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Temporal investigations of transient fuel spray characteristics from a multi-hole injector using dimensionless analysis

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The breakup of high speed liquid jets and the spray formation from a multi-hole direct-injection injector were investigated by analyzing the temporal development of spray penetration and cone angle. Planar Mie scattering was applied to generate spray images under a wide range of operating conditions with ethanol, methanol and gasoline as test fuels. Dimensionless parameters such as Reynolds number (*Re*), Weber number (*We*), and gas-to-liquid density ratio (ρ_a/ρ_l) were used to enumerate the competition and balance of forces that dominated the spray formation, including the inertia force, viscous force, surface tension force and aerodynamic force. The results show that two temporally sequential stages exist during the spray formation, namely the initial stage and developed stage. During the initial stage, the spray penetration increases linearly with time after the start of injection (ASOI). The penetrating speed during the initial stage is primarily controlled by the competition between the inertia and surface tension while the aerodynamic force shows only minor influence. The duration of the initial stage of penetration is dependent on the competing process between inertia and viscous force as well as that between inertia and aerodynamic force. During the developed stage, the effect of aerodynamic forces becomes more influential on the spray penetration. The viscous force shows weak impact on developed stage penetration under low Reynolds number ($Re < 12{,}500$) conditions. In contrast with the strongly time-dependent penetration, the plume angle of the emerging jets stays relatively constant during the entire injection duration. Based on the above analysis, new dimensionless correlations have been established to quantitatively characterize the effects of competing forces on spray penetration and cone angle. Compared to the classical correlations, these new correlations explicitly express the relative importance of each force during different temporal stages of spray formation. Therefore, they provide more insight into the physical mechanism of high pressure spray formation process.

1. Introduction

The breakup and atomization of high speed liquid jets are highly dynamic processes which are widely encountered in today's direct-injection gasoline and diesel engines. The spray characteristics such as spray tip penetration, cone angle, and drop size distribution are crucial for engine combustion and emission formation [1,2]. Therefore, understanding the transient spray behavior and its temporal characteristics are essential for developing advanced engine combustion concepts in meeting the ever-stringent fuel efficiency and emission regulations on internal combustion engines.

Various factors could influence the transient development of spray characteristics. Chief among them are injection pressure, ambient pressure, fuel properties, and nozzle geometry [3]. Extensive analytical and experimental studies have been carried out to investigate the effects of those parameters on the spray characteristics with various correlations and models built by researchers worldwide. For instance, Wakuri et al. [4] developed spray penetration and cone angle correlations by analyzing the momentum exchange between liquid drops and ambient air. They linked the spray penetration and cone angle to the density as well as the viscosity of both liquid and ambient gas. They also concluded that the spray penetration was proportional to the square root of time after the start of injection. Hiroyasu et al. [5] investigated the mechanisms of spray formation from hole-type nozzle under typical diesel injection conditions, and they provided a set of empirical correlations to describe the temporal

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development of spray tip penetration, cone angle, and Sauter mean diameter (SMD) distribution. Naber and Siebers [7], and Desantes et al. [8,9] analyzed the diesel jet breakup process based on the classical atomization theory and suggested a number of correlations to describe the temporal development of spray penetration and cone angle. More recently, Sazhin et al. [10,11] investigated the spray formation process from the point view of relative velocity between fuel droplets and entrained air, which results in identification of three different temporal stages during the spray formation. Separated correlations were established to describe the spray characteristics for each stage. It must be emphasized that the liquid jet penetrating processes are highly dynamic and complex. For instance, multiple stages of spray penetration may exist under different injector operation modes and ambient conditions. For injectors operating in multiple injection scheme or at extremely high injection pressure conditions within an engine cycle, it is very important to be aware of that the initial spray formation at which the time of image acquisition may be shorter than the injection pulse duration. Knowledge on the spray characteristics under those extreme conditions also has significance for understanding the spray formation globally. Kostas et al. [12,13] conducted very detailed studies on the spray characteristics during the valve opening using ultra high speed imaging technique. They found the spray characteristics depending on the valve opening and two different temporal stages could be identified. The nozzle diameter was also found to be an important factor to influence the spray formation and temporal correlations were established to reflect those observations. In general, these correlations have provided direct links between the controlling parameters and the resultant spray characteristics. However, there are numerous factors that could influence the jet breakup and atomization. Directly correlating these factors to the spray characteristics makes it very difficult to reveal the physics behind the breakup processes. In addition, most of those correlations are based on observations of high pressure diesel sprays and only applicable to limited ranges of operating condition for diesel engines [14,15]. More generalized correlations of spray characteristics, which could provide prediction on liquid jet breakup with acceptable accuracy in wide ranges of operating conditions, are needed. This becomes particularly urgent when various alternative fuels with different properties are used for both gasoline and diesel engines [16,17].

Building general correlations to describe and predict the spray characteristics development could be initialized by analyzing the forces involved in the spray formation process. Castleman [18] was the first one to perform such analysis and concluded that the breakup process attributed to two observations: (1) the formation of ligaments under the influence of aerodynamic force resulting from the relative motion between liquid jets and surrounding air and (2) the collapse of these ligaments under the influence of surface tension. Reitz and Bracco [19] studied the effect of aerodynamic force and nozzle geometry on jet breakup using a series of nozzles with different length-to-diameter ratios (L/D). Lin and Lian [20] developed general jet breakup theory based on linear stability analysis of a viscous liquid jet with respect to the spatially growing disturbance. They theoretically proved that three different dimensionless numbers, namely Reynolds number (Re), Weber number (We) and gas-to-liquid ratio (ρ_a/ρ_l), dominate the liquid jet breakup. Liu and Reitz [21] subsequently classified the atomization phenomena into different regions based on the Reynolds number and Weber number of fuel droplets. These theoretical analyses indicate that the competitions between various forces, as quantified by the dimensionless numbers, are the dominating factors for the jet breakup and spray formation. Therefore, correlating the spray characteristics with those dimensionless numbers, rather than using direct physical parameters and fluid properties, could explicitly reveal the breakup mechanism. Based on this idea, Zeng et al. [22] investigated the spray characteristics from a multi-hole injector under wide range of operating conditions. They analyzed the spray penetration and cone angle at 1.0 ms ASOI and found these spray characteristics at that specific ASOI were strongly correlated with the aforementioned dimensionless numbers. However, the spray formation from high pressure injection is a dynamic process in time domain. The roles of each force plays at different time during the injection are varying and unique. Therefore, only through a temporal investigation of the spray characteristics and a set of time-variant dimensionless correlations can adequately reveal the detail process and physical mechanism of liquid jet breakup and spray formation.

The objective of the current study is to investigate the transient development of spray formation from a force competition perspective. The time-variant macroscopic spray characteristics were firstly obtained using planar Mie scattering technique. Those spray data were subsequently analyzed to identify different temporal stages of spray formation. Then, the effects of the various forces (inertia, viscous, surface tension, and aerodynamic) on the temporal development of spray characteristics are investigated. The effects of force competition on spray formation are quantified using dimensionless Reynolds number, Weber number and gas-to-liquid density ratio. New correlations between spray characteristics and those dimensionless numbers are established to reveal the physical mechanism of spray formation. Based on those corrections, the complex mechanisms of high pressure spray formation can be explicitly elucidated.

2. Experimental apparatus

The spray images under various operation conditions were acquired based on planar Mie scattering technique. Fig. 1 shows the experimental apparatus. A high pressure chamber with an optical access was used to provide various ambient pressures for the spray injection. During the experiments, continuous nitrogen was pumped through the chamber to purge the residual droplets away from the chamber. The purging velocity of nitrogen gas was maintained below 1 m/s to minimize its effect on the spray structure. A vacuum pump on the exhaust line evacuated both the nitrogen gas and liquid fuel out of the chamber. A multi-hole direct-injection fuel injector was mounted on the top of the chamber. This injector had 8 individual orifice holes with a length-to-diameter ratio (L/D) of 1.5. A schematic of cross-section of the nozzle hole near the injector tip is depicted in Fig. 2. The fuel system consisted of three different accumulators, pressurized by compressed nitrogen gas and mounted in parallel, to allow for easy switch of different fuels (ethanol, methanol, and gasoline) supplied to the injector. The injector body temperature was regulated through a continuous loop of water circulating in a cooling jacket surrounding the injector. The injector tip temperature was monitored using a specially-designed thermocouple which was embedded in the injector tip. The tip temperature was then used to calibrate the fuel temperature.

The second harmonic of Nd:YAG laser (532 nm, max repetition rate: 15 Hz) was used as the light source to illuminate the spray. After passing through a combination of cylindrical and spherical lenses, the laser beam was optically transformed into a laser sheet with a thickness less than 1 mm. The laser sheet was guided through an optical window and illuminated the cross-section of the spray along the injector axis. The scattered light was collected on a CCD camera with a resolution of 1380×1024 pixels. The injector, laser, and camera were synchronized using the LaVision programmable timing unit (PTU).