

Inner Diesel Injector Deposit Formation Mechanism

Akio Tanaka, Koichi Yamada, Toshihiko Omori, Satoshi Bunne, and Katsuhiko Hosokawa
DENSO Corp.

ABSTRACT

Higher pressure and higher precision are required for diesel fuel injection equipment in response to increasingly severe emissions control regulations. Market diesel fuels have become more diversified than in the past. Diesel fuel quality has also been changing, being affected by crude oil slate, extreme lowering of sulfur content, and diesel reformulated from heavy fuel oil, among other reasons. As a result of this, deposits thought to have a fuel origin have been observed within diesel fuel injectors in certain regions. Related changes in fuel injection quantity have also been observed.

This paper determines injector deposit production mechanisms. It focuses on the structural changes of deposit causative substances by temperature as well as injector design change improvements to prevent deposits. It also reports effects of reduced temperature on fuel injection equipment (FIE) and improved surface treatment methods for the internal parts, based on mechanisms determined from glassware tests.

CITATION: Tanaka, A., Yamada, K., Omori, T., Bunne, S. et al., "Inner Diesel Injector Deposit Formation Mechanism," *SAE Int. J. Fuels Lubr.* 6(3):2013, doi:10.4271/2013-01-2661.

INTRODUCTION

To realize higher pressure injection, Common Rail fuel injection Systems (CRS) have been developed. Compared to conventional fuel injection, CRS requires sliding portions which release high pressure with tight clearance to control valve open/close. Injection pressures are now up to twice as high as first generation CRS.

Common rail (CR) is an accumulator type injection system that was developed for high-pressure fuel injection in the latter half of 1990s. CR injection requires sliding portions with narrow clearance for valve control and for releasing high pressure. Today, nearly two-fold injection pressure is required compared to the early injection equipment. [Figure 1](#) shows that increased pressure not only promotes better atomization of fuel spray but also raises the temperature of leakage fuel generated by the high-pressure fuel release at higher level injections. The heat generated during pressure release promotes oxidization of fuel and may cause fuel ageing [5, 8]. When emission regulations equivalent to EURO 4 were implemented, internal diesel injection deposits (IDID) leading to changes in injection quantity, began to be reported [1, 2, 3, 4, 6, 7]. IDID is supposed to be categorized as described [Figure 2](#), but unlike deposits which clog nozzle spray holes that have been previously reported, internal injector deposits cause different symptoms in engines such as start failure and idle vibration. Many teams around the world are working on this problem in an attempt to determine causes of the phenomena and figure out possible countermeasures. The higher molecular weight carboxylate types as shown at the top of the [Figure 2](#) are the most frequent issue encountered and are addressed by this paper.

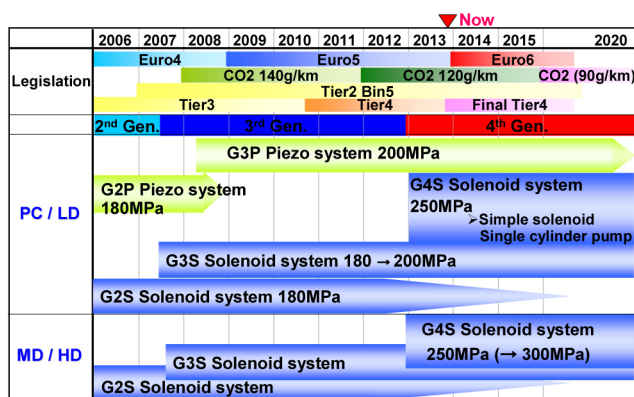


Figure 1. Common rail system roadmap

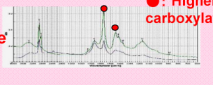
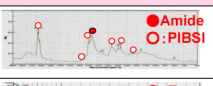
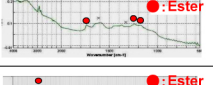
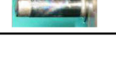
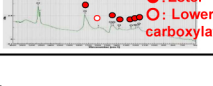
Detected portion	Area	Remark of fuel	Classification of Deposit
 Nozzle needle	> Spain > France > USA etc.	> Higher Acid > Metal Content	Higher carboxylate type 
 Nozzle needle	> UK > Germany etc.	> Additive (PIBSI) > Acid	Amide type 
 Nozzle needle	> Japan	> Additive (CFI)	CFI type 
 Valve needle	> Brazil > USA etc.	> FAME blend rate > Oxidation Stability > TAN	FAME type 

Figure 2. Deposit type

DEPOSIT IMPACT ON CHANGE IN INJECTION QUANTITY

The change in injection rate due to internal deposit adhesion manifests itself in injection start and end timing changes as shown in Figure 3. The injection quantity decreases when the injection start is delayed, while an increase in quantity is observed when the injection end is delayed. In the past, clogged injector spray holes from deposits were found to be due to a change in flow rate in the injection hole throttle section during high nozzle lift, with its effects appearing only during high load. The effects of internal injector deposits are detected in normal use range, too, because they affect the system during valve opening and closing. During pilot range where fuel pressure is low and the injection quantity is small, the effect is relatively large. Change in injection quantity due to internal deposits produces different injection volume quantities among cylinders. As a result, idle vibration or startup failure can occur.

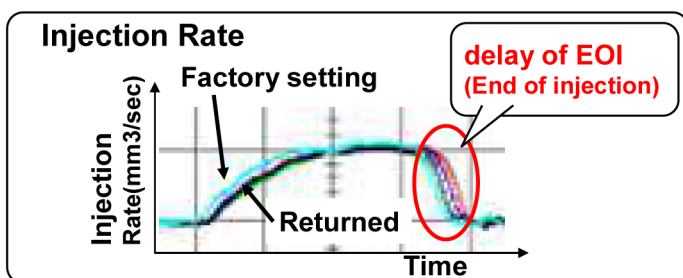


Figure 3. Change of injection quantity

ANALYSIS RESULT OF DEPOSIT

Internal deposits attached to the inside of the injector due to changed injection quantity are dark brown in color due to deteriorated fuel just as it was. They become whitish and can look like salt after being washed in hexane or other organic solvent Figure 4.

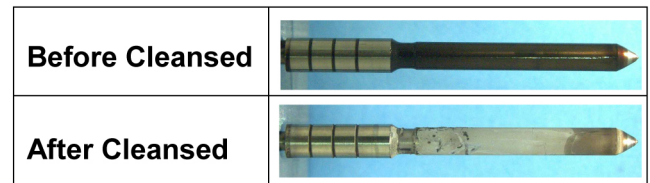


Figure 4. Appearance of deposit

Since the deposits indicated a high likelihood of organic functional group, analysis by FTIR was conducted. Results indicated carboxylate salt peaks were found in almost all deposits even though injectors were collected from different regions (see Figure 5). Additionally, analysis by EPMA was conducted to confirm the presence of trace metals. Metals such as Na and Ca that are not normally found in the deposit base material were also detected. Judging from these results, it can be presumed that the deposits are salts formed by carboxylates and metallic elements such as Na or Ca.

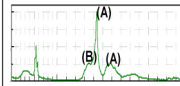
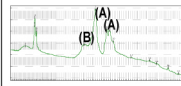
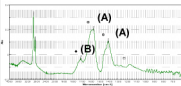
	France	Spain	North America
FT-IR	Carboxylate (A) 	Carboxylate (A) 	Carboxylate (A) 
EPMA	C, O, Na, Ca, Cl, N	C, O, Na, Ca, Cl, N	C, O, Na, Ca

Figure 5. Collected deposit from the EU and the US

In addition, deposit analysis by GCMS was also conducted to determine carboxylate detail. The results show that the carboxylate was a higher molecular weight carboxylic acid such as palmitic (C16) or oleic acid (C18) as shown in Figure 6.

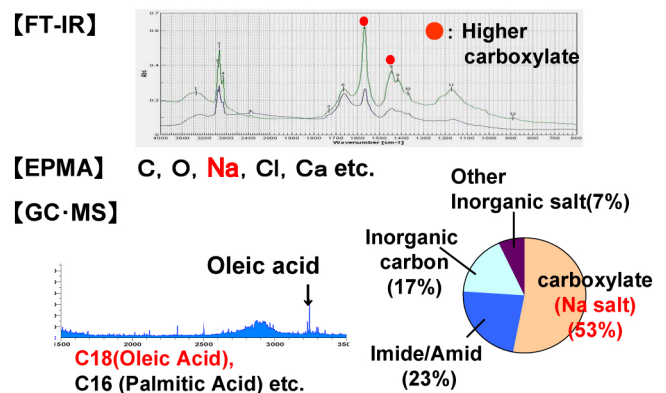


Figure 6. Summary of deposit analysis

ASSUMPTION : FORMATION OF DEPOSIT

It was found that the carboxylates, as a specific constituent of fuel, contributed only to internal injector deposits, and did not occur in the pump or in other fuel

injection equipment. Assuming that there is a clue in the deposit adhesion portion, it was noticed that deposits only adhere to sliding portions of the injector. Further, the high pressure pump also has sliding portions but deposits were not so noticeable there. Common among deposit adhesion to the injector sliding portions seemed to be temperature. As shown in Figure 7, pressure energy is converted to the thermal energy in the injector by release of high-pressure fuel through the sliding portions ("clearance seal"). When, injection pressure of 200 MPa is released to atmospheric air pressure, the temperature rises by approximate 100 degrees C -when the fuel temperature is 50 degrees C, the fuel temperature rises to 150 degrees C at the exit point of the sliding portion. Since the injector nozzle receives heat from the combustion chamber, the nozzle is subject to higher temperatures - it's an environment of much higher temperatures than that found in the injection pump. Therefore, it is highly possible that deposition depends on temperature. To prove this theory, the following tests were conducted to verify the relationship between fuel temperature and deposition.

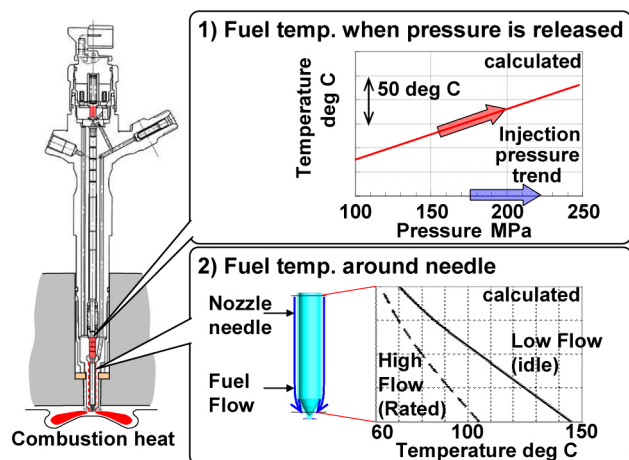


Figure 7. Fuel temperature inside of injector

Reproduction Test of Deposit

In order to understand the temperature effects on deposition, the following test using sodium oleate - the major constituent of deposit - was conducted. The procedure was as follows: saturate the diesel fuel with sodium oleate, and then soak injector pieces (composed of the same material as the sliding portions) in the prepared diesel fuel, then heat the fuel and the test piece. Protective masking was applied to the test piece to assure a reference surface for easily measuring the deposit quantity on the test pieces. Samples were made for each heating temperature as shown in Figure 8 and each piece was heated for 4 hours while soaking in the fuel. Results showed that the quantity of deposits on the test pieces increase in volume as the temperature becomes higher. As shown in Figure 8, deposition increased at 130 degrees C and higher. The theory was thus verified that deposition is affected by temperature.

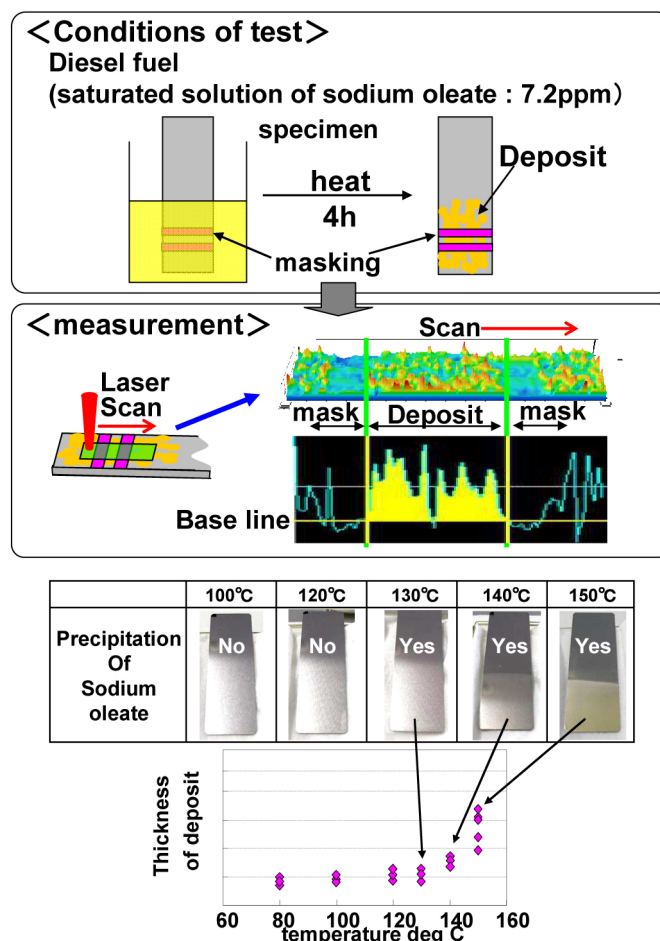


Figure 8. Fuel temperature and precipitation

Additionally, a change in the deposition characteristics of sodium oleate due to temperature was verified by another method. Figure 9 shows the results of heating saturated sodium oleate without the test pieces similar to the previous accumulation test. Sodium oleate is invisible before heating because it is dissolved in the fuel - however, after heating a gel-like material can be seen. It is presumed that the transition from soluble state to gel state occurred when the form of sodium oleate surface activity was changed by temperature thus also causing a change in solubility. The sodium oleate is highly soluble in diesel fuel at normal temperatures in the form of an inverse micelle with the polar water, but the polar substance then becomes excluded as the temperature rises and the form changes to a vesicle. The dissolution temperature rises temporarily in this phase. The vesicle is then flocculated to massive aggregation as a further rise in temperature occurs and falls out from the fuel due to lowered solubility.