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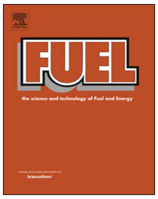

Effect of temperature on fuel adhesion under spray-wall impingement condition

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ABSTRACT

In direct-injection spark-ignition (DISI) engines, spray-wall impingement affects the formation of the air–fuel mixture as well as combustion and exhaust emissions. In this study, the characteristics of fuel adhesion injected by a mini-sac gasoline injector with a single hole were investigated under the evaporation and non-evaporation conditions. The fuel spray was observed using Mie scattering, and fuel adhesion was measured using the refractive index matching (RIM) method under high injection and ambient pressures. The results showed that when evaporation occurs, the thin fuel adhesion evaporates quickly, whereas the thicker adhesion barely evaporates in a short period of time, resulting in a more uniform fuel adhesion on the wall. The maximum adhesion thickness continues to increase even after the end of injection, likely because of the re-deposition of the splashing droplets. Various mechanisms are purposed to explain the spray-wall interaction: fuel droplets primarily impinge on the wall forming primary impingement region, followed by the re-depositing droplets which form secondary impingement region.

1. Introduction

The concept of gasoline direct injection (GDI) contributes immensely towards improved fuel economy and performance in spark ignition (SI) engines [1,2]. However, the short distance between the injector nozzle and the piston head, and the high injection pressure make it difficult to avoid spray-wall impingement [3]. Fuel droplets tend to get deposited on the wall, resulting in “wet wall” on the piston head and cylinder wall [1,4]. This affects the air–fuel mixture formation process, which is a major source of excessive soot and unburned hydrocarbons (UHC), making it difficult for DISI engines to meet the subsequent requirements of particle number (PN) regulations [2,5,6]. In particular, the tendency of reduction in engine size and increase in rail pressure makes it increasingly difficult to prevent the occurrence of adhered fuel. Therefore, it is essential to understand the impingement behavior and formation of fuel adhesion to improve the performance of gasoline engine and make it more environmentally friendly [7].

However, since it is hard to measure fuel adhesion in a real working engine, comprehensive experimental investigations have been carried out in a constant volume chamber. Specific quantitative studies were performed on fuel adhesion, out of which mainly three methods are summarized. Akop et al. [8,9] and Yu et al. [4] calculated the mass of fuel adhered to an impingement disk wall under different conditions. This method is limited to characterization of the total fuel adhesion mass, not its distribution. In the laser-induced fluorescence (LIF) technique, a fluorescent tracer is adjusted to a certain concentration with a given quantum yield and a molar absorption coefficient, and it is excited with a predefined radiation. The adhesion thickness is then determined by measuring the fluorescence intensity. The spatial distribution of fuel adhesion was captured by Senda et al. [10], Okamoto et al. [11], Cheng et al. [12], and Schulz et al. [7,13,14]. However, this method is limited to a perfectly smooth impinging wall, which differs from the real roughness of an engine piston, especially one with carbon depositing after combustion [15]. A more widespread and well-observed technique for measuring the fuel adhesion on a flat wall with roughness similar to that of a real engine piston is the refractive index matching (RIM) method. Drake et al. [16–18] developed this optical technique, which was then used by Yang and Ghandhi [19], Maligne and Bruneaux [20], Zheng et al. [21], Henkel et al. [22], and Luo et al. [15,23] to measure the fuel adhesion under different impingement conditions. In recent times, Ding et al. [24] has also used the RIM method to measure fuel adhesion in a stratified-charge SI engine.

A series of extensive studies have been conducted on fuel adhesion characteristics under non-evaporation conditions. However, the air

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temperature in a real engine during operation is quite high, especially when the engine is under high load. Maligne and Bruneaux [19] observed “discrete pocket” areas of the gasoline fuel that evaporate faster than areas of “continuous film”. Zheng et al. [20] studied the mass and area of gasoline fuel adhesion under conditions of high temperature of the air–fuel mixture, and compared the results with computational fluid dynamics (CFD) calculations. Schulz et al. [7] investigated the effect of flash-boiling on fuel adhesion formation using a multi-hole gasoline injector, and discovered that increasing the fuel temperature to a certain value does not lead to a constant reduction in the adhered fuel on the wall owing to the collapse of spray jets and fuel accumulation in a single region. Piazzullo et al. [25] compared the gasoline footprint at the wall between measured and simulated results under evaporation condition by evaluating the fuel mass adhering to the wall and the wall heat flux. Until now, the formation of fuel adhesion on the wall is still ambiguous and requires more research. In order to enhance our understanding, we have already checked the effects of impingement distance, wall roughness, and droplets behaviors on fuel adhesion in our previous works [15,23,26]. In this study, the effect of ambient temperature on formation of fuel adhesion and the mechanisms behind it have been investigated. First, the images of impinging spray and fuel adhesion were observed via Mie scattering and RIM methods, respectively. Next, the evolutions of fuel adhesion were depicted under room temperature and high ambient temperature conditions, after which the fuel adhesion mass and area were compared under the same conditions. Additionally, the spatial distributions of adhesion thickness were also examined. Finally, the mechanisms for fuel adhesion formation in primary and secondary impingement regions were discussed in detail.

2. Experimental setup

The injector parameters and impingement conditions are listed in Table 1. A mini-sac injector with a nozzle hole diameter of 0.155 mm was used. The nozzle was a conventional straight-hole type without a counterbore, and the length-to-diameter (L/D) ratio was 4.2. The impingement angle was 45 deg, and the impingement distance of 22 mm from the nozzle exit to the point of impingement along the spray axis was the same as the distance near top dead center (TDC). The surface roughness of the new piston used in gasoline engine is approximately Ra (arithmetical mean deviation of the profile) of 1.0 µm, but it may increase up to Ra10.0 µm or more due to deposit accumulation [15,20]. Therefore, the flat wall was made of quartz glass (Sigma Koki, DFSQ1-50CO2) with a surface roughness Ra7.0 µm, measured by a portable high-performance surface roughness and waviness measuring instrument (Kosaka Laboratory Ltd., SE300) with a resolution of 0.0064 µm to represent the rough surface of the piston. As shown in Fig. 1, the impingement plate with a diameter of 50 mm and a thickness of 2 mm was placed under the injector. The point of intersection (*o*) of the nozzle center axis and the wall was defined as the impingement point. The direction of spray after impingement is the positive *y* axis, while the positive *z* axis is parallel to the injector, and the *x* axis is defined as the perpendicular direction to the *yz* plane, pointing out of the figure.

Table 1
Injector parameters and impingement conditions.

Injector Parameters	
Injector Type	Mini-Sac
Hole Number	1
Hole Type	Straight-Hole without Counterbore
L/D Ratio	4.2
Nozzle Hole Diameter (mm)	0.155
Impingement Conditions	
Impingement Plate	Quartz Glass
Impingement Distance (mm)	22
Impingement Angle (deg)	45
Surface Roughness (µm)	Ra 7.0

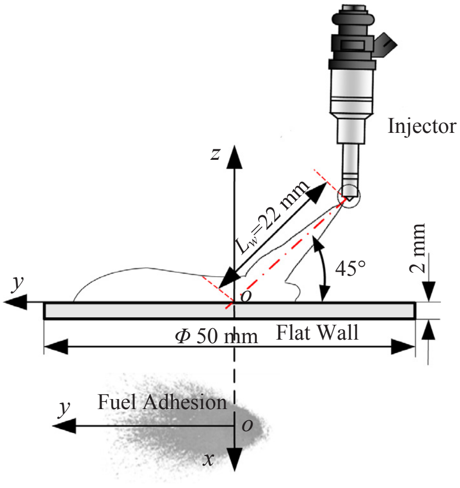

Fig. 1. Specifications of the injector and flat wall.

Table 2
Test conditions.

	Non-evaporation conditions	Evaporation Conditions
Test Fuel	Toluene	
Fuel Temperature (K)	298	
Injection Mass (mg)	4	
Ambient Gas	Nitrogen	
Injection Pressure (MPa)	30	
Injection Duration (ms)	1.7	
Ambient Density (kg/m^3)	5.95	
Ambient Temperature (K)	298	433
Ambient Pressure (MPa)	0.5	0.73

The test conditions are listed in Table 2. Toluene was employed as a substitute for gasoline. The fuel temperature (before injection) was regulated by a cooling system to maintain it at room temperature. The injection mass was 4.0 mg with a pressure of 30 MPa and a duration of 1.7 ms. This experiment was conducted in a constant high-pressure chamber filled with nitrogen gas. In the actual engine, the late fuel injection strategy is used to accelerate warm-up of the catalyst. The fuel adhesion formed on the piston results in a significant increase in PN emissions. To investigate the mechanism of fuel adhesion formation, the ambient conditions (P_{amb} = 0.73 MPa, T_{amb} = 433 K) were determined according to the in-cylinder conditions at the crank angle of about 40 deg before top dead center (BTDC) during the warm-up period. At the same time, the equivalent non-evaporating ambient conditions (P_{amb} = 0.5 MPa, T_{amb} = 298 K) were determined by keeping the ambient density at 5.95 kg/m^3. One thing worth noting that the saturated temperatures (T_{sat}) of toluene at 0.5 and 0.73 MPa are 450 and 472 K, which can be seen that $T_{amb} < T_{sat}$ under both conditions.

The experimental setup for fuel spray observation is shown in Fig. 2. It consists of a constant high-pressure chamber, an injection system, and an optical system. Toluene fuel was directed into the mini-sac injector via a high-pressure injection system. An electric preheater (Toyo Koatsu, Kanthal AF-200V) was installed into the chamber to increase the ambient temperature. The temperature was controlled by a thermocouple placed near the flat wall. A xenon lamp (Ushio SX-131 UID501XAMQ) was positioned to emit continuous, high-intensity light that passed through the window of the chamber. A high-speed video camera (Photron FASTCAM SA-Z) with a frame rate of 20,000 frames per second (fps) and frame size of 512 × 512 pixels was used to capture the fuel spray through the window. The injector and camera were synchronized by a delay generator. Only two windows of the constant volume chamber were used. The layout of the lamp and the camera is