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Research Paper

Sensitivity analysis of the dynamic response of an electronic fuel injector regarding fuel properties and operating conditions

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HIGHLIGHTS

- Effects of 3 fuel properties on the injector dynamic response were studied individually.
- The bulk modulus and viscosity are influential at low and high pressures respectively.
- A large bulk modulus shortens valve delays and closing time, but increases opening time.
- A high density enlarges valve opening/closing delays and times.
- A high viscosity reduces valve opening delay/time but increases valve closing delay/time.

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ABSTRACT

The sensitivity of fuel properties to the dynamic response (needle valve opening/closing delay and needle valve opening/closing time) of a electronic fuel injector was investigated. The fuel properties in different operating conditions were varied individually in bulk modulus, density and viscosity. Firstly, an electronic fuel injector model was built and validated by injection rate and injection mass at three different rail pressures and three different activation times. Secondly, a DOE (design of experiment) model was built and the Uniform Latin Hypercube (ULH) design method was applied to study the influences of the fuel properties on the injector dynamic response from a statistical point of view. The effects of the fuel properties were compared by using a SS-ANOVA (smoothing spline analysis of variance) method at both a low and a high rail pressure. The bulk modulus was found to play a dominant role in influencing the valve opening/closing delay at the low rail pressure. However, at the high rail pressure, the effects of the viscosity are prominent, while the effects of the bulk modulus and the density are negligible. Additionally, how these fuel properties affect the dynamic response were reported by RSM (Response Surface Method) function charts, and the details of the pressure differences and needle valve movements were also disclosed.

1. Introduction

Electronic fuel injectors play an indispensable role in HPCR fuel injection systems and interest numerous researchers to improve their performance. A lot of work has been undertaken in the nozzle area, such as the nozzle structure types [1–3], the hole numbers and arrangements [4–7] and the internal cavitation [8–11] of orifices. They have been thoroughly studied because they have a direct effect on the fuel injection and atomisation. The spray characteristics [12–14], the penetration [15–17] and the lift-off length [18,19] have also been investigated by experiment or simulation in many studies. With the continual focus on the emissions of diesel engines, the use of different alternative fuels has come into the sight of researchers [20]. The differences in fuels lie in their properties [21], such as the density, viscosity and bulk modulus. Fuel properties significantly affect the spray characteristics of a fuel injector, as were studied by Dernotte et al. [22] and Payri et al. [23]. In addition, fuel properties change in vast ranges of different pressures and temperatures, as were revealed by Salvador et al. [24] and Desantes et al. [25].

The multi-injection performance of a solenoid injector was evaluated by Salvador et al. [26] by using a standard diesel fuel

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Nomenclature

1D	one dimensional
AC	accumulation chamber
Ab_Visc	absolute viscosity
B	bulk modulus
Bulk_M	bulk modulus
CC	control chamber
C_f	friction coefficient
D	pipe diameter
Dens	density
DOE	design of experiments
HPCR	high pressure common rail
L	pipe length
n	levels
NN	neural networks
R_e	Reynolds number
RSM	response surface method
s	field
SS-ANOVA	smoothing spline analysis of variance algorithm
T	time constant
ULH	Uniform Latin Hypercube
v	pressure wave propagation speed

Greek symbols

μ	absolute viscosity
ρ	density
τ	delay

Units

cP	centipoise
K	Kelvin
kg/mm^3	kilograms per cubic millimetre
m	metre
mg/st	milligram per stroke
MPa	mega Pascal
ms	millisecond
N	Newton
Pa·s	Pascal second

and a biodiesel fuel. The biodiesel fuel was identified as have a larger valve opening delay and valve opening time due to it have a larger viscosity. This implies that the fuel properties may have an effect on the dynamic response of a fuel injector. However, to date, only a few studies have found considered the effects of fuel properties on the dynamic response of electronic fuel injectors. Han et al. [27] experimentally investigated the injection process of three fatty acid esters on an HPCR system. He pointed out that fatty acid esters have larger injection delays and smoother rising slopes of the injection rate than diesel fuel. They also indicated that a reduced injection delay, along with a prolonged injection duration, was seen at increased rail pressures. Salvador et al. [28] experimentally investigated the impact of fuel temperature on the injection dynamics (stationary mass flow rate, injection delay, and valve opening/closing slope of the mass flow rate) of a ballistic injector, with special attention paid to the needle valve opening and closing stages. They indicated that the temperature had a huge influence on the valve opening delay. In a further study to extend insights into the injector dynamics, Payri et al. [29] developed a one-dimensional model and paid special attentions to the pressure drop in the control chamber, the viscous friction and the needle lifts. These studies investigated the injection dynamic with different fuels or different fuel temperatures and pressures, yet the impact of each fuel property on the injector dynamic response is still not clearly identified. Boudy et al. [30] investigated the influence of the properties of a biodiesel fuel on the injection process; in this study, the fuel density, bulk modulus and absolute viscosity were examined individually in both single- and triple-injection situations. He pointed out that density is one of the most influential fuel properties on the injection process. Han et al. [31] investigated the isolated effect of the fuel density, viscosity and bulk modulus on the injection mass and pressure propagation waves under split injection strategy conditions. They indicated that the fuel density and bulk modulus have a larger impact than the viscosity on the injection mass and pressure propagation. However, in these studies, the fuel properties varied only slightly, and the dynamic response, such as the needle valve opening/closing delay and opening/closing time, was not in their interests. Although it can be inferred that a larger fuel density leads to larger valve opening and closing delays and vice versa, it is still necessary to clearly identify how large the influence is, especially when compared to the other two typical fuel properties (viscosity and bulk modulus). Additionally, the effects of fuel density on the valve opening and closing times are also unknown.

One-dimensional (1D) models are efficient and practical for predicting the performance of electronic fuel injectors, and have been adopted by many studies. For example, a 1D model of a solenoid-driven common rail ballistic injector was built by Payri et al. [32] to study the influences of the inlet fuel temperature on the injection rate. Ando et al. [33] investigated the magnetic aftereffect on the dynamic response of a fuel injector by building a simple and high accurate 1D simulation model. They indicated that a significant delay was caused by a lower maximum activation current, which generated a smaller magnetic force than a higher maximum activation current. Another 1D model was built by Seykens et al. [34] to investigate the elasticity and nonlinearities of the injector needle valve. Additionally, 1D hydraulic models were also established by Han et al. [31] and Rahim et al. [35]. The detailed modelling of fuel injectors was demonstrated by Bianchi et al. [36], Payri et al. [32,37] and Salvador et al. [38].

In this paper, the sensitivity of three fuel properties (the fuel density, bulk modulus and absolute viscosity) to the valve opening/closing delay and the valve opening/closing time were carefully investigated. Firstly, an electronic fuel injector model was built according to Payri et al. [37] and completely validated by the experimental data disclosed in that article. Then, this validated injector model was included in a DOE model, where a Uniform Latin Hypercube method was adopted. Then, the effects of these fuel properties on the injector dynamic response were compared and shown by RSM function charts from a statistical point of view, in which an SS-ANOVA method was adopted.

DOE is a systematic method for building a relationship between the input factors and output factors of a process. A great deal of information can be obtained through a reduced number of DOE simulations; therefore, it is effective to investigate the influences of individual variables on the response. In DOE, "factors" refer to design variables, and "level" refers to a specific value assigned to a factor. A DOE method creates a number of design points, which is a variation in the selected model's parameters [39].

The ULH is one of the most commonly used DOE methods. In it, the design space of each factor or design parameter is divided into *n* uniform levels. On each level of every factor, only one design