

The Effect of Fuel Temperature on the Ethanol Direct Injection Spray Characteristics of a Multi-hole Injector

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ABSTRACT

Ethanol direct injection (EDI) is a new technology to use ethanol fuel more efficiently in spark ignition engines. Fuel temperature is one of the key factors which determine the evaporation process of liquid fuel spray, and consequently influence the combustion and emission generation of the engine. To better understand the mixture formation process of the EDI spray and provide experimental data for engine modelling, experiments were conducted in a constant volume chamber in engine-like conditions. The high speed Shadowgraphy imaging technique was used to capture the ethanol spray behaviours. The experiments covered a wide range of fuel temperature, ranged from 275 K (non-evaporating) to 400 K (flash-boiling). Particularly the transition of the ethanol spray from normal-evaporating to flash-boiling was investigated. The temporal Shadowgraphy spray images, spray tip penetration, angle and projected area were applied to evaluate the evaporation of EDI spray under different fuel temperature conditions. The results showed that the non-evaporating spray's characteristics were similar to the normal-evaporating sprays' in terms of spray tip penetration, angle and projected area. When the fuel temperature increased from 350 K to flash-boiling spray, the spray angle and projected area reduced significantly, but the spray tip penetration increased. Increasing the fuel temperature from 275 K to 325 K did not cause significant increase of the evaporating rate, but with further increase of the fuel temperature, the ethanol spray's evaporation became faster. The transition temperature at which the ethanol spray collapsed at atmospheric pressure was between 355 K and 360 K.

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INTRODUCTION

Ethanol is a widely used alternative fuel to address the issue of sustainability. Compared with gasoline fuel, ethanol has greater latent heat of vaporization, larger octane number, higher flame propagation speed and smaller stoichiometric air/fuel ratio, as listed in [Table 1](#). However, to use the renewable fuel efficiently is still challenging. 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 [1, 2, 3, 4]. The engine knock propensity could be reduced due to the higher octane number of ethanol fuel, and supplemented by the cooling effect enhanced by direct injection and ethanol's greater latent heat. This would make it possible to increase the compression ratio and use turbocharging (engine downsizing) technologies for spark ignition engines, and consequently increase the thermal efficiency.

To exploit the potentials of EDI, the spray and mixture formation characteristics of EDI should be investigated as they are the key factors that affect the combustion and emissions of the engine. Experimental results showed that the NOx emission decreased, CO and HC emissions increased with the EDI injection in an ethanol direct injection plus gasoline port injection (EDI+GPI) engine [1]. The NOx emission might be decreased due to the cooling effect enhanced by EDI and CO and HC emissions increased due to poor mixing. However opposite experimental results were reported in [8]. NOx emission increased and CO and HC emissions reduced when EDI was applied. Furthermore, both HC and NOx emissions were reduced by EDI as reported in [2]. The above different results might be caused by the evaporation process of EDI spray in different engine conditions in different investigations. Numerical studies found the lower evaporation rate of ethanol direct injection than gasoline in a naturally aspirated SI

engine [9, 10]. However the simulated evaporation rate of ethanol was as high as that of gasoline in a turbocharged engine [11]. It was found that ethanol evaporates more slowly than gasoline does in lower temperature conditions, but faster when temperature is higher than 375 K [9].

Table 1. Properties of ethanol and gasoline fuels.

Properties ^② \ Fuel	Ethanol	Gasoline
Chemical formula (-)	C ₂ H ₆ O	C ₈ H ₁₈ ^①
Density (kg/m ³)	785.5 [5]	714.9 [5]
Cp (Specific heat) (J/kg·K)	2339 [5]	2041 [5]
Viscosity (kg/m·s)	0.001007 [5]	0.0004549 [5]
Research octane number (-)	106 [1]	95 [1]
Stoichiometric air/fuel ratio (-)	9.0:1 [1]	14.8:1 [1]
Boiling point (K)	351.44 [5]	372.39 [5]
Diffusion coefficient in air (m ² /s)	1.196 × 10 ⁻⁵ [5]	6.410 × 10 ⁻⁶ [5]
Lower heat value (MJ/kg)	26.9 [1]	42.9 [1]
Enthalpy of vaporization (kJ/kg)	948 [6]	298 [6]
Saturation vapor pressure (kPa)	8.773 [5]	28.828 [6]
Surface tension (N/m)	0.02314 [5]	0.01816 [5]
Laminar burning velocity @ stoichiometric equivalent ratio, 100 kPa, 100 °C (m/s)	~0.62 [7]	~0.49 [7]

^① Iso-octane is used to represent gasoline fuel; ^② Properties at temperature of 300K.

Moreover, the fuel temperature (or injector temperature) can change in a wide range in real engines. For example, during the cold start in the winter, the engine is cold and the temperature of the fuel injected in the first few cycles can be as low as zero degree. The fuel may evaporate very slowly and result in very poor mixture. The consequent ignition and combustion processes may fail and lead to increased HC and CO emissions. In fact, the HC emissions in the first 20 seconds of cold start process can account for as high as 80-90% of the total HC emissions in the Federal Test Procedure (FTP) [12]. However, the engine cylinder head temperature can exceed 200 degrees after the engine is fully warmed up. The fuel injector can be heated and in turn to heat the fuel to a very high temperature. As a result, the fuel spray and evaporation will be greatly affected.

The effect of fuel temperature on gasoline sprays injected by swirl-type injectors was investigated [13, 14, 15]. It was found that the spray collapsed with higher evaporation rate, longer penetration and smaller droplet size when the fuel temperature was above the saturation temperature. Recently, the multi-hole injectors have attracted more attention for gasoline direction

injection spark ignition (DISI) engines because of their advantages in stability of spray pattern and flexibility of spray plume targeting [16]. However the majority of work published to date on multi-hole injectors concerns diesel nozzles [17]. The multi-hole injector spray behaviors of various fuels and ambient conditions were investigated [17, 18]. The flash-boiling sprays (or spray collapse) were achieved by increasing the fuel temperature and decreasing the ambient pressure.

The spray data can also be very useful for engine modellings. The measured values can be used to define the initial settings for the spray simulation. This is believed to be an effective and accurate method [19]. To verify the spray models in IC engines, the most common method is to compare the simulated and measured spray structure in constant conditions [19, 20, 21, 22, 23, 24, 25, 26, 27, 28]. In this study, the effect of fuel temperature on the EDI spray characteristics has been studied by conducting experiments in a constant volume chamber (CVC). The range of the fuel temperature covered that in real engines. The flash-boiling spray was observed by increasing fuel temperature under atmospheric pressure. Moreover, the non-evaporating spray (275 K, saturation vapour pressure was only 1.828 kPa) was also investigated. To the best of the authors' knowledge, there is no publication studying the spray characteristics from a multi-hole injector under such a low temperature condition.

EXPERIMENT APPARATUS AND PROCEDURE

EDI Injector

The EDI injector used in this study is a 6-hole nozzle which has been used in the EDI+GPI engine experiments [1]. Figure 1 shows the distribution of the nozzle holes on the EDI injector tip and the magnified image of the nozzle exit using a microscope. As shown in Figure 1, there are six holes on the injector tip, five located near the edge of the hemispheric boss in the centre of the injector tip and one closer to the boss centre. There is a small chamfer at each orifice exit. The measured nozzle diameter is 110 µm. Since the six nozzle holes have different machining angles in the injector, the emanated spray bends to the direction of the injector solenoid valve, as demonstrated in the Figures 2 and 3. The six plumes are actually consisted of three groups. The first group contains only one plume whose axis is the same as that of the injector. The second group contains three plumes with a bend angle 17° from the injector axis. The third group contains two plumes with a bend angle 34°. As a result, the second group has the darkest colour and the first group has the lightest colour in the image of Figure 2. When the fuel temperature is higher than the saturation temperature, the first and third groups collapse to the middle group. The injection delay of the injector is about 1 ms.

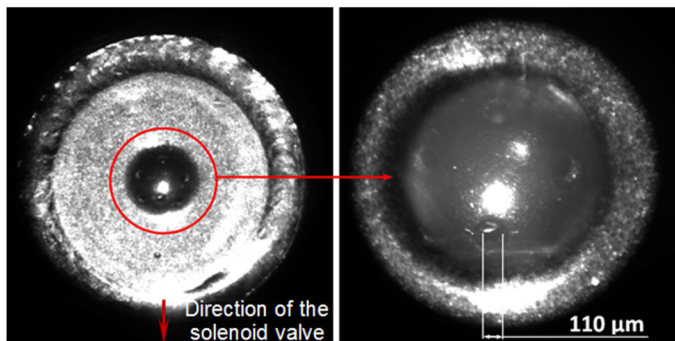


Figure 1. Overall view of the EDI injector tip (left) and the magnified image of the nozzle holes (right).

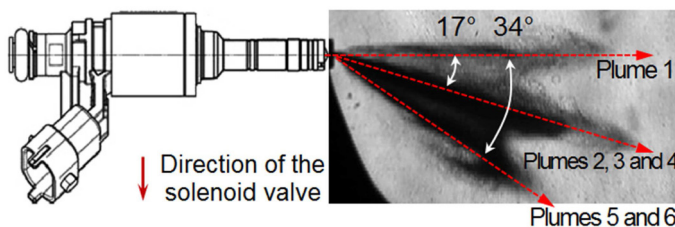


Figure 2. Lateral view of the spray plumes and their directions.

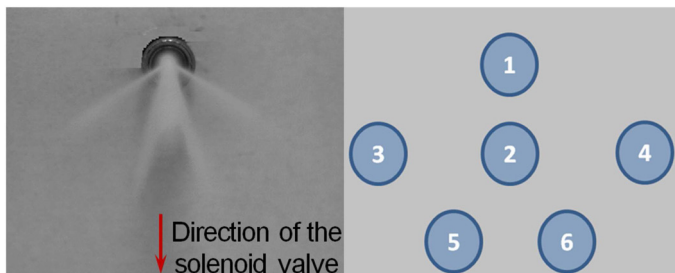
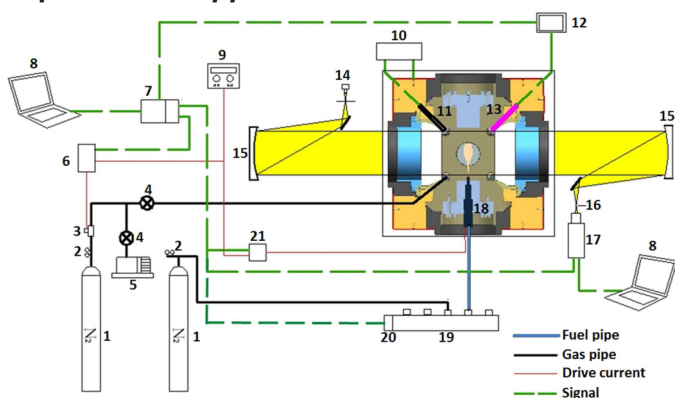


Figure 3. Front view of the spray plumes and their footprints

Experimental apparatus



1. High pressure nitrogen cylinder 2. Pressure reducing valve 3. Solenoid valve
4. Hand valve 5. Vacuum pump 6. Solenoid valve control unit 7. NI USB-6251M data acquisition card 8. Computer 9. Power source 10. CVCB temperature control unit 11. Pt100 temperature transducer 12. Kistler 5018 charge amplifier 13. Kistler 6052C pressure transducer 14. Tungsten halogen lamp 15. Reflective mirror 16. Knife edge 17. MotionPro Y4S1 CCD camera 18. Injector 19. High pressure fuel rail 20. Fuel rail pressure sensor 21. Fuel injection control unit

Figure 4. Schematic diagram of the EDI spray experiment apparatus.

Figure 4 shows the schematic of the experimental apparatus including the constant volume chamber (CVC), the fuel injection system, the Schlieren/Shadowgraphy optical system and the vacuum system. The chamber has a cubic inner length of 136 mm, with six main ports for optical access or injector installation, and eight smaller ports located on the cube corners for installing sensors and spark plug. The diameter of the quartz window is 130 mm. More details about the chamber can be found in [29]. Fourteen silicon heating sheets (six rectangular ones for the main ports and eight triangular ones for the smaller ports) are adhered to the CVC body's surfaces. The CVC is covered by insulating layer. A digital temperature controller is used to control the CVC body temperature with the feedback from a platinum resistance thermometer plugged into the CVC inner wall near the injector. Therefore, without heating by combustion, the fuel temperature (injector temperature) and ambient gas temperature are the same as the CVC body temperature when the heating process reaches a balance. The injector is mounted horizontally in one of the main ports. Its axis was perpendicular to the light pathway. The light source was the GB/T14094-1993 tungsten halogen lamp. The voltage for the lamp was kept at 100 V during the experiments. Two nitrogen cylinders (maximum pressure was 13 MPa) are used to pressurize and control the injection pressure and ambient pressure respectively during the experiments. The injection pulse with a width of 2.0 ms is generated by a single-chip computer. Meanwhile, the driving signal is used to trigger the MotionPro Y4S1 high speed CCD camera simultaneously.

Shadowgraphy and Schlieren techniques are two of the most effective techniques used to visualize the time-resolved non-homogeneous transparent flow fields, such as the evaporating sprays and reacting spray flames. The only difference in these two methods is a knife edge (item 16 in Figure 4) is used in front of the camera in Schlieren technique but not in shadowgraphy technique. Schlieren technique uses the knife edge to enhance the contrast but may lose some information [30, 31]. The knife edge was not used and only the Shadowgraphy measurements were performed because the gas turbulence was weak and light attenuation through the air was low enough to highlight the spray area for the quiescent ambient conditions in this study.

Ethanol fuel properties

The ethanol fuel investigated in this study was the absolute ethyl alcohol with a purity of 99.9%. Some critical physical properties that would influence the spray behaviors were found in the Yaws' Handbook [5]. As shown in Figure 5, with the increase of fuel temperature, the viscosity and surface tension decrease which would lead to a faster breakup rate, and the saturation vapor pressure and diffusion coefficient in air increase which would lead to a higher evaporation rate. Specifically, the saturation temperature (or boiling point) of ethanol fuel in atmospheric pressure is 351 K. This is the critical point where spray may present different patterns.

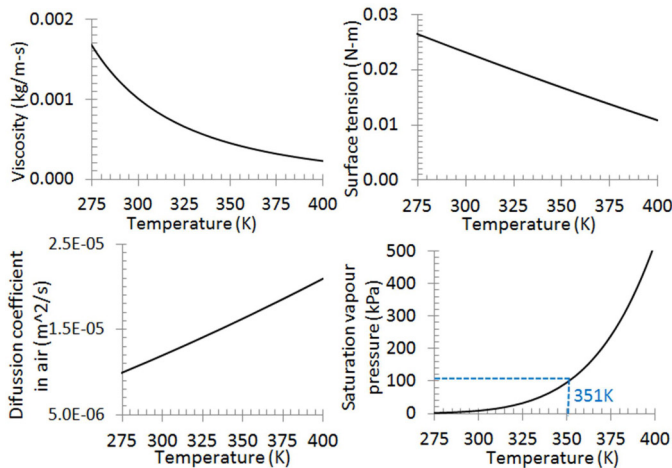


Figure 5. Ethanol fuel properties (data source: [5]).

Experimental conditions

The fuel injection pressure was adjusted using compressed nitrogen at pressure of 6 MPa. 6 MPa was the direct injection pressure of the ethanol fuel applied in the experiments in the EDI+GPI research engine [1]. The ambient pressure was kept at 1 bar which represented the cylinder pressure during early EDI injection with 36% throttle open [9]. The tested fuel temperature was varied from 275 K (non-evaporating spray) to 400 K (flash-boiling spray) with an increment of 25 K. However the temperature increment was reduced to 5 K during the transition process from normal-evaporating spray (350 K) to flash-boiling spray (375 K). The injection duration was held constant at 2 ms. The measured fuel mass of each injection was 10.844 mg @ 6 MPa $\times$ 2 ms. The speed of the imaging was 20000 fps @ 608 $\times$ 288 pixels. The spatial resolution of the images was 0.203 mm/pixel. The liquid fuel spray was always first seen in the 19th or 20th spray image. Therefore the injection delay of the injector was about 1 ms. The large quartz windows (with a diameter of 130 mm) made it possible to measure the spray characteristics until about 8 ms after the start of injection (ASOI). Each spray condition was repeated for five times.

Image Processing

The captured images were 8-bit grey scale images where 0 stands for black and 255 stands for white. The images were processed by a Matlab code. A threshold was defined to determine the boundary between the spray area and the background. The macroscopic spray characteristics were calculated based on the spray boundary. Figure 6 shows the definitions for the spray characteristics. The spray tip penetration was defined as the longest distance that the spray travelled. The spray projected area was the area within the spray boundary. The spray angle was defined according to the SAE J2715 Standard [32]. Four points have been located on the spray edge: two near points have a horizontal distance of 5 mm to the injector tip, and the distance for the two farther points is 15 mm. These four points were used to define two

lines on each side of the spray boundary. The angle of the two lines was defined as the spray angle. The spray tip penetration, angle, projected area and averaged image pixel intensity reported in the following sections were the averaged values of five repeated experiments.

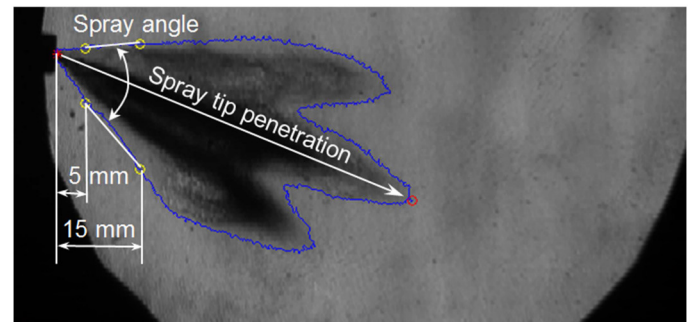
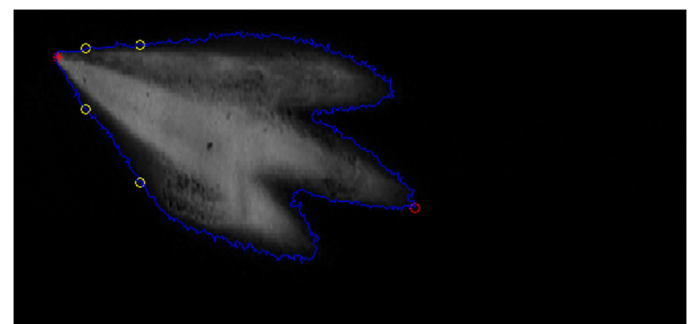
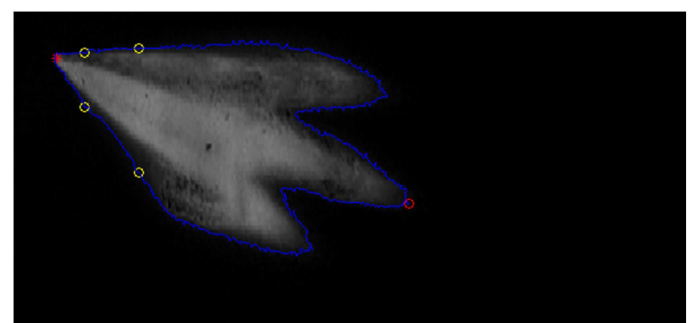


Figure 6. Definitions of the spray characteristics.

Obviously, the identification of the measured spray characteristics were strongly related to the threshold value, especially the spray projected area because smaller threshold would include larger spray area. Figure 7 shows the sensitivity of the threshold values (2.5%, 5% and 10%). Figure 7-c shows that the threshold 10% does not include some spray areas at the spray tip, while the threshold 2.5% covers some areas that does not belong to the spray area as shown in Figure 7-a. Therefore, the threshold 5% was selected for spray image processing. The same threshold value was also used in [33].



(a). threshold = 2.5%



(b). threshold = 5%

Figure 7. Effect of the threshold on the detected spray boundary.