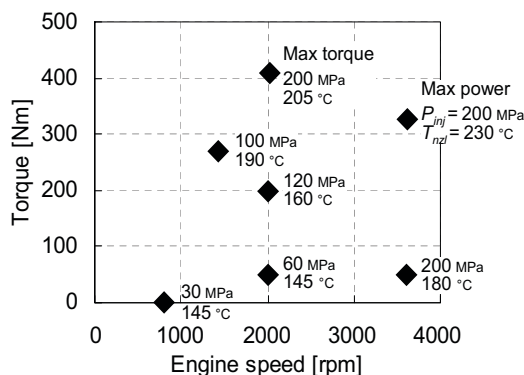


Figure 3 Engine operating conditions

DEPOSIT ANALYSIS METHOD

The tested nozzle was cut to obtain a cross section of the nozzle hole in advance. Then the deposit formed in the nozzle hole was analyzed as follows [15].

Scanning Electron Microscope (SEM)

The appearance of the deposits was observed by SEM, and the states of deposit formation and removal were evaluated.

Electron Probe Micro Analyzer (EPMA)

The elemental composition of the deposits was analyzed by EPMA. Measured locations were inlet, center and outlet of the nozzle hole, respectively.

Fourier Transform Infrared Spectrometer (FT-IR)

The chemical structure of the deposits and its distribution in the nozzle hole were analyzed by FT-IR imaging measurement in reflection mode. In addition, the peak area between 1800 cm^{-1} and 1000 cm^{-1} at IR spectrum was used as an index to express the distribution of deposits.

X-ray Scanning Analytical Microscope (XSAM)

The distribution of zinc element in the nozzle hole was measured by XSAM quantitatively. As described below, since the main components of deposit in the nozzle hole were zinc compounds, the amount of zinc element was used as a representative index for the amount of deposits.

NUMERICAL METHOD

The influence of the flow in the nozzle on deposit removal was analyzed by the internal fuel flow calculation [16]. Table 3 describes the details of the calculation conditions. The AVL FIRE was used for the numerical calculation. It has been reported that deposit removal is influenced by the energy generated when cavitation collapses [8][13]. Therefore, this research attempted to calculate an index for deposit removal force by using an erosion model to calculate the internal flow. Furthermore, the nozzle geometry for the calculation was based on the detailed measurement obtained with the print technique.

Table 3 Calculation conditions

CFD Code	AVL FIRE (Version 2008)
Calculation method of multi-phase flow	Multi-fluid model Fluid 1 (liquid phase): Liquid fuel Fluid 2 (gas phase): Air Fluid 3 (gas phase): Fuel vapor
Differencing schemes	Momentum: SMART scheme Pressure: Central difference scheme
Pressure-velocity coupling method	SIMPLE method
Turbulence model	Standard k-ε model Hybrid wall function
Cavitation model	Simplified Rayleigh's equation Initial void fraction : $\alpha_0=0.001$ Bubble density : $n=10^{12}$