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# Experimental investigation in an optically accessible diesel engine of a fouled piezoelectric injector

Agnese Magno [a,b], Ezio Mancaruso [a,*], Bianca Maria Vaglieco [a]

[a] Istituto Motori – CNR, Via G. Marconi 8, 80125 Napoli, Italy
[b] Università Federico II, Napoli, Italy

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ABSTRACT

This case study is aimed to investigate how the injector fouling can influence both the injection system and engine performances. In particular, the presence of deposits in the nozzle of the injector could affect the injection system performance along its life. The investigation was carried out on transparent compression ignition engine equipped with the head of a commercial multi-cylinder engine and second-generation common rail injection system. Two indirect-acting piezoelectric injectors were tested: one new another fouled. Optical engine was fueled with diesel and tests were performed with engine running in continuous mode. Two operating conditions were investigated. The new and fouled piezo injectors were characterized by injection rate profiles. The injection and combustion phases were investigated by optical measurements. Two-color pyrometry was used to analyze the pollutants formation and exhaust emission. Experimental results showed that the fouled injector has slower dynamic response and it injects a smaller amount of fuel during the main event. It has shorter jets penetration and wider spray angle that affect in negative way the mixing formation and the combustion evolution. High temperature regions and high sooting flames are detected for the fouled injector. Therefore, it emits high nitrogen oxides and particulate matter at the engine exhaust.



## 1. Introduction

The fuel injection system plays an important role in allowing the diesel engine to fulfill ever stricter regulations on exhaust emissions. Injection system can influence combustion process and pollutants formation by acting on the start, the duration and the number of the injections. Modern common rail (CR) systems offer significant potentialities to reduce particulate matter (PM) and nitrogen oxides ($NO_x$) emissions without compromising the engine performance. High needle opening speed and precise and complete needle closing are necessary in order to improve mixture formation and to avoid a deteriorated mixture formation and undesired post injections at the end of each injection. Most of these requirements can be fulfilled if piezo actuators are used to control the motion of the needle instead of the slower and less precise solenoid valves [1]. Suh et al. [2]investigated the injection characteristics of both solenoid and piezoelectric injectors. Their investigation was carried out in a high-pressure chamber at fixed temperature and pressure. They found out that the piezoelectric injectors had a shorter injection delay and guaranteed a better fuel atomization than solenoid ones thanks to a faster response time and a higher injection rate. Payri et al. [3] analyzed the influence of injector technologies on the flow at the nozzle exit by means of the analysis of injection rate and spray momentum measurements. Their case study showed that piezo injectors had a lower hydraulic delay and, so, they opened at a time that was closer to the signal reception than the solenoid ones. Moreover, they found out that piezoelectric system working at full needle lift required shorter energizing times to inject the same amount of fuel than solenoid injector. Furthermore, the piezoelectric system was more suitable to reproduce multiple injections, and therefore it could be used with higher stability and lower delay between the different injections. They also studied the influence of injection technology on the fuel-air mixing process and combustion development in an optical accessible, two-stroke engine [4]. They got to the conclusion that the air-fuel mixing process was faster and more efficient for this kind of technology because of the better dynamic response of the piezoelectric injectors. Benajes et al. [5] presented a comparison between two different injection systems based on a solenoid and a piezoelectric injector working on a single cylinder research engine. They stated that the piezoelectric injection system provided better results in terms of pollutant emissions. It also allowed a more accurate control of the injection

* Corresponding author. Tel.: +39 0817177188; fax: +39 0812396097.
*E-mail address:* e.mancaruso@im.cnr.it (E. Mancaruso).

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parameters including the possibility of injecting very small quantities of fuel at each injection event. However, in the previous studies, no information about spray development in engine like condition, mixing processes, as well as pollutant formation inside the engine bowl, are reported.

In order to meet legislation about emissions not only the fuel injection equipment has developed but also the issue of injector fouling has been investigated. Since modern injection systems allow high injection pressure and precise metering of fuel, they require very tight tolerances within the injectors. They are very sensitive to the deposits contamination [6,7]. Deposits can accumulate after several operating hours on the injector tip, into the holes and into the injector body itself. These deposits can slow down the response of the injector or cause the sticking of moving internal parts, which could then cause the loss of control of injection event timing, as well as of the injected fuel quantity. Accordingly, a buildup of these deposits can lead to variations in power and loss of fuel economy [8]. Some works have been performed to study the consequences of the deposits formation. Birgel et al. [8] developed an accelerated test procedure to assess the relative importance of some motoring parameters in a high-pressure common rail fuel injection system of a single cylinder engine. The results showed that fuels containing 30%and 100% of Fatty Acid Methyl Ester (FAME) that does not meet EN 14214 produced more deposit than an EN590 petroleum diesel fuel. The addition of zinc to the fuel had the most significant effect on deposit formation and ended up in a decreasing indicated mean effective pressure (imep). They also found out that by reducing the common rail pressure, the loss in imep increased. The increase of air and fuel temperatures by 40 °C and 30 °C showed no significant decrease of imep. Moreover, the results have shown that deposit formation could continue after engine shut down. Caprotti et al. [9] reviewed the problem of deposits in the fuel injection equipment. The tests were carried out by the use of the CEC DW10 bench engine and field trials with passenger cars. The used fuels ranged from fossil only to distillate fuels containing up to 10% FAME. They observed that engine performance was significantly affected by the formation of deposits, which could lead to an increased fuel consumption, power loss, poor drivability and start failure.

In order to complete the previous investigations, in this case study the fouled piezo-injector behavior was analyzed in an optical engine running in continuous mode and with diesel fuel. This facility is very close to the operating conditions of a real diesel engine. The differences between a new and a fouled injector were studied in terms of spray injection and combustion evolution. Moreover, it was investigated how the deposits presence in the injectors can affect the pollutants formation. Two indirect-acting piezoelectric injectors were tested. The first one was new; the second one was fouled with diesel fuel through the CEC F-98-08 DW10 injector-coking test. The investigation was carried out on a transparent engine; it is a compression ignition single cylinder equipped with the head of commercial multi-cylinder engine and a second-generation common rail system. The injection system was modified in order to receive a current signal and commutating it into a voltage one that manages the piezo injectors. Two operating conditions were investigated, the conditions at the engine speed of 1500 rpm and 2 bar of brake mean effective pressure (bmep) and at 2000 rpm and 5 bar of bmep. Injection rate measurements were performed and thermodynamic parameters were assessed. A high speed video camera was used to capture images of both injection and combustion phases from the bottom of the combustion chamber. Analysis of both flame temperature and soot concentration by two-color pyrometry method was performed. The correlation between the flame temperature and $NO_x$ in the exhaust and between in-cylinder soot and exhaust PM were analyzed.

## 2. Experimental apparatus and procedures

### 2.1. The fuel injection equipment

The study of the injector deposits influence on both spray injection and combustion efficiency was carried out with a second-generation CR injection system and piezoelectric injectors. The operating principle of piezoelectric injectors is based on the piezoelectric effect that is the property of some ceramic materials to produce an output voltage when they are subjected to a mechanical strain. The piezoelectric effect is reversible; it means that piezoelectric crystals can change shape when they are subjected to an external applied voltage. Piezoelectric injectors exploit a ceramic actuator consisting of a pile of electrically active ceramic layers. The layers are assembled mechanically in series and connected electrically in parallel. In an indirect-acting piezo injector, the actuator does not directly control the movements of the needle but it drives an auxiliary valve. When an input voltage is applied to the stack actuator, an electric field across the ceramic layers induces a mechanical strain, which results in an elongation of the actuator. Therefore, the valve raises and the fuel at the top of the needle returns toward the tank, through a feedback circuit. This causes pressure drop at the top of the needle that makes it rise; because of the strong pressure at the other needle end, the injector opens. As soon as the power supply of the actuator is interrupted, the valve closes again. The pressure at the higher side of the needle increases so that the injector closes. The piezoelectric stack has a very precise motion but its maximal idle displacement is usually small. Amplifiers are used to magnify the piezo element motion and obtain the required amplitude of the control valve [10]. To drive the actuator an impulse of a hundred volts is necessary. In the present investigation, two 6-holes piezoelectric injectors characterized by an indirect needle control were investigated. One injector was new and its break-in time was run; the second one was fouled with the CEC F-98-08 DW10 diesel fuel injector-coking test. The engine used in the test was a DW10 2.0 liter common rail unit with a maximum injection pressure of 1600 bar. The method measured the engine power that is a function of the level of injector fouling. At the beginning of the test, the cycle was run for 16 h to break-in the injector. The break-in time was followed by an 8 h running time and four hours soak time (engine off). The 8 h running cycle and the 4 h soak cycle were repeated four times. In total 32 h of running and 12 h of soak time. Therefore, the total test time was 60 h. After the fouling test, a power loss of about 6% was detected [11]. The injector-coking test was not object of this case study. After the coking test on real engine, the injectors were mounted in the optical research engine to carry out an optical investigation of both injection and combustion phases.

### 2.2. The injection rate measurement system

The injection rate meter consists of a small chamber into which the injector sprays (Fig. 1). It is connected to a constant section pipeline for the wave propagation; the fuel in the pipeline is kept at constant pressure of 50 bar in order to avoid cavitations phenomena. A pressure transducer fitted downstream the nozzle records the pressure variation due to the incoming fuel. The pressure variation $p$ [bar] is proportional to the injected quantity $q$ [g/s] according to the equation:

$$q = \frac{p \cdot A_{tube} \cdot 10^5}{a \cdot \rho}$$

where $A_{tube}$ ($mm^2$) is the area of the bore tube, $\rho$ (kg/l) is the density of the fluid and $a$ (m/s) is the sound speed in the fluid [12]. The