In-Nozzle Cavitation-Induced Orifice-to-Orifice Variations Using Real Injector Geometry and Gasoline-Like Fuels

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Abstract

Many concurrent sources contribute to cycle-to-cycle variability (CCV) in internal combustion engines. This variability is undesirable, as it is responsible for deviations from the expected operating conditions, which in turn affect the engine efficiency and performance. Shot-to-shot variability connected to the fuel injection process is one strong candidate among CCV's many sources. Previous numerical work employing diesel fuel in a nozzle geometry measured with x-ray diagnostics has shown that manufacturing tolerances and needle radial motion are responsible for orifice-to-orifice variations in total injected mass. These variations are significant in the presence of shot-to-shot variability in the needle radial motion. The growing interest for low temperature combustion modes such as gasoline compression ignition has made the use of gasoline-like fuels in compression ignited engines desirable. However, when operating under typical diesel conditions, these fuels generally show considerable propensity for cavitation in the orifices and at the needle seat, due to their high volatility. In previous work, in-nozzle cavitation has been shown to correlate strongly with needle radial motion. This might constitute another source of CCV, as cavitation within the orifices might enhance the already present shot-to-shot variability by reducing the available cross-sectional areas and the relative orifice discharge coefficients. In addition, the systematic presence of cavitation might also result in the local erosion of the nozzle internal geometry, leading to even higher variability with time. This study focuses on the evaluation of orifice-to-orifice variability of gasoline-like fuel injection under diesel operating conditions. High-resolution x-ray geometry characterization of an eight-hole heavy-duty diesel injector has been combined with new measurements of the needle motion using a straight-run gasoline. A well-validated computational setup using the CONVERGE code was employed to perform a series of simulations, which highlighted the influence of cavitation on the internal nozzle flow. This combined effect of cavitation, needle radial motion, and orifice-to-orifice differences found is expected to have a strong influence on shot-to-shot variations.

Keywords: cavitation; gasoline compression ignition; x-ray tomography; needle motion

Introduction

During the last few decades engine manufacturers have played a major role in reducing the transportation sector share of both greenhouse emissions and criteria pollutants. The simultaneous co-optimization of engine design and existing fuels and the exploration of the chemistry of new fuels offer great opportunities of improvements. According to current projections, the partial electrification of the passenger car fleet will cause the demand for gasoline products to decrease while the demand for diesel and middle distillate products will continue to rise as a result of global economy's growth [1, 2]. Under this scenario, gasoline could become a valid alternative for commercial vehicle users if the cost associated with owning and operating such vehicles becomes competitive in comparison to traditional diesel vehicles.
Gasoline compression ignition (GCI), offers a possible solution as it can burn the fuel under low temperature combustion (LTC) conditions while increasing fuel efficiency and reducing criteria pollutant emissions [3, 4]. An interesting candidate for preliminary testing in GCI applications is Straight-run gasoline (SRG). SRG is characterized by diesel-like chemical reactivity and physical properties similar to common gasoline and therefore allows for an intermediate step toward the use of conventional gasoline in compression-ignited engines. If compared to diesel, SRG is characterized by lower viscosity and density as well as higher saturation pressure [5]. Previous work by the authors [5, 6] showed that, for internal nozzle flow applications, fuel properties such as density and viscosity are fundamental in determining the amount of fuel that the injection system is capable to deliver. If compared to diesel, SRG's viscosity enabled higher velocities and volumetric flow rates inside the injector orifices and partially compensated for the lower specific mass of SRG. On the other hand, higher saturation pressures typical of gasoline-like fuels enhance the

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occurrence of in-nozzle cavitation. Phase change due to cavitation commonly occurs at the needle seat and at the inlet of the injector orifices where strong pressure gradients develop [7]. Cavitation's presence causes perturbations in the flow field that result in deviations of the injector behavior from the expected nominal performance. In addition to the fuel property effect, needle lateral motion is also responsible for strong perturbations of the flow field. Previous work [5-9] has shown that the lateral motion of the needle is connected to the fuel tendency to travel along preferential paths inside the nozzle resulting in orifice-to-orifice variability. Furthermore, such variability is enhanced by the presence of in-nozzle cavitation [5, 8], especially for those cases in which the amount of fuel vapor is not homogeneously distributed among the orifices due to the influence of the needle radial motion. Experiments performed by the authors have shown that the needle radial motion can be affected by considerable shot-to-shot variability [9]. As a consequence, the lateral oscillations could likely cause the location of such flow-field and cavitation non-uniformities to change for each injection events (i.e., engine cycle) possibly resulting in cycle-to-cycle variability (CCV). The authors have shown that in simulations, and for a non-cavitating fuel such as diesel, orifice-to-orifice differences as high as 10% could be found for separate injection events [9]. This might become an even more critical issue for heavy-duty GCI applications in which swirl and tumble motions are generally less intense than for light-duty engines and therefore promote lower air-fuel mixing.

The scope of this study is to point out the effect that the physical properties of a high-volatility fuel such as SRG have on in-nozzle cavitation and flow-field development. All the results obtained with SRG are compared against diesel results. The novelty of this work is in the simulation of a production eight-hole heavy-duty diesel injector whose geometry and needle motion were measured with well-established, validated x-ray techniques [9-12].

Methods

The Cummins injector geometry used for the simulations presented in this work was obtained through x-ray nozzle tomography experiments that were performed at the 7-BM beamline of the Advanced Photon Source (APS) at Argonne National Laboratory [13]. Further details on the experimental setup are reported in the authors' previous work [9].

The geometry obtained through the x-ray tomography experiments has been presented in [9] where a detailed description of the geometry preparation and characterization was provided. Table 1 summarizes the main features of the injector geometry and provides the ranges for each reported quantity. Most of the variability was found in the orifice inlet diameter as well as in the orifice included angles.

	Measured Values			Units
	Minimum	Average	Maximum	
Orifice outlet hydraulic diameter	185.43	185.83	186.46	[μm]
Orifice inlet hydraulic diameter	227.71	228.70	230.08	[μm]
K-factor	4.20	4.29	4.42	[-]
Orifice length	1.020	1.027	1.036	[mm]
L/D Ratio	5.49	5.53	5.59	[-]
Domain volume (sac + 8 orifices)	0.667 (needle completely closed)			[mm^3]
Sac diameter	1.00			[mm]
Included angle (half)	73.25	74.36	75.48	[°]

Table 1. Details of the injector geometry [9]

The injector needle motion was recorded at the 32-ID beamline of the APS [14]. A pressure chamber fitted with x-ray transparent windows was employed to host the injector at atmospheric pressure and temperature. A 5.0 standard L/min flow of gaseous N_2 was used to avoid liquid fuel accumulation within the field of view. The fuels were pressurized to the desired injection pressure using a standard common-rail diesel system. Further details about the experimental setup are reported in [9]. The tracking of the needle motion was performed in a two-step fashion, using two lines of sight that varied by 90° and recording 30 injection events per view. A cross-correlation algorithm was used on the resulting image stacks to track the in-axis and radial motions of the needle tip as a function of time. Finally, the combination of the two view's ensemble averages allowed the full three-dimensional motion to be defined. Figure 1 reports a comparison between the two fuels at the three tested injection pressures. The injector energizing times are 2.5, 2.0, and 2.5 ms at 1000, 1500, and 2500 bar injection pressure respectively. The needle lift profiles are not reported here for the sake of brevity. It is worth mentioning that the lift profiles were characterized by high repeatability and the maximum needle lifts were measured as ~450, ~470 and ~495 μm for diesel and ~425, ~453 and ~475 μm for SRG at the three injection pressures (1000, 1500, and 2500 bar). Figure 1 shows that the needle average fluctuations are characterized by some eccentricity in the needle position when the needle is at maximum lift (i.e., between 1.00 and 2.5 ms approximately). The needle vibrations are likely due to an elastic relaxation of the needle from the position it holds in sealed configuration [11]. The main difference between the two fuels is that when diesel is used, the needle tends to follow a circular (elliptical at higher pressures) trajectory around a center point whose location depends slightly on the injection pressure. In the case of SRG and for a given pressure, the needle is located at a much larger distance if compared to the corresponding diesel case. In addition, the oscillations are more limited around the average center point. An explanation to this phenomena might be linked to the different fluid-structure interactions occurring between the needle and the two fuels. In the case of diesel, the flow is characterized by a larger momentum due to the higher fuel density. This likely causes the needle to vibrate with amplitudes that are larger than those found for SRG.

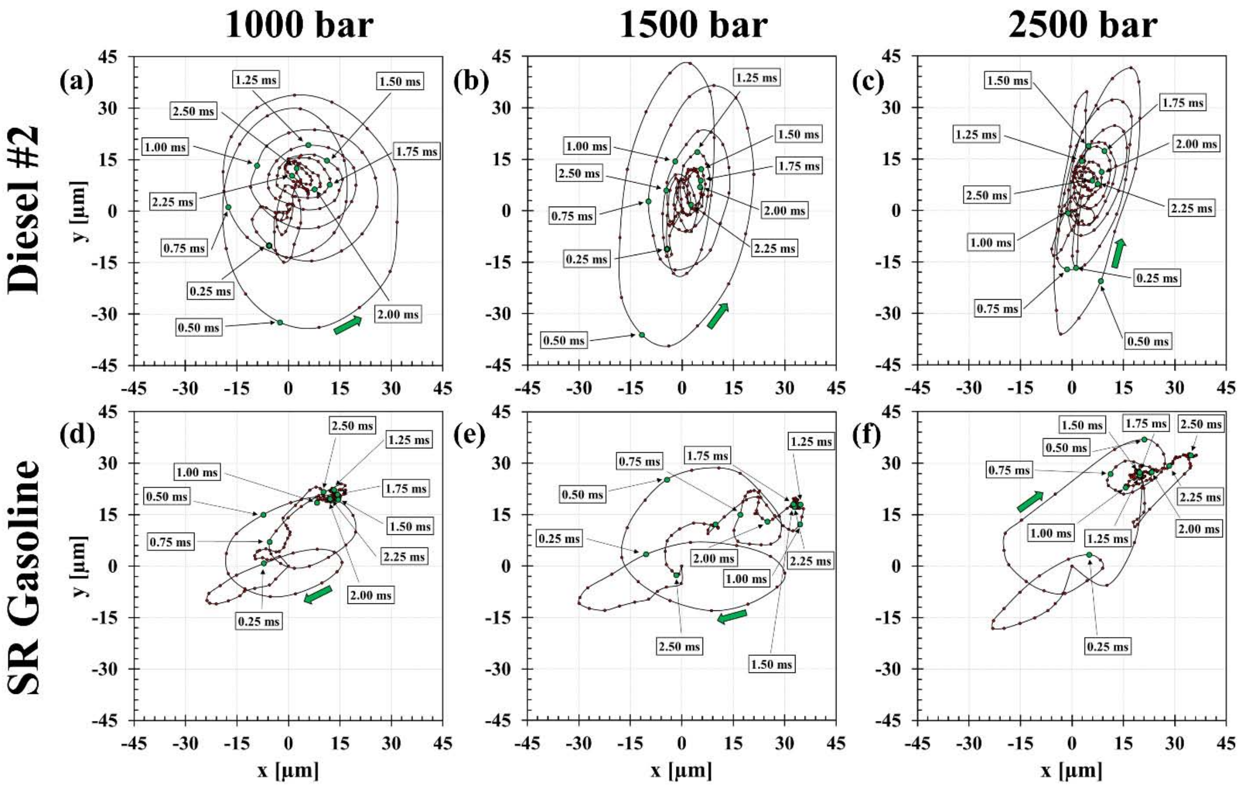

Figure 1. Average lateral motion path of the injector needle at 1000 (a, d), 1500 (b, e) and 2500 bar (c, f) injection pressures for diesel #2 (a, b, c) and SRG (d, e, f) fuels respectively. a), b), and c) are taken from [9].

All the simulations were performed with the CONVERGE CFD code [15] using a Reynolds-Averaged Navier-Stokes formulation closed by the Standard k-ε turbulence model. A volume of fluid (VOF) approach with the assumption of homogenous mixture was employed to describe the multiphase nature of the flow field. All phases (i.e., liquid, vapor, and non-condensable gases) were modeled as compressible. A perfect gas assumption was used for the gaseous species, while the liquid was modeled with a barotropic fluid assumption. The homogenous relaxation model (HRM) by Bilicki and Kestin [16] was adopted to account for the phase changes due to the occurrence of cavitation.

The physical properties of the two fuels, i.e., diesel #2 and SRG, were taken from the CONVERGE code database and [5] respectively. The mesh and numerical setup was consistent with the authors' previous work [9] in which the validation against experimental measurements of diesel mass flow rate at several injection pressures was reported.

Results

This section presents some results that highlight the different behavior between diesel and SRG when operating under the same nominal conditions. In all cases the fuel and ambient temperatures were set at 358 K, while the back pressure was equal to 100 bar. The results are focused on the initial stages of the injection events since cavitation was found to occur at very low lifts where the radial motion of the needle was comparable with the needle lift. Figure 2 shows a comparison of diesel and SRG's mass flow rates at the exit of the eight orifices. The mass flow rate for the two fuels is also compared by disabling the radial needle motion. It is clear how the presence of the needle motion causes high orifice-to-orifice variability to emerge. For the cases in which the needle motion was disabled (Figure 2 a and b) the orifice-to-orifice variations were mostly due to the geometric features captured through the use of the x-ray scanned geometry. Previous work on the same geometry [9] concluded that these variations were mostly due to orifice-to-orifice cross-sectional area differences and asymmetries in the needle vs. needle seat coupling.

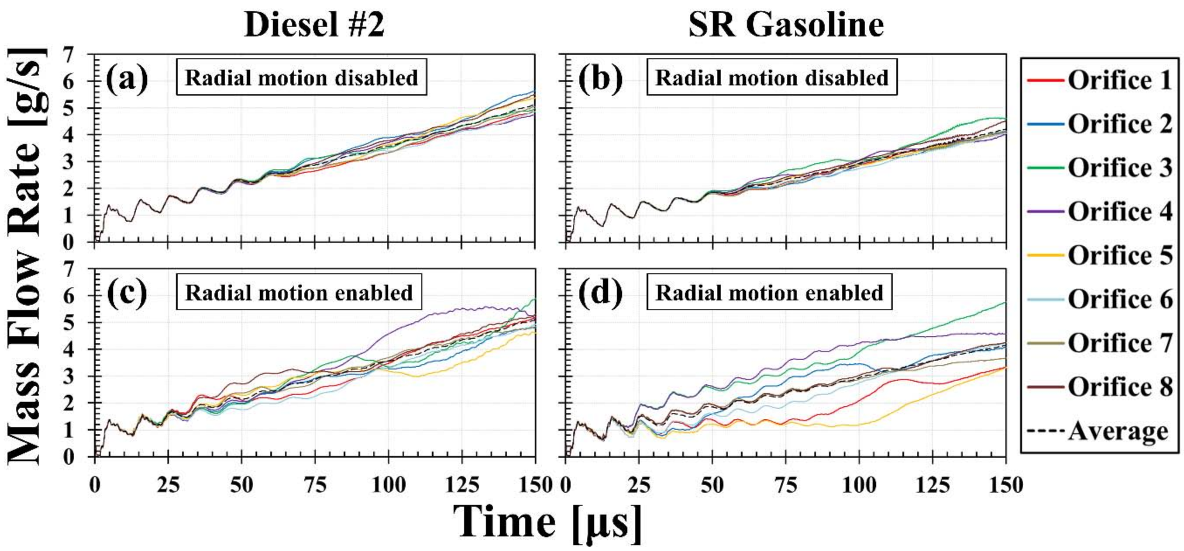

Figure 2. Orifice mass flow rates at 1000 bar injection pressure with radial motion disabled (a, b), and enabled (c, d) using diesel #2 (a, b) and SRG (c, d) fuels respectively. The results plotted in a) and c) are extracted from [9].

Figure 2 a and b also show the effects associated with the density difference. Due to SRG's lower density, mass flow rates for the gasoline-like fuel are consistently lower than diesel for all orifices, resulting in a ~20% difference at 150 µs. The effect of density becomes less distinguishable when needle radial motion is considered. Indeed, the lateral needle oscillations enhance the orifice-to-orifice variability for both fuels (cf. Figure 2 c and d). SRG was most affected by the presence of the needle lateral motion and showed a much wider spread in mass flow rate compared to diesel. This behavior could be caused by two separate sources:

- the experimentally measured needle motion is different between the two fuels, causing the flow fields to differ substantially as a direct result of different fluid-structure interactions;
- the higher saturation pressure of SRG causes the fuel to cavitate more than in the case of diesel leading to cavitation-induced perturbations of the flow field.

Both of the explanations provided above can be confirmed by the plots in Figure 3 which show the contour of fuel vapor volume fraction and velocity magnitude at 140 µs after the start of the injection. The flow structures inside the nozzle are very different between the two fuels. Indeed, in the case of diesel, the needle is located almost at the center of the sac and therefore resulting in a symmetric flow field. On the other hand, SRG's velocity contours show a much higher degree of asymmetry as the needle is located very close to the seat near orifice 4. This caused the fuel to follow a preferential path near orifice 8, which resulted in the detachment of the flow near the seat and the consequent development of a recirculation area near the top part of orifice 8. The jet coming out of the gap gained momentum in the direction of orifice 4 (diametrically opposed to 8) and entered orifice 4 with high speeds. The impact of part of the jet with the bottom of orifice 4 also resulted in a recirculation area at the inlet of the same orifice. This region was characterized by strong velocity (and pressure) gradients, which enhanced the occurrence of cavitation as shown by Figure 3 b. A similar behavior was also observed for orifice 3 (not shown here).

Cavitation was absent for diesel at the selected time-stamp as the velocity gradients were lower than SRG's. Nevertheless, diesel was characterized by much milder cavitation due to its lower saturation pressure even at times where the needle location was similar to the one of SRG in Figure 3. Diesel's peak values of fuel vapor volume fraction never exceeded 0.1 at all times and for all tested injection pressures. On the other hand, SRG showed strong cavitation even at the lowest of the three pressures. At 1500 bar injection pressure (not shown here for the sake of brevity), cavitation started much earlier (85 μs) and persisted for a longer time than it did for the 1000 bar case. A similar and even more accentuated behavior was observed for the 2500 bar case as well (not shown here).

SRG showed some mild cavitation in all orifices and at low needle lifts even in those cases where the radial needle motion was disabled. Although not shown here, the extent of cavitation was very limited and located mainly at the needle seat and at the bottom edge of the orifice inlets (similar to what observed for orifice 8 in Figure 3 b).

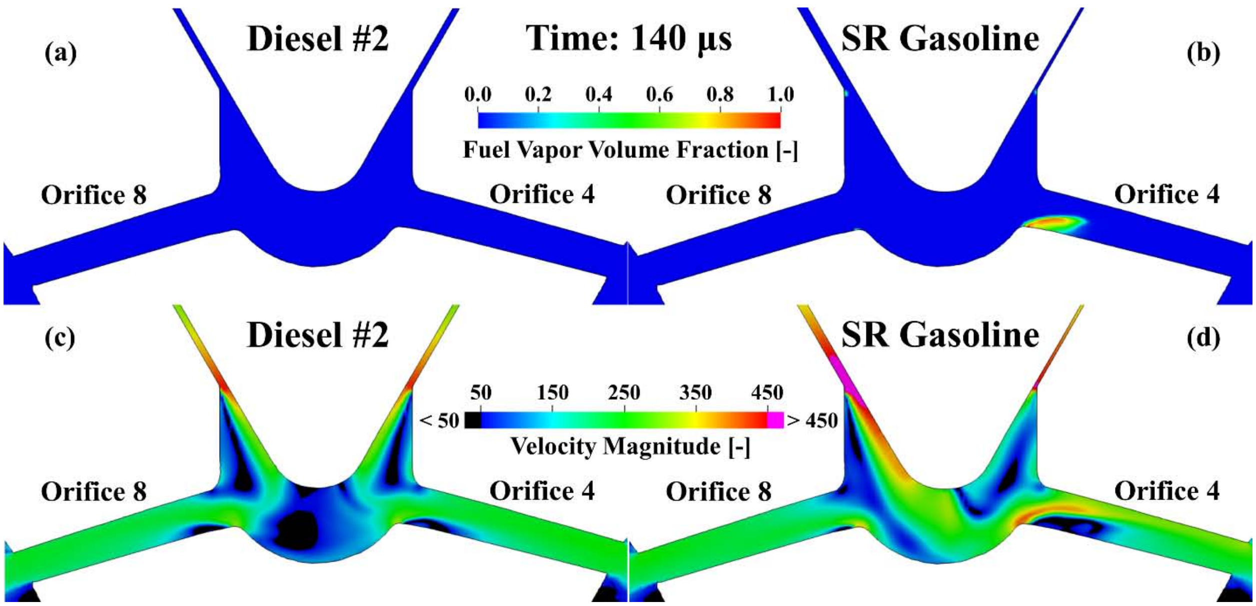

Figure 3. Contours of fuel vapor volume fraction (a, b) and velocity magnitude (c, d) at 140 μs using diesel #2 (a, c) and SRG (b, d) fuels respectively. The results are plotted on a plane that crosses through orifice 4 and 8 and includes the injector symmetry axis.

Conclusions

This study evaluated the in-nozzle flow characteristics of conventional diesel fuel and straight-run gasoline operating under typical diesel injection conditions. CFD simulations were performed to investigate geometry-induced, and orifice-to-orifice variability in a Cummins eight-hole heavy-duty injector using x-ray measured geometry and needle motion. The mass flow rate and the associated flow field were studied at three selected injection pressures and the results obtained at one of the pressures (1000 bar) were discussed. The geometry-induced orifice-to-orifice differences in mass flow rate were pointed out, confirming the unique insights that measured injector geometries can offer compared to nominal ones. The influence of the needle off-axis vibrations was evaluated by alternatively including and excluding the measured average radial motions for the two fuels. The analysis and the results confirmed that the radial displacement was effective only at low lifts. During the initial phase of the injection, jet-like structures formed in those areas where the needle-to-seat gap was larger. This provided a preferential path for the fuel to flow through the injector and reach specific orifices with very high velocities. High velocity and pressure gradients were found to be responsible for the occurrence of cavitation. SRG's different physical properties explained the differences in mass flow rate as well as cavitation magnitude compared to diesel and previous studies. Under all conditions investigated, SRG consistently showed more cavitation than diesel. This high propensity for cavitation, combined with high degree of randomness of the radial motion, is expected to contribute to the existing variability and possibly enhance the orifice-to-orifice differences among injection events. In addition, the systematic and localized occurrence of cavitation is expected to have a profound influence on cavitation erosion characteristics of heavy-duty injectors operating with light-end fuels.

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