ILASS 2008
Sep. 8-10, 2008, Como Lake, Italy

Paper ID ILASS08-P-20

EFFECT OF TIME-VARYING IN-CLYLINDER THERMODYNAMIC CONDITIONS ON THE DEVELOPMENT OF MULTIPLE INJECTION DIESEL SPRAYS

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ABSTRACT
The effect of time-varying in-cylinder thermodynamic conditions on the development of dense Diesel sprays injected from a high-pressure multi-hole injector under conditions typical of direct injection, turbocharged, high-speed automotive Diesel engines is evaluated using a recently validated computational fluid dynamics spray model. The required initial conditions have been estimated by a multi-phase nozzle hole cavitation model, and the spray characteristics are predicted using a dense-particle Eulerian-Lagrangian stochastic methodology, implemented in the in–house GFS (General Fluid Solver) code. Focus is given on the effect of injection of small fuel quantities prior to the main pulse on the evaporating spray development assuming initial air thermodynamic conditions at values corresponding to start of injection, end of injection and interpolating the values from in-cylinder temperature and pressure profiles. The results enlighten the crucial role of detailed information about the in-cylinder thermodynamic conditions on the prediction of spray development, particularly during the initial liquid plume formation.

Keywords: Spray modelling; multiple injection; air thermodynamic conditions.

INTODUCTION

For the Diesel engines, there has been usually a trade-off between several targets, e.g. reducing exhaust emissions, engine noise and fuel consumption and simultaneous increasing specific outputs [1]. High-pressure, common-rail injection systems nowadays allow a very high degree of flexibility in the timing and quantity control of multiple injections, which can be used to obtain significant reductions in Diesel engine noise and emissions [2]. In particular, control of the main injection(s) reduces the temperature peaks, and hence yields lower amounts of NO_x [3]. There are numerous strategies to split a single injection into a series of sequential events using arbitrary referenced cam phases [3]. The 'Pilot' shot yields increased pressure in the engine during the compression stroke, thus reducing the start-up time, noise, and smoke level of the engine at the warm-up stage. The 'Pre-Main' injection event results in a reduction of ignition delay associated with combustion noise. The 'After-Main' shot provides oxidization of the exhaust gas, which reduces the amount of particulate matter. The 'Post-injection' occurs during the exhaust stroke, thus increasing the hydrocarbons at the exhaust, which increases the efficiency of the $DeNO_x$ catalyst. To make multiple injection systems widely practical in automotive industries, it is necessary to provide a very stable timing associated with four factors: the start of injection events, the injection duration of each event, the dwell interval between shots, and the delay factor regarding the time needed for pressure propagation along the high-pressure pass [3].

The injection strategy significantly affects the spray penetration length and rate, which are the parameters commonly used to judge fuel spray performance [4]. Shorter spray penetration may be of an advantage where it reduces fuel impingement, but in larger engines may inhibit maximum air utilisation. Moreover fuel vaporisation, temporal variation of spray penetration and spray dispersion are important factors for the combustion process since they provide the transport of the fuel vapour into the chamber and the mixture of air and fuel vapour to the required chemical ratio provides suitable conditions for autoignition. Correlation of liquid and vapour penetration under highly vaporising conditions typical of direct injection, turbocharged, high-speed automotive Diesel engines have been reported by [4], showing that the vapour does not penetrate further than the liquid core until the maximum liquid penetration length is reached. After this period the vapour continues to penetrate into the chamber. The correct estimation of these spray parameters under the complex matrix of operating conditions actually implemented by the automotive industry requires sophisticated research tools, and innovative CFD methodologies are currently going into this direction.

The present paper presents the continuation of the work recently presented in [5-6], where the effect of fuel nozzle design, fuel composition and temperature, multiple injection timing and strategies on the development of evaporating Diesel sprays was predicted by the GFS spray model [7-8]. This work aims to add further insight on the effect of in-cylinder air thermodynamic conditions on the development of high-pressure multiple injection Diesel sprays. In the next sections of the paper the mathematical modelling of the CFD code used for the purposes of the present investigation is briefly described, whereas detailed information can be founded in the quoted references; then the various test cases are presented followed by a description of the results and a summary of the most important conclusions.

MATHEMATICAL MODELLING

In this section a brief description of the numerical models used is presented, whereas the mathematical formulation and validation of the CFD tools can be found in [7-10]. The simulation of the spray development is performed using the

Eulerian-Lagrangian approximation adopted in the in-house GFS multi-phase flow solver. The spatial and temporal discretisation methods are based on the finite volume approach using second and first order schemes, respectively. Turbulence is simulated by the standard two-equation *k-ε* model. The spray model implements a dynamic local grid refinement technique and a coupling between the continuous and dispersed phases that result to better resolution of the interaction between the two phases and to significantly reduced sensitivity of model predictions on the numerical grid [7]. The internal nozzle flow is simulated by an Eulerian-Lagrangian multi-phase cavitation model [9], which provides the liquid initial properties at the exit of the injector nozzle, in combination with the so-called cavitation-induced atomisation models [10]. Droplet drag coefficient is modelled considering the effect of droplet movement in an evaporating environment, presence of other droplets, internal flow circulation and non-spherical droplet shape [11]. The multi-component fuel vaporisation is predicted assuming that the fuel mixture is composed by a discrete number of pure hydrocarbons, as reported in [8], taking into account effects such as temperature variation within the droplet, diffusion between the different fuel compounds, gas solubility as well as departure from ideal behaviour in the phase equilibrium relationship. Droplet aerodynamic break-up is modelled with the aid of the correlations reported in [12], while droplet turbulent dispersion is modelled according to [13] and droplet collisions according to [14].

TEST CASES

Sprays from high-pressure multi-hole diesel nozzles have been investigated, where details of the nozzle geometry can be found in [5]. Two injection profiles have been selected, as predicted by the multi-phase nozzle hole cavitation model of [9], and the corresponding graphs are presented in Figure 1, which shows the volumetric flow rate for the cases without and with pilot injection of a small quantity of fuel prior to the main injection pulse with dwell-time equal to 0.5ms. In order to investigate the effect of in-cylinder air thermodynamic conditions on the spray development characteristics, three different scenarios have been selected. The first one has variable in-cylinder thermodynamic characteristics according to the profiles shown in Figure 2, which presents the air pressure and temperature along the engine period between 30 crank angles (CA) before and 10 crank angles after top dead centre. The start of injection is fixed at -30CA for both injection cases. The temperature increases from 850K to 1100K for the case without pilot injection and to the same value after having reached its maximum value at top dead centre equal to 1150 for the case with pilot injection, while the pressure increases from 35bar up to 85bar and 95bar for the two injection cases, respectively. The second scenario has fixed in-cylinder air conditions corresponding to the start of injection (-30CA), while the third scenario presents fixed in-cylinder air thermodynamic conditions at the end of injection (-5.6CA and +5.7CA for the cases without and with pilot injection, respectively). Diesel fuel properties have been approximated with the ones of n-$C_{13}H_{28}$. Thanks to the symmetry of the problem, the spray development has been predicted performing 2-D axisymmetric simulations using an unstructured grid refined at the area near the nozzle, composed by 12×10^3 triangular cells with minimum cell size equal to 0.15mm along the injection direction [5].

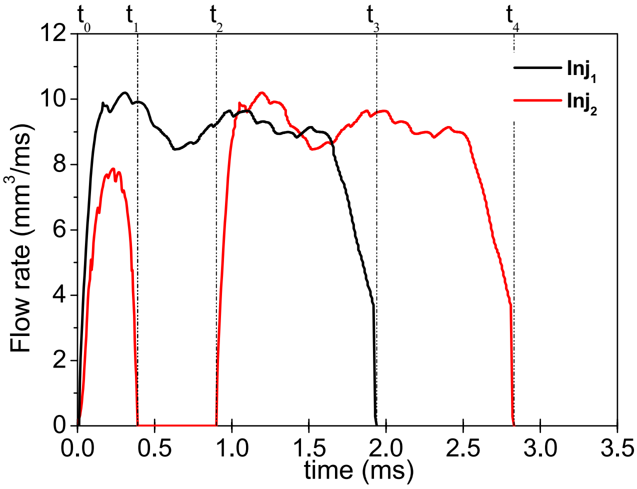

Figure 1: Predicted temporal profiles of volumetric flow rate for the case with only main (Inj_1) and the case with pilot+main injection pulses (Inj_2).

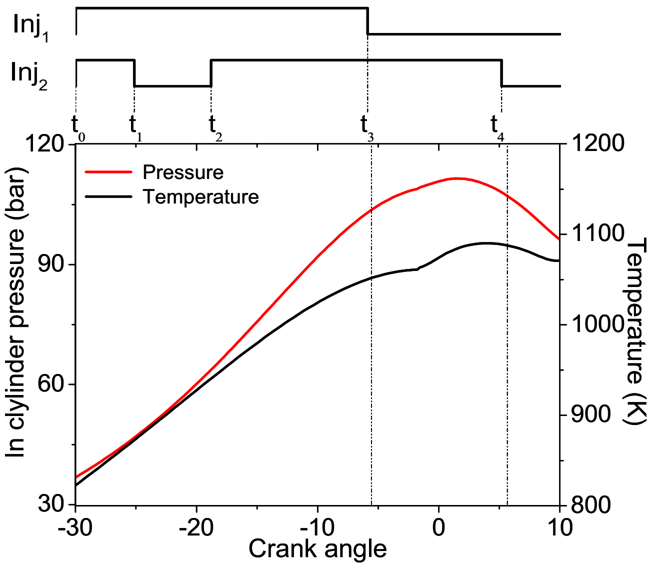

Figure 2: In-cylinder pressure and temperature temporal profiles during the injection period.

RESULTS

This section presents the results from the various simulations performed. The effect of in-cylinder thermodynamic conditions on the spray liquid and vapour penetration temporal profiles for both injection cases are presented in Figure 3. The graphs show that liquid penetration during main injection stops at the same distance from the injection nozzle exit independently on the injection of a small amount of fuel prior to the main injection pulse. On the other hand the vapour penetration curve is significantly affected by the pilot injection, since its slope is determined by the initial stages of liquid spray development, until the liquid has reached its maximum distance from the injector location and vaporises. As far as the effect of in-cylinder thermodynamic conditions on the same spray parameters, the graphs show that for the case without pilot injection the liquid penetration under variable in-cylinder air conditions lies in between the curves corresponding to fixed injection condition at start and end of injection, while the corresponding vapour penetration almost coincides with the vapour penetration for the case with air thermodynamic conditions at start of injection.

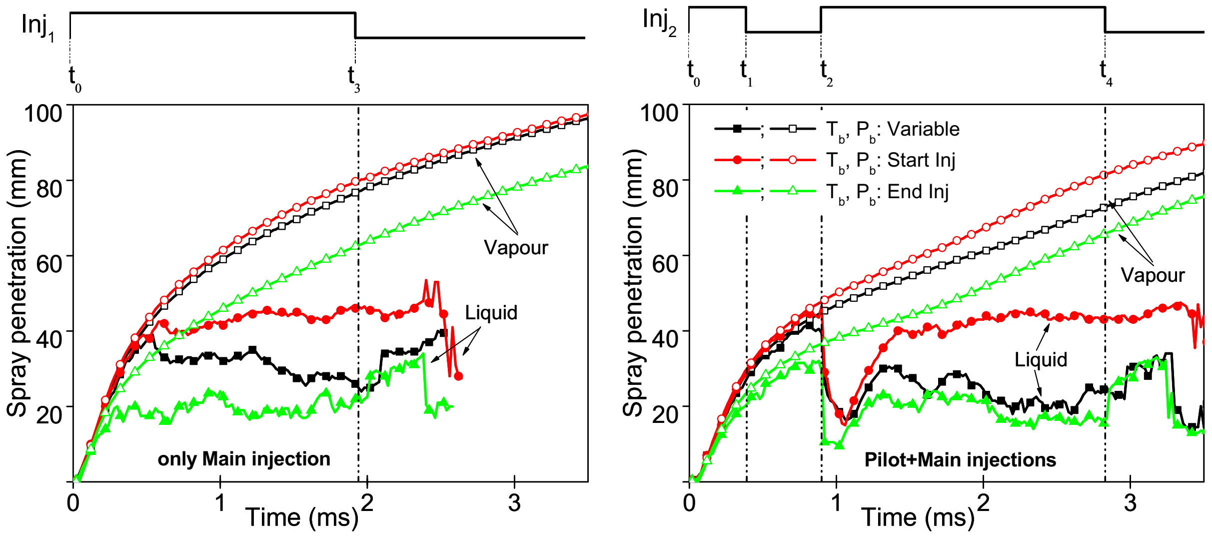

Figure 3: Effect of in-cylinder thermodynamic conditions on liquid and vapour temporal profiles; (left) Inj_1 and (right) Inj_2.

The reason of the first effect is that the liquid vaporisation rate is greater for the case with fixed air thermodynamic conditions at end of injection since pressure and temperature are both higher compared to the other cases, during the initial spray development until it has reached its maximum distance from the injector nozzle. Consequently the liquid penetrates less compared to the other two cases and this also affects the vapour penetration, which slope, as stated before, depends on the initial development of liquid plume. The vapour penetration for the cases with variable in-cylinder air conditions and fixed values at start of injection are rather similar, since the liquid penetration during the initial stage of spray development is almost the same penetrating in similar air environments. A first conclusion from this investigation is that vapour penetration is not significantly affected by the air thermodynamic conditions, provided that the spray initially develops under similar conditions. This enlightens that the vapour convection in flow fields under highly vaporising environment is a substantial dynamic process, while the liquid spray development is mainly driven by thermodynamic mechanisms. The graphs in Figure 3b show the corresponding liquid and vapour penetration for the three in-cylinder thermodynamic scenarios for the case with pilot injection. The results show that liquid penetration under variable in-cylinder pressure and temperature is similar to the cases with fixed air conditions at start and end of injection during pilot and main injection, respectively since the corresponding environments are similar. Moreover the vapour convection in the flow field is accelerated by the liquid injected during the main injection, with the penetration curve changing its slope. Consequently the assumption of fixed air thermodynamic conditions is rather severe for both liquid and vapour penetration predictions. These conclusions are remarked by the results presented in Figure 4, which show the spatial distribution of air-fuel equivalence ratio, in the range between 0.8 and 1.2 around the stoichiometric value, at the end of injection for the six cases investigated. The graphs reveal that the stoichiometric region is convected further downstream in the case of fixed air thermodynamic conditions equal to start of injection, since the air density and consequently the aerodynamic drag are lower and moreover the liquid has penetrated further before stopping thus pushing the vapour further down. The results also confirm that pilot injection contributes up to 10% more stoichiometric fuel vapour present in the area of observed auto-ignition sites [5] independently on the air thermodynamic conditions.

The following results present the effect of air thermodynamic conditions on the liquid mean axial velocity temporal profile on the centreline at 15mm from the injector nozzle exit, for the cases without and with pilot injection. The graphs in Figure 5 reveal that the liquid velocity during the main injection period is totally unaffected by pilot injection. The liquid injected under fixed air thermodynamic conditions at start of injection is faster than the other two cases, due to the reduced aerodynamic drag as a consequence of the lower air density, around 15kg/m^3, which is almost half of the case with fixed air thermodynamic at the end of injection. The liquid velocity during the pilot pulse seems not to be affected by the air thermodynamic conditions, since the interval of time is rather limited to left aerodynamic drag playing a substantial effect. The wider liquid velocity dispersion for the case with fixed air conditions at end of injection is due to the fact that the distance where the liquid velocity is calculated is close to the liquid spray tip and consequently to the most vaporising region.

Finally, these results enlighten the importance of considering detailed time-varying in-cylinder air thermodynamic conditions when predicting the spray behaviour under highly vaporising scenarios typical of direct injection, turbocharged, high-speed Diesel engines.

CONCLUSIONS

The development of multiple injection sprays from a high pressure multi-hole Diesel nozzle has been predicted using a recently validated dense spray model. The effect of time-varying in-cylinder air thermodynamic conditions on the spray characteristics has been investigated in terms of liquid and vapour penetration, air fuel ratio spatial distribution and liquid mean axial velocity. The results enlighten the crucial role of detailed information about the in-cylinder thermodynamic conditions on the prediction of spray development, particularly during the initial injection period. The assumption of fixed air thermodynamic conditions is proved to be rather severe for both liquid and vapour penetration predictions, moreover pilot injection is shown to increase the stoichiometric fuel vapour mixture present in the area of observed auto-ignition sites, independently on the in-cylinder thermodynamic conditions.

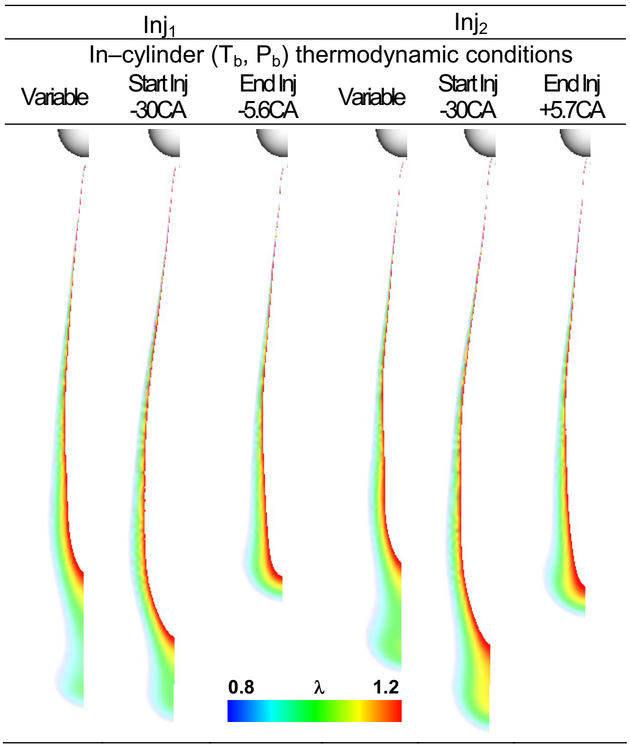

Figure 4: Effect of pilot injection and air thermodynamic conditions on λ distribution for the six cases investigated.

ACKNOWLEDGMENT

The authors would like to acknowledge Dr E. Giannadakis for his contribution in the internal nozzle flow calculations.

REFERENCES

1. Y.E. Selim, Effect of engine parameters and gaseous fuel type on the cyclic variability of dual fuel engines, Fuel, 84: 961–971, 2005.
2. M. Badami, F. Millo, F. Mallamo, E.E. Rossi, Influence of multiple injection strategies on emissions, combustion noise and bsfc of a DI common-rail Diesel engine, SAE Paper 2002-01-0503, 2002.
3. M.M. Ismailov, Stability evaluation of an accurately controllable multiple injection system, Experiments in Fluids, 37: 177–186, 2004.
4. D.A. Kennaird, C. Crua, J. Lacoste, M.R. Heikal, M.R. Gold, In-cylinder penetration and break-up of diesel sprays using a common-rail injection system, SAE Paper 2002-01-1626, 2002.
5. S. Tonini, E. Giannadakis, M. Gavaises, A. Theodorakakos, G.E. Cossali, M. Marengo, Effect of dwell time on multi-component fuel vaporization of high-pressure diesel sprays injected from cylindrical and reverse tapered multi-hole nozzles, Proc. 21st ILASS Conference, Sept 10-12, Mugla, Turkey, 2007.
6. S. Tonini, M. Gavaises, A. Theodorakakos, G.E. Cossali, Numerical investigation of multiple injection strategy on the development of high-pressure Diesel sprays, submitted to Fuel.
7. S. Tonini, M. Gavaises, A. Theodorakakos, Modelling of High-Pressure Dense Diesel Sprays with Adaptive Local Grid Refinement, Int. J. Heat and Fluid Flows, 29, 427-448, 2008.
8. Tonini, S., Gavaises, M. and Theodorakakos, A., The Role of Droplet Fragmentation in High-Pressure Evaporating Diesel Sprays, in Press Int. J. Thermal Sciences, 2008.
9. E. Giannadakis, M. Gavaises, C. Arcoumanis, Modelling of cavitation in Diesel injector nozzles, accepted J. Fluid Mechanics, 2008.
10. C. Arcoumanis, M. Gavaises, Linking the nozzle flow with spray characteristics in a Diesel fuel injection system. Atomization and Sprays, 8: 179-197, 1998.
11. Z.G. Feng, E.E. Michaelides, Drag coefficients of viscous spheres at intermediate and high Reynolds numbers. J. of Fluids Engineering-Transactions of the ASME, 123(4): 841-849, 2001.
12. C. Arcoumanis, M. Gavaises, B. French, B., Effect of fuel injection processes on the structure of diesel sprays. SAE 970799, 1997.
13. P.J O'Rourke, Statistical Properties and numerical implementation of a model for droplet dispersion in turbulent gas, J. of Computational Physics, 83: 345-360, 1989.
14. M. Gavaises, A. Theodorakakos, G. Bergeles, G. Brenn, Evaluation of the effect of droplet collisions on spray mixing. Proc. IMechE, 210: 465-475, 1996.

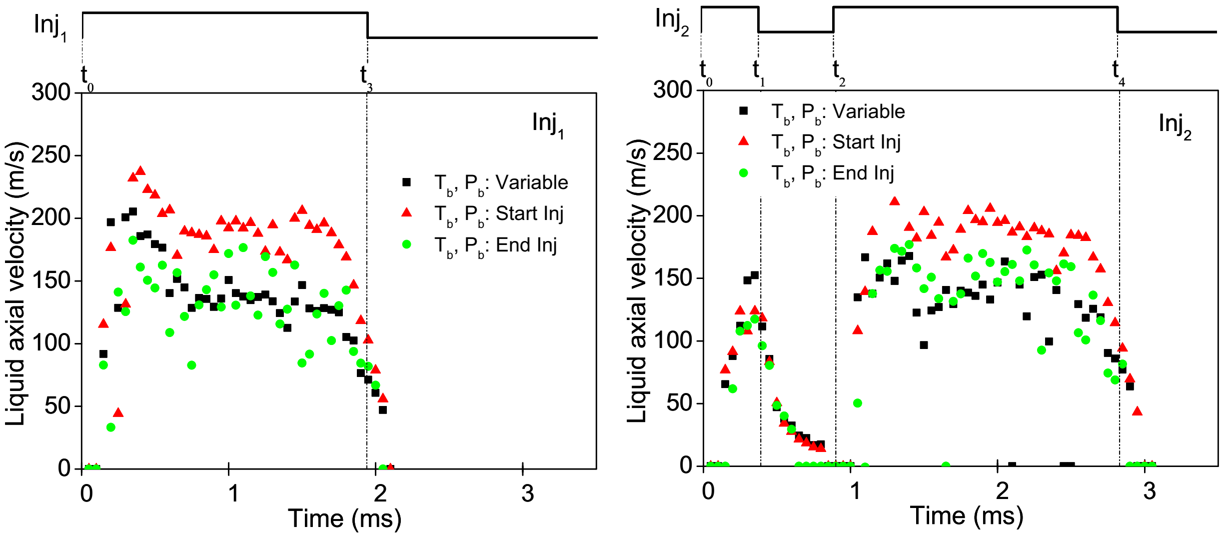

Figure 5: Effect of in-cylinder thermodynamic conditions on liquid axial velocity temporal profiles at 15mm from the injector hole exit along the spray centreline; (left) Inj$_1$ and (right) Inj$_2$.