UNSTEADY EFFECTS ON MIXING AND COMBUSTION PROCESSES IN A REALISTIC IC-ENGINE BY USING LARGE EDDY SIMULATION

Dmitry Goryntsev, Amsini Sadiki and Johannes Janicka
Institute of Energy and Powerplant Technology (EKT),
Department of Mechanical and Process Engineering, Technical University of Darmstadt
Petersenstr. 30, 64287, Darmstadt, Germany
digor@ekt.tu-darmstadt.de

ABSTRACT

Large eddy simulation (LES) based analysis of the unsteady variations of the in-cylinder flow and their effects on mixing and combustion processes in direct injection spark-ignition engine is presented in this paper. The configuration under study represents a four-stroke internal combustion engine with variable tumble-system. The KIVA-3V code extended to LES has been used to perform 40 consecutive engine cycles in order to characterize cycle-to-cycle fluctuations of the flow field quantities. The impact of parameters of fuel spray injection on mixture preparation and combustion processes is pointed out. For this purpose non-reacting as well as reacting two-phase flows have been analyzed.

INTRODUCTION

Fuel spray injection is one of the key processes in direct injection spark-ignition (DISI) engines, which strongly affects the possibility to reduce emissions and specific fuel consumption. Among other conditions, unsteady in-cylinder flow generally leads to cycle-to-cycle fluctuations (CCF) of mixing as well as combustion processes. The LES method has proved to be a reliable tool in order to provide detailed information about highly unsteady phenomena of in-cylinder flows. Recent reviews of LES applications in IC-engines can be found, for example, in Thobois et al. (2007) and Vermorel et al. (2009). A discussion about ignition and combustion models was provided by Tan and Reitz (2006).

The application of the AVBP code to the investigation of CCF in spark ignited IC-engine dealing with a homogeneous mixture is reported in the following recent references. Laget et al. (2011) carried out LES simulation covered nine cycles of a four cylinder IC-engine in order to investigate cylinder to cylinder influence and variability. An attempt to perform reactive LES in a realistic four-valve IC-engine using coherent flame model was reported by Vermorel et al. (2009). Analysis of cycle-to-cycle combustion variations was based on nine consecutive engine cycles. Cyclic combustion variability in a single cylinder IC-engine was investigated by Enaux et al. (2011). Multi-cycle LES of flow and combustion in a whole engine set-up covered 25 consecutive engine cycles. The issues of boundary conditions for LES applications are given by Pera and Angelberger, 2011. Thereby a statistical analysis over 15 consecutive engine cycles was used to compare LES results with particle image velocimetry (PIV) measured data.

A transient flow field and spray structures inside an optically accessible DISI IC-engine were investigated using PIV imaging by Müller et al. (2011). One hundred consecutive cycles were saved every 1 crank angle degree (CAD) allowing a detailed investigation of cyclic variations. An interaction of the in-cylinder charge motion and the fuel spray injection along with a correlation between the in-cylinder flow and the subsequent spray momentum of different injector types were pointed out. Application of PIV to the investigation of the charge motion generation and evolution of CCF for various intake port designs was reported by Adomeit et al. (2011) while Heim and Ghandhi (2011) analyzed the bulk fluid motion and small-scale turbulence in a two-valve IC-engine.

Application of the KIVA-3V code extended to LES in order to characterize CCF of the in-cylinder flow and the charge motion in a realistic DISI IC-engine was reported by Goryntsev et al. (2007a). A parallelization strategy based on variation of initial conditions has been used to simulate 40 full engine cycles. The impact of the velocity CCF on mixing processes and a qualitative analysis of the intensity of CCF below the spark plug was provided by Goryntsev et al. (2007b; 2009).

The present paper focuses on detailed investigation of fuel-air mixture preparation and combustion processes under various spray boundary conditions in a DISI IC-engine using LES. The unsteady effects of in-cylinder velocity as well as mixing on combustion processes are pointed out. Finally a qualitative analysis of the intensity of CCF of in-cylinder pressure is provided. Multi-cycle LES covers 40 consecutive engine cycles of two-phase flow for each considered case.

INVESTIGATED CONFIGURATION AND NUMERICAL METHOD

A four stroke DISI engine with variable charge motion system (VCM) shown in Figure 1 was used for LES analysis. The compression ratio of the engine is 10.5, engine speed is 2000 rpm. The main parameters of the IC-engine as described by Pischinger et al. (2007) are shown in Table 1. CAD values are given relative to combustion top dead centre (TDC). The main parameters of fuel spray injection are summarized in Table 2.

Table 1: Parameters of DISI IC-Engine.

Bore	Stroke	Squish	Engine speed
85 mm	85 mm	0.8	2000 rpm

Inlet valves		Exhaust valve	
opening	closing	opening	closing
-384 CAD	-120 CAD	120 CAD	384 CAD

Table 2: Parameters of fuel spray injection.

P_{INJ}	T_{INJ}	Fuel	Start of injection	Duration
60 bar	393 K	C_8H_{18}	-66.6 CAD	21.6 CAD

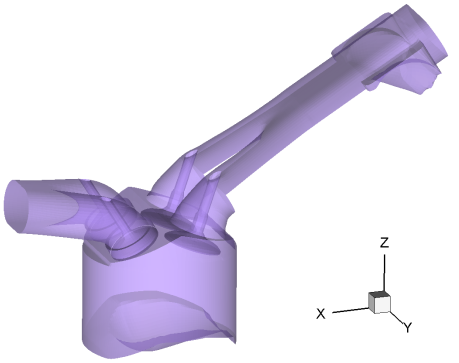

Figure 1. Geometry of DISI IC-engine with VCM system.

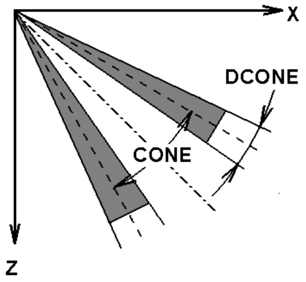

Figure 2. Parameters of a hollow spray injection.

The injection starts at 66.6 CAD before TDC, duration of injection is 21.6 CAD. For the spray simulation a hollow spray profile shown in Figure 2 has been used. Various cases designed for LES calculations are shown in Table 3.

The KIVA-3V code (Amsden et al., 1989) used in this paper has been extended to LES (Goryntsev et al., 2007a) by integrating the standard Smagorinsky model among others. The mesh movement is based on an arbitrary Lagrangian Eulerian technique. The 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 accounted for by means of a number of sub-models that are described in detail in the literature (see, for example, Amsden et al., 1989). The KIVA-3V spray model has been calibrated by using a number of spray-bomb benchmark test cases described by Goryntsev et al. (2007b; 2009). For the simulation of reacting two-phase flow a simple standard Arrhenius-based combustion model has been used together with an ignition model described by Amsden et al. (1989). A parallelization strategy based on variation of the initial conditions proposed by Goryntsev et al. (2005) has been applied in order to perform LES analysis of CCF with reasonable statistical accuracy.

Initial and boundary conditions for LES calculations were formulated as following. Engine wall temperature including piston and cylinder walls, was set equal to 298K. No-slip velocity boundary conditions at the walls were applied. The intake/exhaust pressure at the intake/exhaust ducts was set corresponding to the measured data (Pischinger et al., 2007). In order to minimize the effects of initial and boundary conditions on LES predictions, first three engine cycles were excluded from consideration.

Table 3: Variation of parameters of fuel spray injection.

No.	CONE	DCONE	Ignition point
1	40°		
2	40°±3°[1]	12.5°	-45 CAD
3	50°		

RESULTS AND DISCUSSION

In the present work the previous investigations of the authors (Goryntsev et al., 2009; 2010) are extended to combustion processes under various parameters of fuel spray injection in a realistic IC-engine using LES method. The discussion is reported in terms of mean and rms quantities of velocity, mass fraction, temperature and pressure.

The investigation involves the following stages in the context of unsteady effects of the in-cylinder charge motion: 1) the structure of in-cylinder motion including single- and two- phase (non-reacting and reacting) flows at the combustion TDC was first discussed. 2) The spray injection under fixed as well as stochastic variations of the hollow-cone angle according to experimental data[1] was considered. This analysis helps to investigate the interaction between the in-cylinder charge motion and fuel spray jet along with the effect of cyclic variations of the mixing field on preparation of flammable mixture close to the ignition point. 3) Finally, the effect of the spray injection parameters on CCF of in-cylinder pressure was pointed out.

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[1] E-mail communication: Dr.-Ing. Unger, Thorsten, Dr.-Ing. h.c.F. Porsche AG, Weissach, thorsten.unger@porsche.de

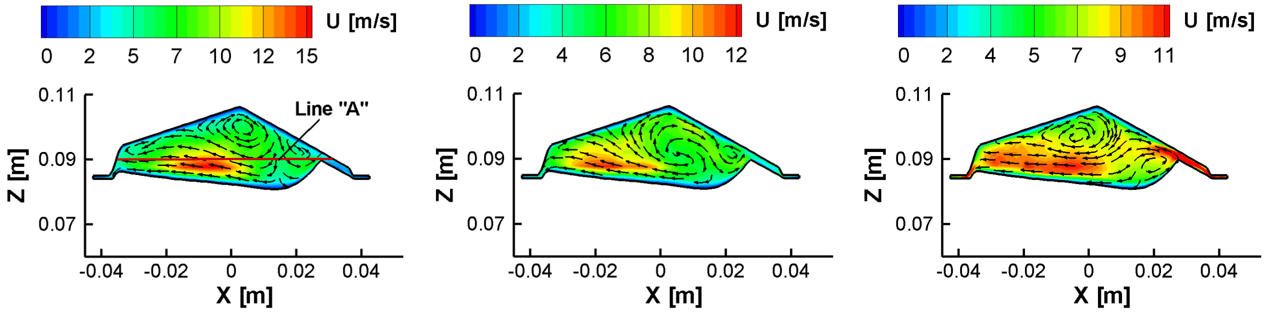

Figure 3. The in-cylinder flow field structure of single-phase (left), non-reacting (middle) and reacting (right) two-phase flows at TDC. Mean velocity flow field in the cross section of the combustion chamber averaged over 40 engine cycles.

In-cylinder flow field structure at combustion TDC

As it has been shown by Goryntsev et al. (2009; 2010), the cycle-to-cycle velocity fluctuations strongly affect the mixture preparation and combustion processes. The interaction of the in-cylinder charge motion with fuel spray jet results in appreciable increasing of the intensity of cycle-to-cycle velocity fluctuations. As it was pointed out in the previous works of the authors, see for example, Goryntsev et al. (2007), the region with maximal intensity of cyclic variations is directly located below the spark plug at the time close to the ignition point.

The structure of the in-cylinder charge motion in the cross section of the combustion chamber for considered cases is shown in Figure 3 at TDC of compression stroke. In the case of single-phase flow (see Figure 3, left) due to the VCM system and specific piston bowl configuration the in-cylinder flow during compression stroke represents a tumble flow with the vortex located at the centre of the combustion chamber.

Figure 3 (middle) depicts the in-cylinder flow structure along with the mean velocity flow field in case where the fuel spray injection takes place. The flow field structure forms as a result of interaction between the in-cylinder tumble motion and injected fuel jet. During injection process fuel spray affects but not destroys the tumble flow. The flow filed under combustion processes is shown in Figure 3 (right). It can be concluded that in both single- and two-phase cases the flow field within the combustion chamber close to TDC represents a tumble motion due to the VCM system and specific piston geometry.

Figure 4 presents direct comparison of mean (top) and rms (bottom) velocity profiles obtained along the red line shown in Figure 3 (left) at z = 0.09 m for single- and two-phase flows including non-reacting and reacting cases. In the case of single- and non-reacting two-phase flows Figure 4 (bottom) depicts a similar level of velocity CCF while combustion processes lead to an increasing of the intensity of cyclic velocity variations. The maximal intensity of velocity CCF with a peak value of $u_{rms} \approx 10.8$ m/s at x = 0.03 m is achieved in the case when combustion takes place.

Influence of the spray parameters on fuel-air mixing and combustion processes

A non-reacting two-phase flow under different spray parameters described in Table 3 is considered first in this section. The impact of different CONE angles of the hollow-cone spray on cycle-to-cycle variations of velocity and mass fraction is pointed out. Figure 5 (top) depicts the average profiles of mass fraction obtained along the line marked “A” (see Figure 3 (left)) at the end of spray injection at 45 CAD before TDC. Mean mass fraction profiles show marginal effect of stochastic variations of the CONE angle while the differences between first (cone = 40°) and third (cone = 50°) cases are visible. The distinction in peak values of mass fraction profiles is the order of 11%. Nevertheless, the influence of spray parameters on mean velocity profiles shown on Figure 6 (top) and intensity of velocity cyclic variations (bottom) is negligible.

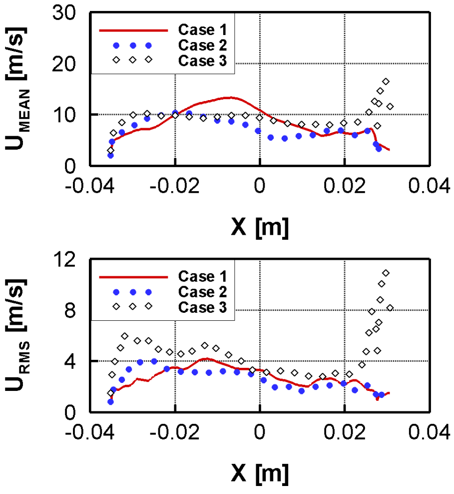

Figure 4. Mean (top) and standard deviation (bottom) of velocity profiles at TDC, z = 0.09 m. Single-phase (case 1), two-phase non-reacting (case 2) and reacting (case 3) flows.

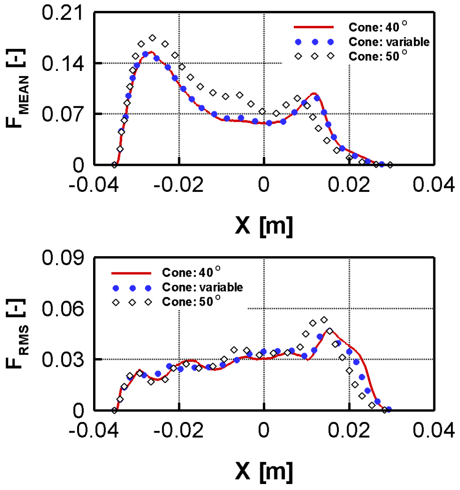

Figure 5. Mean (top) and standard deviation (bottom) profiles of mass fraction at 45 CAD before TDC, z = 0.09 m.

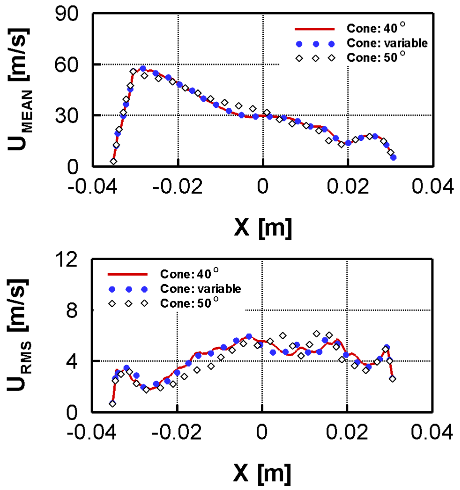

Figure 6. Mean (top) and standard deviation (bottom) profiles of velocity at 45 CAD before TDC, z = 0.09 m.

Let us now focus on the consideration of the two-phase reacting flow. Mean profiles and standard deviation of mass fraction and temperature at different crank angles are presented in Figure 7 and 8, respectively. Averaged mass fraction profiles shown in Figure 7 (left) demonstrate two peaks at x = 0.3 m and x = 0.13 m. Maximal intensity of CCF of mass fraction is observed at the right side of the combustion chamber behind the spark plug at x = 0.02 ÷ 0.03 m with a peak value of 0.042 at 25 CAD before TDC and monotone decreases to almost zero value at x = -0.034 m. Evolution of mean temperature profiles is depicted in Figure 8 (left). The maximal intensity of temperature CCF is achieved during the initial stage of combustion and was found to be equal to 800K as depicted in Figure 8 (right). At TDC the intensity of temperature cyclic variations is two times less compared with the values at 25 CAD and 15 CAD before TDC. While the effect of different spray parameters is appeared for the mean mass fraction profiles as depicted in Figure 7 (left), this effect is negligible for the mean temperature profiles as shown in Figure 8 (left.)

Cycle-to-cycle variations of in-cylinder pressure

As an example, Figure 9 demonstrates the instantaneous and mean in-cylinder pressure for 40 consecutive engine cycles close to TDC corresponding to CONE angle equals to 50°. Direct comparison of the in-cylinder pressure for three considered cases is presented in Figure 10 (top). LES predicts the same in-cylinder pressure for CONE = 40° and variable spray boundary conditions while differences of the in-cylinder pressure obtained at the CONE angle equals to 50° are of the order of 5%. Evolution of the intensity of in-cylinder pressure cyclic variations is shown in Figure 10 (bottom) in terms of standard deviation. Maximal intensity is observed at 10 CAD before TDC. Stochastic variations of spray boundary conditions result in moderate increasing of intensity of pressure CCF compared with the constant values of the cone angle.

CONCLUSIONS

The paper demonstrates the influence of spray injection parameters on flow field pattern and intensity of CCF of temperature, pressure and mass fraction within a DISI IC-engine. Single-phase along with non-reacting and reacting two-phase flows were analyzed. Multi-cycle LES have been performed to cover 40 consecutive engine cycles for each case under consideration. The in-cylinder charge motion plays an important role in the fuel-air mixing processes affecting the fuel jet penetration and forming fuel vapor cloud. The analysis shows an impact of velocity CCF and spray injection parameters on the fuel-air mixing and combustion processes through the temperature and pressure.

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REFERENCES

Adomeit, P., Jakob, M., Pischinger, S., Brunn, A. and Ewald, J., 2011, “Effect of Intake Port Design on the Flow Field Stability of a Gasoline DI Engine“, *SAE Technical Paper 2011-01-1284*, DOI: 10.4271/2011-01-1284.

Amsden, A., O’Rourke, P. and Butler, T., 1989, “KIVA-II: A Computer Program for Chemically Reactive Flows with Sprays”, *Tech. Rep. LA-11560-MS*, Los Alamos National Laboratory, USA.

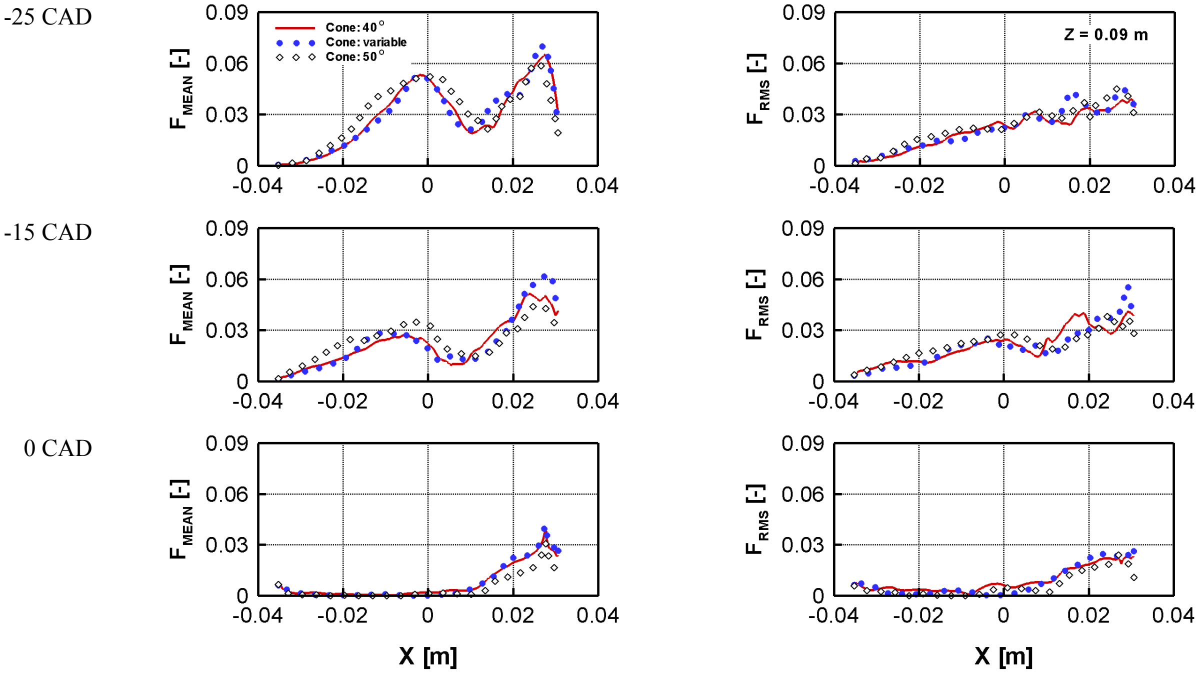

Figure 7. Mean mass fraction profiles (left) and the standard deviation of mass fraction (right) obtained along z = 0.09 m at different crank angles before TDC.

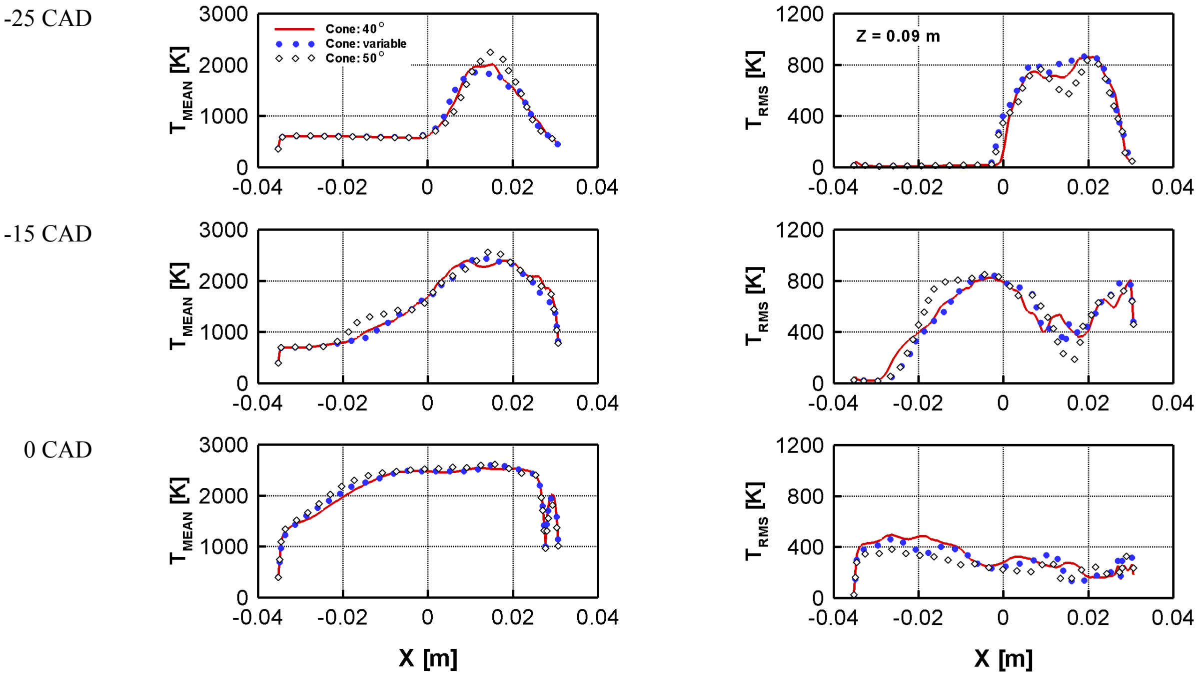

Figure 8. Mean temperature profiles (left) and the standard deviation of temperature (right) obtained along z = 0.09 m at different crank angles before TDC.

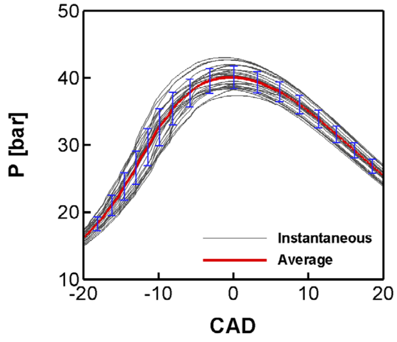

Figure 8. Instantaneous, mean and rms of in-cylinder pressure for 40 engine cycles, CONE = 50°.

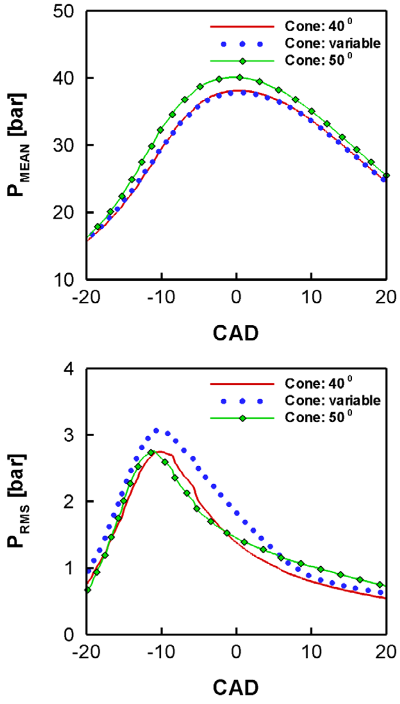

Figure 9. Comparison of mean (top) and rms (bottom) of in-cylinder pressure for three considered cases.

Enaux B., Granet V., Vermorel O., Lacour C., Pera C., Angelberger C. and Poinsot T., 2011, "LES study of cycle-to-cycle variations in a spark ignition engine", *Proceedings of the Combustion Institute*, Vol. 33, No. 2, pp. 3115-3122.

Goryntsev, D., Stein, O., Klein, M. and Janicka, J., 2005, "Characterization of cyclic fluctuations of the in-cylinder flow field of a direct injection SI engine using large eddy simulation", 7th Int. Congress: Engine Combustion Process, Munich, Germany.

Goryntsev, D., Klein, M. and Janicka, J., 2007a, "Large eddy simulation of cycle-to-cycle variations in a realistic direct injection SI engine, 8th Int. Congress: Engine Combustion Process, Munich, Germany, pp. 361-370.

Goryntsev, D., Klein, M., Sadiki, A. and Janicka, J., 2007b, "Large Eddy Simulation of Fuel-Air-Mixing in a Direct Injection SI Engine, *5th International Symposium on Turbulence and Shear Flow Phenomena (TSFP-5)*, Munich, Germany, Vol. 2, pp. 879-884.

Goryntsev, D., Sadiki, A., Klein, M. and Janicka, J., 2009, "Large Eddy Simulation Based Analysis of the Effects of Cycle-to-Cycle Variations on Air-Fuel Mixing in Realistic DISI IC-Engines, *Proc. of the Combustion Institute*, Vol. 32-2, pp. 759-2766.

Goryntsev, D., Sadiki, A., Klein, M. and Janicka, J., 2010, "Analysis of Cyclic Variations of Liquid Fuel-Air Mixing Processes in a Realistic DISI IC-Engine using Large Eddy Simulation, *Int. J. Heat and Fluid Flow*, Vol. 31, pp. 845-849.

Heim, D. and Ghandhi, J., 2011, "A Detailed Study of In-Cylinder Flow and Turbulence using PIV", *SAE Technical Paper,* 2011-01-1287, DOI: 10.4271/2011-01-1287.

Laget, O., Reveille, B., Martinez, L., Truffin, K., Habchi, C. and Angelberger, C., 2011, "LES Calculations of a Four Cylinder Engine", *SAE Technical Paper,* 2011-01-0832, DOI: 10.4271/2011-01-0832.

Müller, S., Arndt, S. and Dreizler, A., 2011, "Analysis of the In-Cylinder Flow Field / Spray Injection Interaction within a DISI IC Engine Using High-Speed PIV", *SAE Technical Paper,* 2011-01-1288, DOI: 10.4271/2011-01-1288.

Pera, C. and Angelberger, C., 2011, "Large Eddy Simulation of a Motored Single-Cylinder Engine Using System Simulation to Define Boundary Conditions: Methodology and Validation", *SAE Technical Paper,* 2011-01-0834, DOI: 10.4271/2011-01-0834.

Pischinger, S., Aymanns, R., Graf, M., Stapf, G., Adomeit, P. and Lang, O., 2007, "Analysemethoden zyklischer Schwankungen in direkteinspritzenden Ottomotoren", *Motorische Verbrennung. Aktuelle Probleme und moderne Lösungsansätze (VIII. Tagung)*, München, Germany, pp. 421-432.

Tan, Z. C. and Reitz, R. D., 2006, "An ignition and combustion model based on the level-set method for spark ignition engine multidimensional modeling", *Combustion and Flame*, Vol. 145, No. 1-2, pp. 1-15.

Thobois, L., Lauvergne, R. and Poinsot, T., 2007, "Using LES to investigate reacting flow physics in engine design process", *SAE Technical Paper*, 2007-01-0166, DOI: 10.4271/2007-01-0166

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

Vermorel O., Richard S., Colin O., Angelberger C., Benkenida A. and Veynante D., 2009, "Towards the understanding of cyclic variability in a spark ignited engine using multi-cycle LES", *Combustion and Flame*, Vol. 156, No. 8, pp. 1525-1541.