

Investigation of Key Mechanisms for Liquid Length Fluctuations in Transient Vaporizing Diesel Sprays

Jaclyn Johnson
Michigan Technological Univ.

Hai-Wen Ge
ESI Mindware Inc

Jeffrey Naber and Seong-Young Lee
Michigan Technological Univ

Eric Kurtz and Nan Robarge
Ford Motor Co

ABSTRACT

Diesel combustion and emissions formation is spray and mixing controlled and understanding spray parameters is key to determining the impact of fuel injector operation and nozzle design on combustion and emissions. In this study, both spray visualization and computational fluid dynamics (CFD) modeling were undertaken to investigate key mechanisms for liquid length fluctuations. For the experimental portion of this study a common rail piezoelectric injector was tested in an optically accessible constant volume combustion vessel. Liquid penetration of the spray was determined via processing of images acquired from Mie back scattering under vaporizing conditions by injecting into a charge gas at elevated temperature with a 0% oxygen environment. Tests were undertaken at a gas density of 34.8 kg/m^3 , 2000 bar injection pressure, and at ambient temperatures of 900, 1100, and 1300 K. Under these conditions there are noticeable fluctuations in liquid phase penetration once the steady state liquid length has been established, on the order of 10% of the mean liquid length. These fluctuations in penetration were seen in each plume. An analysis of the experimental data, along with CFD modeling of the liquid spray is undertaken to identify the key mechanisms for liquid length fluctuations. Results are presented comparing experimental and CFD results of the liquid spray and its fluctuations, including a quantification of fluctuation magnitude. Based on the experimental and CFD analysis it is concluded that a key mechanism for liquid length fluctuations in a transient diesel spray is due to spray induced turbulent eddies near the edge of spray plume.

CITATION: Johnson, J., Ge, H., Naber, J., Lee, S. et al., "Investigation of Key Mechanisms for Liquid Length Fluctuations in Transient Vaporizing Diesel Sprays," *SAE Int. J. Engines* 6(2):2013, doi:10.4271/2013-01-1594.

INTRODUCTION

Diesel combustion is governed by the fuel-spray behavior including its vaporization and mixing with ambient air. This directly controls combustions and emissions formation [1]. From experimental results, it is evident that under vaporizing conditions (0% oxygen) the diesel fuel spray plume liquid length (LL) will undergo fluctuations plume to plume in a multi-hole injector, but also temporally for each plume about a quasi-steady nominal value. It is desired to quantify, and validate causes for these fluctuations as a follow up to previous studies [2].

Past literature on liquid length fluctuations has attributed them to turbulence [3, 4, 5, 6], fuel pressure vibrations [7], injector needle fluctuations [7], spray structure with discontinuous regions of droplet clouds [8], and large-scale spray structure evolution at the liquid length tip [9]. Furthermore, causes of liquid length fluctuations including injection pressure oscillation have been eliminated along with hydraulic wave dynamics [2].

Liquid length fluctuations greatly influence diesel spray structure, and diesel flame dynamics along with pollutant emissions. The current work investigates and refines causes of these liquid length fluctuations, which could be further

studied in combusting conditions to understand the implications for emissions and flame characteristics.

The goal of this publication is to further explore the causes of liquid length fluctuations. By using computational fluid dynamics (CFD) modeling, coupled with experimental testing, a better understanding is gained on a potential cause for these fluctuations. The CFD model is firstly validated against available experimental data. Different hypotheses are assessed to identify the key mechanisms determining the liquid length fluctuations.

EXPERIMENTAL SETUP

Experimental tests were undertaken in the Michigan Tech constant volume combustion vessel as shown in [Figure 1](#). Full details of the combustion vessel and its operation are provided in [10, 11, 12]. The combustion vessel can replicate temperatures, pressures, and charge-gas composition of a diesel engine for fundamental spray studies.

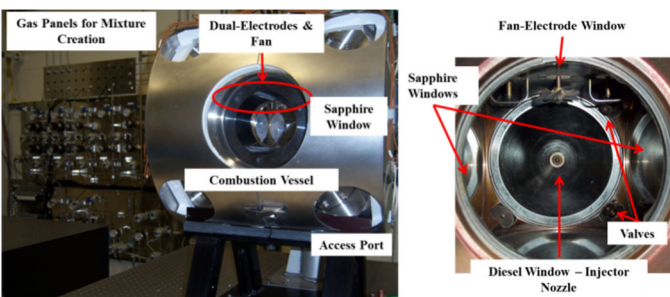


Figure 1. External CV View (Left) and internal view of the CV (Right).

A 0% oxygen environment is used in these studies to provide vaporization conditions in the absence of combustion, achieved through the following procedure. A homogeneous premixed mixture of acetylene, hydrogen, oxygen and nitrogen is metered into the combustion vessel and subsequently spark-ignited, resulting in a preburn combustion process. Pressure (temperature) is monitored during the cool-down period, where there is heat transfer from the preburn combustion products to the cooler vessel walls (electrically heated to 453 K). At the desired pressure (temperature) conditions that replicate the charge-gas state resulting from compression in a diesel engine, the fuel injection is triggered.

Mie back scattering diagnostics to visualize the liquid phase of the vaporizing spray was used. The orientation of the imaging setup enables visualization of the spray, as if we were viewing the spray from the cylinder center-line from below the piston with the imaging setup shown in [Figure 2](#). Images were acquired at 30,000 frames per second at a reduced resolution of 256×256 using a 2 microsecond exposure duration, with a Photron Ultima APX RS high speed camera with a Nikon Nikkor 50 mm lens, f-stop 16. A Cooke SensiFlash flashlamp provided illumination to the

chamber, uniformly illuminating the region of interest by reflection off of a mirror.

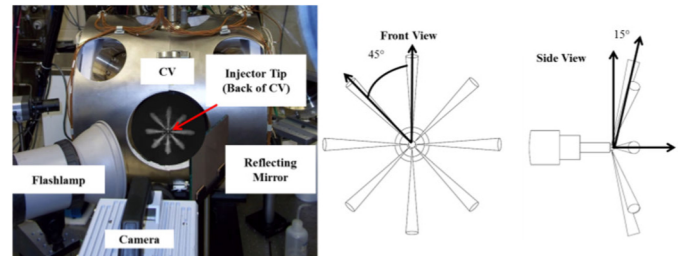


Figure 2. Mie back scattering imaging setup, along with plume orientation.

Spray plume orientation is shown for the multi-hole (MH) (8 plume) injector in [Figure 2](#). The single-hole (SH) injector has the same injector properties including included angle and hole diameter. The injector hole diameter is nominally 145 μm and each hole is 1 mm in length, with a length to diameter ratio of 6.9. Included angle of the spray is 150°, and the eight holes (for the multi-hole injector) are equally spaced from each other 45° azimuthally. The injector is driven by an EFS IPoD piezoelectric injector driver, with parameters of open and close voltage, peak current, and current slope being user-defined inputs to match production driver traces. The fuel used is an ultra-low sulfur diesel fuel, being pressurized by a Hydraulics International high pressure multi-fuel compatible system, capable of injection pressures to 4140 bar. Injection duration was 1.6 ms electronic trigger length, actual injection duration was 2.8 ms for the MH injector and 3.9 ms for the SH injector.

Images were processed using Mathworks Matlab to determine liquid length of each spray plume. Liquid length is experimentally defined in the processing as the length from the injector hole to the leading edge of the fuel spray, over the fully connected liquid spray plume, neglecting any detaching fuel slugs or spray structure with discontinuous regions of droplet clouds [2]. Images are scaled to account for the 150° included angle of the spray. Images are processed by background subtraction, and then thresholding to black and white, using a threshold defined based on the image intensity distribution. This black and white image then has its boundary defined, with the leading edge of the boundary defining the liquid length. Refer to Nesbitt [11] and Nesbitt et al. [12] for additional details on the image processing method.

NUMERICAL MODELS

In the present work, the commercial CFD software Converge (Version 1.40) was used to simulate the diesel spray. The numerical results were compared with experimental test results and provide insights on the vaporizing liquid length fluctuations. Both RANS (Reynolds-Averaged Navier-Stokes equations) and LES (Large Eddy Simulations) were used to simulate the spray. Rapid

distortion RNG (Re-normalization group) k-e model [13] and dynamic structure model [14] were used for RANS and LES, respectively. The secondary breakup process was modeled using a Kelvin-Helmholtz breakup model [15] and a Rayleigh-Taylor breakup model [16]. No-time-counter (NTC) numerical scheme [17] was used to calculate the droplet collision process. Droplet evaporation was computed using the baseline evaporation model in Converge. Details about the numerical models have been provided in [18]. Adaptive mesh refinement (AMR) and fixed mesh embedding techniques [18] were used to improve accuracy and consistency with minimal loss in computational efficiency. Base mesh size was set to 4 mm. Except for Figure 14, all numerical results were from RANS simulations.

Liquid penetration is determined based on the fraction of total liquid mass in the whole domain [18]. The liquid penetration is defined as the distance from the nozzle exit that encompasses a defined percentage of the total available liquid mass injected from this nozzle. The percentage was set to 98% in this work.

Effects of Parcel Number on Numerical Results

In modern spray simulations, the spray is usually represented by a set of droplet parcels, which contains several identical droplets. With this technique, it is not necessary to track each droplet. Computational cost is then reduced significantly. Average number of the droplets per parcel depends on an input parameter, the total number of droplet parcel for injected liquid. The higher this number is, the lower the average number of droplets per parcel is, and the statistics are then more accurate. The number of droplets in a parcel is a number describing the relative probability of the droplet and thus is not necessarily an integer. For instance, 0.5 droplets in one certain parcel means that the chance of this parcel appearing in physics is only half of another parcel which has one droplet. To determine how many droplet parcels should be used in the simulation, an initial parametric study of preset total droplet parcel number was conducted. Four cases with total parcel numbers of 5k, 30k, 60k, and 100k were simulated with the other settings, including AMR level of 3 for both velocity and temperature, kept consistent. The resulting liquid penetration profiles are plotted in Figure 3.

It can be seen that the magnitudes of liquid penetration are very close to each other. However, the fluctuation in liquid penetration of the 5k case is more than two times larger than the others; the results of 60k and 100k are very similar. Figure 4 shows the standard deviation of liquid penetration as a function of total parcel number.

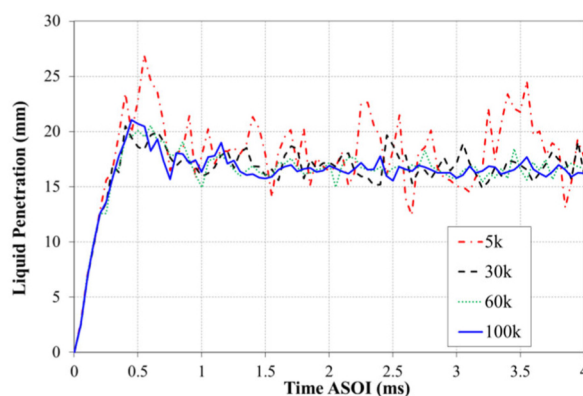


Figure 3. Influence of total parcel number on liquid penetration profiles.

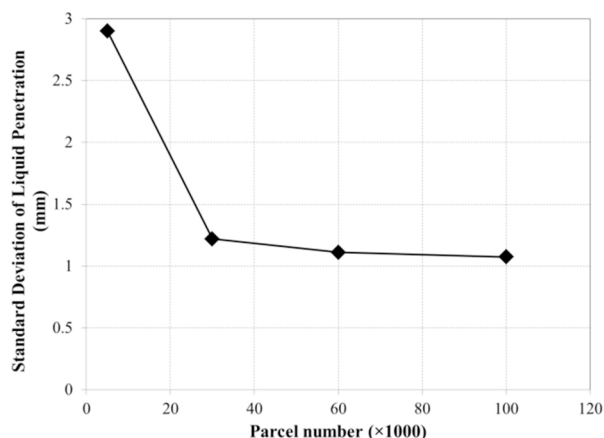


Figure 4. Standard deviation of liquid penetration as a function of total parcel number.

The standard deviation of the liquid penetration during the quasi-steady state (1-2 ms ASOI (after start of injection)) decreases with increasing total parcel number. When the total parcel number is larger than 30k, the standard deviation converges to a value of approximately 1.1. Assuming that the initial droplet diameter is equal to the nozzle hole diameter, the total number of injected droplets during the injection can be calculated from the total injected mass and diameter of the nozzle hole, which is estimated as 33k. If the total parcel number is greater than or equal to 33k, the number of droplets in each initial parcel is one or less than one. Hence, the errors caused by insufficient droplet parcel number can be reduced significantly if the total parcel number is set to a value that is equal or larger than 33k. Since the computational cost does not increase significantly with total parcel number, the total parcel number is set to 100k in the cases presented in the results of this paper.

VALIDITY OF COMPARISON OF SH CFD AND MH EXPERIMENTAL TESTING

Experimental tests were conducted using both a SH and MH injector at the same test condition to determine the validity of a comparison of MH experimental data to SH modeling data. Tests were conducted at 2000 bar injection pressure, 900 K bulk charge-gas temperature, and 34.8 kg/m^3 bulk charge-gas density, in a 0% oxygen environment. Three tests were conducted using each injector, with images analyzed to define the steady state liquid length, temporal liquid penetration, and fluctuation magnitudes. In this comparison, the same plume of the MH injector in regards to placement on the injector was compared to that of the SH injector. Experimentally, the SH injectors on average produce a 1 mm longer quasi-steady liquid length than the MH injectors, as seen in Figure 5.

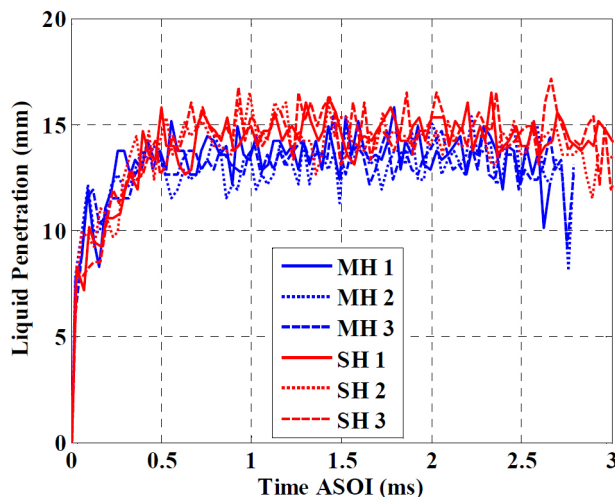


Figure 5. Comparison of SH and MH liquid penetration, over three experimental tests. Baseline test conditions of 2000 bar injection pressure, 34.8 kg/m^3 bulk charge-gas density, 900 K bulk charge gas temperature.

Although there are slight differences in liquid penetration, both the SH and MH injectors exhibit fluctuations whose normalized magnitudes (normalized by the quasi-steady state liquid length over 1-2 ms ASOI) are similar as shown in Figure 6. These fluctuations are defined as positive and negative fluctuations, meaning larger or smaller, respectively, than the mean quasi-steady state value.

The normalized magnitudes of the fluctuations are similar for both the MH and SH injectors, with an average 5.1% positive and 4.5% negative fluctuation for the MH injector, and an average 5.2% positive and 3.9% negative fluctuation for the SH injector. This results in a maximum percent difference of 16% between MH and SH fluctuations, being observed for the negative fluctuations.

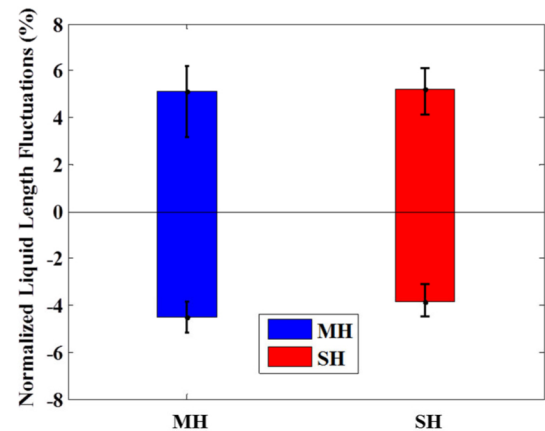


Figure 6. Normalized liquid length fluctuations for all experimental tests at this baseline test condition, looking at both the positive and negative fluctuations. Limit bars define the range of the three tests, with the data presented is the average fluctuations over the three tests, for each injector.

A T-Test is applied to check if these differences are statistically significant in terms of positive and negative fluctuations during the quasi-steady state period for the SH and MH injector (considering only the plume representative of the SH injector). Using a T-Test with a 2-tailed distribution and assumption of equal variance, the result is a p-value of 0.68, which is larger than the cut-off value of 0.05 for statistical significance, meaning that the differences in positive and negative fluctuations are statistically insignificant. Additionally, conducting a frequency analysis on the data (not shown) to determine if there exist repetitive frequencies in the fluctuations, both the SH and MH injectors exhibit random peak frequencies for all cases, there are no trends. Based on this, it can be concluded that the fluctuations for the SH and MH injector experimentally do not differ significantly. This lack of differences in MH and SH injectors from experimental testing validates the use of CFD modeling of a SH injector. Hence, CFD modeling was only applied to a single-hole nozzle, with the majority of experimental testing being done using a multi-hole nozzle. In addition to no fluctuation differences between injectors used experimentally, further motivating the use of SH CFD modeling was that MH CFD modeling cannot reproduce the hole to hole variations which are known to exist in the sprays [12] and could influence the liquid length fluctuations.

TEST CONDITIONS

Modeling and experimental tests are undertaken at a range of charge-gas conditions, as defined in Table 1. These represent a high density condition ($\rho = 34.8 \text{ kg/m}^3$ $P_{inj} = 2000 \text{ bar}$) for a modern light-medium duty diesel engine based on the combined density and injection pressure conditions. All tests are undertaken at vaporizing conditions, without combustion (0% oxygen) to isolate the understanding