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Fuel temperature influence on the performance of a last generation common-rail diesel ballistic injector. Part I: Experimental mass flow rate measurements and discussion

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ABSTRACT

An experimental study is conducted in this paper in order to assess the influence of the fuel temperature on the performance of a last generation common-rail ballistic solenoid injector. Mass flow rate measurements are performed for a wide range of temperatures, extending from 253 to 373 K, representative of all the possible operating conditions of the injector in a real diesel engine, including cold start. The high pressure line and the injector holder were refrigerated, making it possible to carefully control the fuel temperature, whereas measurements at cold conditions were carried out with the help of a climatic chamber. Relevant features such as stationary mass flow, injection delay or the behaviour at the opening and closing stages are analysed together with parameters governing the flow, such as the injector discharge coefficient.

Results show an important influence of the fuel temperature, especially at low injection pressure. A low injection temperature results in a lower stationary mass flow rate, whereas injection duration is also reduced. These results will be explained mainly through the fuel properties variation induced by temperature, together with the ballistic nature of the injector used for the study.

A second part of the paper introduces a one-dimensional model that makes it possible to reproduce these results and further explain them through the analysis of other relevant variables, such as the needle lift.

1. Introduction

The importance of the direct injection system in the diesel engine has attracted the interest of researchers in the field. Being responsible for the fuel delivery, its role on the ultimate outcome of the engine has been demonstrated in several works: its influence on the quality of the air-fuel mixture has been largely proved [1–3], thus highly impacting the combustion phenomenon, fuel consumption and emissions [3–7], key features in the global cleanliness demanded to modern power plants.

Even though many studies, both experimental and computational, have focused on how the diesel injection process and spray development are influenced by factors as the nozzle geometry [8–14], discharge ambient conditions simulating those of the combustion chamber [15–18] or fuel injection pressure [19,20], not much attention has been paid to the influence of the fuel temperature itself. However, its effects are deemed to be important, especially when dealing with cold start problems [21–23], which are being gradually introduced in the new standards and regulations [24]. Needless to say, the fuel temperature strongly affects the fuel properties, as the authors have reported both at atmospheric and high pressures [25], which in turn play a key role on the injection process. Indeed, Seykens et al. [26] tried to assess the influence of fluid properties on the fuel injection behaviour by means of a one-dimensional computational model. From the experimental point of view, Dernotte et al. [27] or Payri et al. [21,28] analysed the influence of the fuel properties on the spray macroscopic features, also paying attention at the discharge capabilities of the nozzle in the latter case, but left the injector dynamics (transient opening and closing stages) out of the study.

A few works have tried to directly assess the influence of the fuel temperature on the nozzle internal flow and spray formation of diesel direct injection engines. However, most authors focus on a certain range of temperatures. Hence, Tinprabath et al. [24] studied the fuel temperature influence for several biodiesel and diesel blends, focusing on cold temperatures, whereas Park et al. [29] performed a combined numerical and experimental study

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Nomenclature

A_{eff}	orifice outlet effective area
A_o	orifice outlet area
C_a	area coefficient
C_d	discharge coefficient
C_v	velocity coefficient
c_f	fuel speed of sound
D_i	orifice inlet diameter
D_o	orifice outlet diameter
k-factor	orifice conicity factor
L	orifice length
$\dot{m}$	fuel mass flow
$\dot{m}_{th}$	theoretical fuel mass flow
P	pressure
P_0	reference pressure
P_i	injection pressure
P_t	pressure measured in the IRDCI
Re	Reynolds number
r	orifice inlet rounding radius
T_i	fuel temperature at the injector inlet
t_d	delay between SOE and SOI
t_{inj}	injection time
u_{eff}	effective velocity
u_{th}	theoretical velocity

Greek symbols

ΔP	pressure drop
μ_f	fuel absolute viscosity
ν_f	fuel kinematic viscosity: $\nu_f = \frac{\mu_f}{\rho_f}$
ρ_f	fuel density

Abbreviations

ET	energizing time
FAME	fatty acid methyl ester
FT-IR	Fourier-transformed infrared spectrometry
IRDCI	injection rate discharge curve indicator
SOE	start of energizing
SOI	start of injection

paying attention to the spray characteristics for relatively warm temperatures only. Finally, Wang et al. [30] studied the cases of 255 and 298 K also paying attention to the influence of fuel temperature on cavitation, but again leaving the injector dynamics out of their scope. It is important to note that nozzle transients, however, have a strong impact on the injection process and spray development as several authors have reported [31–33].

In this study, an experimental work on the influence of the fuel temperature on the performance of a Bosch CRI 2.20 injector is conducted. Mass flow rate measurements were performed for a wide range of temperatures (from 253 to 373 K), thus representing all the possible operating conditions of the injector in a real diesel engine, including cold start and the usual situations where the injector is heated by the proximity of the cylinder head. The measurements at cold conditions were carried out with the help of a climatic chamber, and the temperature was carefully controlled through refrigeration. The injector is a solenoid-driven unit [34] of ballistic nature, which means that the needle lift is not mechanically limited to a value that is usually achieved during the normal operation of the injector. Thus, the influence of the fuel properties (which, as it has been said, are strongly affected by the fuel temperature) on the dynamic behaviour of the injector is here deemed to be of even more crucial importance, since the maximum lift reached by the needle will directly depend on its friction with the fuel due to viscous effects. The importance of the fuel temperature is here investigated in terms of stationary mass flow rate, total mass injected, injection delay (time difference between the SOE – start of energizing – and SOI – start of injection), opening and closing slopes or injector discharge coefficient, with the objective of determining in which circumstances these effects should not be neglected due to their subsequent importance in the combustion phenomenon.

As far as the structure of the paper is concerned, it has been divided in 5 sections. First of all, in Section 2, a description of the theoretical foundation on which the internal flow features are based is presented. Following, in Section 3, the experimental setup is thoroughly described, with special attention to the temperature control. Details on the used fuel and the test matrix analysed are also given in this section. In Section 4, results of mass flow rate for all the tested conditions are shown and discussed. From the mass flow rate curves, attention will be paid to the stationary mass flow, total mass injected, injection delay, opening slope, injection duration and injector discharge coefficient (derived from the stationary mass flow values). Finally, the main conclusions of the investigation are drawn in Section 5.

In a second part of the paper, a computational one-dimensional model is developed and validated against the experimental results hereby presented. In addition to making it possible to extend the results for any engine operating condition, this model makes it possible to analyse the findings of the present paper in light of internal variables of the injector, such as the needle lift, thus making it possible to acquire a deeper understanding of the phenomena involved.

2. Theoretical foundation

As it has been said, the study is focused on the analysis of mass flow rate measurements at different temperatures. In order to understand how fuel temperature influences the results, it is necessary to introduce the discharge coefficient (C_d) of an orifice, defined as the ratio among the real mass flow rate through the orifice and the theoretical one, as stated in Eq. (1):

$$C_d = \frac{\dot{m}}{\dot{m}_{th}} \tag{1}$$

The theoretical mass flow rate comes from the mass conservation equation (Eq. (2)):

$$\dot{m}_{th} = \rho_f\, A_o\, u_{th} \tag{2}$$

where ρ_f is the fuel density, A_0 is the cross-sectional area of the orifice outlet and u_{th} is the theoretical velocity through the orifice, which can be derived from Bernoulli's equation assuming negligible upstream velocity, resulting in the definition of Eq. (3):

$$u_{th} = \sqrt{\frac{2\Delta P}{\rho_f}} \tag{3}$$

where ΔP is the pressure drop at the orifice. With all, Eq. (1) can be rewritten to express the mass flow rate through an orifice as:

$$\dot{m} = C_d A_o \sqrt{2\rho_f \Delta P} \tag{4}$$

A direct relation of the fuel temperature to the mass flow rate can already be noticed in Eq. (4) through the fuel density.

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