Numerical Simulation of Unsteady Nozzle Flow and Spray Formation under Diesel Engine Conditions

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Abstract

In this paper a numerical approach for the prediction of the unsteady atomization process of liquid fuel in Diesel engine is presented. The dependences between the transient nozzle flow and spray formation are analysed. For that purpose models to simulate unsteady nozzle flows including the transient behaviour of cavitation and two-phase atomization process are employed. Results of transient flow through various 3D nozzle shapes (one- and multi-hole nozzle) and the resulting spray development are discussed. The flow predictions agree well with quantitative characteristics of nozzle flows and spray structures and with experimental results obtained for the case of the flow in a high speed diesel injector.

Introduction

The quality of liquid atomization is probably the most essential factor for reducing emissions in Diesel engines. The atomization process depends among other things on the velocity of the fuel exiting the injection nozzle and on the extent of cavitation within the nozzle. Exit velocity modulations strongly influence the break-up processes, the spray penetration and also the inter-droplet and wall-droplet interactions.

The internal flow through diesel fuel injector nozzles is very important for the reduction of emissions. But the relation between the injector flow and spray formation appears to be quite complicated. A typical nozzle is roughly 0.2 *mm* in diameter and 1 *mm* long. The fluid is moving at several hundred meters per second, making measurements of the flow difficult. Furthermore, cavitation within the nozzle and the unsteady nature of the flow complicates both, experiments and computations. Despite the importance of injector nozzle flows, the difficulties associated with their direct observation are most likely the reason for the limited the number of the available experimental data.

Chaves, Obermeier [2-4] and Kubitzek [11] studied the relation between unsteady nozzle flows and spray structures modulations. Considering a time-dependent flow they have shown that cavitation can decrease due to increasing the supply pressure which is in contrast to observations made for steady conditions.

Schmidt, Rutland and Corradini [16] studied numerically the formation of cavitation in different 2D nozzles for stationary flows. They also studied the effect of the nozzles shape on the development of cavitation [17] and found that the results of the single bubble calculations in 2D nozzles were acceptable and similar to simulations considering an axisymmetric nozzle. However the calculated behaviour of flows through an asymmetric nozzle was considerably different from the flow through a plan orifice. The asymmetric flow field tended to exhibit strong transients which would have a dramatic influence on the spray breakup.

The transient nature of cavitation under stationary flow conditions has been investigated numerically by Chen and Heister [5]. Their results indicate that partially cavitating flows are typically periodic, with a period of the order of the orifice transit time.

Time-dependent cavitation phenomena induced by pressure variation are presented in [7, 10]. In these papers the disappearance and re-occurrence of cavitation have been reproduced in numerical simulations. Further, non-stationary effects in 2D nozzles generated injecting water have been computed in [19, 20]. In these studies cavitation in an injection nozzle under time-depended inlet pressure conditions were investigated.

Among recent publications the paper of Marcer et al. [12] deserves attention. They applied a VOF method to simulate a stationary Diesel injector flow considering three-phase flow (liquid, vapour Diesel fuel and external gas). Further, Giannadakis et al. [8] compared and evaluated Eulerian and Lagrangian cavitation models for steady pressure conditions. They addressed different physical mechanisms associated with the formation and further development of cavitation as well as their numerical modelling.

In the literature a variety of injection conditions are considered. The injection velocity is modulated due to the passage of cavitation zones or bubbles through the hole exits and due to the fluctuations of the Diesel fuel pressure upstream the needle seat. According to Chaves [2] this modulation may contribute significantly to spray breakup. For any of these mechanisms there exist a number of semi-empirical models [1, 2, 9, 13 and 18]. But in order to use these models one needs to compute the injector flow which serves as initial conditions for the spray simulation.

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Numerical Method

The whole process of fuel injection is split in two problems. First the exit velocity and mass flow rate at the nozzle outlet are simulated solving the Navier-Stokes equations together with a cavitation model which assumes a barotropic flow. The resulting flow field is afterwards applied as boundary and initial conditions for the spray computations. The two-phase nozzle flow (liquid and cavitation bubbles) is replaced mathematically by a single-phase flow characterized by an artificial barotropic equation of state, where density varies sharply between the density of vapour, if the pressure value decreases to the vapour pressure, and the density of liquid, when the pressure is slightly above the vapour pressure. The model includes the compressibility of both the liquid and the vapour phase. The governing continuity and momentum equations are the same as those of a single-phase flow. In Cartesian coordinates they read

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j\right) = 0$$

$$\frac{\partial}{\partial t}\left(\rho u_i\right) + \frac{\partial}{\partial x_j}\left(\rho u_j u_i - \tau_{ij}\right) = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial S_{ij}}{\partial x_j}$$

where x_j (j=1,2,3) denotes the Cartesian coordinates, u_i the velocity vector, τ_{ij} the Reynolds stress tensor, p the pressure, ρ the fluid density, μ the dynamic viscosity and S_{ij} the shear rate tensor

$$S_{ij} = \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right).$$

The viscosity used in the viscous term is estimated to be linearly proportional to the density as in [16]

$$\mu = \mu_l \left(\frac{\rho}{\rho_l} \right)$$

where the subscript *l* denotes the liquid phase.

Additionally, the barotropic equation for the pressure is used for closure.

$$\rho = \left(p - p_0\right)\frac{\partial \rho}{\partial p} - \rho_0$$

For the gas domain this dependence was specified using the Ideal-Gas-Law and for the liquid domain assuming a constant velocity of sound. These two domains are connected with the intermediate zone which assumes coexistence of gas and liquid phases as shown in Figure 1.

The calculated mass flow rates are used as boundary conditions in the spray computation. For the latter, the break-up model of Hsiang and Faeth [6], collisions model of O'Rourke [14], wall-interaction model of Bai and Gosman [1] and atomization model of Reitz-Diwakar [15] have been used which depend on the nozzle parameters.

The calculations were performed using the CFD codes of STAR-CD with the second-order differencing schemes MARS and CD (for density only). For the nozzle flow simulations the supply pressure and chamber pressure were prescribed at the in- and outlet, respectively. The simulations were carried out considering laminar as well turbulent flows. In the latter case the Reynolds-averaged Navier-Stokes equations were solved together with the k-ε RNG model.

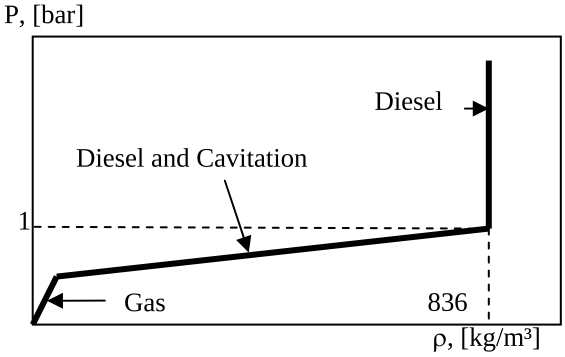

Fig. 1. Schematic diagram of density-pressure dependency

Numerical Results

Firstly, a time-dependent flow through an axisymmetric one-hole nozzle has been calculated. The time-dependent supply pressure was specified as boundary condition as follows. During the first 10 *µs* the pressure magnitude was increased from 200 to 450 *bar*, then decreased for the next 10 *µs* to 200 *bar* and stayed constant for some time afterwards.

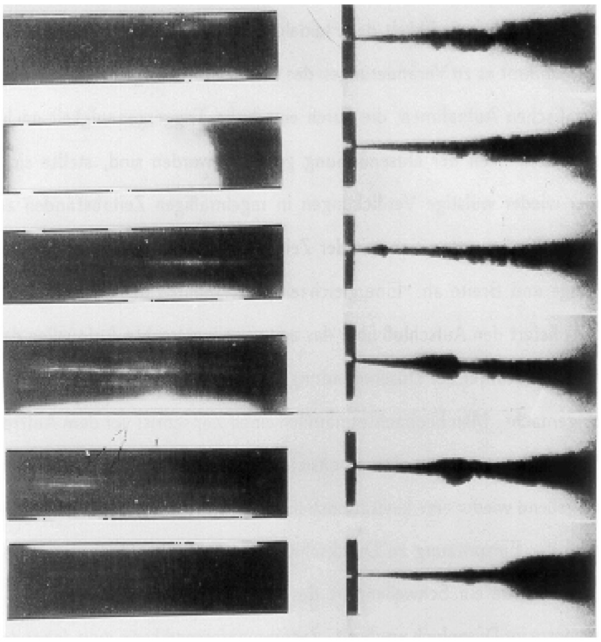

Fig. 2. Visualizations of the time-dependent nozzle flow and the resulting Diesel spray structures injected into the atmosphere obtained in the experiment [11].

Figure 2 includes a sequence of pictures showing the time-dependent behaviour of cavitation as function of specified supply pressure and the according spray structures from an on-hole axial-symmetric nozzle [11].

On the photos dark areas reflect cavitation zones, while the light ones indicate the disappearance of cavitation.

For comparison the numerical results of time-dependent nozzle flow calculation and the resulting spray formation are presented in Figure 3.

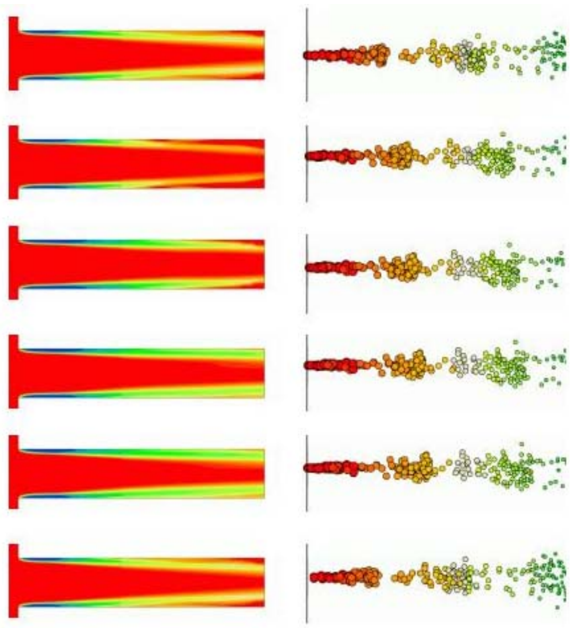

Fig. 3. Computed density (left) and droplet (right) distributions for a time-dependent supply pressure.

The colours in the pictures on the left represent the computed density, where red denotes the liquid phase, blue the vapour phase and green the cloud cavitation zones. Regarding the spray structure (Figure 3 right) the colours reflect droplet diameters from 0.2 *mm* (red) to 0.0002 *mm* (blue).

Starting from the top of Figure 3, the first two pictures show the density distribution and spray structures obtained by increasing the supply pressure from 200 to 450 *bar*. One clearly observes the retreating area of very low density which corresponds to the cavitation zone. The next four pictures reflect the extension of the cavitation zones at the nozzle and the spray distribution during the phase when the pressure is decreased. The resulting injection velocity strongly influences the breakup process, the spray penetration and internal droplet collisions.

The obtained results demonstrate clearly that the cavitation zones disappear for increasing supply pressure levels and afterwards grow again when the supply pressure is sharply reduced. The generation and disappearance of cavitation modulates the shape and values of the initial velocity profile at the outlet and therefore influences the liquid atomization. Chaves and Obermeier [2] and Kubitzek [11] made similar observations in their experiments.

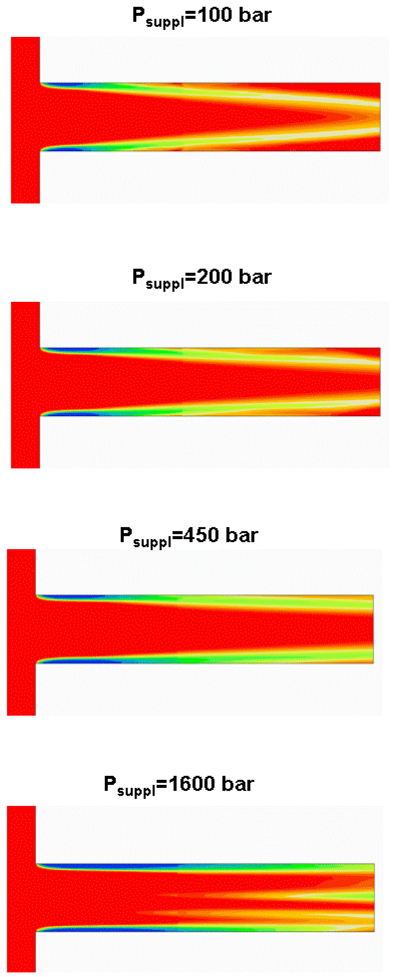

Fig. 4. Computed density distribution in an axisymmetric nozzle for steady-state conditions.

For steady-state flows, cavitation in the nozzle behaves rather differently. The higher the injection pressure is, the more nozzle volume is taken by cavitation. Figure 4 shows the density distribution for four different cases of pressure drop. For very high supply pressure of p = 1600 *bar* the numerical results suggest that the obtained flow field is non-axisymmetric.

The injection flow through a multi-hole nozzle (Figure 5) represents an even more complicated case. The supply pressure variation specified in the simulation is presented in Figure 6. In this case the supply pressure is first reduced from 450 *bar* to 300 *bar*, than increased to 450 *bar* and finally reduced to 300 *bar again*. In Figure 7 the density oscillations in two selected nozzle holes (1 and 3 in the Figure 5) computed for the time-dependent supply-pressure shown in Figure 6 are presented. It is observed that the cavitation is unsteady, more irregular and the flow is non- axisymmetric. Further, the mass flow rates through different holes are different and the extension of cavitation depends on the angle and position of nozzle holes.

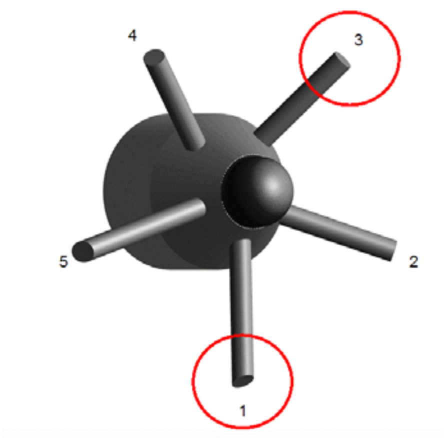

Fig. 5. View of the multi-hole nozzle CFD model.

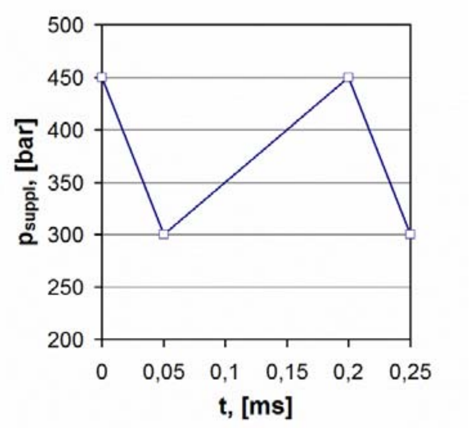

Fig. 6. Time-dependent supply pressure variation.

For future calculations of spray formation more realistic mass flow rates than the prescribed pressure variation are required, which can be either obtained from numerical simulations or measurements. An example of a realistic time-dependent mass flow rate by pilot and main injection in diesel engine is presented in Figure 8.

The according droplet distributions in the spray downstream a multi-hole injector is represented in Figure 9 for six times. The first two pictures reflect the start and the end of the pilot injection. The next four pictures show the spray atomization during the main injection. In this injection phase higher droplet velocities lead to a better spray atomization.

Conclusions

The presented numerical approach includes the simulation of a compressible flow and makes possible to predict cavitation and its time-variation without *a-priori* knowledge of the position and form of the cavitation region. It was found that for a sharply increasing supply pressure the cavitation zones first disappear and redevelops and extends, if the pressure is decreased again. Further, it was shown, that a detailed modelling of spray formation and liquid atomization is possible if the time-dependent injection mass flow is computed.

With the presented approach quantifiable characteristics of nozzle flow and spray structures have been accurately predicted and the results agreed well with observations made in measurements of the flow in high speed diesel injectors.

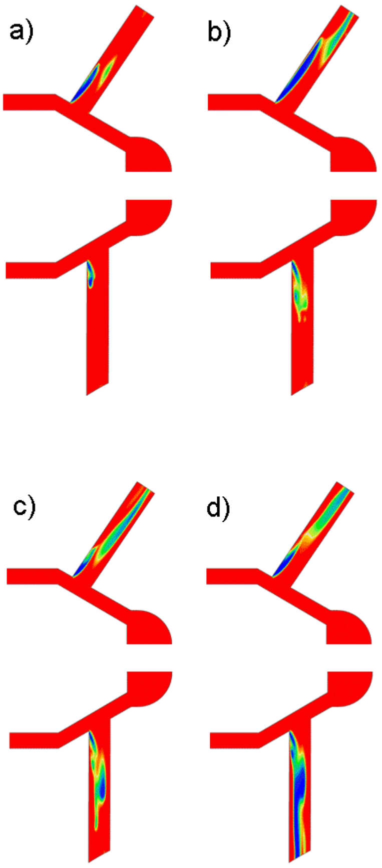

Fig. 7. Computed density distribution in multi-hole injector for four times.

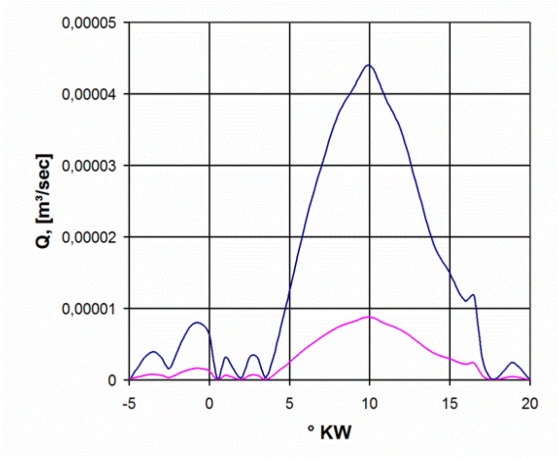

Fig. 8. Volume flow rate distribution. Blue: flow from five holes, magenta: flow only from one hole.

Finally it was found that modeling of cavitation is sensitive to the shape of the nozzle geometry and temporal variation of the supply pressure. For a better understanding of the physics involved in the whole process, considering of thermal effects might be useful.

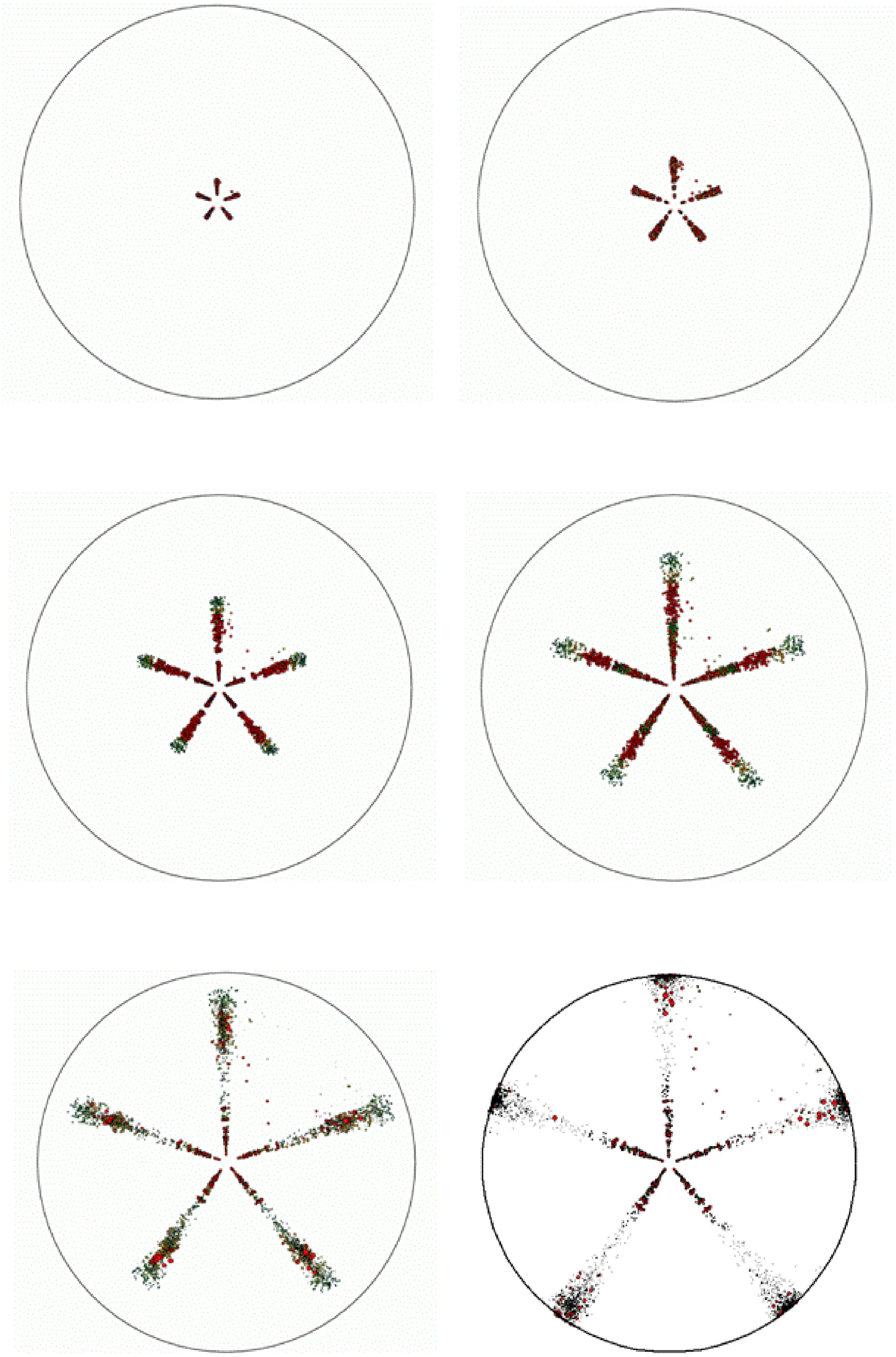

Fig. 9. Time-dependent spray formation emitting from a multi-hole nozzle.

References

[1] **Bai B C & Gosman A D**, *Development of methodology for spray impinging simulation,* SAE Paper No 950283, 1995.

[2] **Chaves H & Obermeier F**, *Modelling the effect of modulations of the injection velocity on the structure of diesel sprays,* SAE Paper No 961126, 1996.

[3] **Chaves H, Knapp M, Kubitzek A & Obermeier F**, *High speed flow measurements within an injection nozzle,* In Proc. Laser Anemometry Advances and Applications, Koningshof, Veldhoven, The Netherlands, 1993.

[4] **Chaves H, Kirmse C & Obermeier F**, *The influence of nozzle inlet curvature on unsteady cavitation in transparent diesel injection nozzles,* In Proc. 1st International Colloquium on Microhydrodynamics, Paris, France, 2000.

[5] **Chen Y & Heister S D**, *Modeling cavitating flows in Diesel injectors,* Atomization and Sprays, **6**, 1996.

[6] **Faeth G M, Hsiang L-P and Wu P-K**, *Structure and breakup properties of sprays,* Int. Journal Multiphase Flow **21**, 1999.

[7] **Findeisen B & Konstantinov M**, *Numerische Simulation der instationären Wechselwirkung zwischen Düseninnenströmung und Strahl-zerstäubung bei der Dieseleinspritzung,* SPRAY 2002, Freiberg, 2002.

[8] **Giannadakis E, Papoulias D, Gavaises M, Arcoumanis C, Soteriou C and Tang W**, *Evaluation of the predictive capability of Diesel nozzle cavitation models,* SAE Paper No 2007-01-0245, 2007.

[9] **Huh K Y & Gosman A D**, *A phenomenological model of Diesel spray atomization,* Proc. Int. Conf. on Multiphase flow, Tsukuba, Japan, 24-27 September 1991.

[10] **Konstantinov M & Obermeier F**, *Numerical simulation of transient nozzle flow,* ZAMM **79**, 1999.

[11] **Kubitzek A M**, *Experimentelle Untersuchungen einer Düseninneströmung und des zerstäubenden Flüssigkeitsstrahles bei hohen Strömungsgeschwindigkeiten,* Bericht 105/1993 MPI für Strömungsforschung Göttingen, 1993.

[12] **Marcer R, Le Cottier P, Chaves H, Arguerolles B, Habchi C & Barbeau B**, *A Validated numerical simulation of Diesel injector flow using a VOF Method,* SAE Paper No 2000-01-2932, 2000.

[13] **Murphy J, Schmidt D, Wang S P and Corradini M L**, *Multi-dimensional modelling of multiphase flow physics: high-speed nozzle and jet flows – a case study,* Nuclear Engineering and Design **204**, 2001.

[14] **O'Rourke P**, *Collective drop effects on vaporising liquid sprays,* PhD Thesis, University of Princeton, 1981.

[15] **Reitz R D and Diwakar R**, *Structure of high-pressure fuel spray,* SAE Paper No 870598, 1987.

[16] **Schmidt D P, Rutland C J & Corradini M L**, *A numerical study of cavitating flow through various nozzle shapes,* SAE Paper No 91597, 1997.

[17] **Schmidt D P, Rutland C J, Corradini M L, Roosen P & Genge O**, *Cavitation in two-dimensional asymmetric nozzles,* SAE Paper No 1999-01-0518, 1999.

[18] **Stanton D W, Lippert A M, Reitz R D & Rutland C J**, *Influence of spray-wall interaction and fuel films on cold starting in direct injection diesel engines,* SAE Paper No 982584, 1998.

[19] **Vortmann C, Schnerr G H & Seelecke S**, *Thermodynamic modeling and simulation of cavitating nozzle flow,* Int. Journal of Heat and Fluid Flow **24**, 2003.

[20] **Yuan W & Schnerr G H**, *Modeling of unsteady cavitating flows in fuel injection,* ILASS-Europe 2000, Darmstadt, Germany, 2000.