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Macroscopic characteristics for direct-injection multi-hole sprays using dimensionless analysis

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ABSTRACT

The macroscopic spray characteristics were quantified using dimensionless analysis by examining the role of the dominating forces associated with liquid-jet breakup. The Weber number, Reynolds number, and air-to-liquid density ratio dimensionless numbers were used to capture the primary forces including the inertia, viscous, surface tension, and aerodynamic drag forces. Planar Mie-scattering technique was applied to generate spray images over a broad range of conditions found in today's spark-ignition-direct-injection (SIDI) engines, providing a relatively large range of dimensionless numbers. The effect of fuel properties were examined using gasoline, methanol and ethanol fluids. Six regions described on a Weber number versus Reynolds number domain were selected to identify the relative importance of the inertia force, surface tension force, and viscous force on macroscopic spray structure. The effect of aerodynamic drag was individually determined by characterizing the spray over a range of ambient air-to-liquid density ratios. As a result, for the non-flash-boiling multi-hole sprays in this study, the Weber number and air-to-liquid density ratio have much more profound effect on the spray penetration and spray–plume angle compared to the Reynolds number contribution. The inertia force and air drag force are more important factors compared to the viscous force and surface tension force. This analysis yielded dimensionless correlations for spray penetration and spray–plume angle that provided important insight into the spray breakup and atomization processes.

1. Introduction

Macroscopic spray characteristics, such as spray penetration, spray–plume angle and droplet size distribution are critical parameters that influence the in-cylinder air–fuel mixture and combustion process of the internal combustion engine. The spray performance is influenced by a large number of parameters, including the fuel pressure, fuel temperature, ambient pressure, ambient temperature, fuel properties, and nozzle geometry [1]. A number of previous studies have investigated these parameters and the corresponding effect on macroscopic spray structure [2–8]. For example, Hiroyasu [2,3] has investigated both the macroscopic and microscopic spray characteristics of the diesel spray under various conditions, providing a set of empirical formulations that describes the spray penetration, spray–plume angle, and Sauter-Mean-Diameter (SMD). More recently, Naber and Siebers [9] and Desantes et al. [10,11] suggested the models for spray penetration based on the characterization of diesel spray and some classical atomization theories. However, these formulations were based on diesel sprays that may not be directly applicable to gasoline and increasingly used gasoline substitutes, such as methanol and ethanol. Zigan et al. [12,13] investigated the fuel effects on spray characteristics and the results indicate that the internal nozzle flow, the injected mass and the spray droplet size distribution is different due to viscosity. Also, Wang et al. [4], Aleiferis et al. [5] and Lee and Reitz [6] characterized sprays for different fuels over various conditions and reported considerable dependence on fuel type and test conditions. These data illustrate the need to establish new and generalized correlations to comprehend the fuel type and test conditions over the operating range of the internal combustion engines.

The primary breakup of the liquid jet into ligaments and droplets represents the initial and critical transition that has significant influence on the spray. The physical process and mechanisms associated with the initial breakup process is known to depend on the competition among the jet inertial force, surface tension force, viscous force, and drag force. Previous studies have used dimensionless numbers to identify the relative importance of these forces [1,14], working toward establishing a better physical description of the jet breakup process. For example, Ohnesorge classified this breakup phenomenon into three regions using the Ohnesorge number and Reynolds number to characterize the transitional rate of droplet formation [1]. Liu and Reitz [15] classified the spray

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atomization phenomena into four regions within a Weber number versus Reynolds number domain based on droplet shape. In each region, the dominant forces were identified and the effects of these forces on spray breakup were qualitatively analyzed. The domain was divided into four isolated regions where each region had a unique model. However, correlations that characterize the spray using dimensionless numbers and cover the entire domain have not yet been developed.

This work focuses on the characterization of a multi-hole spray using dimensionless analysis. Weber number, Reynolds number, and air-to-liquid density ratio were used to represent the four primary forces that are known to influence the spray. The planar Mie-scattering technique was implemented to characterize the macroscopic spray structure over a broad range of conditions found in a today's direct-injection engines, providing relatively large ranges of the dimensionless numbers. The effect of fluid property was described in this analysis for gasoline, methanol and ethanol fuels. Correlations relating the spray penetration and spray–plume angle to dimensionless numbers have been generated over the entire domain, providing important insight into the spray breakup and atomization processes. For the experimental conditions used in this study, flash-boiling occurs at the conditions that the ambient pressure is below the saturation pressure. The atomization mechanism of the flash-boiling spray is a different phenomenon compared to that of the non-flashing-boiling sprays and requires a separate analysis [16]. Therefore, the correlations do not apply in the flash-boiling region.

2. Apparatus

Fig. 1 shows the schematic of the experimental apparatus consisting of a constant pressure chamber, a high-pressure fuel supply system, a fluid temperature control system, a chamber pressurization system, a vacuum system and a laser diagnostic system. The injector was installed vertically at the top of the chamber that has an inner diameter of 203 mm and a height of 692 mm. Four quartz windows around the chamber provided full optical access. The chamber ambient pressure was maintained with either the vacuum system or the high-pressure nitrogen filling system. A heat exchanger system was designed to control the fuel temperature over a range of −15 °C to 90 °C. The fuel temperature is managed using a water conditioning system, where a water jacket was designed to surround the injector and an external system conditions the water to reach the desired fuel temperature. An injector with thermal couple was used to correlate the water temperature with the fuel temperature. Three accumulators were used to provide injection pressures up to 10 MPa for gasoline, methanol, and ethanol fluids.

Planar Mie-scattering technique was implemented to characterize the spray. The injected fuel was illuminated by a thin laser sheet of approximately 1 mm generated by a Nd:YAG laser (pulse width: 4 ns, power: 220 mJ at 532 nm). Images of the illuminated spray were captured by a CCD camera (12 bit, 1376 × 1040 resolution, and 15 fps recording rate). A programmable timing unit (PTU) was used to synchronize the laser, the CCD camera, and the injector driver.

The images were post-processed using our recently developed image analysis tool. At each test condition, the background image was recorded and subtracted from the spray images. A threshold value, selected according to the SAE J2715 standard, was used to distinguish between background noise and fuel spray droplets. The in-house developed software was used to produce a histogram of the image intensity for determining the threshold value. Pixel values below this threshold value were set to zero. Spray penetration and spray–plume angle were measured for individual single-shot images. By acquiring 15 images for each test condition at each time-step, averaged data along with statistical variance were generated. More than 150 images were generated and the average value and standard deviation as a function of image number at typical conditions were analyzed. The average value and standard deviation become constants when the image number is above 15 so that 15 images were taken at each condition. The maximum standard deviation for spray penetration is about 2.3 mm, which is observed at a 10 MPa injection pressure condition, see Fig. 10 below.

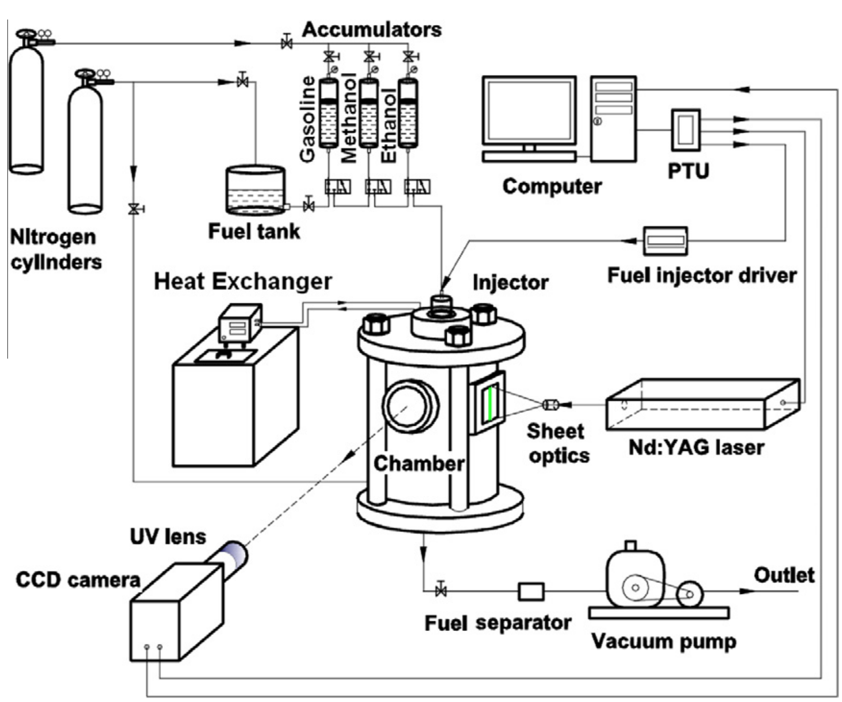

Fig. 1. Schematic of experimental apparatus.