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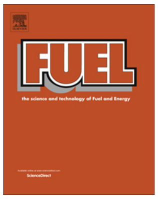

Experimental study of temporal evolution of initial stage diesel spray under varied conditions

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HIGHLIGHTS

- Ultra-high speed imaging techniques were used to study the near-field diesel spray.
- Timing of the maximum spray tip velocity was investigated.
- A new way to discriminate between the two stages of fuel spray penetration was proposed.
- Equations to predict the transition timing and near-field penetration was proposed.

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ABSTRACT

Understanding of the initial stage of spray development is important in modelling of the injection process for optimisation of diesel engine design. The near-field spray characteristics of a single-hole diesel injector were studied using an ultra-high speed CCD digital video camera with the speed of up to 1 M fps. The effects of injection and ambient pressure on the spray behaviours have been examined in terms of initial spray penetration and tip velocity. Acceleration was observed during the initial stage of the spray process and the time corresponding to the spray tip peak velocity (t_p) was extracted and compared to the breakup time (t_b) in Hiroyasu correlation. It was found that t_p is a natural and effective way to discriminate between the two stages during the spray process. The ambient pressure increase reduces the transition length considerably before the value reaches 1.5 MPa and after that, the effect becomes much smaller. Finally, empirical correlations for the prediction of spray penetration development were proposed.

1. Introduction

Fuel spray characteristics such as fuel penetration, dispersion, breakup, injection rate and atomisation significantly affect both performance and emissions of diesel engines. With the maximum possible injection pressure approaching 300 MPa [1], the injection duration becomes very short for a given fuel injection quantity. Insight into the short and transient injection process is important for modelling of engine fuel spray and combustion, in order to optimise the engine design.

Fuel spray characteristics have been studied over one hundred years, and a number of correlations characterising the fuel injection are summarised [2]. A typical spray penetration process can be divided into two stages by the time corresponding to the transition of the two stages, t_{tr}. The most well-known correlations were proposed by Hiroyasu and Arai [3], based on their experimental and analytical investigation, as shown in Eqs. (1)–(3):

$$0 < t < t_b \quad S(t) = 0.39\sqrt{\frac{2\Delta p}{\rho_f}}t \tag{1}$$

$$t \geqslant t_b \quad S(t) = 2.95\left(\frac{\Delta p}{\rho_a}\right)^{1/4}\sqrt{d_o t} \tag{2}$$

where

$$t_b = \frac{28.65\rho_f d_o}{(\rho_a \Delta p)^{\frac{1}{2}}} \tag{3}$$

t is the time after start of injection (ASOI), S is the penetration length, d_o is the nozzle diameter, Δp is the pressure difference between injection pressure and ambient pressure, ρ_f is the liquid density and ρ_a is the ambient density. Here, t_{tr} is associated with t_b, where the intact liquid column issued from the nozzle exit starts to breakup. Clearly, in the first stage, the penetration length is linear

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Nomenclature

t_b	breakup time
t_p	time to reach peak tip velocity
t_{tr}	transition time
P_{inj}	injection pressure
P_{amb}	ambient pressure
P_a	compressible pressure
ρ_a	surrounding gas density
U_0	droplet velocity
U_{T0}	spray tip velocity
γ	volume fraction
κ	ratio of the ambient gas specific heats constant pressure and constant volume
ρ_f	fuel density
U_i	mean injection velocity
ΔP	pressure difference between P_{inj} and P_{amb}
C_d	discharge coefficient
S	penetration length
d_o	nozzle diameter
l/d_o	ratio of nozzle length to nozzle diameter

with the time ASOI (t), and in the second stage, the penetration length (S) is proportional to the square root of time ASOI.

A number of other subsequent studies [4–9], however, have improved the understanding of the spray process and several differences were found. Firstly, an acceleration period in the initial stage of fuel spray penetration was observed in common rail fuel systems. Naber et al. [4] observed an nonlinear spray penetration development using a linescan camera on a magnified field of view when penetration length was less than approximately 6 mm, but they artificially neglected this process because the injected fuel quantity during this period was small, and it was quickly overtaken by the fuel from main injection period. Hillamo et al. [7] calculated the spray tip velocity through the penetration length difference obtained by a double imaging method and concluded that the measurement of tip velocity development is a way to divide the spray development into an acceleration region and deceleration region. Kostas et al. [8] used an ultra-high speed camera and found that spray tip penetration length is proportional to $t^{1.5}$. Secondly, no consensus has been reached on the mechanism of t_{tr} formation. Hiroyasu et al. [2] associated the transition with the spray jet breakup time. According to Naber et al. [4], the transition began when the ambient condition started to dominate the spray development. Densants et al. [10] believed that the transition was caused by the increasing mass flow rate with needle lifting. A recent model proposed by Roisman et al. [6] tried to explain the spray tip velocity behaviour by taking into account the compressibility effect of the gas ahead of the spray that is induced by the high spray velocity, and they demonstrated that the shock wave propagation plays an important role at the initial stage of the spray injection. Furthermore, this model is validated by other researchers [11]. Thirdly, it is worth considering whether the assumption of the existence of an intact liquid column is true or not. The subsequent studies have provided further understanding of this process. Smallwood et al. [12–14] reported that the spray jet is highly atomised at the exit of nozzle or within a few nozzle diameters and no intact cores exist based on the experimental data using two-dimensional laser light scattering and transmission techniques. Bruneaux et al. [15] proved that a transition from fuel flow of high optical density at the exit to a fully atomised spray occurs within a few nozzle diameters, using laser induced exciplex fluorescence (LIEF). Recent studies [16–18] on diesel spray breakup using X-ray technology further confirmed the abovementioned conclusion.

Therefore, it seems that a complete understanding of the near-field spray development (including the first stage and the transition) has not been achieved. This situation is more prominent as the injection pressure is continuing to increase and thus the injection duration becomes shorter and shorter for certain fuel injection quantities (especially the pilot and post injections). The authors believe that one of the reasons for lack of in-depth understanding is attributed to the imaging facilities. Modern imaging technology is widely used in spray studies and generally, two methods are used to acquire the spray images. One is to take one snapshot from one injection and apply different imaging delay times from SOI for different events of injections [5–7,19]. The other method is to record the spray process in a series of consecutive images using a high-speed camera [20,21]. Both methods are adequate to study the far-field spray process, but they have some limitations for the study of the near-field spray process, which is approximately less than 300 μs ASOI. The first method cannot record the real penetration curve due to the shot-to-shot injection variations, and in the second method, the temporal resolution may not be adequate to capture the initial-stage spray behaviour unless the frame speed of the camera is fast enough.

Therefore, the objective of the study is to provide an in-depth examination of the near-field spray process. An ultra-high speed camera with a constant resolution of 312 × 260 pixels was used to capture the temporal evolution of diesel spray under different injection and ambient pressures in terms of penetration length. The peak tip velocity calculated from the penetration curves was used to validate Roisman's model; then the timing corresponding to the peak velocity, t_p, was compared with t_b from the Hiroyasu correlation to examine the transition process of the fuel spray. Finally, empirical correlations to predict the development of spray penetration length and t_p were proposed using t_p as the transition for the two-stage spray development.

2. Experimental setup

2.1. Vessel and fuel injection system

The schematic diagram of the test bench is shown in Fig. 1. A cubic was used for the spray imaging in this study. Three sides of the vessel provided optical access using 100 mm diameter windows. The remaining flanged sides were used to fix the injector, gas inlet and outlet valves, along with the pressure gauge. A single-hole injector with a nozzle diameter of 0.14 mm and hole length/diameter (l/d_o) of 5.7 was fitted centrally into the top flange.

The high-pressure fuel pump capable of producing an injection pressure of up to 160 MPa was driven by a 5.5 kW 3-phase AC motor and the speed of the motor was controlled by a 3-phase frequency inverter. The returning fuel from the common rail, high-pressure pump and injector was cooled by a heat exchanger before it flowed back into the fuel tank. The injection pressure was controlled by a purposed-built control unit, using a feedback signal from the pressure transducer on the common rail.

The testing conditions and the properties of the diesel fuel used for the experiments are listed in Tables 1 and 2, respectively. Each of the tests were repeated 10 times and the data was averaged in order to provide a satisfactory statistical certainties.