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Spray and evaporation characteristics of ethanol and gasoline direct injection in non-evaporating, transition and flash-boiling conditions

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ABSTRACT

Ethanol direct injection plus gasoline port injection (EDI + GPI) represents a more efficient and flexible way to utilize ethanol fuel in spark ignition engines. To exploit the potentials of EDI, the mixture formation characteristics need to be investigated. In this study, the spray and evaporation characteristics of ethanol and gasoline fuels injected from a multi-hole injector were investigated by high speed Shadowgraphy imaging technique in a constant volume chamber. The experiments covered a wide range of fuel temperature from 275 K (non-evaporating) to 400 K (flash-boiling) which corresponded to cold start and running conditions in an engine. The spray transition process from normal-evaporating to flash-boiling was investigated in greater details than the existed studies. Results showed that ethanol and gasoline sprays demonstrated the same patterns in non-evaporating conditions. The sprays could be considered as non-evaporating when vapour pressure was lower than 30 kPa. Ethanol evaporated more slowly than gasoline did in low temperature environment, but they reached the similar evaporation rates when temperature was higher than 375 K. This suggested that EDI should only be applied in high temperature engine environment. For both ethanol and gasoline sprays, when the excess temperature was smaller than 4 K, the sprays behaved the same as the subcooled sprays did. The sprays collapsed when the excess temperature was 9 K. Flash-boiling did not occur until the excess temperature reached 14 K. The fuel temperature changed not only the spray evaporation modes but also the breakup mechanisms.

1. Introduction

Gasoline direct injection (GDI) has several advantages over port fuel injection, including improved fuel economy and transient response, more precise air–fuel ratio control, extended EGR tolerance limit, selective emissions advantages and enhanced potential for system optimization [1–3]. On the other hand, ethanol is a widely used alternative fuel to address the issue of sustainability. Compared with gasoline fuel, ethanol has greater enthalpy of vaporization, larger octane number, higher flame speed and smaller stoichiometric air/fuel ratio [4–6]. Recently, ethanol direct injection (EDI) has attracted much attention due to its great potential in taking the advantages of ethanol fuel to increase the compression ratio and thermal efficiency [7–10]. The engine knock propensity could be reduced by the higher octane number of ethanol fuel, and supplemented by the strong cooling effect enhanced by EDI. These advantages make it possible to increase the compression ratio and use turbocharging (engine downsizing technologies) for spark ignition (SI) engines while avoiding the knock issue, and consequently increase the thermal efficiency.

To exploit the potentials of EDI, the spray and mixture formation characteristics should be investigated as they are the key factors that influence the combustion and emissions of an engine. Experimental results showed that the NOx emission decreased, and CO and HC emissions increased with EDI injection in a gasoline port injection engine [7]. The NOx emission was decreased due to the cooling effect enhanced by EDI and CO and HC emissions were increased due to poor mixing, local over-cooling and fuel impingement at high ethanol ratio conditions [11,12]. However

Abbreviations: ASOI, after the start of injection; EDI, ethanol direct injection; GDI, gasoline direct injection; SI, spark ignition; EDI + GPI, ethanol direct injection plus gasoline port injection; Pa/Ps, ambient-to-saturation pressure ratio; ΔT, spray excess temperature; *We*, droplet Weber number; ρ, density; u, velocity; σ, surface tension; d, diameter.

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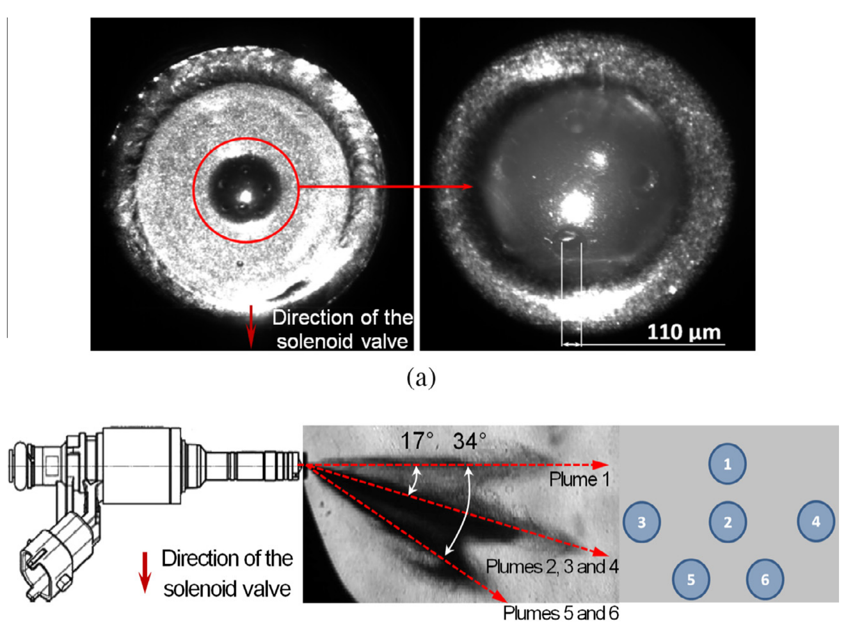
opposite experimental results were reported in [13]. NOx emission increased and CO and HC emissions decreased when EDI was applied. Furthermore, both HC and NOx emissions were reduced by EDI as reported in [8]. The above different results might be caused by the evaporation process of EDI spray in different engine conditions in different investigations.

The fuel evaporation process strongly affects the consequent mixture formation, combustion and emission processes. This is because the droplets must vaporize before they can burn [14,15]. However, little work has been done in this field. A better vaporization of ethanol fuel was used to explain the experimental results of decreased spray tip penetration and increased spray angle with the increase of ethanol/gasoline fraction [16]. Some reported a slower vaporization of ethanol spray than gasoline's because of the light components in gasoline fuel [17]. It was found that ethanol had a faster vaporization rate due to its higher vapour pressure in high temperature conditions in experiments [18]. Numerical studies showed that the evaporation rate of ethanol direct injection was lower than that of gasoline in naturally aspirated SI engines [4,19]. However the simulated evaporation rate of ethanol was as high as that of gasoline in a turbocharged engine [20]. It was found that the fuel temperature played an important role in the evaporation process of ethanol spray. Ethanol evaporated more slowly than gasoline did in low temperature conditions, but faster when temperature was higher than 375 K [4].

The fuel temperature can change in a wide range from non-evaporating (cold start in winter) to flash-boiling sprays in real engine conditions. The effect of fuel temperature on gasoline spray injected by swirl-type injectors was investigated [21–24]. It was found that the spray collapsed with faster evaporation rate, longer penetration and smaller droplet size when the temperature was above the saturation temperature. Recently, the multi-hole injectors have attracted more attention for direct injection SI engines because of their advantages in stability of spray pattern and flexibility of spray plume targeting [25]. However the majority of work published to date on multi-hole injectors concerns diesel nozzles [26]. Aleiferis et al. conducted extensive experiments on the multi-hole injector spray behaviours of various fuels and ambient conditions [26–30]. The studies were focused on the spray shape transformation of flash-boiling sprays (or spray collapse: transition from multi-jet spray to single-jet spray) either by increasing the fuel temperature or decreasing the ambient pressure. Zeng et al. investigated the transition process from non-flash boiling to flare flash boiling sprays using alcohol fuels [31]. It was reported that the spray flash boiling occurred at Pa/Ps = 1 (ambient-to-saturation pressure ratio) and spray collapsed at Pa/Ps = 0.3. However, recent study for ethanol spray from a multi-hole injector found that the spray flash boiling did not occur as soon as the liquid temperature was higher than the boiling point (Pa/Ps = 1) [32].

The adequate performance of direct injection systems is the key factor to achieve the benefits of GDI and EDI. Since ethanol fuel has lower stoichiometric air/fuel ratio and heating value, more mass of ethanol should be injected into the cylinder in order to maintain the same output power and equivalence ratio. More injected fuel results in larger spray momentum and longer spray tip penetration, which may lead to fuel impingement on cylinder and piston walls. Besides, gasoline and ethanol sprays would show different breakup regimes (Bag Breakup, Stripping Breakup, or Catastrophic Breakup) or vaporization patterns (flash or non-flash boiling sprays) due to their different physical properties [31,33]. The spray flash-boiling may occur in engine conditions which would destroy the designed spray directions and mixture distributions [26,31]. Therefore, investigating the spray and evaporation characteristics is of great importance for extending the use of ethanol fuel.

In this study, the effect of fuel temperature on the ethanol and gasoline spray characteristics from a multi-hole injector has been studied in a constant volume chamber as part of investigation of a novel fuel system, ethanol direct injection plus gasoline port injection (EDI + GPI) [7]. The fuel temperature varied from 275 K (non-evaporating) to 400 K (flash-boiling) which corresponded to cold-start and running conditions that the injector may have in real engines. The effect of fuel temperature on evaporation rates of ethanol and gasoline was investigated. The flash-boiling was observed by increasing fuel temperature in atmospheric pressure. Particularly, the spray transition process from normal-evaporating to flash-boiling was investigated in greater details than the existed studies.



(b)

Fig. 1. Schematic of the injector: (a) distributions of the nozzle holes, (b) plume directions and footprints.