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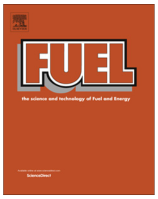

Full Length Article

An indirect method for the real-time evaluation of the fuel mass injected in small injections in Common Rail diesel engines

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ABSTRACT

The pilot injected fuel masses generally are in the 1–4 mg range for automotive diesel engines and are affected by significant dispersion, which represents an issue for injection control systems. A new methodology has been developed for real-time evaluation of the fuel injected in small injections in diesel engines.

The measurement requires the installation of a single pressure transducer on a pipe connecting the injector to the rail. A simple algorithm, which is based on the mass conservation and momentum balance equations, written with respect to a reference frame that is integral with the pressure wave front, has been elaborated to convert the experimental pressure time history into an instantaneous flow rate. The results on the flow-rate through the pipe that connects the injector to the rail are compared with the corresponding numerical outcomes from a 1D model of the fuel injection system.

The estimated fuel quantities that enter the injector have been verified to be well correlated with the measured volumes of the fuel injected in small injections. The relation that has been found could be implemented in the engine electronic control unit and employed together with the pressure transducer installed at the inlet of the injector for a more accurate real-time control of both the injected mass and the system high-pressure.

1. Introduction

Current Common Rail (*CR*) diesel injection systems are capable of performing various injection strategies [1–3] that are aimed at enhancing fuel burning and at optimizing NO_x and PM engine-out emissions, as well as fuel consumption and combustion noise [4–7]. For this purpose, sophisticated multiple injection schedules with double pilot shots and after shot are implemented as well as injection strategies featuring continuous rate shaping of the main injection [8,9]. Electroinjectors and electronic control unit (*ECU*) are required to accurately control injection timing, nominal rail pressure (p_{nom}), energizing time (*ET*) and dwell time (*DT*) between consecutive injection shots. The quantities of fuel that should be injected into the combustion chamber can be determined for the considered *ET* and p_{nom} values, on the basis of the injector characteristic curves. However, the fuel volumes that are effectively injected can deviate from their nominal values, due to different reasons. The pressure in the injector nozzle is not monitored during engine operations and can be significantly different compared to the measurable value in the nozzle at the hydraulic test bench, which in turn can be considerably lower than p_{nom}. Furthermore, the injected flow-rate is affected to a great extent by the needle motion [10], which is not accurately controlled by the *ECU* and is characterized by high dispersion. Finally, the pressure waves, which are triggered by the injector nozzle closure, travel back and forth along the high-pressure hydraulic circuit of the injection apparatus and can interfere with the injection dynamics of the consecutive shots of the multiple injection schedule. As a consequence, the fuel amounts injected in these subsequent shots and thus the overall injected mass can be altered [11,12]. All the above-mentioned effects can have a major impact on the accuracy of small injections, such as pilot and after, and the influence of these shots on the combustion process development and conclusion is known to be relevant [13,14].

State-of-the-art injection system controls are performed in open-loop strategy with respect to the injected flow rate, whereas *ET* and p_{nom} are closed-loop controlled. Many studies are focused on the real-time estimation of the actual injected mass. An example is given by a miniaturized volumetric flow sensor that is directly integrated inside the injector nozzle [15]. The working principle of the sensor is based on a thermoresistive measurement. A hot wire anemometer with a Ti/Pt metallization on a low temperature cofired ceramic substrate is applied to the nozzle and

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Nomenclature

a	sound speed
A	pipe internal cross section
CR	Common Rail
d	pipe diameter
f	Moody factor
DT	dwell time between consecutive injection shots
ECU	electronic control unit
EOI	end of injection
ET	energizing time
FMV	fuel metering valve
G	mass flow rate
ICEAL	internal combustion engine advanced laboratory
KMM	continuous flow-rate meter
M	fuel mass
NO_x	nitrogen oxides
p	fuel pressure
PM	particulate matter
PT	Politecnico di Torino
PCV	pressure control valve
Q	volumetric flow rate
R	Riemann variable
SOE	electric start of injection
SOI	start of injection
t	time
u	flow velocity
V	volume
x	spatial coordinate
ρ	fuel density
τ	wall shear stress

Subscripts

0	initial value in the graphs
1	referring to the backward travelling characteristic variable
2	referring to the forward travelling characteristic variable
cc	control chamber
dc	delivery chamber
h	hydraulic
Inj	injected (mass); injector inlet (pressure)
Inj, in	injector inlet (mass)
min	minimum
nom	nominal
num	numerical
pv	pilot-valve
Rail	rail pressure
s	sac
start	initial value in the integration process
up	upper
w	wall

the injected fuel quantity is detected using the maximum deviation of a balanced Wheatstone bridge. Another solution oriented towards on board monitoring of the injection performance is the i-ART technology recently developed by Denso [16]. A pressure sensor, featuring an integrated circuit memory, detects the pressure in the hydraulic circuit of the injector. This pressure waveform is related to the needle lift time history and the sensor therefore allows the effect of the needle dynamics on the injected flow rate to be taken into account in order to improve the control of the injected mass. Other methods are based on the measured in-cylinder pressure, even though it is difficult to infer a consistent injected flow-rate time history from the heat release rate curve at all the engine working conditions [17].

The pressure variations inside the rail-to-injector pipe, which are caused by the injection events, can be related to the fuel expelled through the injection holes. However, the relation between injected mass and fuel mass entering the injector from its supply pipe is not obvious for hydraulically controlled servo-injectors since a significant portion of fuel can go out of the pilot-valve during injector working. Furthermore, two or three pressure transducers are generally required to evaluate the instantaneous flow-rate in the rail-to-injector pipe.

The method proposed in the present work to evaluate the injected fuel quantity during small injections is based on the detection of the pressure time history at one location along the pipe connecting the injector to the rail. The control system can therefore monitor the injected flow-rate by using the data on the flow-rate entering the injector and realize corrective actions in order to reduce the differences between actual injected masses and nominal values stored in the *ECU* maps. The method can be applied to production fuel injection systems because does not require any modification of the injector internal layout.

2. Experimental setup and experimental facility

The *CR* injection system that has been employed for the experimental tests is made up of a high-pressure rotary pump with a displacement of 700 mm^3, a rail with an internal volume of about 20 cm^3 and three injectors. These are indirect-acting solenoid injectors (maximum operative pressure at 1800 bar), equipped with a pressure-balanced pilot-valve and a Microsac nozzle featuring 7 injection holes. The high-pressure ducts that connect the injectors to the rail have length and internal diameter equal to 400 mm and 3 mm, respectively.

A pressure sensor and a pressure control valve (*PCV*) are integrated in the rail in order to control the system high-pressure level [18]. A fuel-metering valve (*FMV*) is also installed at the pump inlet to regulate the sucked-up flow rate, on the basis of the injector requirements. The rail pressure (p_{Rail}) can be either *PCV* or *FMV* controlled. From an energetic point of view, the *FMV* increases the efficiency of the high-pressure control system [18], but features poorer dynamic response than *PCV* during engine transients. The rail pressure has been controlled by means of the *FMV* for all the steady-state tests carried out in the present investigation.

The experimental campaign on the *CR* injection system has been performed at the Moehwald-Bosch hydraulic test bench [11] installed in the ICEAL-PT (Internal Combustion Engine Advanced Laboratory at the Politecnico di Torino). The bench can supply a nominal power of 35 kW, a torque of 100 N m and the pump shaft can reach a speed of 6100 rpm.

The Shell V-Oil 1404 (ISO 4113) calibration fluid is employed in the hydraulic test bench since it reproduces the diesel oil properties at low temperatures ($\leqslant$120 °C) in order to allow an accurate hydraulic characterization of diesel injectors.

The hydraulic test rig is equipped with several instruments for measuring injected quantities, leakages through the injectors, instantaneous injected flow-rates, pressure time histories and temperature levels at different points in the high-pressure circuit and electric driving signals to the injectors. A high-frequency piezoelectric transducer has been installed on the rail-to-injector pipe for acquisition of the pressure trace at the injector inlet (p_{Inj}). Another piezoresistive pressure transducer has been placed at one rail extremity in order to detect the p_{Rail} transients with a satisfactory accuracy.