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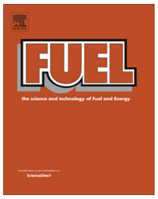

Gas/fuel jet interfaces under high pressures and temperatures

Zachary Falgout [a], Mattias Rahm [a], David Sedarsky [a], Mark Linne [b,*]

[a] *Institute for Applied Mechanics, Chalmers University, Gothenburg, Sweden*
[b] *School of Engineering, University of Edinburgh, Edinburgh, UK*

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ABSTRACT

We report observations regarding changes in surface morphology for transient fuel jets as the ambient conditions approach the critical properties of pure fuels. Both ballistic imaging and ultrafast shadow imaging were applied to four fuels as they were injected through a single hole Diesel injector into a spray research chamber operated at three different ambient conditions that span the range of critical properties for the pure fuels that were studied. The results indicate that the pure fuels (butanol, dodecane, and hexadecane) tend to undergo a change in image structure that usually scales with estimated mixture critical properties. Commercially available Diesel fuel is not strongly affected, even at the highest pressure and temperature conditions.

1. Introduction

The conventional paradigm for Diesel engine fuel injection begins with ejection of an intact stream of liquid fuel from a nozzle into a high pressure and high temperature charge of air. Spray formation occurs when the surface of the stream breaks up via primary breakup mechanics; driven by turbulence, shear, cavitation, or other instabilities, ultimately to produce primary drops. These primary drops can break up further or collide and coalesce in regions of high drop density. The drops then vaporize and mix with the air to produce a spatially and temporally varying gas-phase fuel/air mixture suitable for combustion.

This description of the atomization process is considered to be correct for sprays in laboratory settings when the air pressures and temperatures are not fully representative of the combustion chamber in a modern compression–ignition engine. Recent experimental and theoretical findings by Dahms and co-workers [1–4], however, have rekindled speculation that the pressure and temperature in modern Diesel engine combustion chambers at the time of injection could potentially exceed supercritical conditions for the liquid/gas mixtures at locations that would normally be called the spray formation region. If that were true the liquid/gas interface at the edge of the liquid core, and from which ligaments and droplets are stripped, could potentially cease to exist [2]. It would be replaced by a turbulent, thickened diffusive mixing layer. The existence of such states in that region would change conventional understanding of mixture formation in engines, and so the question is important.

Under supercritical conditions, transport properties are both pressure and temperature dependent. The solubility of air into fuel grows significantly and surface tension goes nearly to zero, meaning that well defined drops are not identifiable; neither is the liquid/gas interface of a jet core. Thermal conductivity and mass diffusivity can vary much more strongly, and the latent heat of vaporization goes almost to zero owing to the practical absence of surface tension. Vaporization from a well-defined surface is replaced by diffusive mixing through a thickened layer.

It is not universally accepted that these jets enter a transitionally supercritical condition. In theoretical studies, Reitz and co-workers [5–7] have asserted that one must include a second-law-based phase stability analysis which indicates that a single (supercritical) phase is unstable under these conditions, while a two-phase state is stable. They anticipate, therefore, that the edge of the liquid core maintains a well defined liquid/gas interface.

In the experiments reported by Dahms et al. [1], shadowgram images of n-dodecane drops and ligaments were acquired after the end of injection from a single hole Diesel injector. The jet issued into a pre-burn type of spray research vessel, and various gas phase conditions were evaluated. At high pressures and temperatures there were no defined liquid/gas interfaces identifying ligaments and drops; the structures that existed in the images seemed to be fully transmissive. The hypothesis was that they had transitioned into a supercritical state as the pressure and temperature were increased. As Qiu and Reitz [7] point out, however, isolated drops (e.g. those surrounded by an entrainment wave of hot gas at the end of injection) will not experience the same ther-

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* Corresponding author.

E-mail addresses: falgout@chalmers.se (Z. Falgout), rahmmatt@chalmers.se (M. Rahm), sedarsky@chalmers.se (D. Sedarsky), mark.linne@ed.ac.uk (M. Linne).

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modynamic conditions found at the edge of the liquid core where the temperature will be lower owing to injector cooling and the evaporative history of the initial fluid injected into the same volume. Qiu and Reitz argue that single-drop experiments do not accurately represent the thermodynamic states at the edge of the spray core.

Chehroudi et al. [8] published a well-accepted and often-cited article on transitionally supercritical jets. They injected liquid nitrogen into a chamber filled with gaseous nitrogen at 300 K. The critical temperature for N_2 is $T_c = 126.2$ K, and so their reduced temperature (defined by $T_r \equiv T/T_c$) was $T_r = 2.4$. The chamber pressure was varied from well below the critical pressure to well above it; they investigated reduced pressures ($P_r \equiv P/P_c$) in the range $0.23 < P_r < 2.74$ (for N_2 the critical pressure is $P_c = 3.4$ MPa). Chehroudi et al. used shadowgraphy to observe changes in jet morphology as they varied conditions. A clear change in spray image structure was observed near $P_r = 1$. At low P_r the jet images indicated a well-defined liquid/gas interface, formation of surface waves, stripping of ligaments, and formation of easily identifiable drops (despite the fact that T_r was bigger than one). For $P_r > 1$ the formerly obvious drops and ligaments had disappeared and the jet had become somewhat more transparent. The well-defined edges disappeared and the sides of the jet looked more like a gas jet, even though there were clearly denser regions in the core. Chehroudi et al. asserted that under supercritical conditions the well-defined and very thin liquid/gas interface disappears and is replaced by a more gradual, continuous distribution of density (a thickened diffusive mixing layer [4]). Note that shadowgram images do not measure a thermodynamic state, they simply depict the flow. In the case presented by Chehroudi et al., however, the change in image structure has been generally accepted as a representation of changes to the thermodynamic state.

In the work reported here we use related diagnostic techniques to those of Chehroudi et al. Similar to their work, we observe and discuss image structures. One clear trend noted by Chehroudi et al. was a transition in image structure from a well defined liquid/gas interface to one that resembles a Schlieren image of a gas jet at nominally supercritical conditions. These are characterized by a cellular image structure that is produced by many small flow structures (e.g. turbulent vortices near the jet surface) that are bordered by a gradient in the index of refraction. In optical terms one could think of this specific type of flowfield as a transient, three-dimensional collection of micro-lenses of varying size and focal length distributed across the surface of the jet. They concentrate light in some regions but steal light from others; creating an image consisting of distributed cells of light. The image produced is markedly different from a contiguous liquid column with a well defined edge, as one would expect to find during classical atomization. Chehroudi et al. reported this image evolution with changing conditions, and we will note the same type of evolution in the text that follows. The main difference between our work and that of Chehroudi et al. is that we investigate hydrocarbon fuel jets issuing into high pressure and temperature air, which causes species to blend in the mixing layer. The critical pressure of a mixture could be from two to five times higher than the critical pressure of a pure substance [9], so the difference is not trivial.

Recently, our group [10] reported on the application of ballistic imaging (BI, see e.g. [11]) to a transient, n-dodecane fuel jet. The experiments were performed in a steady flow spray research chamber using air (a reactive case, although the ballistic images were all acquired well upstream of the flame liftoff point). Two chamber conditions were examined: 2.9 MPa gas pressure and 440 K temperature (producing a gas density of 22.8 kg/m^3) and 6 MPa gas pressure and 900 K temperature (same density). The lower temperature and pressure case produced images of a well defined and thin liquid/gas interface while the higher temperature and pressure case generated images of a darker core surrounded by cellular image structures. The image results were not as clear as the images in Chehroudi et al. [8] because high pressure and temperature spray chambers cause some image degradation via strong index gradients in the ambient gas. There were clear differences in the ballistic images of edge structure between the two cases, however, and they were consistent with the idea of a transition to a turbulent, thickened diffusive mixing layer at the high pressure and temperature conditions.

Here we report further experimentation using three pure fuels that span a range of critical properties, together with a measurement using commercially available Diesel fuel. Three gas conditions are also explored, to refine the range of the observations.

2. Experiments

2.1. Experimental facility

The cylindrical spray research chamber (see Fig. 1) used for these experiments is operated with a steady flow of heated, high pressure air moving vertically downwards through the vessel interior. The speed of the flow is sufficient to clear the chamber of fuel vapor and combustion products fairly quickly allowing rapid experiment turn-around, with no observable effect on the operating spray. The chamber can achieve up to 9 MPa gas pressure and 900 K gas temperature. It has large vertical oval windows mounted in a cross pattern allowing optical access from a number of directions, including the line-of-sight format required by the ballistic and shadow imaging diagnostics used here. Three gas phase conditions were evaluated as shown in Table 1. The three cases listed in the table all produce the same gas density (22.8 kg/m^3) to ensure that dynamic interactions don't change among the three cases.

It is important to emphasize that the control temperature in a spray chamber is not necessarily the local temperature where an observation is made, especially in the case of a transient vaporizing jet. This issue applies to all spray research chambers; the core can be cooled somewhat by injector cooling systems (if used) and by fuel vaporization. The quoted values for chamber temperature are thus a reference point only (measured near the exhaust before injection via thermocouples in our case).

The fuel injector used in this work was a Bosch model CRIP-2 with a single hole on centerline. The nozzle hole was cylindrical

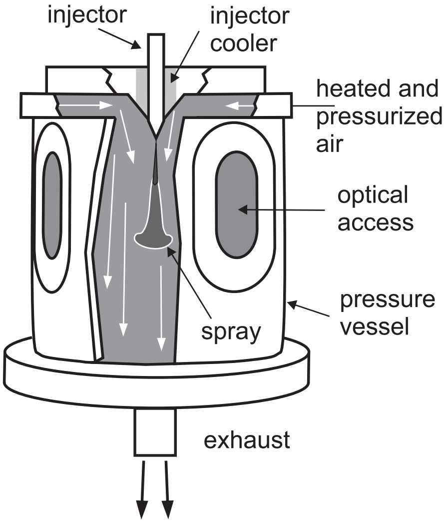

Fig. 1. Schematic of steady flow spray chamber.