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Experimental study on diesel fuel injection characteristics under cold start conditions with single and split injection strategies

Ziman Wang, Haichun Ding, Miroslaw L. Wyszynski *, Jianyi Tian, Hongming Xu

School of Engineering, Mechanical and Manufacturing Engineering Department, The University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

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ABSTRACT

Studies on fuel flow characteristics under both room temperature (25 °C) and low temperature (−18 °C) were carried out under a wide range of injection pressures and back pressures using a long tube real-time fuel flow rate measuring instrument. Both single and split injection strategies were employed. Several modified correlations were proposed to analyze fuel injection characteristics. It was found that low fuel temperature caused longer injection delay, shorter injection duration, lower mass flow rate and less injected fuel mass. The injector discharge coefficient was affected more by fuel viscosity changes due to low temperature than by the geometric structure of the injector. Cold start conditions effectively limited the inception of cavitation as seen in the flow rate/pressure dependence and accelerated the transition of flow regime from cavitation to turbulent and laminar flow with the decrease of injection pressure. This contributed to increased chances for the existence of laminar flow and thus to reduction of the discharge coefficient. Besides, low fuel temperature significantly weakened the degree of interaction between individual parts of split injection and split mass flow rate shapes became much less continuous than those under room temperature. These findings are of great importance for engine cold start studies.

1. Introduction

Fuel injection is a key factor for engine performance and emissions, and various basic studies on fuel injection behaviour are available [1]. Payri [2] studied the flow regimes by measuring the instantaneous fuel mass flow rate (MFR) and momentum flux. It was reported that for convergent injectors, turbulence and the transition from laminar to turbulent flow are the main flow regimes. For laminar flow, the discharge coefficient (C_d) is quite low partly due to the reduction of effective area while high C_d can be achieved for turbulent flow. The injection pressure difference, thereby the resulting velocity and Reynolds number (Re), is the main factor that changes the flow regime in the injector. According to Soteriou et al. [3], the cavitation does not tend to occur for convergent injectors, and the hole convergence allows fuel and nozzle wall to interact strongly. Therefore, the effects of both Re and viscosity are important. Others [4–7] studied the influences of fuel properties on injection characteristics. It was reported that MFR and velocity depend mainly on fuel density, and that viscosity mainly affects the injector opening and closing. The rise of fuel viscosity leads to obvious reduction of C_d, especially under low injection pressure. These studies were carried out under room temperature (RT).

Recent studies of light duty diesel engine show the trend that lower compression ratio with boosted air intake eases the emission control. However, the engine cold start becomes a big problem [8,9]. This is because the variation of temperature contributes to the change of ignition delay thus changes of in-cylinder pressure [10]. Consequently, the injection characteristics under low temperature (LT) require to be deeply studied. Payri [11] investigated the impacts of fuel properties on injection characteristics under both RT (25 deg C, 298 K) and extremely LT (−18 deg C, 255 K). The results showed that viscosity and density, both varying with temperature, clearly affect the flow and spray characteristics. However, the influences of viscosity are more apparent under low temperature because of its significant variation with temperature. Besides, it was also reported that low temperature contributes to lower Re thereby to lower C_d. Vergnes et al. [12] also reported that low temperature leads to sharp reduction of C_d. By utilising a recycling fuel delivering system, Mark [13] studied the fuel MFR and pressure drop across the fuel filter under low temperature. This system shares many similarities with the ones used for modern engines. It was shown that the reduction of temperature leads to decrease of MFR and higher pressure drop across the filter. Kazancev et al. [14] and Rushang et al. [15] also found that low temperature leads to low MFR.

Multiple injection strategy can considerably stabilise the engine performances and reduces misfire for cold idle operation [8]. Carlucci [15] studied the engine cold start by utilising multiple injections. It was shown that the ignition delay was halved for nearly all working

* Corresponding author. Tel.: +44 121 414 4159, +44 7968 157 909(mobile).
E-mail address: M.L.Wyszynski@bham.ac.uk (M.L. Wyszynski).

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conditions and that split injection can effectively control the ignition, giving high flexibility to control the emissions.

The aforementioned studies have given details on the basic injection features. However, it is still unclear how the flowing regime changes under cold start condition when injection parameters vary. As a cutting edge injection strategy, split injections have not been fully studied under cold conditions. Besides, the impacts of fuel temperature on the interaction between splits also require a deep study. Aiming to throw some light on these questions, the present paper investigates the fuel injection behaviour using a long tube fuel flow rate measuring instrument under both RT (25 °C) and LT (−18 °C). Both single and split injection strategies were employed under these conditions. Several equations or correlations were employed to discuss the distinctive injection characteristics under both RT and LT.

2. Theoretical background

Discharge coefficient is a useful parameter used to study the flow characteristics in a nozzle hole. It denotes the effective fuel flow of the nozzle. It can be calculated by the ratio of actual and theoretical fuel MFR, shown in Eq. (1):

$$C_{\mathrm{d}} = \dot{m}_{\mathrm{act}}/\dot{m}_{\mathrm{th}} \tag{1}$$

where $\dot{m}_{\mathrm{act}}$ is the actual MFR measured through the long tube measuring instrument and $\dot{m}_{\mathrm{th}}$ is the theoretical MFR calculated through Bernoulli's equation expressed as

$$\dot{m}_{\mathrm{th}} = n_{\mathrm{hole}} * \left(\pi {D_o}^2/4\right) * \sqrt{2\rho\Delta p} \tag{2}$$

where n_{hole} is the number of orifices, D_o is hole diameter, ρ is fuel density and Δp is the pressure difference between injection pressure and back pressure.

The variation of C_{d} generally links to the phenomenon of cavitation, which leads to the flow detachment or cavities between liquid and the hole wall [2]. The degree of cavitation can be expressed as

$$K = \frac{p_{\mathrm{inj}} - p_{\mathrm{v}}}{p_{\mathrm{inj}} - p_{\mathrm{b}}} \tag{3}$$

where p_{inj} refers to injection pressure, p_{v} refers to fuel saturation pressure and p_{b} refers to back-pressure.

As the tests were carried out under room temperature and low temperature, p_{v} is quite low and is considered to be zero in this study.

Reynolds number Re is another important parameter that denotes the significance of injection pressure difference for the flow characteristics. The injection pressure difference results in different outlet velocities. Re can be calculated using Eq. (4):

$$\mathrm{Re} = V_{\mathrm{act}} * D_{\mathrm{o}}/\nu \tag{4}$$

where ν is fuel kinematic viscosity and V_{act} is the actual flow velocity at the injector outlet, which can be calculated using the following equation:

$$V_{\mathrm{act}} = \frac{\dot{m}_{\mathrm{act}}}{n_{\mathrm{hole}}\left(\pi d^2/4\right)\rho} \tag{5}$$

More detailed information about the explanation of these equations can be found in [2,3,11].

3. Experimental setup and test conditions

The MFR was measured using an in-house built long tube real-time measuring instrument based on Bosch method. Strain gauges were used to detect the real time fuel pressure at the outlet of the injector and the signals were recorded by an ultrahigh speed data acquisition card. These data were then conditioned and processed with an in-house built software. The schematic of the instrument is shown in Fig. 1(a). The injector (2) is fixed on the injector holder (3) which connects to measuring tube (5). Two strain-gauges (4) positioned at the very outlet of the injector are used to detect the pressure signals. A relief valve (7) is employed to avoid damaging the instrument if over pressurised. The needle valve (9) is used to regulate the back pressure (Pb) in the measuring pipe (5) and Pb can be read through the pressure gauge (8). The volume of the injected fuel can be measured through the cylinder (10) while the weight can be measured through the weighing scale (11). High measuring accuracy (over 94%) can be obtained with this instrument after careful calibration. The error bars in the following subsections suggest high measuring accuracy.

An 8-hole piezoelectric injector with the degree of conicity AF $= (d_i^2 - d_o^2)/d_i^2$ of 19% was utilised. The outlet diameter of the holes is 0.118 mm. A freezer, which can maintain a stable low temperature, was employed to refrigerate the injector parts for LT tests, as presented in Fig. 1(b). The injector and its fixing accessories (the circled parts by red dot dash line) were kept in the freezer (the long pipe and these parts located after are not shown, but the pipe is connected to the schematic one by red dash line). The pressure signal was delivered to the

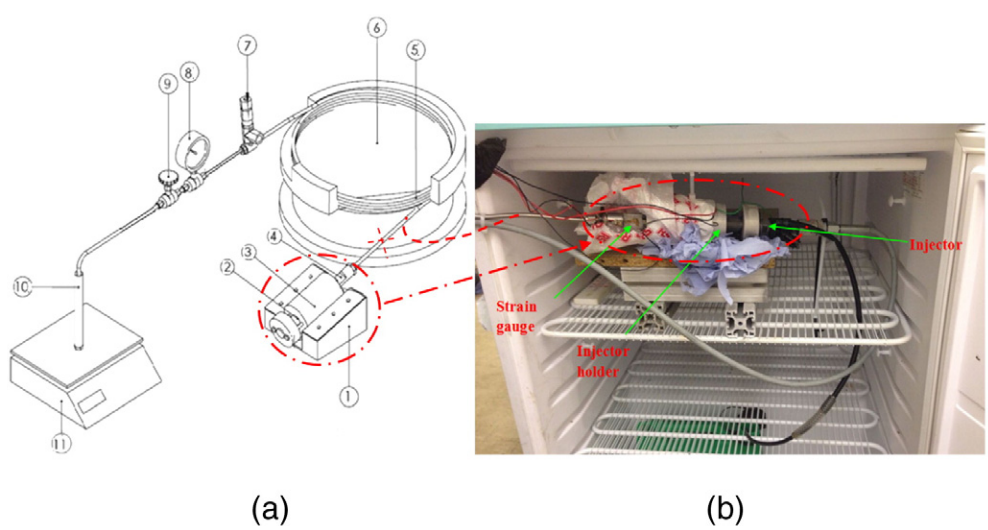

Fig. 1. Isometric view of the MFR measurement instrument (a) and experimental setup under LT (b).