



Microscopic investigation of the atomization and mixing processes of diesel sprays injected into high pressure and temperature environments



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HIGHLIGHTS

- Droplet breakup was evident at low pressure and temperature conditions.
- Surface tension effects were also observed at conditions above the critical point.
- Mixing becomes diffusion-dominated under typical diesel engine pressure and temperature conditions.
- Theoretical analysis supports a transition to supercritical mixing processes.

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ABSTRACT

Atomization and mixing of sprays are key parameters to successfully describe and predict combustion in direct-injection engines. Understanding these processes at the conditions most relevant to engines (high pressures and temperatures) is of primary interest. The present work investigates the atomization and mixing processes of sprays injected into environments with progressively higher pressure and temperature. An Engine Combustion Network Spray A single-hole injector is used to inject *n*-dodecane fuel into an optically accessible combustion chamber. High-speed imaging is performed using long-distance microscopy and diffused back-illumination to resolve ligament structures and droplets in the near-nozzle region. A unique aspect of this study is the application of high-speed imaging of sprays in the near-field under realistic diesel conditions, particularly those near top-dead-center. Imaging showed droplet and ligament dynamics at low pressure and temperature, but not at high pressure and temperature typical of engine operation, indicating diminished effects of surface tension. Relating the ambient conditions to the fuel critical pressure and temperature showed that when the ambient conditions are slightly above the critical point of the fuel, surface tension remains in effect at gas–liquid interfaces. However, for higher pressure and temperature conditions, the surface tension appears to diminish significantly as expected for supercritical fuel–air mixtures.

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1. Introduction

The mixture preparation of fuel and ambient gases is of primary importance to control combustion and emissions of current and future direct-injection engines [1–3]. Unfortunately, correct modeling and prediction of the spray breakup, development, and mixing stands as one of the most significant challenges for engine design. Relating the spray properties in the near field (up to 100 injector's orifice diameters) to mixtures in the far field (downstream of 100 diameters) is limited by a variety of factors. Most

approaches suffer from the necessity of using coarse grids in the near field to allow Lagrangian particle treatment, relying on sub-grid models to simulate the primary and secondary breakup processes [4–6]. Understanding the atomization and mixing processes of sprays from various injection systems and operating conditions, particularly in the near-nozzle region, where spray breakup occurs, is a primary need.

Previous experimental studies have measured the development and instabilities of diesel sprays in the near-nozzle region. Using optical long-distance microscopy, many studies have shown successful visualization of sprays injected into atmospheric or relatively low ambient pressure conditions [7–11]. Because of the optically thick, fast-moving spray, special diagnostic considerations must be

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implemented. For example, short duration light pulses (in the nano-second range) are required to “freeze” the motion of spray structures moving at velocities of hundreds of meters per second. Illuminating the spray from both sides has demonstrated to be necessary to capture features surrounding the spray stream if the light scattered by the spray droplets is acquired [12,11]. Back-illumination imaging of the shadow created by the spray [13–15,10] has also been applied to provide a more efficient lighting arrangement while providing a reference intensity. High-speed imaging has been applied in several instances to track the temporal history of single injection events [14,7,16].

The studies mentioned above apply to fuel sprays injected at room temperature or lightly vaporizing environments (e.g., 540 K reported by Crua et al. [14]). For conditions relevant to diesel sprays (gas temperature exceeding 800 K), such microscopic imaging information is nonexistent in the literature, except for a preliminary attempt at measuring droplet size at high-pressure (60 bar) and high-temperature (approx. 850 K) by Crua et al. [17]. Considering the importance of fuel and ambient gas properties on the breakup, development and mixing processes, investigation at high pressure and temperature is needed. Direct observations of the liquid structures or droplets can provide fundamental information to modelers enabling more accurate predictions of spray development.

The aim of this work is to fill this gap in global understanding of mixing processes by applying long-distance optical microscopy to the near-nozzle field of diesel (*n*-dodecane) sprays at engine-relevant conditions. Low charge gas temperature and pressure measurements are also performed to compare and contrast the fuel structures when mixing with gases at conditions found in the combustion chamber. The thermodynamic properties of the fuel are utilized to support the observations made from the optical microscopic measurements concerning the mixing processes when ambient temperature and pressure conditions are varied.

The present manuscript has been divided into six sections. Following the introduction, section two gives an overview of preceding studies and supporting works from experimental and theoretical perspectives. This section details the key studies in microscopic visualization of the spray breakup, demonstrating the lack of information at engine-relevant conditions. The third section presents the experimental equipment used in this work as well as the development of optical apparatus and diagnostic to perform high-speed microscopic visualization of the spray breakup and mixing. The issues and limitations of performing measurements in a high-pressure, high-temperature environment are also discussed in this section. The fourth section compares the mixing of sprays at microscopic scales when ambient conditions are changed from low to high pressures and temperatures. The results are discussed in the fifth section, making use of the recent studies involving the thermodynamic aspects of the flow under such conditions. The last section of this document concludes this manuscript by providing a summary of the outcomes of this work.

2. Experimental and physical background

Liquid spray breakup and mixing are complex processes and many experiments have been performed to analyze and understand the associated phenomena. At the injection pressures used in current diesel injection systems, the velocity of the flow exiting the orifice is relatively high (in excess of 500 m/s). As a consequence, the breakup of diesel sprays falls into the atomization regime [18], or the highest level of breakup. Flow turbulence at the exit and the instabilities of the liquid–gas interfaces quickly initiate the breakup process with the action of aerodynamic forces. It has been observed that fluid properties such as density, viscosity and surface tension affect spray breakup processes in general applications as discussed in Refs. [18,19].

Long-distance microscopy of fuel injection from working diesel injectors confirms a sensitivity of spray breakup to fuel viscosity and surface tension [16]. However, these observations apply to atmospheric conditions during the starting period of the spray. Questions remain about how these effects will change when injected into high pressure and temperature environments.

Some of the early microscopy imaging studies have focused on the spray transients, measuring the penetration rate or the microscopic features observed during the start and end of injection. They found that the penetration rate was slower in the first instants of the event than during the quasi-steady period due to a lower fuel pressure in the nozzle [14,10,16]. The spreading angle of the sprays in the near-field has also been studied by many authors [20,12,7,10,11]. The conclusions vary depending on nozzle geometry and lay-out, but geometries comparable to those currently used in diesel engines have sprays that open more during the transient beginning or end of injection, producing a higher spreading angle than during the quasi-steady part of the event [21,10]. The quasi-steady value of the spreading angle in the near-field is also lower than the one measured further downstream when the sprays are fully developed [10].

Other works examined microscopic instabilities on the edges of the liquid spray mixing with the ambient gases during the quasi-steady period of the injection event. They observed that higher injection pressure and/or ambient gas density increase the frequency and the amplitude of the surface wave instabilities due to higher disturbances in the flow [22,12,23,24]. Droplet size in the near-field has also been measured by direct visualization on the edges of the sprays. As expected, an increase in injection pressure or ambient density produces smaller droplets, due to higher breakup intensities [25,7,11,17].

Recent advances in lighting technologies and high-speed imaging systems enable experiments that can expand our knowledge about the temporal fate of liquid structures, ligaments and droplets. The understanding of liquid spray disintegration, the breakup speed and the formation of droplets represent critical information for spray modeling. Several parameters influence the breakup of liquid sprays: The list would probably start first with the fluid physical properties such as density, viscosity and surface tension, but also the velocity of the flow and the thermodynamic state of the charge gases. A review of the numerous parameters affecting the atomization process of liquid sprays is given in Ref. [19].

Finally, the lack of understanding concerning development and mixing of sprays at microscopic scales under high-pressure, high-temperature conditions confirms that detailed studies are needed in this area. The target condition proposed by the Engine Combustion Network (ECN) called Spray A is intended to simulate engine charge conditions at top-dead-center (TDC) (6.0 MPa ambient pressure, 900 K ambient temperature) using a diesel surrogate fuel (*n*-dodecane) at a typical engine coolant temperature (363 K) and nominal injection pressure (150 MPa).

Considering these “typical” diesel conditions, it is useful to address how fuel and mixture properties may vary over this range of pressure and temperature spanning early or late injection timing up to TDC for instance. Fig. 1 is the pressure–temperature (P–T) diagram for pure *n*-dodecane, with color indicating the density of the fluid. The liquid–vapor saturation line is shown on the left-bottom corner of the plot, starting from atmospheric conditions and going all the way to the critical point of *n*-dodecane: 1.82 MPa in pressure and 658 K in temperature. Different state diagrams have to be generated for specific fuel–ambient mixture fractions [26], ranging from pure *n*-dodecane (mixture fraction, $Z = 1$) to pure ambient gas (mixture fraction, $Z = 0$). Fig. 1 applies to the pure fuel as it exits the nozzle, not a mixture of *n*-dodecane and nitrogen for example. The initial conditions of the fuel as it first exits the nozzle are indicated by white points on the left side of the diagram.

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