Spray injection and development realizations and investigations of the effect of droplets coalescence and recirculation on ensemble-averaged predicted data

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Introduction

The recent unfavorable climate change phenomena are enhanced by transport emissions, and cleaner engines with the improvement of engine performance are required. For the development of engines using conventional fossil fuels, as well as alternative liquid and gas fuels, it is required to employ accurate modeling and simulation methodologies, along with realistic initial and boundary conditions, in order to predict the in-cylinder fuel injection, air-fuel mixing, combustion characteristics and emissions. For diesel and gasoline internal combustion engines, high-pressure injectors are employed in direct-injection common rail systems, which result in sprays which may lead to non-premixed, or partially-premixed or premixed in-cylinder combustion. The fuel injection process and the development of spray produces a wide range of droplet sizes and velocity distributions, which affect the air fuel-mixing, thus the various accompanying phenomena require further understanding especially the averaging of data imposed by the ensemble-average of the turbulence modelling closure approach. Computational fluid dynamics (CFD) modelling and simulations of Eulerian/Lagrangian two-phase flow, along with validation of predicted spray data for a wide range of operating conditions are crucial, including various injection pressure and chamber temperatures and pressures conditions. The main objective of the present work is to assess the effect of the number of spray realisations on droplet size and spray penetration, as well as assess the spray droplets coalescence and recirculation phenomena for simulations and their prediction against measured data.

Methodology

In the present work, the Eulerian-Lagrangian modelling methodology was employed for the simulation of direct-injection (DI) diesel and gasoline sprays. The overall engine simulation including spray injection, air-fuel mixing, as well as the preparation of combustible mixture are validated against experimental data, in order to assess the validity of the modelling methodology used. The validation framework requires to assess the characteristics of the single-pulse predicted spray against ensemble-averaged estimated from multiple-pulse predicted sprays. Furthermore, the present work accounts for the spray droplet raw data measurements over around 1000 injection pulses, placing emphasis on droplet size data scatter, ensemble-averaged data and the standard deviation.

The Eulerian-Lagrangian included the governmental equations of the gas phase (Eulerian approach) and liquid phase (Lagrangian approach), the turbulence modelling of the gas phase (k-ε high Reynolds number and variants), spray atomization modelling (Reitz-Diwakar spray atomisation model for diesel spray and the variant of Taylor Analogy breakup for gasoline spray (Model A)), the Reitz-Diwakar droplet break-up model and O'Rourke inter-droplet collision model for injector type) were employed. For the spray simulations, the differencing scheme MARS was employed and the conjugate gradient algorithm was used. For the simulations of the present work, sensitivity studies of the key numerical parameters, namely mesh size, time step size and parcel introduction rate have been performed.

Results and discussion

Two case studies with spray simulation and validation investigations are presented, namely a DI diesel spray (for pure diesel and biodiesel injection), and a DI gasoline spray for single and multiple pulses assessment. First, the case study of DI diesel injector simulations with two different fuels, namely pure diesel (B0) and pure biodiesel (B10) are presented, including spray pattern qualitative comparisons against photgraphs and spray penetration validation. Second, the DI gasoline spray simulations are compared against photographs and spray penetration simulations are compared against measured penetration. It is emphasized that the experimental data considered a number of spray realisations, while the simulation data was from a single pulse simulation. Since experimental data of size and penetration deviations from pulse to pulse were not available, then droplet size raw data was utilised for estimating deviation.

For case study of DI gasoline spray, the number of spray realisations was assessed for a statistically representative number of injection pulses, notably 30 injection pulses of spray simulations using different random sizes of droplets from the same droplet size distribution employed in the DI gasoline atomization model.

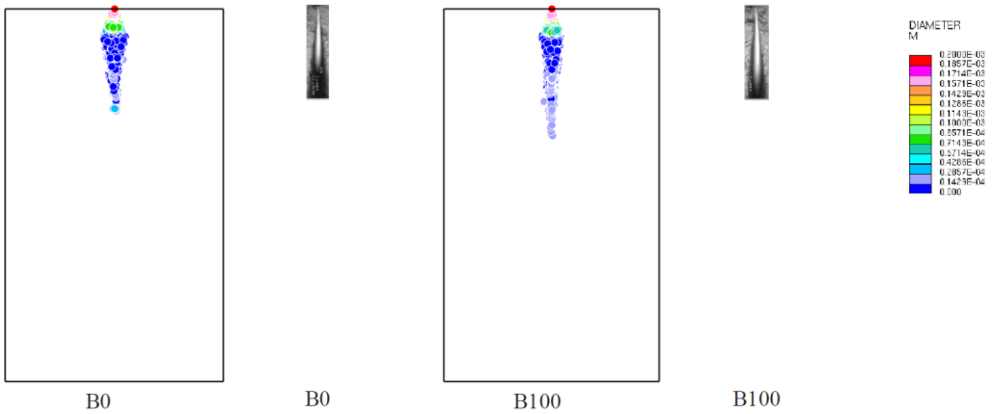

Figure 1. Diesel (B0) and biodiesel (B100) spray simulations comparison with photographs in high pressure (42 bar) and temperature (1000 K) chamber at 1.5 ms ASOI (from [1]).

As it can be seen in Figure 1, the simulated spray produced with biodiesel penetrates further downstream and it is narrower than the simulated spray with pure diesel. The prediction of increased spray penetration with increasing biodiesel blending percentage agrees with the experiment. Figure 2 shows comparisons of spray penetration between the simulations with B0 and B100 and the experimental data. The penetrations from the experiment were measured from the spray photographs at 1.5 ms after start of injection (ASOI). The penetration definition for the simulation was set as the vertical line to the nozzle symmetry line, behind which the 90% of the total mass of injected spray droplets resides. For both test fuels, spray penetration is slightly overpredicted and is in good agreement with the trend observed in the experiment, where biodiesel penetration is longer than diesel penetration.

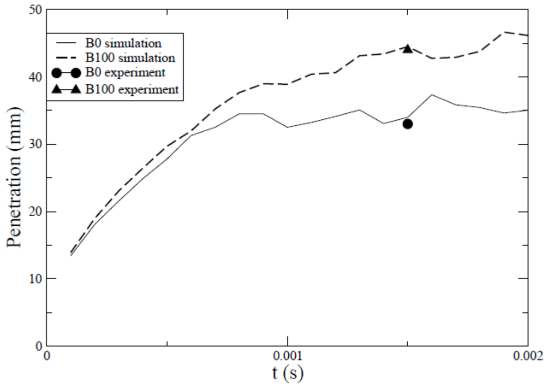

Figure 2. Diesel (B0) and biodiesel (B100) spray penetration comparisons for high pressure (42 bar) and temperature (1000 K) chamber (from [1]).

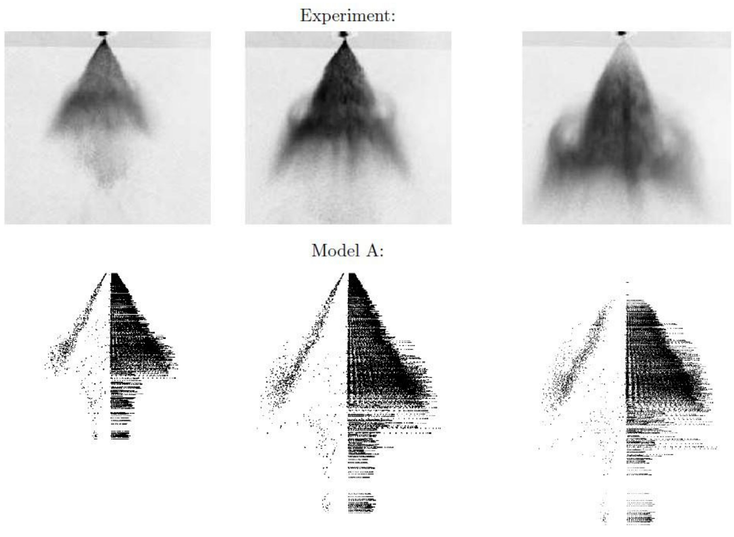

Figure 3. Gasoline spray simulation comparison with spray photographs at 0.8, 1.2 and 1.5 ms ASOI for injection pressure 70 bar at atmospheric chamber (from [2]).

For the DI gasoline spray, comparisons of the spray simulation against spray photographs are presented in Figure 3 at elapsed time ASOI. It can be seen that the simulation predicts the shape and structure of the spray, and the droplets' recirculation zones at the outer region of the spray are correctly captured. Therein, clustering and coalescences of droplets may occur which affect the spray penetration and the droplet size as it is explained below.

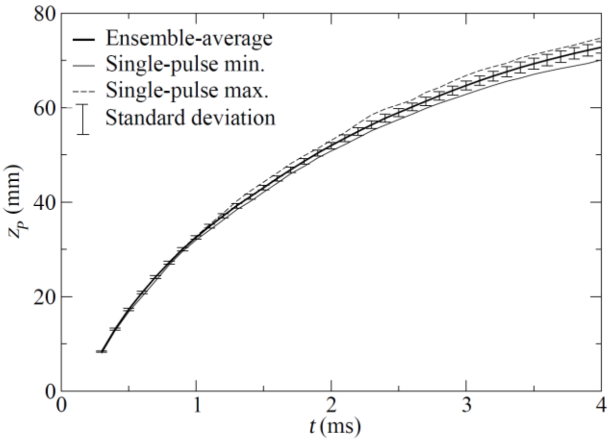

Figure 4. Gasoline spray penetration simulation comparison with standard deviation bars for single pulse minimum and maximum penetration and ensemble-average penetration from multiple pulses, for injection pressure 70 bar at atmospheric chamber (from [2]).

Figure 4 shows the penetration of spray as function of time from the number of realisations investigation. It can be seen that until 1 ms ASOI the differences of the single pulse data and the ensemble-averaged data are negligible. The single-pulse data fluctuates around the ensemble-average data. However, with elapsed time the minimum and maximum penetration from single pulses show increasing difference, which can be attributed to the decreasing droplet size, and the enhanced recirculation and coalescence of droplets.

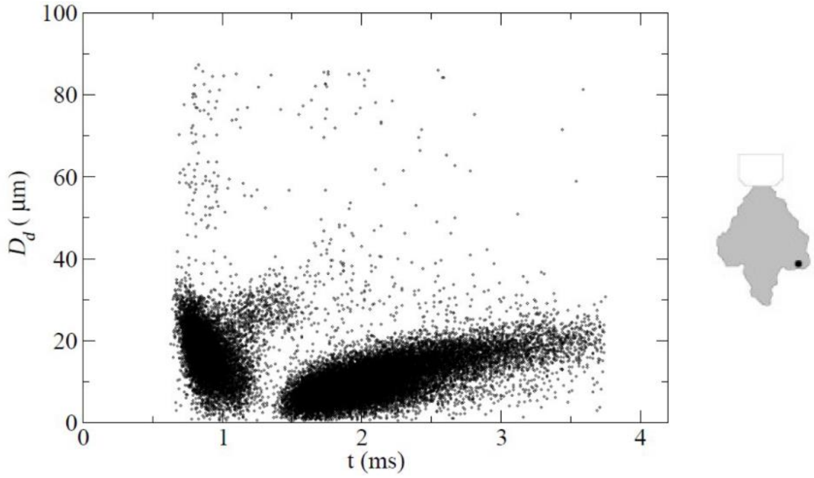

Figure 5. Raw droplet size data from multiple-pulse PDA local measurement (z=25mm, r=13mm), for injection pressure 70 bar at atmospheric chamber (from [2]).

Figure 5 illustrates experimental measurement of droplet diameter with the phase Doppler anemometry (PDA) technique. On the right side of Figure 5, the location of the measurement is provided in a schematic diagram which shows the injector tip and the spray pattern. The location was 25 mm axial distance from the nozzle exit and 13 mm radial distance from the nozzle symmetry axis. At around 1.3 ms ASOI, there is limited droplet data recorded, presented as a data gap, either because of the dense spray or because the main body spray and droplets cluster have passed the measurement location. From Figure 5, it can be observed that bigger droplets are measured at the early stages of spray injection and at later time at around 1.5 ms ASOI smallers droplet are captured, and there is a trend to accumulate because of recirculation which may create an increased size of droplets after 2 ms ASOI. The amount of droplets captured after 3 ms ASOI is decreasing, which reveals that the spray clustering and droplets that are recirculating travel far downstream.

The raw droplet size data from Figure 5, which was recorded with PDA over around 1000 injection pulses during the experimental measurement was ensembled-averaged, and the standard deviation of the droplet diameter was estimated and it is presented in Figure 6. In Figure 6, it can be observed that smaller droplets are measured after 1.5 ms ASOI and size deviation decreases with elapsed time. This might be explained by the fact that small droplets can be affected by the gas motion, and these are recirculating and remaining at the vicinity of the measurement location for longer period than 3 ms.

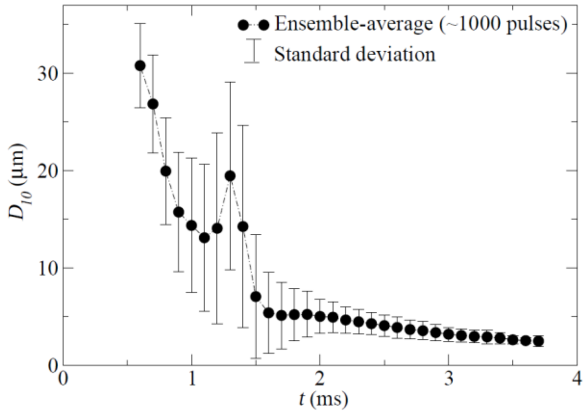

Figure 6. Ensemble-average and standard deviation of droplet diameter data from multiple-pulse PDA local measurement (z=25mm, r=13mm), for injection pressure 70 bar at atmospheric chamber (from [2]).

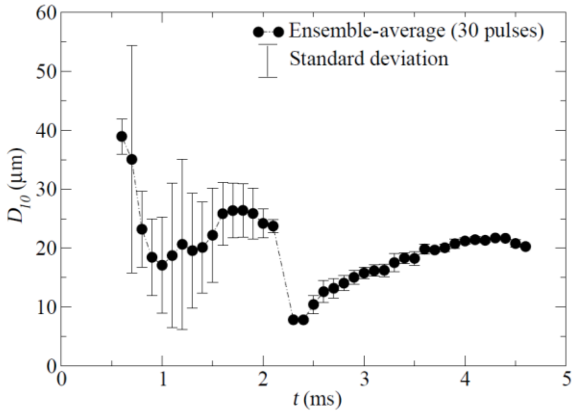

Figure 7. Ensemble-average and standard deviation of droplet diameter data from multiple-pulse CFD simulations (z=25mm, r=13mm), for injection pressure 70 bar at atmospheric chamber (from [2]).

Figure 7 includes the ensembled-averaged and the standard deviation droplet diameter data estimated from the multiple-pulse spray simulations for 30 different spray pulses. At the initial stages of spray injection, when the droplets arrive at the location for averaging, big droplets are predicted and the deviation of droplet size is relatively high. Also, a similar finding to the finding of experimental data is reached, which reveals that droplet size deviation becomes negligible during the later stages of spray injection at the particular location.

Conclusions

The experiment can provide raw data, where randomness exists, for example in the injector operation (needle opening and closing), the atomisation process, and the flow field interactions due in part to the turbulence. The spray measured at each injection pulse is different, and the difference in spray penetration and droplet size can be characterized with standard deviation resulting from big amount of measured data. In spray simulations of the kind which were considered in the present work, the Navier-Stokes equations are ensemble-averaged, while the Lagrangian spray equations are not ensemble-averaged, therefore a single spray pulse may in principle be not sufficient to describe the stochastic spray behavior, thus a representative number of spray realisations could be required. Scatter and deviations of data should be considered for spray validation studies.

References

[1] Chasos, C. A., Christodoulou, C. N. and Karagiorgis, G. N. "CFD simulations of multi-hole Diesel injector nozzle flow and sprays for various biodiesel blends". Proceedings of ICLASS 2012, 12th Triennial International Conference on Liquid Atomization and Spray Systems, Heidelberg, Germany, September 2-6, 2012. (Paper ref. No. 1263).
[2] Chasos, C. A. "Computational fluid dynamics simulation of direct injection gasoline sprays". PhD thesis, Imperial College of Science Technology and Medicine, University of London, England, 2006.