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Rate of injection measurements of a direct-acting piezoelectric injector for different operating temperatures

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ABSTRACT

As the regulations for pollutant emissions in diesel engines are increasingly restrictive, the introduction of the piezoelectric direct-acting injectors seeks to improve the overall efficiency of the injection system, and consequently reduce combustion contaminants. In such systems, the needle lift is governed by the charge, or voltage, applied to the piezo stack, allowing for a more precise control over the fuel injection process. Although it is known that the performance of the piezoelectric crystals depends on its temperature of operation, the effect this has on the rate of injection is still unclear. In this research, a particular setup was used to measure the rate of injection of a direct-acting injector for different operating temperatures. It was mounted into an injection discharge rate curve indicator with a particular holder that has a cooling sleeve connected to a circuit running ethylene glycol, which is driven by a thermoregulator unit. A parametric sweep of different piezo stack control voltages for three rail pressures and operating temperatures was carried out. On the results, when needle lift does not influence internal flow development, the rate of injection was controlled by the injection pressure, with minimal impact from the working temperature, resembling results from conventional hydraulic injectors. At partial needle lift, two operating regions were observed, delimited by a particular voltage level. Above it, the needle throttling was able to control mass fuel flow accurately. But below it, the stabilized rate of injection values decreased drastically. The rate of this decline was dependent only on the injection pressure. The threshold level, named critical voltage, increased linearly with increasing injection pressure and working temperature. Also, to maintain a constant fuel mass flow for decreasing operating temperature, the voltage level of the control signal had to be reduced. These results highlight the importance of monitoring and controlling the operating conditions of the direct-acting injectors, as their performance and efficiency are both influenced by the working temperature of the piezo stack.

1. Introduction

It is known that the standards regarding pollutant emissions generated by diesel engines are increasingly restrictive. Different solutions have been proposed to fulfill the limits established in the regulations, which includes the improvement of diesel injection systems [1,2]. With the evolution from the conventional solenoid actuators into the hydraulic piezoelectric injectors, a more precise control over the fuel injection process was achieved, reducing combustion noise, fuel consumption and, consequently, pollutant emissions [3]. Furthermore, these injectors can produce short injection delays, due to a fast opening time of the needle, enabling them to perform multiple closely coupled pulses [1,2].

The use of piezoelectric actuators in fuel injectors is still a science in development and presents some disadvantages. Furukawa et al. [4] and Fukada [5] established a direct link between temperature and changes of the charge constant and permittivity of the piezoelectric material, affecting its performance. Mitrovic et al. [6] concluded that operating (or working) temperature significantly influence the positioning accuracy and electric-field magnitude required to drive the piezoelectric actuators. Moreover, the actuators generate heat when operating both at high frequency and high electric field, and such situations could produce degradation of the piezoelectric stack [3,6].

In the direct-acting injectors, the absence of hydraulic circuits, and thus the direct drive of the needle, provides greater accelerations in its opening phase [7]. In these injectors, it is possible to control the rate of injection (ROI) and momentum flux by only modifying the voltage signal, because of flow throttling due to partial needle lift [8–10]. Additionally, the control signal applied to the piezoelectric actuator further influences the spray penetration, both in the liquid and vapor

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Nomenclature

ΔP	difference between injection and back pressure
$\dot{m}_{exp}$	stabilized rate of injection (mass flow)
ρ_f	density of the fuel
A_o	outlet area of a nozzle
C_d	discharge coefficient
N_o	number of orifices
P_{inj}	injection pressure
Top	operating temperature
BP	back pressure
ECN	Engine Combustion Network
IDRCI	injection discharge rate curve indicator
ROI	rate of injection
SOE	start of energizing

phase [11–13]. Consequently, as more parameters can be controlled, the possibilities for diesel combustion optimization are greater [14–16].

The direct-acting mechanism is the link between the actuator and the needle that amplifies the displacement of the piezo stack. Ferrari and Mittica [17] used a detailed mathematical model to study the influence of how the injection pressure affected this mechanism (a swinging rocker arm) and concluded that deformations caused by the high forces on the system have a significant impact in the lifting of the needle, especially at high pressures. Subsequently, Viera et al. [9] reported these deformations reduced the operational window of the injector. The authors suggested a minimum voltage limit, dependent on the injection pressure, where above this limit the injector performance was stable and controllable, and below it, it performed inconsistently. Payri et al. [13] observed spray penetrations in liquid and vapor phases for different control voltages (95–150 V) and injection pressures (50 and 150 MPa), linking the results with needle lift and ROI measured by Viera et al. [9]. However, as measurements were carried out in different facilities, spray penetration, and hydraulic measurements did not correlate as expected near this critical voltage value, justified by the different injector operating temperatures between test vessels. Altieri and Tonoli [18] performed experimental measurements of the piezo stack displacement for different working temperatures (20–85 °C) and charge (voltage) levels (70–150 V), and reported that increasing the working temperature resulted in longer displacement for a constant voltage level, with almost a linear ratio. Similar results were obtained by Li et al. [19], who performed a quasi-static thermo-electro-mechanical experimental analysis of a piezoelectric actuator, and found that the electric-field-induced stroke increased steadily with temperature.

Even though it is known that the operating temperature of the piezo stack affects its behavior, it is still necessary to identify how this effect is translated into the hydraulic performance of the direct-acting injector. Furthermore, experimental results could prove useful for validation and improvement of mathematical models. Accordingly, this paper studies the influence of different operating temperatures (30, 60 and 90 °C) in the ROI, for sweeps of the control voltage at three injection pressure levels. For the ROI measurements, a conventional Bosch long tube method tester has been used [20]. A cooling jacket, fitted with a thermocouple, was designed to monitor and control the temperature of the injector body.

This paper is divided into four sections. Following this introduction, the experimental facility and measurement methodology are detailed. Then, results and discussions are presented, organized by the effect of the different boundary conditions studied. In the last section, the conclusions are drawn.

2. Materials and methods

This section presents the experimental equipment and data processing methodology.

2.1. Fuel delivery system

The injection system is comprised of commercially available components. The high-pressure unit consists of a Bosch CP3 pump, powered by an electric motor, and a common-rail equipped with a pressure regulator, which is driven by a proportional-integral-derivative controller. The whole subsystem is assembled on a moving cart, that encloses all components. The pressurized fuel is delivered to a second common-rail (volume = 22 cm^3, length = 28 cm), and fed to the injector through a high-pressure rigid line (inside/outside diameter = 2.4/6 mm, length 24 cm). The configuration was selected to replicate the setup used by previous authors [9,13], and complies with Engine Combustion Network (ECN) standards [21].

The injector, also utilized in the research of other authors [9,13], is equipped with a piezoelectric actuator directly connected to the needle through a mechanical link. This direct-acting coupling is similar to the one presented by Ferrari and Mittica [17], and consists of a swinging rocker arm that amplifies the displacement of the piezo stack when a control signal is applied. The injector is equipped with a 7-hole nozzle, with an averaged outlet diameter of 110.6 µm. Following the guidelines

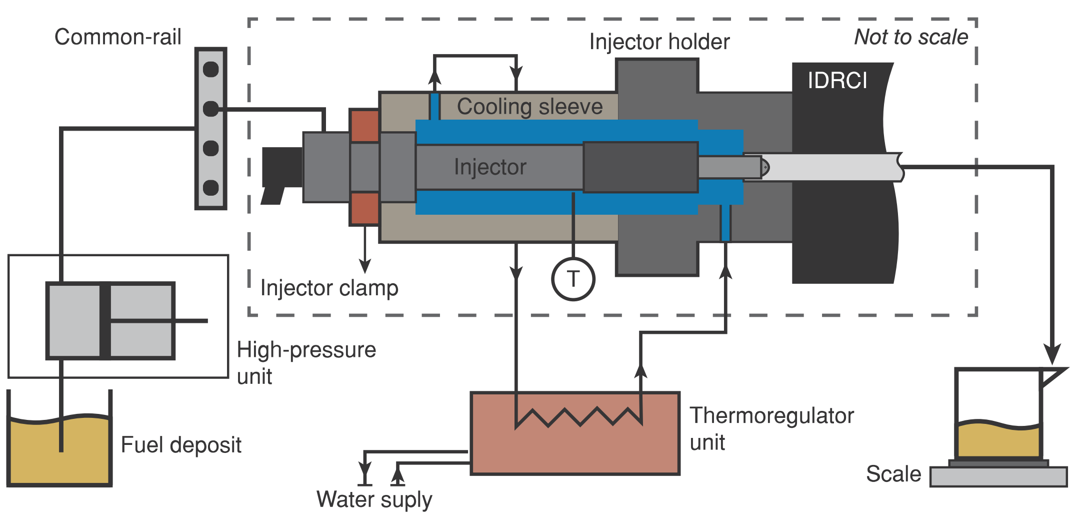

Fig. 1. Schematic diagram of the experimental setup with the temperature control circuit. The thermocouple T was used as reference for the piezo stack operating temperature.