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Fuel temperature influence on the performance of a last generation common-rail diesel ballistic injector. Part II: 1D model development, validation and analysis

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ABSTRACT

A one-dimensional model of a solenoid-driven common-rail diesel injector has been developed in order to study the influence of fuel temperature on the injection process. The model has been implemented after a thorough characterization of the injector, both from the dimensional and the hydraulic point of view. In this sense, experimental tools for the determination of the geometry of the injector lines and orifices have been described in the paper, together with the hydraulic setup introduced to characterize the flow behaviour through the calibrated orifices.

An extensive validation of the model has been performed by comparing the modelled mass flow rate against the experimental results introduced in the first part of the paper, which were performed for different engine-like operating conditions involving a wide range of fuel temperatures, injection pressures and energizing times. In that first part of the study, an important influence of the fuel temperature was reported, especially in terms of the dynamic behaviour of the injector, due to its ballistic nature. The results from the model have allowed to explain and further extend the findings of the experimental study by analyzing key features of the injector dynamics, such as the pressure drop established in the control volume due to the control orifices performance or the forces due to viscous friction, also assessing their influence on the needle lift laws.

1. Introduction

The fuel injection system has attracted the interest of researchers in the diesel engine field due to the importance of key aspects such as nozzle geometry, fuel injection pressure or ambient conditions on the air–fuel mixture, combustion efficiency and emissions [1–6]. These are key features in the frame of the new standards and regulations in the automotive world, the increasing environmental awareness and the cost of the fossil fuels [7,8]. It is then of crucial importance to understand the diesel injection process in order to propose alternatives that make it possible to optimize its aforementioned outcomes.

In this context, it is helpful to develop computational tools that allow to predict the behaviour of the injection system under several operating conditions, properly catching their influence on the fuel rate of injection and even shaping it as desired [9]. In this sense, one-dimensional modelling seems to be a suitable solution due to its low computational cost as compared to full 3D-CFD approaches, which for this reason are typically focused on specific parts of the injector, such as the nozzle [10,11]. In fact, 1D modelling has already been successfully applied by the authors to study the hydro-dynamic behaviour of the injection system, both in its piezo [12] and solenoid-driven [13,14] variants.

It is important to understand how fuel temperature affects the fuel injection rate, since it is more difficult to control it during the engine operation than it is to control other relevant parameters such as the injection pressure or energizing time. Indeed, fuel temperature strongly affects the fuel properties [15], thus influencing the injected mass flow rate and spray development [16,17], as also noted in the first part of this study. This influence is even more important at extremely low temperatures, representative of cold start conditions [18,19].

Therefore, the computational models need to incorporate the effect of fuel injection temperature to their simulation capabilities in order to increase the accuracy of their predictions. Previous works by the authors regarding fuel injector 1D modelling were restricted to a single fuel temperature [12–14]. Different approaches were undertaken by several researchers in order to include fuel injection temperature variations in the simulations.

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Nomenclature

A_o	orifice outlet area
C_d	discharge coefficient
c_f	fuel speed of sound
D_{cl}	clearance diameter
D_i	orifice inlet diameter
D_o	orifice outlet diameter
D_{pist}	piston diameter
D_{rod}	rod diameter
D_{spire}	diameter of a spring's single spire
D_{spring}	spring diameter
E	elastic modulus
F_{pist}	piston force
F_{visc}	viscous friction force
$F_{\Delta P}$	force due to the pressure difference at both sides of the needle
G	shear modulus
K_{eq}	equivalent stiffness
K_{spring}	spring stiffness rate
k-factor	orifice conicity factor
L	length of contact
$\dot{m}$	fuel mass flow rate
$\dot{m}_{th}$	theoretical fuel mass flow rate
N_{spires}	number of spires of a spring
P	pressure
P_b	discharge backpressure
P_{dw}	downstream pressure
P_i	injection pressure
P_{up}	upstream pressure
P_v	vapour saturation pressure
p	perimeter
Re	Reynolds number
T_i	fuel injection temperature
t_d	delay between SOE and SOI
t_{inj}	injection time
u	flow velocity
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
IRDCI	Injection Rate Discharge Curve Indicator
OA	control volume outlet orifice
OZ	control volume inlet orifice
SEM	Scanning Electron Microscope
SOE	start of energizing
SOI	start of injection

Seykens et al. [20] investigated the effects of the fuel properties on the injection rate by means of a computational 1D model that made it possible to compare the performance of a diesel fuel and a biodiesel fuel at room temperature. Nevertheless, the difference among the properties of these fuels is not representative of the ones that could be induced by differences in temperature when running a diesel engine on its wide range of operating conditions. A similar work by the same authors involved the investigation of a model for a single fuel assuming adiabatic flow inside the injector, but the temperature variations studied were only in the range from 293 to 313 K [21]. Catania et al. [22] emphasized the importance of the effect of the fuel temperature evolution along high-pressure injection systems, also considering temperatures at room conditions or above, as Mohammed et al. [23] also did for the case of hydrogen fuel injection. On the other hand, Plamondon and Seers [24] studied the problem for a piezo-driven injector without considering viscous friction, whose effects are deemed to be important on a solenoid injector at low pressure conditions. Different approaches were performed by Rahim et al. [25], who implemented a 1D model of the whole engine to study the direct effect of the fuel properties on macroscopic variables like fuel consumption, without paying much attention to the injection event itself; or Shi et al. [26], who only focused on the lower part of the nozzle without considering the influence of the control volume orifices performance or the needle movement on the flow, which could also be affected by fuel temperature.

This work aims at the implementation of a 1D model to serve as a tool to predict the performance of a solenoid-driven common-rail ballistic injector (Bosch CRI 2.20), with special attention to the proper modelling of the inlet fuel temperature effects on the injection rate. The model is implemented in the multidisciplinary modelling platform AMESim [27] and validated against data experimentally gathered for a wide range of injector operating conditions (namely injection pressure, energizing time and injection temperature), as described in the first part of the paper. The fuel injection temperature ranges from 253 to 373 K, thus ensuring a proper behaviour of the model within the whole range of engine-like conditions, including cold start. The isothermal approach is considered for the flow, which means that for each simulation the fuel temperature is assumed to be constant along the injector and equal to the one at the injector inlet. Thus, the fuel properties also remain constant within the same simulation. However, the validation highlights that the model is still able to exhibit accurate results while reducing the simulation computational costs, even though the ballistic nature of the injector makes its dynamics more sensitive to the changes in fuel properties (as opposed to previous generations of solenoid-driven injectors studied by the authors [13,14] in which the needle lift was limited to a value – 250 μm – easily achieved during its regular operation, which led to the injector dynamics not being strongly affected by the fuel properties).

Once the model is validated, the simulation results will be used to confirm and explain the findings of the first part of the paper by means of an analysis of the physical processes behind the dynamic behaviour of this kind of injector under extreme temperature conditions. In this respect, the influence of fuel temperature on key features such as the pressure drop established in the control volume, due to the control orifices performance; or the forces on the needle, due to viscous friction, is studied. This allows to link them to the influence on the needle lift laws and the mass flow rate response.

The paper is divided in 6 sections. Section 2 deals with the explanation of the experimental tools used for the injector characterization needed to develop the computational model. This includes both a dimensional and a hydraulic characterization of the injector. Next, Section 3 describes how the different parts of

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