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Spray development and droplet characteristics of high temperature single-hole gasoline spray

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HIGHLIGHTS

- Sprays were totally blurred and uniform under supercritical temperature.
- Spray penetration and core angle meet a reverse trend after critical point.
- Droplet size dropped dramatically as fuel temperature approximates critical point.
- Extremely large droplets will completely disappear when temperature exceed 173 °C.

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ABSTRACT

As increasing fuel injection pressure in GDI (Gasoline Direct Injection) engines has been used for improving atomization quality, raising fuel temperature is also receiving more and more attention as another promising method to improve mixing quality and combustion process. In order to understand atomization process with increased fuel temperatures, spray development and droplet characteristics of high fuel temperature spray were investigated by using back-illumination imaging technique and Phase Doppler Particle Analyzer (PDPA) with fuel temperature up to 376 °C as supercritical state. Results show that sprays dispersed more widely and became more transparent with increasing fuel temperature. Spray penetrations had some reduction and spray cone angle had obvious increase with increased fuel temperature not more than critical temperature. While droplet arithmetic mean diameter (D_{10}) and Sauter Mean Diameter (SMD) was reduced from about 10 μm to 1.5 μm and from 30 μm to 3 μm as fuel temperature rise from 25 °C to 261 °C, high temperature more than 261 °C resulted in droplets became too small to be measured by the PDPA instrument.

1. Introduction

As GDI (Gasoline Direct Injection) engines have substantial potentials for providing about 10–15% lower fuel consumption and better transient performance than PFI (Port Fuel Injection) engines, they have experienced a rapid growth in recent years [1]. However, PM (Particulate Matter) emissions are major obstacle to its future development [2,3]. Compared with PFI engines, PM emissions in GDI engines mainly come from poor air-fuel mixing quality caused by limited mixing duration and possible wall-wetting [4–6]. The time for mixing may be even shorter in new developed technologies such as multi-injection strategy and stratified burning strategy [7,8].

As conventional method to address this problem is to raise injection pressure, recent publications have shown a number of researches had GDI injection pressure increased to the range from 20 MPa to about 40 MPa or even 150 MPa [9,10]. Generally, multi-hole injectors enable spray to disperse with an arithmetic mean droplet diameter (D_{10}) between 10 μm and 20 μm along the central line of a specific hole under an injection pressure of 10 MPa [11–14]. When injection pressure is elevated, obvious improvement on atomization quality could be found. According to the PDPA experiment results from Lee and Park [11], D_{10} of the spray reduced from 12 μm to 9.5 μm as injection pressure rose from 10 MPa to 20 MPa and further to 9.0 μm as injection pressure increased to 30 MPa. In addition, mean velocity of droplet varied slightly in their work. Allocca et al. [12] also reported a similar D_{10} of about 7.5 μm when injection pressure increased from 10 MPa to 20 MPa. However, together with such benefit on reduced droplet size, high injection pressure will bring a vital

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shortcoming known as wall-wetting caused by its longer penetration [15,16]. Poor mixing near the fuel films generates pool fire phenomenon and produces heavy unburned hydrocarbon and PM emissions [4,5,17].

On the other hand, increasing fuel temperature is another possible approach to improve mixing process since viscosity, surface tension and latent heat of vaporization of fuel droplets will all decrease with increasing temperature, which can sufficiently improve injecting and mixing processes [18,19]. Apart from that, flash evaporation produced by super-heated spray will brings a number of benefits for mixing process. Meanwhile, enhanced turbulence and cavitation in internal passages of injectors were found by Serras-Pereira et al. [20] through a real-size optical direct-injection nozzle with headed GDI fuel spray. Furthermore, with the help of bubble rupture and larger amount of entrained gas, smaller droplets, wider radial propagation and slower penetration speed were obtained in a number of reported works with aid of Phase Doppler Particle Analyzer (PDPA) and high-speed photography [21–23]. In addition, higher vapor/liquid ratio was found with no surprise by Zeng et al. [24] with Laser Induced Exciplex Fluorescence (LIEF) method.

Although all reported works which demonstrated flash evaporation had fuel temperature around 100 °C, and few works could be found when it comes to higher fuel temperature or even to supercritical state in the field of internal combustion engine, George Anitescu et al. [25] found a more transparent spray with fuel blend of diesel and gasoline at 450 °C. This suggests in those measured super-critical fuel sprays/jets, there is almost no liquid but all fuel vapor. Shown in Fig. 1, super-critical status is demonstrated. In a series of experiments carried out by Arnab Roy and Corin Segal [26–28] with FK-5-1-12 (or "fluoroketone") and Planar Laser Induced Fluorescence (PLIF), they showed density-gradient magnitudes of spray continue to decrease and a smooth jet-gas interface was found. Meanwhile, droplets and ligaments are considerably reduced. Other works on aero-engine and rocket-engine provided similar results. [29,30].

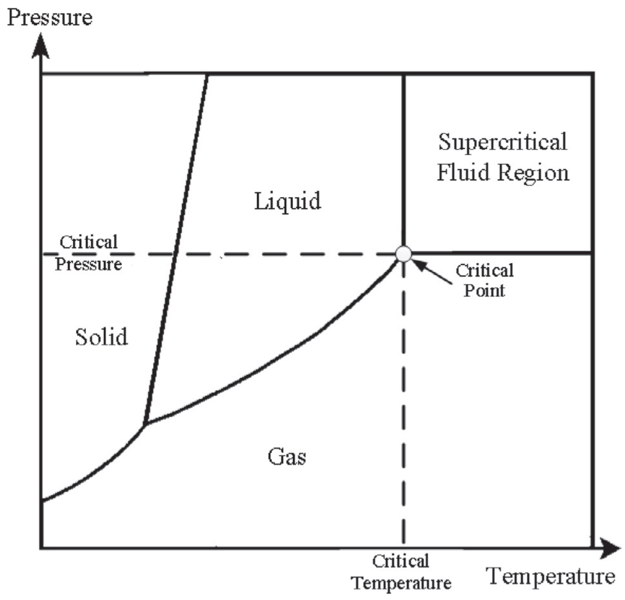
In this study, potentials of high temperature GDI fuel sprays for improving atomization quality and air-fuel mixing process have been investigated. Back-illumination method and PDPA were employed to observe spray development and droplets characteristics with increased fuel temperature up to 376 °C which has exceeded gasoline fuel's critical temperature (about 278 °C) [31]. The surrounding condition was set to atmospheric pressure and room temperature (25 °C) in order to simplify the experimental procedure.

2. Experimental system

2.1. Experimental apparatus

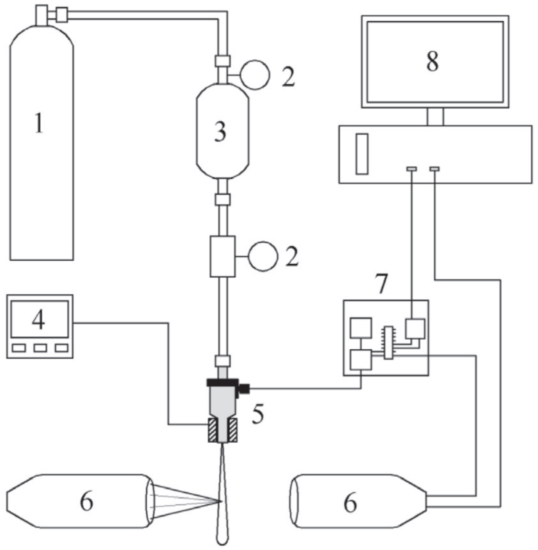
As shown in Fig. 2(a), it is the schematic of the experimental rig which was built just for fuel injection. To provide high injection pressure, a 4-l hydraulic pocket-type accumulator which was operated by compressed nitrogen (up to 25 MPa) was used in the fuel delivery system. A pressure transducer is installed on the high pressure pipe just before the injector for monitoring injection pressure. The injection was controlled by an in-house controller. In this study, injection pressures were set at 6 MPa, 9 MPa, 12 MPa and 14 MPa, respectively. The single injection pulse with a width of 5 ms was used, as shown in Fig. 3.

Still as shown in Fig. 2(a), a Dantec Dynamics PDPA (Phase Doppler Particle Analyzer) system whose system parameters can be found in Table 1 was employed to investigate droplet sizes and velocities.



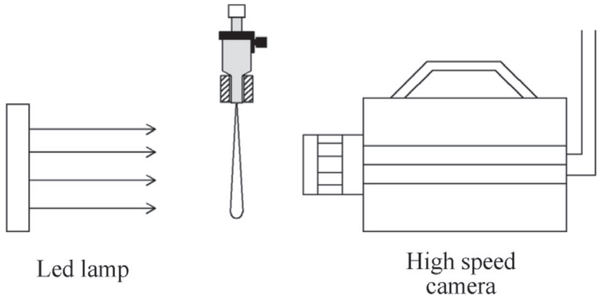
Critical point for gasoline [31]	278 ºC	3.1 MPa

Fig. 1. Phase diagram for supercritical fluid and the critical point for gasoline.



(a) with PDPA measurement system

1. High pressure nitrogen gas 2. Pressure gauge 3. Pocket-type accumulator
4. PID controller for fuel temperature 5. Injector with heating device
6. Laser emitter and receiver for PDPA system 7. Control unit 8. PC



(b) with high speed imaging system (Back-illumination method)

Fig. 2. Schematic of experimental systems.