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Near-nozzle spray and spray collapse characteristics of spark-ignition direct-injection fuel injectors under sub-cooled and superheated conditions

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HIGHLIGHTS

- Effects of nozzle L/D and nozzle number on near-nozzle flash boiling spray characteristics are revealed.
- In-nozzle fuel evaporation and outside nozzle fuel boiling govern fuel spray characteristics under superheated conditions.
- Spray collapse characteristics and its formation process under superheated conditions are revealed.
- Flash boiling spray has great potential to solve injector deposit issue caused by residual fuel trapped in the nozzle.

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ABSTRACT

There is limited literature available regarding the spray collapse process and the characteristics of flash boiling spray near the critical location of the nozzle exit, even though flash boiling has been proven to produce finer fuel spray with much improved vaporizing quality, and liquid fuel atomizes quickly soon after it is discharged from the nozzle. In this study, the near-nozzle fuel spray of various types of spark-ignition direct-injection prototype multi-hole injectors was investigated under a wide range of sub-cooled and superheated conditions using a high-speed backlit imaging technique. The effects of fuel temperature, ambient pressure, nozzle L/D ratio, and nozzle number, as well as near-nozzle spray characteristics and spray collapse phenomenon under superheated conditions, were studied. Experimental results revealed that both increasing fuel temperature and decreasing ambient pressure resulted in faster fuel jet disintegration and wider fuel plume due to flash boiling. In-nozzle fuel evaporation and outside-nozzle fuel boiling were the primary influences governing flash boiling spray atomization under superheated conditions. Spray collapse length increased with decreasing Pa/Ps ratio; it also increased with the elapse of injection time. Flash boiling spray also has the potential to resolve injector deposit issues with significantly improved end-of-injection performance.

1. Introduction

Since the widespread adoption of spark-ignition direct-injection (SIDI) gasoline engines in today's vehicles, fuel spray has drawn more attention from engine researchers. In port fuel injected engines, the fuel is injected into the intake manifold and undergoes relatively long atomization and evaporation processes before ignition. Fuel injectors work under low temperature and pressure conditions; thus, the requirements of injector and spray characteristics are not as crucial. In SIDI engines, a fuel injector is mounted inside the engine cylinder and fuel is directly injected into the combustion chamber. Fuel spray characteristics not only affect fuel economy and engine performance, but also govern exhaust emission quality. Moreover, more stringent emission regulations prompt greater demands on spray performance and quality. Thus, substantial research must be conducted on injector performance and fuel spray improvement.

Faster fuel atomization can lead to more efficient mixture preparation and combustion processes, resulting in higher fuel economy and lower exhaust emissions [1]. High fuel pressure injection and high fuel temperature injection are two methods

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Nomenclature

SIDI	spark ignition direct injection
VCO	valve covered orifice
L/D	length to diameter ratio
ASOF	after start of fuel
P_a	ambient pressure
P_s	fuel saturation vapor pressure
T_f	fuel temperature
L	nozzle length
D	nozzle diameter

which have been proven to improve fuel atomization [2–5]. It has been documented that by increasing fuel injection pressure to a level of 40 MPa, fuel consumption can be improved and harmful emissions reduced [2]. The effect of fuel pressure on fuel atomization was significant when injection pressure was increased from 5 MPa to 20 MPa. However, the incremental benefits of fine atomization were diminished when fuel pressure was higher than 20 MPa. In addition, the requirements of a higher pressure fuel injector and a fuel pump with greater strength reduced cost-effectiveness, and the reliability of these components was lowered [6].

High fuel temperature injection, also known as flash boiling injection, has been experimentally proven to effectively improve fuel economy and reduce particulate matter emissions due to enhanced fuel atomization and evaporation [7–10]. Flash boiling spray can be realized by heating fuel to a certain value, when its saturation vapor pressure is larger than the local ambient pressure [5]. Fuel temperature and ambient pressure – rather than fuel pressure – are two dominant factors which govern the fuel atomization process and spray pattern [11]. High fuel temperature injection can produce finely atomized fuel spray at relatively low injection pressure [12,13], eliminating the need for high fuel injection pressure and reducing the cost of an ultra-high pressure injector and fuel pump. Hot coolant and exhaust heat are two potential power sources which can be recycled to heat the fuel near the injector. For this reason extensive numerical and experimental studies have focused on flash boiling spray characterization [5,14–20]. Flash boiling spray can enhance fuel atomization and evaporation via the fuel boiling effect soon after the hot fuel is discharged into ambient pressure conditions. However, most current research focuses on the macroscopic spray characterization; only limited study has been made on near-nozzle sprays, especially under superheated conditions. Although Moulai [21] and Zhang [22] conducted both experimental and numerical investigations on near-nozzle spray characteristics under superheated conditions, no research on the effect of nozzle length to diameter ratio and nozzle number on near-nozzle spray characteristics has been documented.

In addition, the dramatic transformation of spray structure, especially under flare flash boiling conditions, (usually referred to as the spray collapse) has yet to be thoroughly studied. Zeng [11], Aleiferis [23], and Yang [24] conducted experiments which confirmed that higher superheat degree led to stronger spray collapse in constant volume chambers, which featured longer spray penetration and narrower spray width. Wood [25] studied injector cone angle effect on the spray collapse phenomenon and concluded that a smaller injector cone angle resulted in easier spray collapse. However, even under conditions with complex ambient air motion, a dramatic transformation of spray structure under flash boiling conditions was also identified [7,26–28]. In addition, fuel pressure and superheat degree governed the extent of transformation [26]; but the collapse process and characteristics are still unclear.

Injector tip deposit formation in the injector orifice is another key engineering problem which must be taken into consideration in SIDI engines, especially when various fuel properties and fuel qualities are involved [29,30]. New engine technologies such as downsizing, stratified combustion and application of bio-fuels make injector operating conditions more challenging and more susceptible to injector deposit. Deposits in the orifice can reduce fuel flow and alter fuel spray characteristics, resulting in increments of fuel consumption and particulate matter emissions [1]. Although significant changes of injector mass rate could be adapted using closed loop air-fuel ratio control, degraded spray characteristics can cause engine misfire and drivability issues [29]. Research into new fuel additives has been conducted by many groups seeking to control and reduce deposit formation [31–33], these proved to be limited for practical application. Since liquid fuel already evaporates inside the nozzle under flash boiling conditions, the amount of liquid fuel that adheres to the nozzle wall can be greatly reduced [15,34]. Thus, flash boiling spray has shown great potential for reducing injector deposit formation caused by residual fuel in the nozzle [29].

This study analyzes both near-nozzle spray characteristics and far field, fully developed spray structure of four step-hole valve-covered orifice (VCO) SIDI injectors under a wide range of sub-cooled and superheated conditions. The effects of fuel temperature, ambient pressure, nozzle L/D ratio and nozzle number on near-nozzle sprays are investigated to reveal the formation process of spray collapse. The end of injection characteristics of liquid fuel spray and flash boiling fuel spray are also discussed.

2. Experimental information and results post-processing procedure

2.1. Experimental setup

Fig. 1 shows the experimental model of a high speed microscopic backlit imaging system to record near-nozzle spray characteristics. A high pressure constant volume chamber with optical access was used to produce various ambient pressure conditions in which the ambient pressure was adjusted from 20 kPa to 2 MPa. A high pressure nitrogen cylinder and a vacuum pump were connected directly to the chamber to generate high back pressure or vacuum conditions, respectively. To remove residual fuel, pure nitrogen flushed the chamber continuously during testing. Fuel pressure was produced by an accumulator pressure system. Compressed nitrogen gas was applied to actuate the accumulator by pumping the liquid fuel inside the accumulator to a target pressure below 20 MPa. During the experiments prototype injectors were mounted on top of the chamber. A high intensity Xenon lamp with continuous light (power: 300 W) illuminated the fuel spray. A high-speed CMOS camera (image resolution of 640 pixels by 480 pixels, frame rate of 30,000 fps) equipped with a long distance microscopic lens was used to record the magnified near-nozzle spray images. Synchronization between injection and imaging was achieved via a programmable timing unit (PTU). Fig. 2 depicts one near-nozzle spray image under sub-cooled conditions. After image calibration, the image covers an area of 8 mm by 6 mm. Based on this image, the plume width can be calculated using a post-processing code written in MATlab.