NUMERICAL SIMULATIONS OF DIESEL FUEL SPRAYS

Marcel Diviš, Jan Macek, Karel Kozel
Czech Technical University in Prague, Faculty of Mechanical Engineering,
Josef Božek Research Center, Technická 4, Praha 6
(CZ-16607), Czech Republic
phone: +420 2 2435 1827, +420 2 2435 2504, +420 2 2435 7365
e-mail: Marcel.Divis@fs.cvut.cz; macek@fsid.cvut.cz; Karel.Kozel@fs.cvut.cz

Abstract

The contribution reviews our recent research activities on numerical simulations of diesel fuel spray evolution. The simulations are performed by means of an in-house mathematical model. The developed model is capable of predicting the two-phase flows constituted by the dispersed liquid phase (droplets) injected into gaseous environment. Both the multi-component compressible gas-phase flows as well as the "droplet-phase" flows are solved using governing equations written in Eulerian coordinates. The conservation of mass, momentum, and energy is balanced on finite volumes with arbitrarily movable boundaries. Thus, the model enables the computation of movable boundary problems, which facilitates the solution of in-cylinder flow with moving engine piston. The model features the two-way coupling between phases in mass, momentum, and energy equations. The phenomena as spray induced gaseous flow, gas-to-droplet heat transfer, and fuel evaporation with consequent vapor transport are, therefore, taken into account. The predictive capabilities of the developed model have been tested in simplified, axisymmetric flow cases of diesel fuel injection process. The results of these computations are presented.

1. Introduction

Spray formation is an essential process in fuel combustion of direct-injection (DI) diesel engines. It requires understanding and control to deliver low emissions and high efficiency of engine performance. Recent advances in fuel injection system technology have made it possible to control accurately the fuel injection process. This, on the other hand, calls for an in-depth analysis of the influence of rate-of-injection (ROI) shaping on fuel spray evolution, mixture formation and subsequent processes of combustion and emission production. Detailed temporal and spatial information are prerequisites for such an analysis. Besides being time consuming and costly experimental techniques, the methods of computational fluid dynamics (CFD) are being proven to be so useful an aid that they have received increasing attention over the past years.

The aim of this study is to develop an in-house CFD code that would be capable of adequate description of the two-phase flows constituted by liquid sprays injected into gaseous environment at conditions prevailing in diesel DI engines.

2. Basic methodology

The multidimensional mathematical model of the two-phase flow has been formulated solely on the basis of the Eulerian approach. In correspondence to this, the governing equations for both phases are developed starting with the balances of basic laws of conservation over an arbitrary control volume. As seen in Fig. 1, the volume V is bounded by the surface ∂V, which can move arbitrarily at the velocity $\vec{w}_B$. The volume contains a mixture of a gas (index G) and a dispersed liquid (index L) each of which having its own flow field. Thus, the balance of a generic, volume specific, quantity ϕ over this volume may be written as follows,

$$\frac{d}{dt}\int_{V(t)} \phi\, dV = -\oint_{\delta V} \phi(\vec{w}-\vec{w}_B)\cdot\vec{n}\, dS + \oint_{\delta V} \vec{s}_\phi^{\,I}\cdot\vec{n}\, dS + \int_{V(t)} s_\phi^{II}\, dV \tag{1}$$

The terms in RHS stand for convective fluxes, surface sources (e.g. viscous forces, heat conduction, or molecular diffusion), and volume sources (e.g. gravity forces, combustion, inter-phase transfer), respectively. The arbitrarily movable boundary of the control volume is respected by using the relative velocity of flows $\vec{w}$ (i.e. velocity of gas $\vec{w}_G$, or droplets $\vec{w}_L$) to that of volume boundary $\vec{w}_B$ in convective term definition. This formulation enables us to employ the model directly to the in-cylinder computations with moving piston.

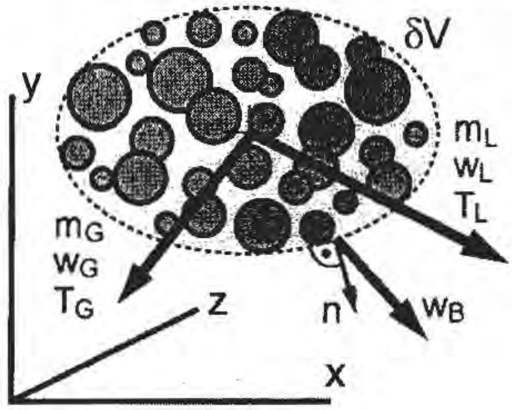

Figure 1. An Eulerian control volume arbitrarily chosen within the domain of two-phase flow

The governing equations for the both gas- and liquid-phase flows are derived by balancing the basic laws of conservation (mass, momentum, energy) in terms of inserting the appropriate, conserved quantities into Eq. (1). The balanced quantities can be summarized into vectors in the form as follows,

$$_m\phi_L = \begin{bmatrix} _m n_L \\ _m\bar{\rho}_L \\ _m\bar{\rho}_L\ _m\vec{w}_L \\ _m\bar{\rho}_L\ _m h_L \end{bmatrix}; \qquad \phi_G = \begin{bmatrix} \rho_G \\ _s\rho_G \\ \rho_G\,\vec{w}_G \\ _s\rho_G \cdot\, _s\tilde{h}_G \end{bmatrix} \tag{2}$$

where for the liquid phase, $_m\phi_L$, we balance the droplet number-density, bulk liquid density, momentum, and enthalpy, respectively. For the gas phase, ϕ_G, the balances of density, partial density of species (index s), momentum, and total enthalpy $(\,_s h_G + w_G^2/2)$, respectively, are used. The other terms in Eq. (1) will not be detailed here, see Ref. [1, 2] for more information.

3. Liquid phase description

Up to now, the dispersed, liquid phase was perceived in the model as filling space i.e. as continuum. However, the physical reality is that the dispersed phase consists principally of empty space with an occasional bits of matter — droplets. This discrete character of the liquid phase plays a role in inter-phase transfer of mass, momentum, and energy, which takes place through the interfacial area, see the next section.

For the reconstruction of the discrete distribution of droplets in continuous "droplet-phase" flow-field described by Eq. (1), a twofold formulation of liquid-mass balance is employed, see also ${}_m\phi_L$ in Eq. (2). On the basis of droplet number density and droplet bulk density balances, the instantaneous single droplet mass can be evaluated at any point of the flow simply as ${}_m m_D = {}_m\rho_L / {}_m n_L$.

To respect correctly the behavior of droplets of different diameters (as they can be found in typical diesel fuel sprays), a discrete approximation of the continuous droplet size distribution in the spray is used, sometimes referred to as multi-continua approach. Thus, separated flow-field is solved for each from a number of droplet "classes" while each class represents a given droplet diameter range. The index m in Eq. (2) refers to this discretization.

4. Two-way phase coupling

The coupling between both phases takes place through the interfacial processes of mass, momentum, and heat transfer. For spray applications, two-way coupling needs be used to respect correctly the mutual effects between the flows of both phases. In practical spray problems, the analysis involves so many droplets that it is necessary to avoid the costly solutions of detailed flow-field around each droplet. Making the use of approximate sub-grid models for the interfacial transfer phenomena is, therefore, inevitable. Analytical models can be developed, assuming the quasi-steady, spherically symmetric transfer processes, depending on transport properties and on the nature of boundary-layer flow parametrized in terms of average similarity numbers, see Ref. [4]. The coupling between phases appears in governing equations as special source terms, see discussion to Eq. (1).

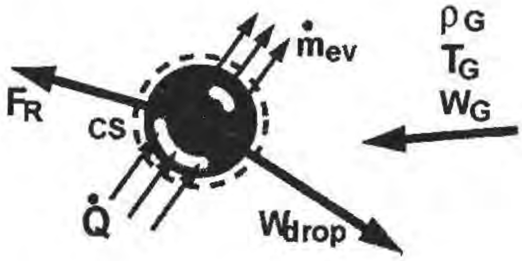

Figure 2. Interfacial transfer processes for evaporating droplet moving in carrier gas

5. ROI calculation

For ROI calculations, a hydrodynamic model of injection process for all the commonly used fuel injection systems, including electronically controlled common-rail systems (CRS) and electronic unit injectors, has been developed. For CRS, the model involves equations governing the one-dimensional unsteady flow in a high-pressure piping with the boundary conditions at the rail (constant pressure) and at fuel injector, where the zero-dimensional model is solved accounting for equation of motion of the nozzle needle and the continuity equation for flow through the needle seat and multi-hole nozzle orifice. The model also includes the effect of the pressure multiplicator which is typically used in common-rail injectors to control needle lift. Next, the influences of compressibility of fuel and deformation of pipe-wall material are taken into consideration. Both single and multiple injection patterns calculations are possible. Fig. 4 gives an example of ROI profile computed by means of the hydrodynamic model.

6. Results

The computations, the results of which are reviewed in this section, were calculated for the simplified case of axisymmetric in-cylinder flows. This simplified geometry has been adopted to cut down the computational costs during the stage of model development. Thus, a simple computational domain in the shape of cylindrical sector can be used, as sketched in Fig. 3. Correspondingly, the fuel-spray has a shape of hollow-cone. The engine piston movement is considered. The mesh consists of 204x63 cells in radial and axial direction, respectively.
The simple geometry of the computational domain used would correspond to an engine with a flat piston. Therefore, a test engine was considered in computations, which basic cylinder geometry corresponds to that of the real diesel engine (bore 102mm, stroke 110mm), however, a flat piston is used. Due to absence of a toroidal combustion chamber in the piston crown, it is impossible to reach a conventional high compression ratio while ensuring enough space for fuel-spray evolution. The test engine has a compression ratio of 8. Therefore, the initial air-charge parameters were tuned to maintain the in-cylinder pressure and temperature at TDC comparable to values found in the real diesel engine. Thus, despite the simplified computational geometry, the spray evolution is computed at nearly realistic in-cylinder conditions.

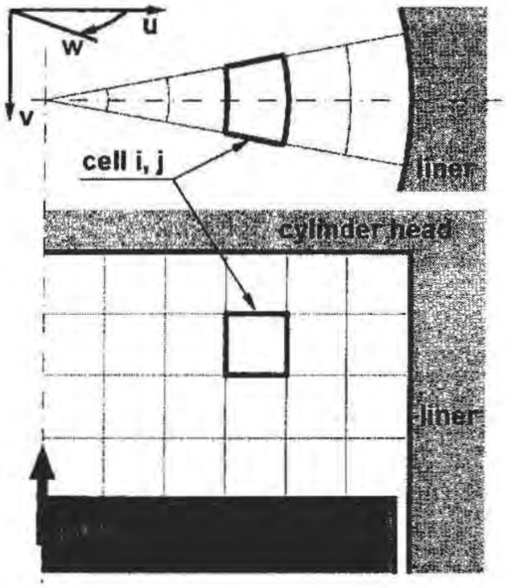

Figure 3. A sketch of the computational domain for axisymmetric ibw-case

The engine was assummed to be equipped with Common Rail injection system. The boundary conditions of nozzle flow rate and initial fuel velocity are calculated using the intantaneous values of injection pressure and mass flow rate obtained by means of the hydrodynamic model, as shown in Fig. 4. The injection profile is split into the two patterns i.e. pilot and main injection. The pilot injection holds about 10 % of the fuel amount delivered. Initial fuel temperature is constant and set to 350 K.

The initial droplet size distribution is evaluated using the empirical distribution function proposed by Hiroyasu and Kadota, see Ref. [3]. The droplets are sort out into five droplet classes with corresponding droplet diameter ranges: $0 \div 8$, $8 \div 17.5$, $17.5 \div 27$, $27 \div 37$, $37 \div 48\mu m$. No secondary droplet breakup, coallescences or other dense-spray effects are taken into account.

Fig. 5 shows only the overall geometry of the computational domain. The details of computed flow-fields are plotted in following Fig. 6 and 7. The instants at which the flow-fields are displayed are identified using the flags A, B, C, and D in Fig. 4. The upper and middle plotts in Fig. 6 and 7 show the fuel concentrations in terms of fuel/air equivalence ratio* for the liquid fuel and fuel vapors, respectively. The bottom plotts show the gas-temperature fields. Due to the use of flat piston, there is no significant vortex flow generated by the piston movement during the compression stroke, that is why the plotts presented show only the situation after injection commences.

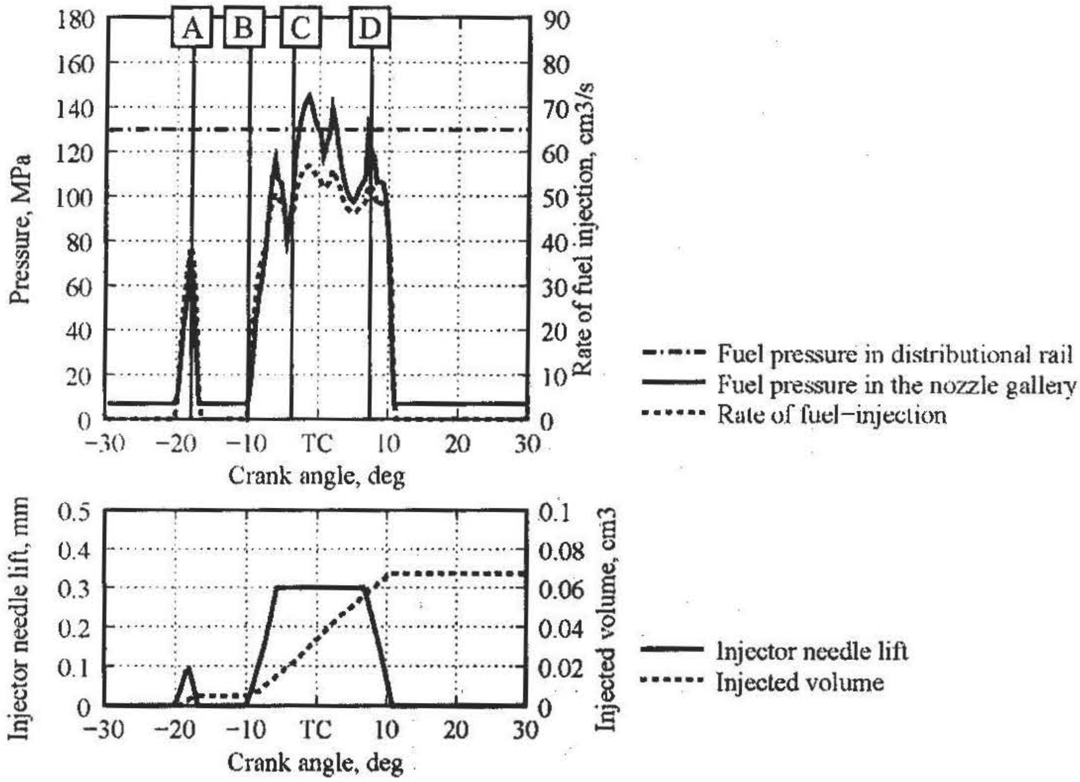

Figure 4. Results of ROI computations with a pilot injection; CRS of a commercial vehicle engine: bore 102mm, stroke 110mm; computed for maximum power 75 kW at 2600min^{-1}; fuel pressure in rail of 130MPa

The case (A) shows the situation within the pilot injection. Due to relatively low injection pressures, fuel is discharged at low velocities and spray with lower maximum penetration results. The droplets gradually evaporate and thus fuel vapor region occurs close to the spray tip. The depression in gas temperature field can also be observed, which is caused by rapid heat transfer to evaporating droplets. The case (B) shows the flow-field imediately before the start of main injection. All the fuel, which was injected during the pilot injection, has already evaporated. Vapor-rich region has spread further from the injector. Maximum vapor concentration are comparable to those of stoichiometric mixture (F/A eq. ratio $\approx$ 1). At about this instant one would expect the spontaneous ignition. The case (C) displays the begining of the main injection. Due to large pressure differences at the injector, fuel is injected at high velocities, which results in fast spray penetration into surrounding gas. The vapor region, which has formed from the fuel evaporated during pilot injection, is being blown away from the injector. The gas temperatures withing the spray further decrease. The case (D) shows the flow-fields close to the end of main injection. The spray has approached the piston surface and its interaction with solid wall results in occurence of significant vortexes. The vapors are blown

*ratio of fuel mass to air mass related to that of stoichiometric mixture around by the spray induced vortex flow. Maximum vapor concentrations observed close to the spray tip greatly exceed those of stoichiometric mixture. The depression in gas-temperature field has also become significant.

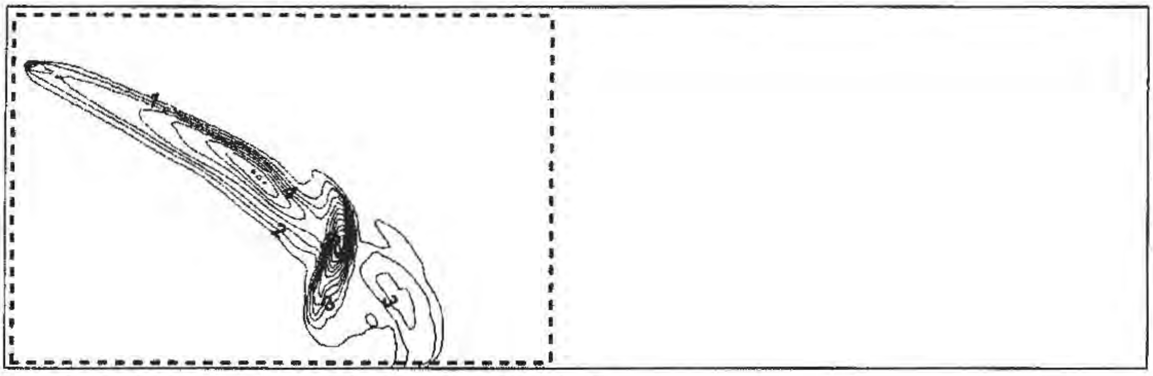

Figure 5. Computational domain for the test engine with a fat piston; left boundary corresponds to cylinder axis, right boundary to cylinder liner; dashed rectangle marks out the area plotted in the following details, see Fig.6 and Fig.7

7. Conclusions

An Eulerian multidimensional mathematical model has been developed for the analysis of diesel fuel sprays. It comprises the unsteady compressible multi-component gas-phase and liquid-phase flows with two-way coupling between the phases, taking into account interfacial mass, momentum, and heat transfer. The formulation of governing equations on Eulerian control volumes with arbitrarily movable boundaries facilitates movable boundary problem calculations. As a benefit of the approach chosen, the model features transparency, modularity, and clear droplet-to-gas interface, ensuring the conservativness. Several test computations have been performed for simplified axisymmetric flow-case of in-cylinder flow using a test engine with a flat piston. The presented results do not correspond to the real geometry of the diesel injection process using common multi-hole injectors, nevertheless, they illustrate the qualitative features of evaporating fuel sprays.

Acknowledgments

This research has been subsidized by the Research Center project #LNOOB073 of the Ministry of Education, the Czech Republic. This support is gratefully acknowledged.

References

[1] Diviš M., Macek J. and Kozel K.; 'Eulerian multidimensional model for computing the fuel sprays," in *SAE Technical Paper 2004-01-0537*, (USA), Society of Automotive Engineers, Inc., 2004.

[2] Macek J. and Steiner T.; "Advanced Multizone Multidimensional Models of Engine Thermoaero-dynamics"in *Proceedings of 21st CIMAC Congress Interlaken*, (London), 1995.

[3] Heywood J.; *Internal Combustion Engine Fundamentals.* New York: McGraw-Hill, Inc., 1988.

[4] Bird R., Stewart W. and Lightfoot E.; *Transport Phenomena.* New York: John Willey & Sons, Inc., 2002.

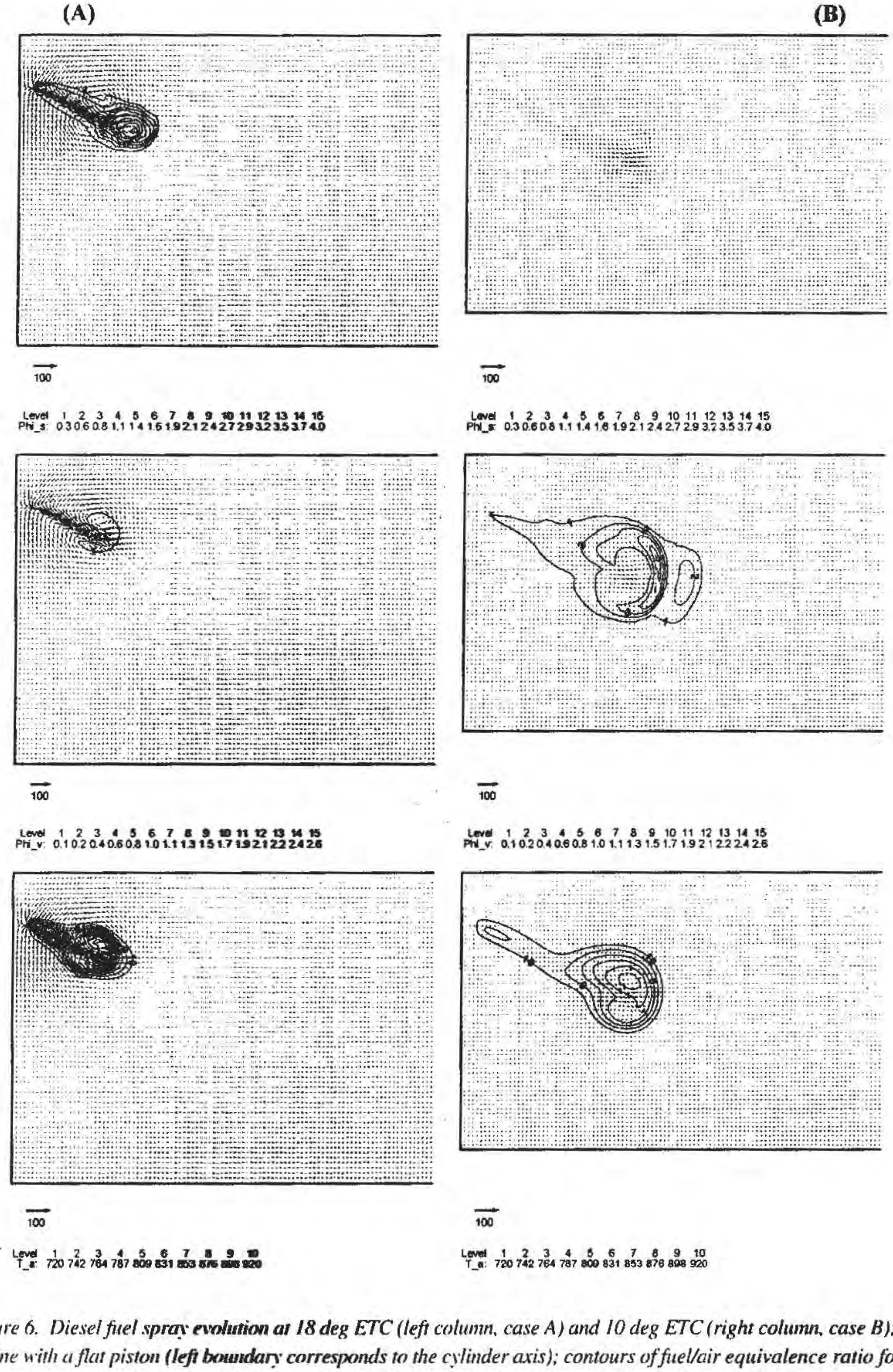

Figure 6. Diesel fuel spray evolution at 18 deg ETC (left column, case A) and 10 deg ETC (right column, case B); test engine with a flat piston (left boundary corresponds to the cylinder axis); contours of fuel/air equivalence ratio for liquid fuel (upper), fuel vapors (middle), and temperature of gas (bottom); ROI according to Fig. 4, five classes of droplets, initial spray-cone angle of 130 deg.

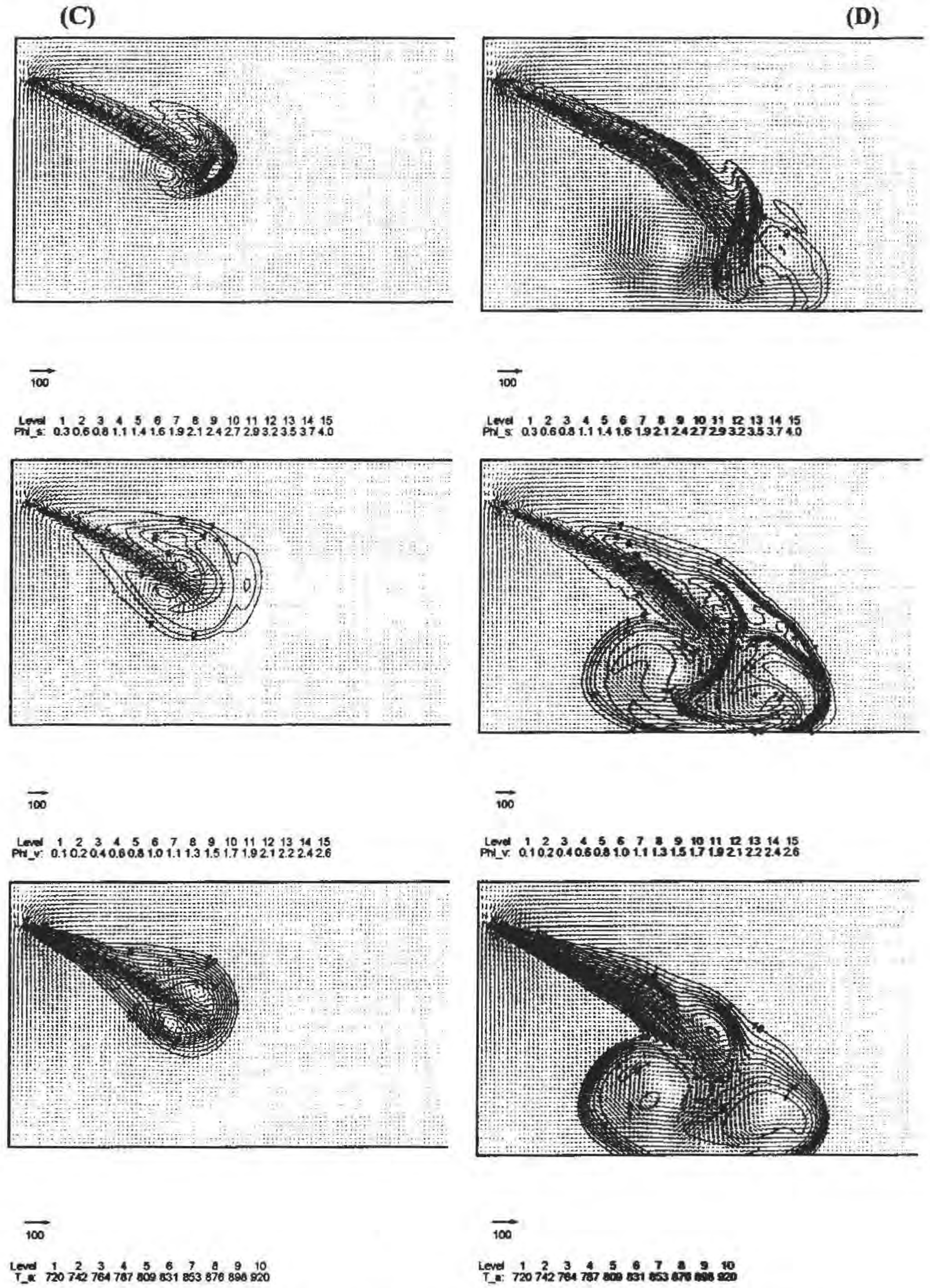

Figure 7. Diesel fuel spray evolution at 4 deg ETC (left column, case C) ***and 8 deg ATC*** *(right column, case D); test engine with a flat piston (left boundary corresponds to the* ***cylinder axis); contours*** *of fuel/air equivalence ratio for liquid fuel (upper), fuel vapors (middle), and temperature* ***of gas (bottom); ROI*** *according to Fig. 4, five classes* ***of droplets,*** *initial spray-cone angle of 130 deg.*