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EFFECTS OF THE VARIATION OF INJECTION PRESSURE AND ENERGIZING TIME ON INJECTORS FUEL MASS FLOW RATE

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Abstract. *The fuel injection system affects engine performance and pollutant emissions. This work aims to analyze the fuel mass flow rate from variations on injection pressure and energizing time of Diesel injectors. A commercial injection system was adapted to a test bench designed for the execution of the experiments. An analytical analysis of the fuel mass flow rate as a function of the injection pressure was developed to calculate the discharge coefficient of the injector at each operating point. The experiments were carried out using diesel oil with 10% of biodiesel and a mixture of diesel oil-biodiesel and ethanol, varying the injectors energizing time, between 700 and 1700 μ s, and injection pressure, between 40 and 100 MPa. The use of the diesel oil-biodiesel ethanol blend reduced the fuel mass flow rate and discharge coefficient, moving away from the blend injection process from the ideal process.*

Keywords: *common rail, solenoid injector, fuel blends, energizing time, mass flow rate, injection pressure.*

1. INTRODUCTION

The basic parameter in the control of modern Diesel engines, equipped with common rail fuel injection systems, is the injector energizing time. The fuel injection control has an open-loop typology, that is, the injected fuel flow is not measured at each instant of time (FERRARI; PAOLICELLI, 2017).

Baumgarten et al. (2002) proposes a new model for cavitation and turbulence induced by flow separation, which is able to map the influence of the cavitation nozzle flow on spray break-up. Pogulyaev et al. (2015) and Ferrari et al. (2016) performed numerical modelling of a common rail injection system and observed that the fuel mass flow rate varies linearly with the increase of the injector energizing time and that the injection pressure changes the angular coefficient of the "mass flow rate vs. the energizing time" function. Pietras et al. (2017) performed experimental tests in order to relate the energizing time of a solenoid valve injector to the injection pressure and the amount of fuel injected. The mass of fuel injected presented a linear behavior as a function of the energizing time, at pressures above 70 MPa.

D'Ambrosio & Ferrari (2018) compared the performance of solenoid valve and piezoelectric injectors, varying the injection pressure and the energizing time. The authors obtained results similar to those of Ferrari et al. (2016) and Pogulyaev et al. (2015), where the injection pressure influences the angular coefficient of the "mass flow rate vs. the energizing time" function, for both injectors type.

Armas et al. (2012) studied the diesel-ethanol blend effect on the common rail system performance and durability and observed that the system presented a 30% reduction in the amount of fuel delivered using the blend compared to the diesel oil operating system. Tutak et al. (2017), Corral-Gómez et al. (2019) and Pradelle et al. (2019a and 2019b) investigated the diesel-biodiesel-ethanol blend influence on the fuel physical properties and on the engine performance by means of experimental tests. Kuszewski et al. (2017) evaluated the diesel-ethanol blend lubricity.

Park et al. (2012), Khoobakht et al. (2019), Krishna et al. (2019) and Patel et al. (2019) tested diesel-ethanol blends and compared the effects on performance and emissions with the engine operating using only diesel oil. Depending on the operating conditions and the ethanol concentration, emissions may increase or decrease

This work aims to analyze the fuel mass flow rate behavior of Diesel injectors from the variation of the injection pressure and the energizing time for different fuels: diesel oil with 10% of biodiesel (DB) and DB-anhydrous ethanol blends (DBE).

2. METHODOLOGY

The discharge coefficient is defined as the ratio of the actual discharge from an orifice to the theoretical discharge from the orifice. The analytical analysis of the fuel mass flow rate as a function of the injection pressure is necessary to calculate the discharge coefficient of the injector at each operating point. To simplify the analytical analysis, the following assumptions were used: constant fluids specific weight; steady-state flow; incompressible flow; adiabatic flow; without change of potential energy; without return of fuel by the injector; constant pressure throughout the entire fuel rail.

The Bernoulli equation was algebraically manipulated to obtain the theoretical injected fuel mass flow rate, considering that the injector remains open for the entire time period, as shown by Equation (1).

$$\dot{m}_1 = \dot{m}_2 = \sqrt{\frac{2\rho \cdot (P_1 - P_2)}{\frac{1}{\pi \cdot d_1^2} - \frac{1}{\pi \cdot N_{holes} \cdot d_2^2}}} \quad (1)$$

where \dot{m}_1 and \dot{m}_2 are the inlet and outlet mass flow rate (kg/s), respectively, ρ is the fuel specific weight (kg/m³), P_1 and P_2 are the pressures in the fuel rail and in the injector holes (Pa), respectively, d_1 and d_2 are the rail and injector holes diameter (m), respectively, and N_{holes} is the number of injector holes. Figure 1 shows the control volume diagram, indicating the location of each parameter.

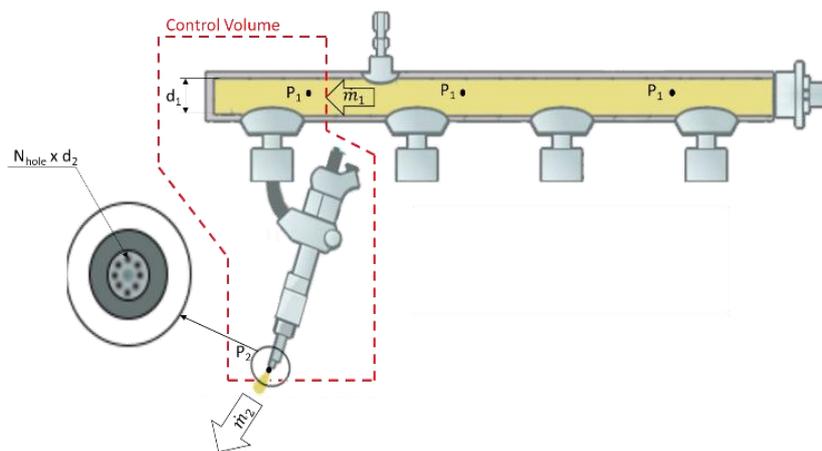


Figure 1. Control volume representation

The boundary condition values for mass flow analytical calculations are shown in Table 1.

Table 1. Injector and fuels characteristics

Number of holes	8
Hole diameter	0.138 mm
Rail internal diameter	12.6 mm
DB specific mass	840.8 kg/m ³

DBE specific mass	831.5 kg/m ³
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2.1 Experimental apparatus

The experimental apparatus used to simulate an automotive diesel injection system, therefore the signals sent by the control unit follow the drive logic in a four-cylinder engine, so three parameters can be described: the same injector is actuated; Maximum trigger time (T_{max}) is the maximum time interval that each injector can remain energized; Energizing time (T_{on}) is the command pulse width for energizing the injector. The parameters are shown in the Figure 2.

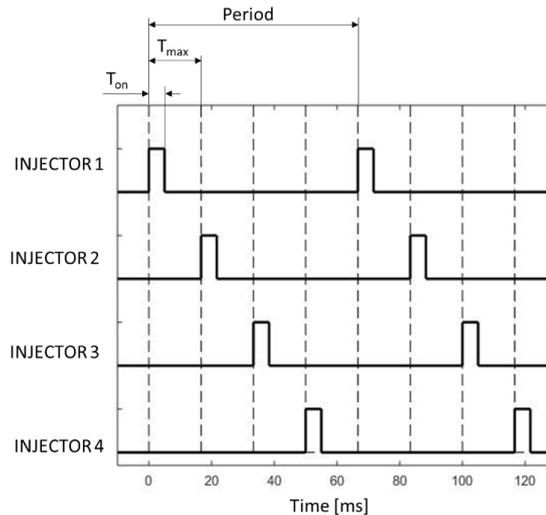


Figure 2. Injector switching logic

The experimental apparatus (Figure 3) consists of an instrumented common rail system for measuring the fuel injected mass, fuel rail pressure, fuel temperature, besides a computer-controlled system, that defines the test inputs, as the injection pressure and the energizing time. It consists of an electric motor (1) coupled to a high-pressure volumetric pump (2), whose function is to ensure the pressure in the rail (4). The pressure control is carried out by the metering valve (3) by means of feedback provided by the pressure sensor (5). Part of the fuel after passing through the high-pressure pump flows through the solenoid injectors (6) to a secondary reservoir (9), another part returns to the fuel tank (11), being cooled by the heat exchanger (10). The injected fuel mass is measured by a digital scale (13) located beneath the fuel tank (11). The low-pressure pump (12) contained in the tank (11) is responsible for supplying fuel to the high-pressure pump (2).

To avoid damaging the circuit components, the fuel must be filtered in (16). In addition, its pressure and temperature must be contained within a range determined by the pump manufacturer. These properties are measured respectively by the low-pressure sensor (17) and by the NTC temperature sensor (15).

The commands for the actuators and the sensors signals reading is carried out by a set of electronic modules (7) communicating with a computer (8) via a serial protocol and a graphic interface.

The test environment conditions are measured by the ambient temperature sensor (14) and the Torricelli barometer (18).

Flow "B" represents the low-pressure path in which the fuel flows from the low-pressure pump to the high-pressure pump. The "R" flow represents the return pipe, in which the fuel returns from the actuators to the tank. Flow "A" represents the high-pressure pathway that drives the fuel from the high-pressure pump to the injectors. Flow "I" represents the fuel injected collection system.

The "S" signal represents the analog signals received from the sensors, the "At" signal represents the actuators drive commands and the "C" signal represents the serial communication between the computer and the electronic modules.

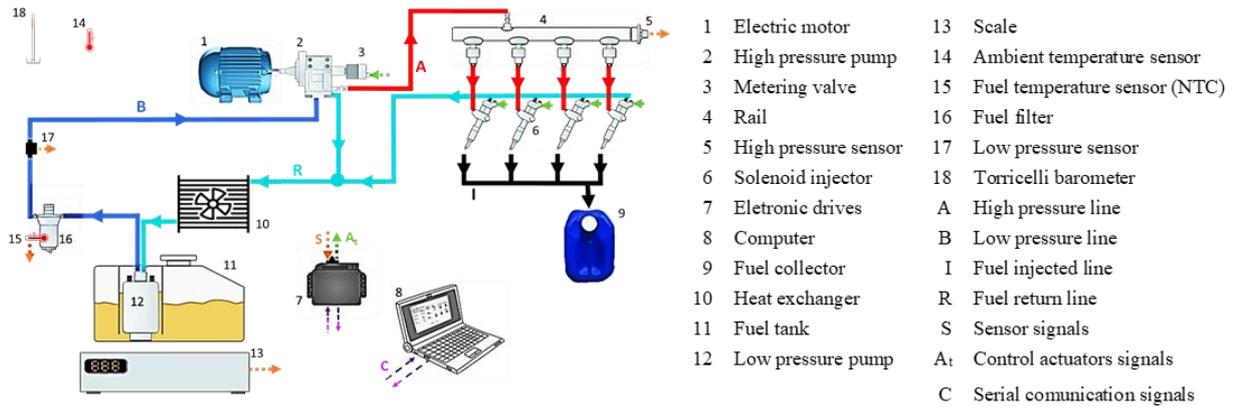


Figure 3. Experimental apparatus

The experimental tests were performed using diesel oil with 10% of biodiesel (DB) and a blend of DB and anhydrous ethanol (DBE), at a proportion of 10:1 (v/v) of DB.

For both fuels, the same solenoid valve injector was used. Seven different injection pressure were used for the DB tests: 40, 50, 60, 70, 80, 90 and 100 MPa. For each pressure value, six different injection energizing times were tested: 700, 900, 1100, 1300, 1500 and 1700 μs . The tests using DBE were executed for the same injection pressure values used for the DB tests, however only the minimum and maximum energizing times were used (700 and 1700 μs).

An injection frequency of 15 Hz was used for the tests and the parameters were measured during 180 seconds for each injection condition. Three tests were performed for each injection condition and the average results are presented with the total uncertainty, which is the combination of both the statistical spread and the instrument uncertainty.

3. RESULTS

Figure 4 shows the experimental curves of fuel mass flow rate and discharge coefficient as a function of the energizing time and injection pressure, for the tests using DB. For the tested range, both increases of energizing time and injection pressure increased the fuel mass flow rate. The injected fuel mass flow rate as a function of energizing time approximates of a linear curve, as shown by Pogulyaev et al. (2015) and Ferrari et al. (2016). The discharge coefficient shows growth for energizing times lower than 1100 μs and has a downward behavior for energizing times higher than 1300 μs .

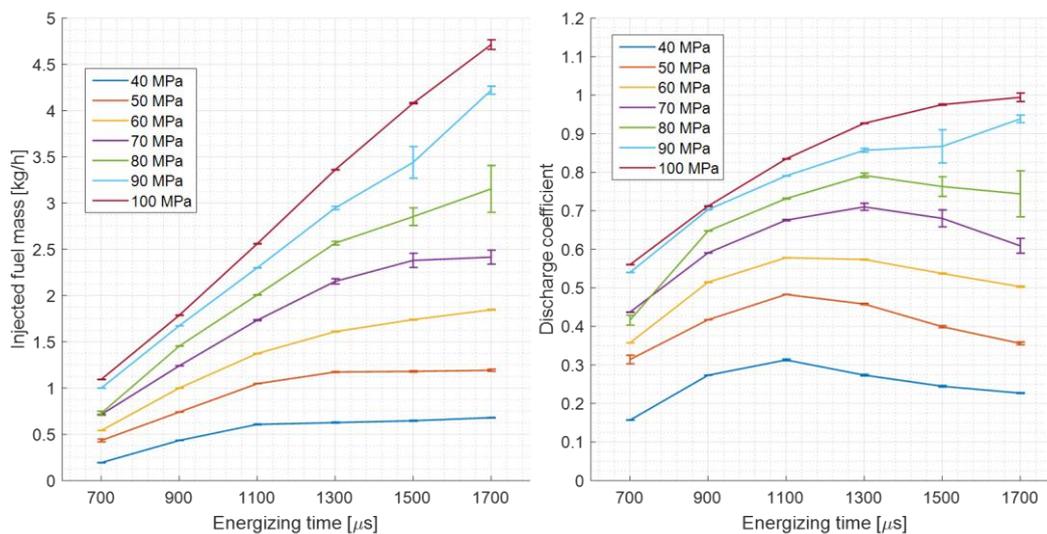


Figure 4. Experimental results for B10

Figure 5 shows the tests results using the diesel oil-biodiesel and ethanol blends. The injected mass flow rate of DBE is lower than using DB for all operating conditions. The decrease of DBE specific mass, compared to DB, due to the percentage of ethanol has not enough to present such a difference in mass flow. The ratio between the specific mass of

the DBE relative to that of the DB is 98.9%. For a pressure of 100 MPa and an energizing time of 1700 us, the relationship between DBE and DB flow is 71.6%, which shows that the difference in the specific mass is not the main factor for the decrease of the injected fuel mass. For this condition, the reduction in injected fuel mass was similar to that presented by Armas et al. (2012).

According to Baumgarten et al. (2002), due to increased fluid acceleration, the pressure at the injector orifice inlet edge may be reduced to the extent of reaching the fluid vapor pressure, resulting in the formation of cavitation along the walls, extending to the outlet. In addition, the flow separation reduces the useful section of flow, which tends to increase the discharge coefficient. Therefore this reduction in the injected mass could be explained due to the cavitation phenomenon inside the injector.

The discharge coefficient also presents smaller values when comparing DBE to DB at all pressure points, showing that this system is farthest from an ideal flow, which contributes to the hypothesis of the flow section decrease due to the fluid separation.

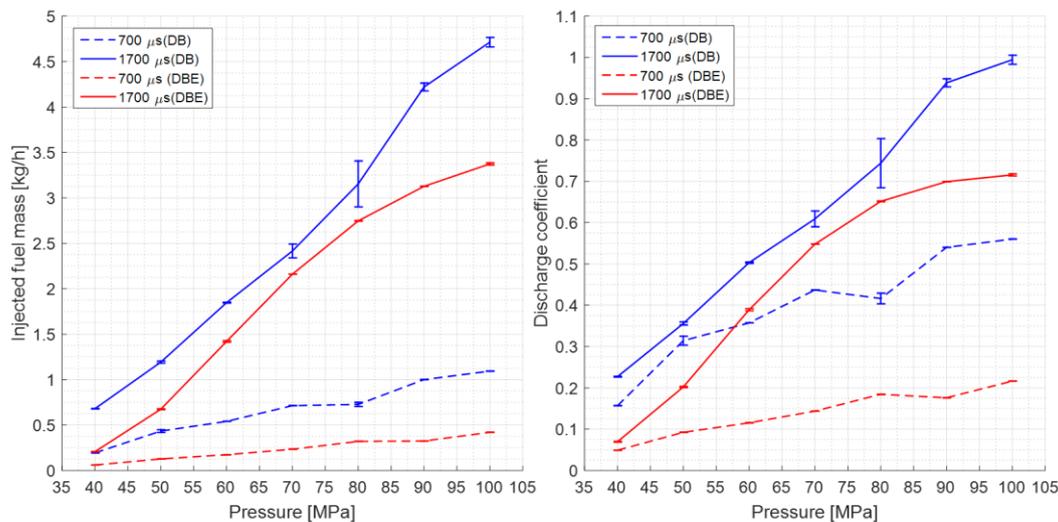


Figure 5. Experimental results for diesel-biodiesel and ethanol blends

4. CONCLUSION

In contrast to the fuel mass flow rate, the discharge coefficient showed a behavior with growth and subsequent decrease, from the increase of the injector energizing time, except for the tests performed with injection pressures of 90 and 100 MPa, which showed increasing behavior in all operation points.

The fuel mass injected in the DBE tests showed a tendency to linear increase as a function of the injection pressure, but the values were lower than the tests compared to DB for pressures between 40 and 100 MPa and energizing times between 700 and 1700 μs. The difference in the specific mass of the blends is not sufficient for the fuel flow obtained reduction. The discharge coefficient values presented by the DBE blend were also lower than the results of the DB tests.

5. ACKNOWLEDGMENTS

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