LARGE EDDY SIMULATION OF FUEL-AIR-MIXING IN A DIRECT INJECTION SI ENGINE

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ABSTRACT

This work extends the investigation by Goryntsev et al. (2007) of cycle-to-cycle variations of flow and mixing field using Large Eddy Simulation (LES) method to fuel spray injection driven flows using the CFD KIVA-3V code (Amsden et al., 1989) as extended to LES. Especially the effect of the cycle-to-cycle variations on the fuel-air-mixing close to the ignition point will be investigated. The configuration investigated represents the "BMBF" generic four-stroke direct fuel injection engine with variable charge motion system. Some experimental data for single phase flow and spray are available. They will be used for model validation.

INTRODUCTION

The call for environmentally compatible and economical vehicles, still satisfying demands for high performance, necessitates immense efforts to develop innovative engine concepts. However, such engines involve liquid fuel along with multiphase flow phenomena such as droplet evaporation and spray combustion. A good knowledge of the spray evolution properties, the heating and evaporation as well as the interaction with the gas-phase phenomena such as turbulence, mixing and chemical reactions is important for the design and flow control of such engineering devices.

While numerous experimental and RANS-based numerical investigations concentrated on the way to gain insight into the behavior of the spray in IC-Engines, LES may help in delivering detailed unsteady information needed to better understand the strongly transient phenomena going on the combustion chamber. A recent review of LES in IC-Engines was provided by Celik et al. (2001) focused on single-phase flows while Sadiki et al. (2006) deal with turbulent two-phase flows.

It turns out that modern internal combustion engine concepts like the Gasoline Direct Injection (GDI) offer a great chance to meet current and future emission standards. Especially air-guided direct injection systems used to instantiate stratified charge at part load allow for an optimized fuel consumption and a low level of emissions. During this crucial process, the engine is very sensitive to cycle-to-cycle variations of the flow and mixing field.

Therefore, this work extends the investigation by Goryntsev et al. (2007) of cycle-to-cycle variations of flow and mixing field using Large Eddy Simulation (LES) method to fuel spray injection driven flows using the CFD KIVA-3V code (Amsden et al., 1989). Especially the effect of the cycle-to-cycle variations on the fuel-air-mixing close to the ignition point will be investigated.

The paper proceeds as follows. The configuration, numerical method and models are briefly described in the next section. The presentation and discussion of the results for single- and two-phase flow are given further. The main findings are summarized in the final section of the paper.

CONFIGURATION AND NUMERICAL MODELS

The KIVA-3V code allows for the solution of the 3-dimensional, unsteady, compressible equations of fluid motion. The conservation equations are discretised using the Finite Volume Method (FVM) on an arbitrary hexahedral mesh applying the Arbitrary Langrangian Eulerian (ALE) method. For details see (Amsden et al., 1989, Amsden, 1993, Amsden, 1997) and references therein. KIVA offers two different RANS models ($k-\varepsilon$ and RNG) to account for turbulence effects and is widely used for the simulation of ICE fluid dynamics, especially for in-cylinder flows. The current study is based on a LES approach using the classical Smagorinsky model (Smagorinsky, 1963), which has been implemented in the code (Amsden et al., 1989).

In the present implementation, the model constant was taken to be 0.1, following typical literature values. A square duct configuration was used to validate the new KIVA-3V-LES code and results were found to be in good agreement with available DNS data (Goryntsev at al., 2005).

Simulations of spray were carried out using the standard Smagorinsky SGS model for the SGS stress tensor implemented in KIVA-3V. The so-called DDM (discrete droplet model of Dukowicz) (Amsden et al., 1989) with Lagrangian, computational particles that represent parcels of spray droplets with uniform properties was applied for the spray description. The spray and fluid interactions are

Table 1: Parameters of the “BMBF” IC-Engine.

Bore [mm]	Stroke [mm]	Clearance height [mm]	Crankshaft rotational speed [rpm]
85	85	0.8	2000

Table 2: Definition of valve motion.

Intake valve opening [deg]	Intake valve closure [deg]	Exhaust valve opening [deg]	Exhaust valve closure [deg]
-24°	240°	480°	744°

thereby accounted for by means of a number of submodels including the droplet aerodynamic drag, turbulence effects, evaporation, droplet oscillation and distortion, droplet breakup, collision and coalescence (Amsden et al., 1989). The properties of each computational particle at the time of injection are assigned a Monte Carlo sampling technique with appropriate probability distribution. Different validation tests of these submodels are reported in (Sone at al., 2001).

Configuration

The configuration investigated in this paper represents the “BMBF” generic four-stroke direct fuel injection engine with variable charge motion (VCM) system (see figure 1). This is a realistic IC-Engine with 4 canted valves with asymmetric cylinder head and asymmetric bowl. Different parameters of this engine are shown in Tables 1, 2.

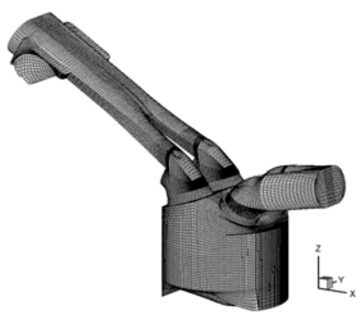

Figure 1: Geometry and computational grid.

The computational geometry and grid with 320.000 control volumes (70×60×50 in the cylinder at bottom dead center) were created using ICEMCFD program. No-slip velocity boundary conditions at the walls and pressure inlet/outlet boundary conditions for the intake/exhaust ports were applied.

RESULTS AND DISCUSSION

The following paragraphs describe the mean flow properties during intake, compression and expansion strokes. First a single-phase flow is considered. Location and intensity of the velocity cycle-to-cycle variations are discussed in terms of standard velocity deviation. Later results of LES for a two-phase flow are given. Validation of the KIVA-3V-LES code for two-phase flow and comparison with experimental data are provided. Finally the influence of the cycle-to-cycle fluctuations on the mixing field is analyzed.

Single-phase flow

In order to characterise the cycle-to-cycle fluctuations in a combustion chamber LES calculations using a suitable parallelisation strategy have been performed to simulate up to 40 full engine cycles.

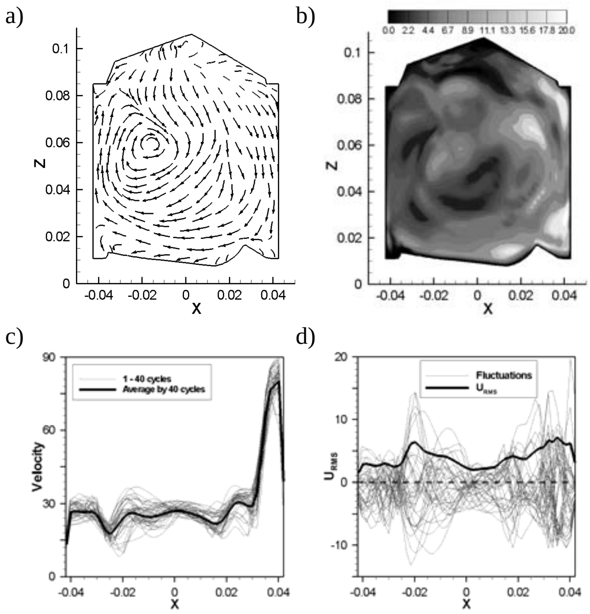

Figure 2: Velocity vector plot in a cross section for CA=105°, averaged over 40 engine cycles (a), standard deviation of velocity (b), velocity profiles at z = 0.05 m (c), u_{rms} profiles at z = 0.05 m together with the instantaneous fluctuations for each individual cycle (d).

Intake stroke. Figure 2 (a, b) shows the velocity distribution during intake stroke at CA=105°, close to maximum valve lift. Due to the VCM system there is a pronounced intake jet towards the cylinder head, impinging on the cylinder wall at the exhaust side and forming a tumble motion. Figure 2 (b, c) shows the cyclic fluctuations in terms of the velocity standard deviation. Clearly the strongest absolute velocity fluctuations occur at the exhaust side, at the tip of the jet. Normalizing the velocity fluctuations with local mean velocity a second peak is observed (see Figure 5) located roughly at the center of the vortex (Figure 2 (a)) at x = 0.02 m.

Table 3: Parameters of injection.

P_{Gas}	T_{Gas}	P_{Inj}	T_{Inj}	Fuel
5 bar	573 K	60 bar	363 K	C_8H_{18}

Duration	Cone	DCone	Area of nozzle
2.01 ms	40°	12°	1.452E-3 cm^2

Compression stroke. The flow field during compression stroke (CA=255°, see Figures 3) shows a pronounced tumble flow with the vortex center located at the center of the combustion chamber. CA=15° after intake valve closure the peak velocity, i.e. the tip of the intake jet, has moved to the intake side. Velocity magnitudes are considerably smaller compared to intake stroke. The same holds true for the velocity fluctuations. However, the normalized standard velocity deviation (Figure 5) reaches the highest values over the whole engine cycle with a peak intensity of $u_{rms} / u_{mean} > 0.4$. This peak value is found at the center of the tumble motion as depicted in Figure 3 (a).

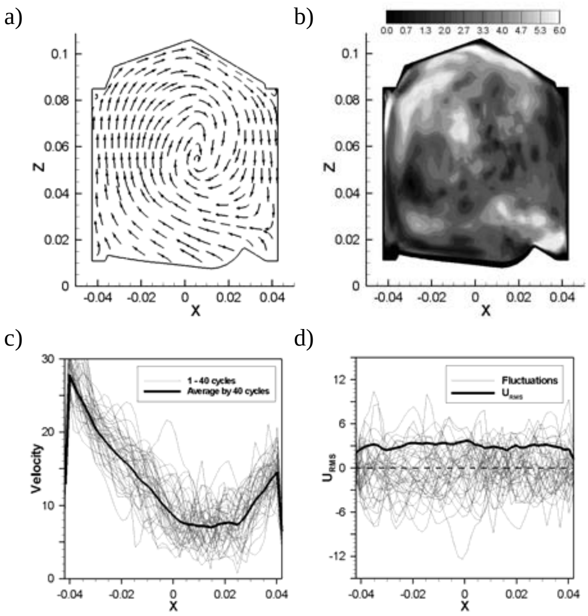

Figure 3: Velocity vector plot in a cross section for CA=255°, averaged over 40 engine cycles (a), standard deviation of velocity (b), velocity profiles at z = 0.05 m (c), u_{rms} profiles at z = 0.05 m together with the instantaneous fluctuations for each individual cycle (d).

Expansion stroke. The mean flow during expansion stroke is, at crank angle 450°, dominated by the descending piston (Figures 4, 5). Absolute velocity and fluctuations are rather small compared to intake and expansion stroke. It should be noted that the flow field under realistic conditions, including injection and combustion, would look quite differently in this phase.

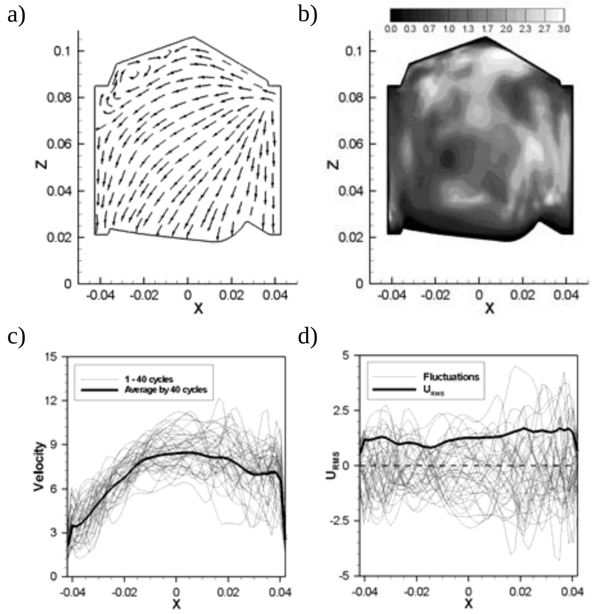

Figure 4: Velocity vector plot in a cross section for CA=450°, averaged over 40 engine cycles (a), standard deviation of velocity (b), velocity profiles at z = 0.05 m (c), u_{rms} profiles at z = 0.05 m together with the instantaneous fluctuations for each individual cycle (d).

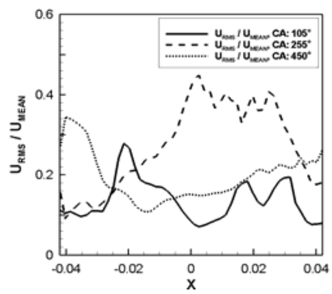

Figure 5: Standard velocity deviation normalized with the local mean velocity at z = 0.05 m.

Two-phase flow

Let us now focus on the consideration of the two-phase flow. Validation of fuel spray injection and investigation of the influence of initial parameters on characteristics of spray injection penetration has been carried out. The impact of the cycle-to-cycle velocity fluctuations on fuel spray injection and mixing processes are considered.

Parameters of injection and computational grid. For the test cases a simple cylindrical geometry (Figure 6 (left)) and grids with 3 various resolutions (33×33×33, 66×66×66 and 99×99×99 were used. The injector was located at the top of cylinder. Configuration of injector and coordinate system are shown in Figure 6 (right). Parameters of injection are given in Table 3. For the spray simulation a hollow spray profile has been used.

Table 4: Parameters of fuel injection for the spray simulations of IC-Engine.

Start of injection	Injection duration	Injection installation angle	Injector mass flow rate
293.4°	21.6°	107°	0.0076 kg/s

a) b)

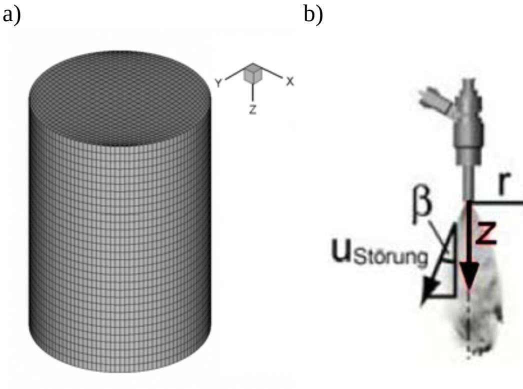

Figure 6: Geometry and computational grid (a), injector and system of coordinates (b).

Comparison of LES and measurement data. The quantitative comparison of spray penetration at t = 1.0 ms between numerical (instantaneous velocity flow fields, obtained on the coarse (a) and fine (c) grids) and experimental data (b) is shown on Figure 7. Some Laser-Correlation-Velocimetry (LCV) and Phase-Doppler-Anemometry (PDA) measurements data (Unterlechner, Kneer, 2005) were used to validate the KIVA-3V-LES code regarding spray properties prediction.

Figure 8 (a) shows direct comparison of the spray jet shape between PDA experimental data and mean LES data at t=1.0 ms averaged over 20 samples, and jet penetration (Figure 8 (b)) accordingly. A small delay of spray jet penetration is visible in the time-range 0.2-0.8 ms and can be explained with the peculiar break-up model for the particles, which is used in the KIVA-3V code.

Averaged velocity and mixture fraction fields at different times were obtained on the coarse and fine grid and comparison of LES results with experimental data for mean axial velocity profiles for both grids have been made. Averaging was carried out over 30 samples for the coarse grid and over 20 samples for the fine grid. Axial velocity of the spray can be found in a good agreement with experimental data for both cases. Small distinctions in velocity profiles for the fine grid can be explained by the lack of statistics (not show here).

In-cylinder flow during spray injection. Some parameters of fuel injection for the spray simulations of IC-Engine are listed in Table 4. Figure 9 and 10 show the instantaneous velocity flow field and fuel mixture fraction in the cross section of IC-Engine for CA: 300° and 310° accordingly.

a) b) c)

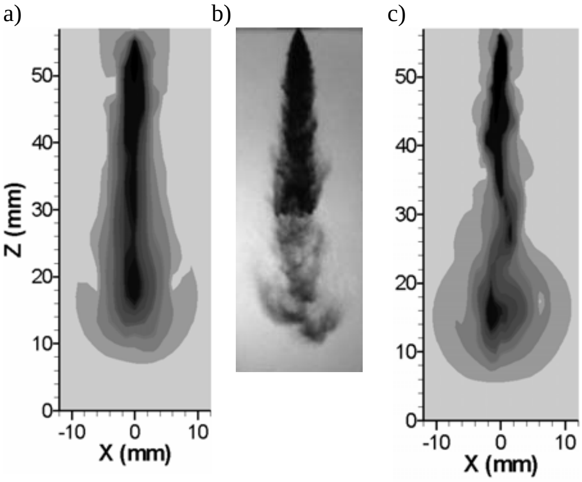

Figure 7: Comparison of fuel spray jet propagation, time: 1.0 ms; Instantaneous velocity (a) on the coarse grid; (b) – Experimental data; Instantaneous velocity (c) on the fine grid.

a) b)

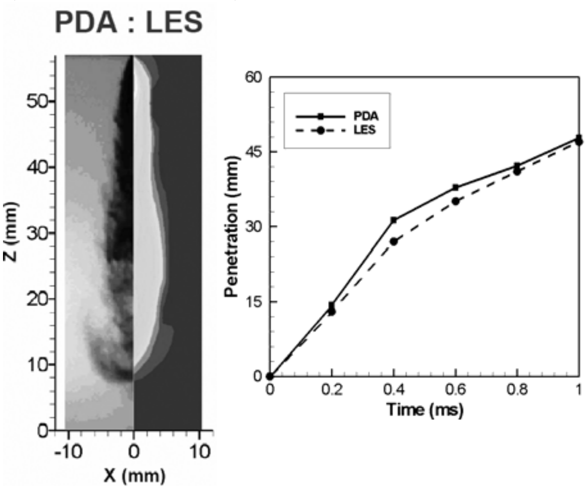

Figure 8: Comparison of the spray jet form between PDA and LES data (a), spray jet penetration (b).

a) b)

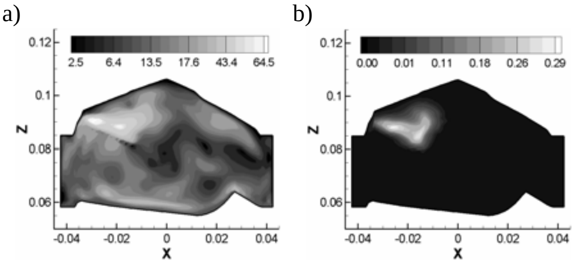

Figure 9: Instantaneous velocity flow field (a) and fuel mass fraction (b) at CA: 300°.

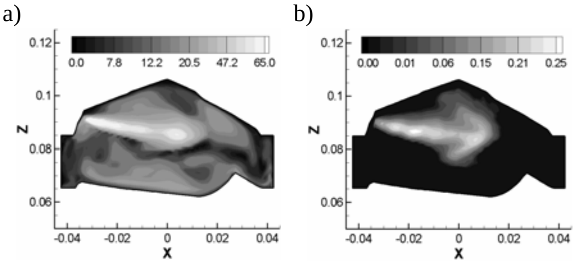

Figure 10: Instantaneous velocity flow field (a) and fuel mass fraction (b) at CA: 310°.

Influence of velocity cyclic variations on fuel-air-mixing. In this paragraph comparison of velocity structure in the cross section of an IC-Engine and cycle-to-cycle variations for single- and two-phases flow are presented. Figure 11 shows the structure of the flow (left) and cyclic variations (right) for single (a) and two-phase (b) flow respectively. Mixing field and cycle-to-cycle fluctuations of mass fraction are shown on Figure 12. Profiles of parameters were obtained along white line (see Figure 12 (left)).

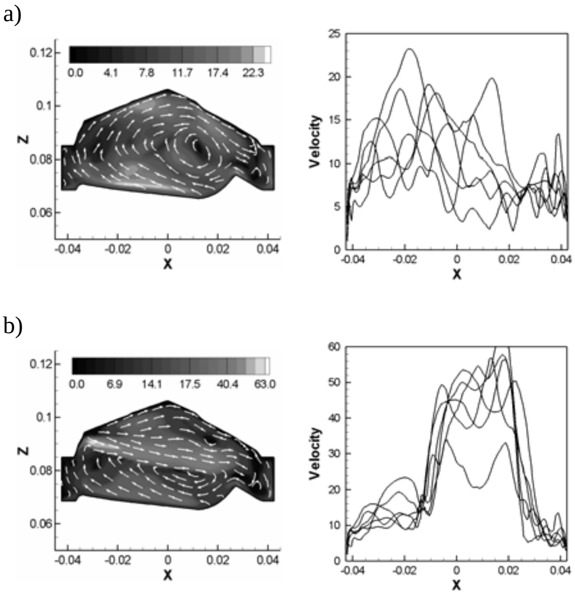

Figure 11: Velocity flow field (left) and velocity cyclic variations at z = 0.08 m (right) at CA: 315°, 6 engine cycle. (a) single-phase flow; (b) two-phase flow.

Distinctions between the single-phase case and the fuel spray injection case are well visible on Figure 11. At the end of compression stroke velocity flow field in the combustion chamber for undisturbed case is determined by tumble motion. The flow structure for two-phase flow in this stage is much different and represents a superposition of tumble flow and fuel spray jet. Cyclic velocity fluctuations result in the cycle-to-cycle variations of mass fraction as shown on Figure 12 (right). 6 full engine cycles for the two-phase flow have been carried out based on the existing results for the single-phase flow. The outlier curves for the single-phase flow (Figure 11a, right) correspond to the outlier curves for the two-phase flow (Figure 11a-12a, right).

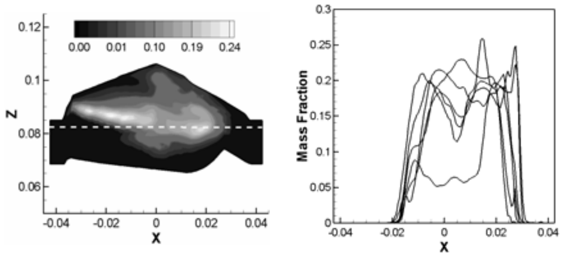

Figure 12: Mass fraction field (left) and cyclic fluctuations of mass fraction at z = 0.08 m (right) at CA: 315°, 6 engine cycle.

CONCLUSIONS

The obtained results can be summarized as follows: In order to characterise the cycle-to-cycle variations for single-phase flow in an Internal Combustion Engine. LES calculations have been performed using a realistic four stoke IC-Engine geometry. A suitable parallelization strategy has been used to simulate up to 40 full engine cycles. Investigation of the cyclic fluctuations has shown that cycle-to-cycle variations in the combustion chamber are strongly dependant on crank angle and becomes strongest close to the injection point. Phase-averaged statistics have been presented for characteristic crank angles. They show strong cyclic variations during intake, mainly at the tip of the intake jet, and during compression, mainly at the center of the tumble motion.

Validation of fuel spray injection for the two-phase flow and investigation of the influence of initial parameters on characteristics of spray injection penetration have been carried out. Results have been found in a reasonable agreement with existing experimental data. The impact of the cycle-to-cycle velocity fluctuations on fuel spray injection and mixing processes has been discussed.

REFERENCES

Amsden, A.A., O'Rourke, P.J., Butler, T.D., 1989, "KIVA-II: A Computer Program for Chemically Reactive Flows with Sprays", Tech. Rep. LA-11560-MS, Los Alamos National Laboratory.

Amsden, A.A., 1993, "KIVA-3: A KIVA Program with Block-Structured Mesh for Complex Geometries", Tech. Rep. LA-12503-MS, Los Alamos National Laboratory.

Amsden, A.A., 1997, "KIVA-3V: A Block-Structured KIVA Program for Engines with Vertical or Canted Valves", Tech. Rep. LA-13313-MS, Los Alamos National Laboratory.

Celik, I., Yavuz, I., Smirnov, A., 2001, "Large Eddy Simulations of In-Cylinder Turbulence for Internal Combustion Engines: A Review", International Journal Engine Research, Vol. 2, No. 2.

Goryntsev, D., Stein, O., Klein, M., Janicka, J., 2005, "Characterization of Cyclic Fluctuations of the In-Cylinder Flow Field of a Direct Injection SI Engine Using Large Eddy Simulation", 7th International Congress: Engine Combustion Process, Munich.

Goryntsev, D., Klein, M., Janicka, J., 2007, "Large Eddy Simulation of Cycle-to-Cycle Variations in a Realistic Direct Injection SI Engine", 8th International Congress: Engine Combustion Process, Munich.

Sadiki, A., Hahn, F., Chrigui, M., Janicka, J., 2006, "LES-Based Methods for the Prediction of Turbulent Reacting Two-Phase Flows: A Review", Progress in Energy and Combustion Science, submitted.

Smagorinsky, J., 1963, "General Circulation Experiments with the Primitive Equations, 1. The Basic Experiment", Monthly Weather Rev., 91:99-164.

Sone, K., Patel, N.V. and Menon, S., 2001, "Large-Eddy Simulation of Fuel-Air Mixing in an Internal Combustion Engine", AIAA Paper, 2001-0635.

Unterlechner, P., Kneer, R., 2005, "Experimentelle und numerische Untersuchung zum Einfluss Zyklischer Schwankungen auf die Struktur Motorischer Einspritzstrahlen", BMBF Workshop, Turbulenz in der Energietechnik, RWTH Aachen.