VALIDATION OF AN ENHANCED LIQUID SHEET ATOMISATION MODEL AGAINST QUANTITATIVE LASER DIAGNOSTIC MEASUREMENTS

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Abstract

An enhanced modelling approach for predicting the characteristics of high-pressure swirl sprays commonly used in commercial DISI applications has been developed by extending the physics of the earlier proposed Linear Instability Sheet Atomisation model (LISA). The new spray model incorporates the effect of spray swirl by preserving the angular velocity component of droplets, which are injected in a circle, and also includes a transition between the initial solid cone pre-spray and the ensuing hollow cone spray. Laser-induced fluorescence, Mie scattering and Particle Image Velocimetry were used to image a high-pressure fuel swirl spray at room temperature and pressure and results were compared against modelling predictions in order to evaluate the code's ability to capture the resulting atomisation and mixing phenomena. Measured data include spray tip penetration, simultaneous spray and air entrainment velocities in a plane through the spray's axis, and two-dimensional droplet size distributions. Both visual and quantitative comparisons were made to assess the predictive capabilities of the model.

Introduction

The design of more powerful, fuel-efficient, and environmentally friendly gasoline engines is one of the main goals of engine researchers and manufacturers worldwide. One of the solutions presently promoted by car manufacturers is the use of Direct-Injection Spark-Ignition (DISI) engines. This approach offers some significant advantages, including improved fuel economy and reduced greenhouse gas emissions, but presents challenges due to the very short amount of time available for the fuel spray to atomise and form an adequate mixture for satisfactory combustion. The requirements for adequate engine operation including fast atomisation rates and appropriate tip penetration are currently being met by the use of high-pressure swirl-injectors. However, the pre-swirl spray from this type of injector, which consists of very large droplets and is found after the start of injection before the spray can develop significant angular motion, is a major contributor to soot and HC emissions in DISI engines.

Understanding and controlling the spray atomisation process and its evolution inside the combustion chamber is an essential step towards achieving favourable ignition and combustion conditions. An established tool for the design and understanding of physical systems including fluid flows and/or combustion processes are multidimensional CFD codes. KIVA-3V [1,2,3] is a powerful code, especially designed for in-cylinder simulations in internal combustion engines and is being used in this work for the spray break-up simulation. The developed model is implemented into KIVA-3V and a first assessment of its performance is done via a comparison of model predictions to experimental results obtained in an optical static box, under atmospheric conditions.

Modelling Approach

The conical liquid sheet formed in the vicinity of the injector nozzle can be modelled using simple concepts from fluid mechanics, such as conservation of mass and momentum. The break-up length and time of the liquid sheet can be predicted by considering wave oscillations on the film surface. Three models have been proposed over the last few years dealing with the problem of liquid sheet formation and break-up. The first one, proposed by Dorfner et al. [4] in 1995 is strictly based on experimental observations and empirical correlations. The second, published by Han et al.[5] in 1997, is based on physical principles but still contains a number of empirical constants that have to be adjusted to meet the experimental data. The third model, which is adopted for further improvement in this work, has been presented in 1999 by Schmidt et al.[6,7] and is called LISA method (Linear Instability Sheet Atomisation). This model is utilizing physical concepts to determine the important parameters of the spray and includes a limited number of empirical constants for the calculation of injection velocity, which is given from the equation:

$$U = K_v \sqrt{\left(\frac{2\Delta p_l}{\rho_l} \right)}, \tag{1}$$

where Δp_l is the difference between injection and ambient pressure, ρ_l the density of the liquid fuel and K_v is given by the empirical correlation:

$$K_v = \max \left[0.7, \frac{4 \dot{m}_l}{\pi d_o^2 \rho_l \cos\theta} \sqrt{\frac{\rho_l}{2\Delta p_l}} \right]. \tag{2}$$

In the model developed in this work, this equation is being retained and used only in cases where the injection velocity profile is not being measured experimentally. Instead of assuming that the angular velocity of the spray is converted into a radial component of velocity, as in the LISA model, the angular velocity component is conserved and assigned to the injected particles, considering the conservation of angular momentum. The axial and angular velocity components of the liquid film are assumed to be:

$$U_{xo}=U\cos\theta \text{ and } U_{\theta o}=U\sin\theta \tag{3}$$

respectively, at the exit of the injector hole. The break-up length and the film thickness at the break-up location are calculated using the equations derived at the original LISA model.

A further change in the KIVA code was required in order to implement the swirl motion of the spray. Instead of injecting parcels at a single point, the concept of circle-injection has been introduced; therefore, droplets are injected at a plane downstream from the injector, as shown in Figure 1.

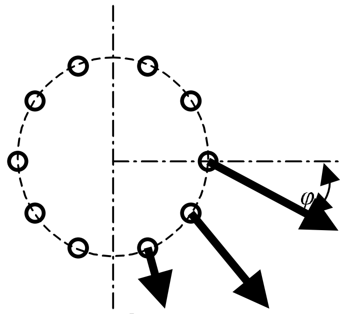

Figure 1. Circle-Injection Strategy

The angle φ is the swirl-angle and has been included in the input file in order to offer the flexibility to the user to deactivate this option. Throughout this work, a value of $\varphi=90^o$ has been used to obtain the tangential velocity component. This injection strategy not only allows the introduction of the tangential component of velocity, but also permits to inject the droplets at the point where the liquid film breaks up. This has the advantage that the droplets are inserted at the point where they are generated and have the calculated size, avoiding any changes that could be imposed by the break-up, collision or evaporation models. Also, it does not require a very fine grid in the vicinity of the injector to catch the initial position of the droplets.

Transient Injection Phenomena

As pointed out in the introduction, transient phenomena at the beginning of the injection process strongly affect engine-out emissions. The internal geometry of the injector causes the initial amount of fuel to be injected with only an axial component of velocity. That results into the pre-swirl spray, containing large droplets moving along the injection axis that cannot be easily atomised or evaporated and have a tendency to impinge on the piston surface and create a liquid film on it. As the injection proceeds, the velocity increases and the swirl component starts to rise and create the required centrifugal force in order to form a liquid film on the injector walls and keep the liquid film rotating. The liquid film is converted into a hollow-cone structure as it flows out of the nozzle and the disintegration of this liquid sheet into droplets leads to the main spray.

In order to represent this behaviour, an additional process has been included in the KIVA code. First, a solid-cone-like injection is performed, representing the pre-spray, and the cone angle is gradually being increased. After some point, defined by the user in the input file, the code switches into hollow-cone structure, while the cone angle is still increasing until the steady-state value is reached. Alternatively, if the internal geometry of the nozzle is known a detailed CFD analysis can be used to predict the exact point of transition between the pre-swirl and the main spray [8]. Nevertheless, this is a time consuming process and the internal geometry is in most cases not available.

Secondary Droplet Break-up

After the liquid film breaks up into ligaments and droplets, the secondary break-up is being treated with the TAB break-up model [9]. The droplets are being distributed according to a Rosin-Rammler size distribution, to match experimental measurements, as noted in [5]. The original collision model incorporated in KIVA has been found to produce a wider spray than the one indicated by the experimental data and has been turned off. With these additions the model represents more realistically the spray structure and its evolution with time, as will be shown in the comparison with the experimental measurements.

Experimental Set-up

The model was validated with data taken from a high-pressure swirl injector (60^o cone angle) operating at 5 or 8.5 MPa injection pressure inside an optically accessible static test cell of cubic geometry (1000 cm^3) at room temperature and pressure. Relative droplet size distributions were determined in a plane through the spray's axis using the ratio of laser-induced fluorescence (LIF) and Mie scattering signals [10]. An average of 150 laser-induced fluorescence images of the spray (iso-octane with 3-pentanone as tracer) was taken, followed by an average of 150 Mie scattering images. Since the LIF signal is proportional to liquid volume in the spray, while the Mie scattering signal is proportional to spray area, a ratio of the LIF to Mie signals gave a relative droplet Sauter-mean diameter (SMD) in a plane through the centre of the spray. Calibration to absolute SMD values is in progress by measuring the SMD with Phase Doppler Anemometry at selected locations. Planar measurements were made at 14 different timings after start of injection to capture spray development.

Particle Image Velocimetry (PIV) was utilized to obtain simultaneous velocity vector fields of the spray and the surrounding air to assess the amount of air that is entrained into the spray. A new two-laser (double-pulse), two-camera (double-frame) set-up was developed for this purpose [11] that allows the measurement of the air phase and the liquid phase simultaneously. The difference of the velocity magnitude between air and fuel droplets necessitated the use of two pairs of laser pulses with time delays matched to the expected velocities. The spray was visualized through Mie scattering, while the air motion was tracked through the fluorescence of seeding particles introduced prior to measurement. This way, the signals from the two phases could be unambiguously separated. Velocities of each phase were determined using a cross-correlation technique applied to corresponding image pairs of droplet distributions. The measurement plane and timings probed were chosen to correspond to those selected for the SMD experiment. Images taken with this set-up were also used to determine general spray characteristics including spray structure and tip penetration.

Injection Pressure [MPa]	5.0
Hole diameter [μm]	440
Cone angle [degrees]	60
Ambient Pressure [kPa]	101.3
Ambient Temperature [K]	293
Injection Duration [ms]	3.0
Fuel mass per injection [mg]	16.6

Table 1. Injector Characteristics and Experimental Conditions

Discussion of Results

The comparison of experimental measurements with numerical calculations shows a good agreement between modelling and experiments, as shown in Fig. 2 where the shape of the spray is shown at various timings after the start of injection. All the images represent 30×60 mm areas of the static cell and the computational grid respectively. For this calculation a 2.5×2.5 mm cell size has been used, constant throughout the computational domain and 5,000 computational parcels have been injected.

It is very important to note here that the model cannot account for random variations that appear in the experimental observations. Also, the criteria used for comparison can play a significant role in the degree of agreement that is being achieved, as demonstrated in Fig. 3, where the experimental measurements for spray tip penetration are compared to estimates obtained using three different criteria when post-processing the numerical results. Two of these criteria are based on the location of the fuel parcels that are located furthest away from the nozzle; while the next one is based on the amount of fuel mass (98% has been selected here). In the first case, either the farthest parcel can be selected or the average location of the farthest ten parcels. The second choice is more conservative, to avoid determining the tip penetration by using a parcel that might be found away from the bulk mass of the spray. The comparison shown here has been performed for the entire spray, including the pre-spray, but the same procedure can be followed only for the main spray. From Figure 3 it can be concluded that the aerodynamic drag is underestimated at the beginning of injection and overestimated for later timings.

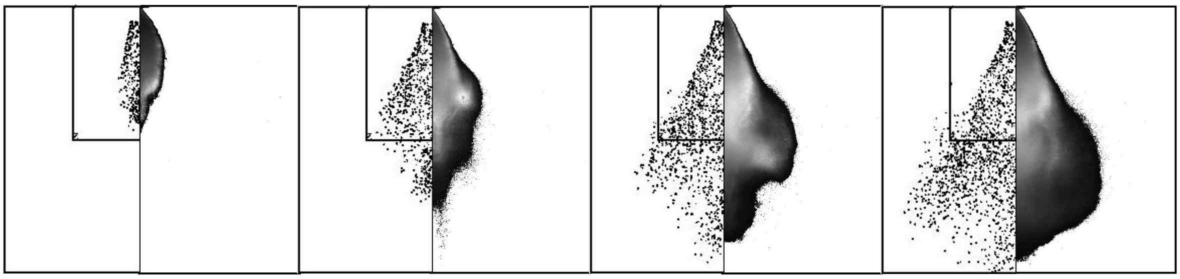

Figure 2. Comparison of Spray Structure (experiment on the right of each image shows average of 150 Mie scattering images)

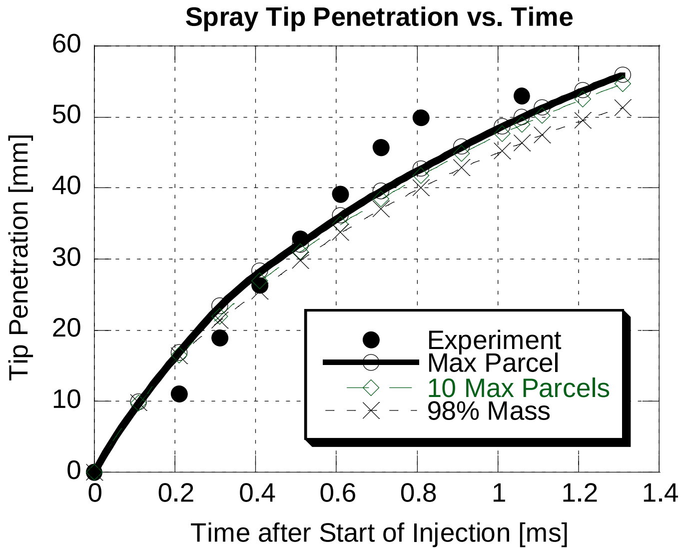

Figure 3. Comparison of Spray Tip Penetration Measurements

In order to visualize the air-entrainment process into the spray, velocity vector plots at various times have been obtained, Fig. 4. It appears that as the injection proceeds the velocity vortices developed at the sides of the spray become stronger and larger amounts of ambient air are transferred into the spray cone structure. This phenomenon enhances mixing and is very important when a homogeneous air-fuel mixture is desired. The comparison of experimental and calculated data results in very good agreement at early timings but a discrepancy can be noticed as injection proceeds. This trend is due to the fact that the spray penetration is underestimated by the model, as shown in Figure 3.

The atomisation characteristics of the injector can be studied by measuring the size of the fuel droplets. Both temporal and spatial variations have been measured, as illustrated in Figures 5 and 6, respectively. Overall, there is a good agreement with the experimentally measured (relative) SMD. Experimental values have been scaled to match the model at a single location (lowest point for the temporal variation and midpoint for the horizontal profiles). General trends of the local SMD are in reasonable agreement between model and experiment as shown in Figure 6. In both Figures 5 and 6 there is a computational noise, introduced by the fact that sampling of individual droplets in KIVA has been performed over an area with thickness of 4 mm and then SMD has been calculated. The asymmetry observed in the experimental measurements is probably due to scattering effects that can influence the measurement of LIF and Mie scattering signals in different ways. At present, it can also not be excluded that the injector has some non-ideal behaviour. PDPA measurement in progress will provide more details on this in the future.

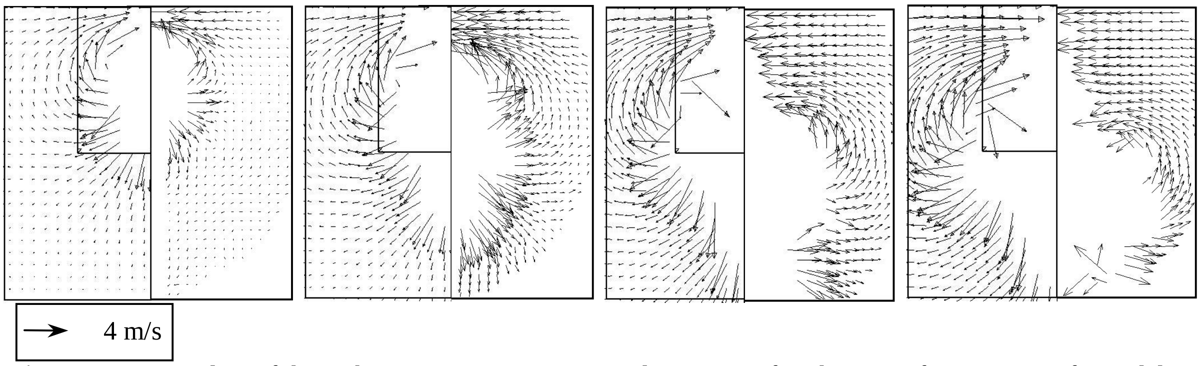

Figure 4. Vector plots of the ambient air at 0.4, 0.8, 1.3 and 1.8 msec after the start of injection. Left: model, right: experiment, note that the length of the experimental velocity vector for the two late times are scaled by ½

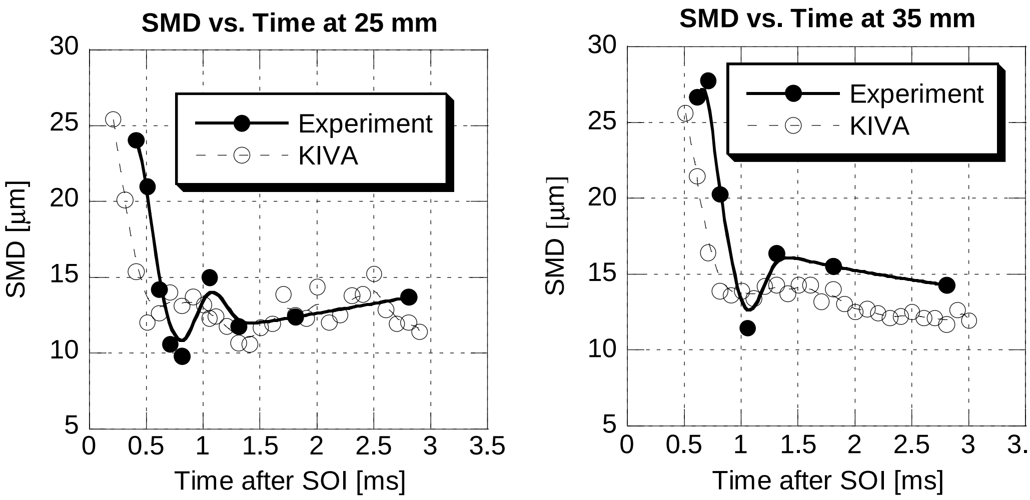

Figure 5. Temporal Variation of SMD, at 25 and 35 mm below the injector nozzle.

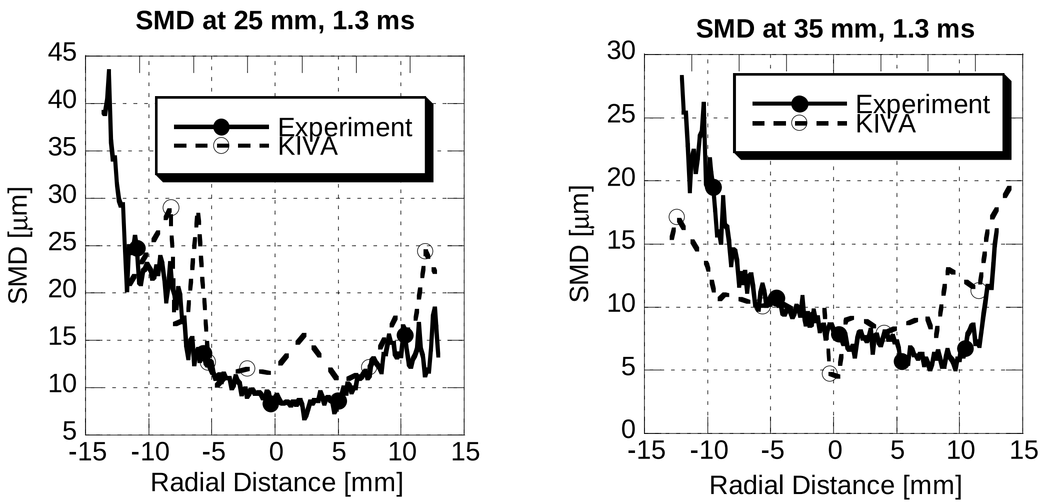

Figure 6. Horizontal Profiles of SMD and 25 and 35 mm, 1.3 msec after SOI.

Concluding Remarks and Future Work

An improved model for hollow-cone sprays with application in Direct-Injection Spark-Ignition engines has been developed based on earlier approaches, by taking the effect of spray swirl into consideration, to enhance the predictive capability of the model. The effect of the pre-spray has also been introduced and the numerical calculations have been successfully compared to experimental measurements. The information obtained on droplet size and velocity, as well as on ambient air velocity can lead to valuable conclusions towards achieving optimal mixing conditions in low ambient pressures.

Since injection under higher ambient pressures and temperatures is important in part-load operation of DISI engines, the current model has still to be validated using experimental data under these conditions. It is expected that fuel evaporation will become significant as temperature increases and an appropriate model has to be used. Furthermore, more validation is required for the pre-swirl spray, since this is the part of the spray that is most likely to impinge on the piston surface and cause high soot and unburned HC emissions. It is crucial to ensure that the droplet size and velocities of these droplets are accurately predicted, in order to be able to use an impingement model in full cycle simulations including injection, wall impingement, ignition, combustion and emission formation.

Acknowledgements

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