

Effects of Pressure on the Fundamental Physics of Fuel Injection in Diesel Engines

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Abstract

Past works have suggested that two extremes exist with regard to liquid injection in high-pressure systems. At lower pressures, the classical situation exists where a well defined interface separates the injected liquid from ambient gases due to the presence of surface tension. Under these conditions, surface tension forces form a discontinuous non-continuum interface that promotes primary atomization, secondary breakup and the resultant spray phenomena that has been the well recognized and is widely assumed. At high-pressure conditions, however, the situation can become quite different. Under these conditions, a distinct gas-liquid interface may not exist. Effects of surface tension become diminished and the lack of these inter-molecular forces minimizes or eliminates the formation of drops and promote diffusion dominated mixing processes prior to atomization. In this paper, we present some of the first evidence that diffusion dominated mixing, not atomization, occurs at certain Diesel engine conditions. In addition, we derive a theoretical model that explains why and quantifies the change in the interfacial dynamics that leads to the transition between the classical non-continuum "jump" conditions associated with two-phase flows and the continuous gas-liquid interfacial diffusion layers. To facilitate the analysis, we apply the Large Eddy Simulation (LES) technique using a detailed real-fluid model that is designed to account for key high-pressure phenomena. We perform a series of calculations of key target experiments associated with the Engine Combustion Network (see www.sandia.gov/ECN): namely the "Baseline n-heptane" and "Spray-A (n-dodecane)" cases, which are designed to emulate conditions typically observed in Diesel engines. Calculations are performed by rigorously treating the experimental geometry, operating conditions and thermo-physical gas-liquid mixture properties. To further augment the analysis, the real-fluid framework used in the LES is then combined with vapor-liquid equilibrium and linear gradient theory to facilitate calculations of the detailed vapor-liquid interfacial structure associated with the multicomponent mixtures of interest. In applying this integrated theoretical framework, we focus on two particularly relevant reference conditions where the ambient gas is $p_1 = 29 \text{ bar}$, $T_1 = 440 \text{ K}$ and $p_2 = 60 \text{ bar}$, $T_2 = 900 \text{ K}$. We then compare the results with corresponding observations from high-speed imaging data. The high-temperature interface showed a substantially reduced surface tension and a wider interface thickness compared to the low-temperature interface. An applied Knudsen-number criterion then revealed a major finding. Contrary to conventional wisdom, gas-liquid interfacial diffusion layers develop not necessarily because of vanishing surface tension forces, but because of broadening vapor-liquid interfaces. These interfaces become so thick that they enter the continuum length scale regime. Thus, independent of any residual surface tension forces that might be present, the Navier-Stokes equations apply across the high-temperature vapor-liquid interface if the viscous stress term is modified appropriately. Similarly, continuum based diffusion laws apply across the vapor-liquid interface, producing a continuous phase transition not a "jump" condition. Our analysis suggests that at certain conditions in Diesel engines, the classical view of spray atomization as an appropriate model is questionable. Instead, nonideal real-fluid behavior must be taken into account using a multicomponent formulation that applies to arbitrary hydrocarbon mixtures at high-pressure supercritical conditions.

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