Investigation of Cyclic Variations Effects on Mixing and Combustion Processes in a DISI IC-Engine by Using Large Eddy Simulation

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Abstract
One of the most important problem in the design of direct injection spark-ignition (DISI) engines is the cycle-to-cycle variations of the flow and their effects on mixing and combustion processes. The LES based analysis is used to characterize the cycle-to-cycle fluctuations of the flow field and their impact on the mixture preparation and combustion processes in a realistic four-stroke IC-engine with variable charge motion system.

Introduction

Direct injection spark ignition (DISI) engines have a large potential to reduce emissions and specific fuel consumption. One of the most important problem in the design of DISI engines is the cycle-to-cycle variations of the flow, mixing and combustion processes. To characterize the cycle-to-cycle fluctuations of the flow field and their impact on the mixture preparation and subsequent combustion processes in a realistic four-stroke internal combustion engine with variable charge motion system, the Large Eddy Simulation (LES) has proved to be a reliable method. In LES the large energy carrying structures responsible for large scale mixing are directly simulated while the small scales less than the filter (grid) size are modelled through the so-called subgrid scale models. A review of LES applications in simulating IC engines can be found in [3-5, 12-14]. The first investigations of the effect of the flow fluctuations or the cyclic variations of the flow on the mixing have been reported in [7]. As the combustion is highly affected by the flow and mixing field variations focus is put in this paper on the effect of the cyclic variations of the flow and the mixture preparation on the combustion in a DISI IC engine. Based on the analysis of cycle-to-cycle velocity fluctuations of in-cylinder flow, the impact of various fuel spray boundary conditions on injection processes and mixture preparation is first investigated. The joint effect of both cycle-to-cycle velocity fluctuations and variable spray boundary conditions is discussed in terms of mean and standard deviation of relative air-fuel ratio, velocity and mass fraction. Finally a qualitative analysis of the intensity of cyclic fluctuations below the spark plug is provided. The effect of cycle-to-cycle fluctuations of the flow as well as mixing on combustion processes is pointed afterwards.

Investigated Configuration and Numerical Method

The investigated configuration (see Figure 1a) represents a four stroke direct spray injection engine with variable charge motion (VCM) system [8]. This is a realistic IC-engine with four canted valves, an asymmetric cylinder head and an asymmetric piston bowl. The variable tumble system controls the in-cylinder charge motion which enables controlled guidance of the fuel penetration towards the spark plug. The main parameters of the engine are summarized in Table 1. The valve lift curves are given in Figure 1b. The geometry and computational grid with 320.000 control volumes (78x68x50 in the cylinder at bottom dead center, mesh resolution is the order of 1.0 mm.) were created using ICEM CFD Hexa. No-slip velocity boundary conditions at the walls and pressure inlet / outlet boundary conditions for the intake / exhaust ports were applied. The intake and exhaust duct pressure was set equal to the atmospheric pressure.

The KIVA-3V software [1] used within this work has found widespread applications for the simulation of IC-engine flows. The code has been extended to LES by integrating the standard Smagorinsky model among others. The application and validation of the LES based version of KIVA-3V are reported in [3]. The so-called DDM (discrete droplet model of Dukowicz, for more details see [2]) 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, which are described in detail in the literature [1]. Several validation tests of the sub-models are documented in [9]. A simple standard Arrhenius-based combustion model [1] has been used.

A newly developed parallelization strategy [6] has been used in order to increase the number of samples allowing to perform LES of cyclic fluctuations in an IC-engine with reasonable statistical accuracy.

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Results, Discussion and Conclusions

The present work extends the previous investigations of the authors [4, 7] of cycle-to-cycle variations of in-cylinder flow field and mixing in a realistic IC-engine (Figure 1a) using LES method to fuel spray injection. As an example the flow field during the intake stroke is governed by the negative pressure resulting from the descending piston. Figure 1c shows the typical velocity flow field in the cross section of the engine during the intake stroke at CA = 120°. Due to the variable tumble system there is a pronounced intake jet towards the cylinder head, impinging on the cylinder wall at the exhaust side and forming a circular motion at the center of combustion chamber or in other words, normal-tumble motion.

The flow field during the compression stroke (CA = 255°, see Figure 1d) shows a pronounced tumble flow with the vortex center located at the center of the combustion chamber. The results obtained in [4, 7] have shown that during compression stroke the normalized standard velocity deviation reaches the highest value over the whole engine cycle with a peak intensity at the center of tumble motion as depicted in Figure 1e.

After the calibration of the fuel spray injection model [5] using available experimental data [11] the impact of the cycle-to-cycle velocity fluctuations on fuel spray injection and mixing processes within a combustion chamber has been considered. The main parameters of fuel injection are summarized in Table 2. The injection starts at CA = 293.4°, duration of injection is 21.6°. For the spray simulation a hollow spray profile has been used. Figure 2 presents the comparison of mean mass fraction (top) and intensity of cyclic variations (bottom) for the following cases: two-phase flow with constant (a) and variable (b) spray boundary conditions as well as two-phase flow with the joint effect of both velocity cyclic fluctuations and variable spray boundary conditions (c).

The investigation has been done in 4 stages: 1) In order to highlight the effect of velocity cyclic variations on the mixing field, the initial and boundary conditions for the spray injection were kept identical for all considered cycles during the first stage (Figure 2a). 2) In the second stage the spray injection under variable spray boundary conditions [10] takes place into a typical in-cylinder flow field which was kept identical for all engine cycles. Figure 2b illustrates the effect of variable spray boundary conditions on the mass fraction pattern. This analysis helps to separate the effects of velocity and spray cyclic fluctuations on the mixing process. 3) In addition the joint effect of both velocity cyclic fluctuations and variable spray boundary conditions is presented in Figure 2c. 4) Finally the effect of cycle-to-cycle fluctuations of the flow as well as mixing on combustion processes has been pointed out.

In the last step we focus on simulation of ignition and combustion processes in spark-plug IC engine. Figures 3 and 4 demonstrate the preliminary results of the evolution of the ignition and combustion processes. Figures show a temperature field in the cross section of combustion chamber obtained using RANS (top) and LES (bottom) for various crank angles. Ignition starts at CA = 315.0°, duration of ignition is 10°. Initial stage of ignition process is shown in Figure 3a. RANS calculations are able to predict the mean flow properties right while information about instantaneous quantities is lost, a cyclic variations effect cannot be expected from these. Figure 4 (top) shows the averaged temperature field during combustion. LES approach is able to capture highly instantaneous effects as it is shown in Figure 4 (bottom). The results displayed in Figure 4 (bottom) have been obtained under consideration of inflow conditions gained after 10 engine cycles. Comparing to Figure 4 (top), one can get a first insight of the cyclic variations effect on the flow and mixing on the combustion. Detailed studies in which various cyclic variations will be involved are left for the future work.

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Table 1. Parameters of the internal combustion engine

Bore [mm]	Stroke [mm]	Clearance height [mm]	Crankshaft rotational speed [rpm]	Intake valve opening [deg]	Intake valve closure [deg]	Exhaust valve opening [deg]	Exhaust valve closure [deg]
85	85	0.8	2000	-24°	240°	480°	744°

Table 2. Example of a table appearing at the end of the paper

p_{gas}	T_{gas}	p_{inj}	T_{inj}	Fiel	Cone	DCone
5 bar	573.15 K	60 bar	363.15 K	C_8H_1	40°	12°

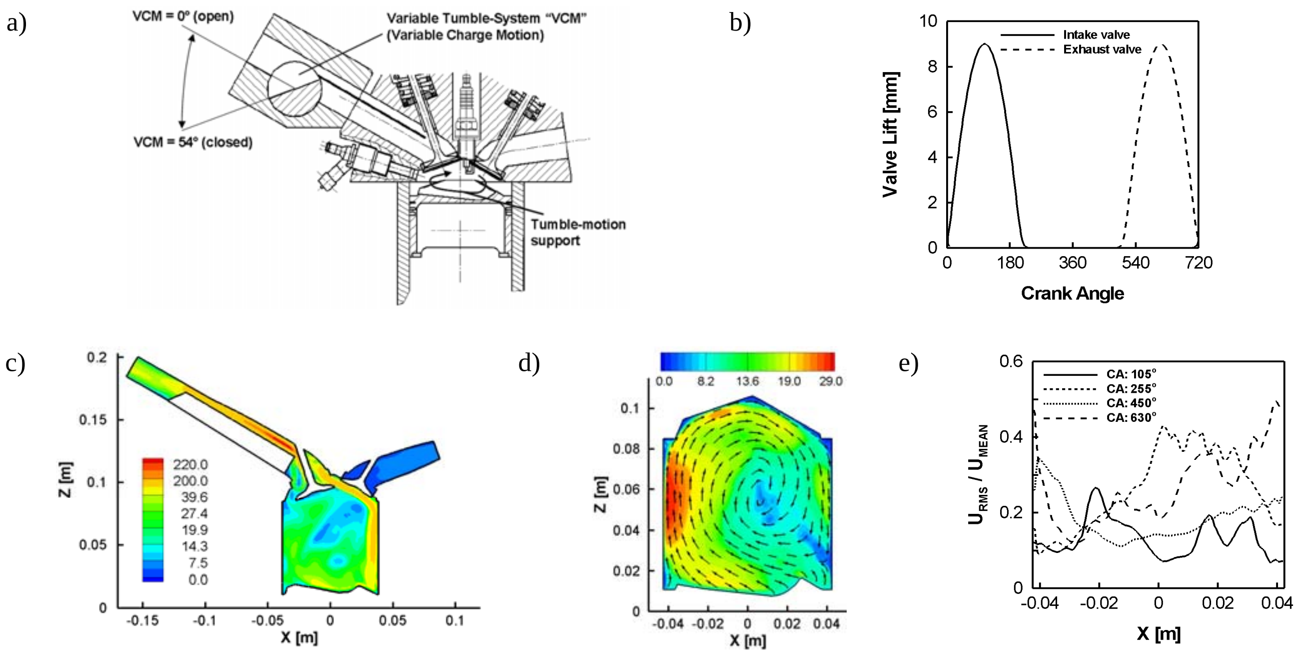

Figure 1. Configuration of the "BMBF" IC-engine (a); Valve-lift definition (b); Mean velocity flow field in the cross section of the combustion chamber at CA = 255°, averaged over 50 engine cycles (c), the standard velocity deviation normalized with the local mean velocity at z = 0.05 m for different engine strokes (d).

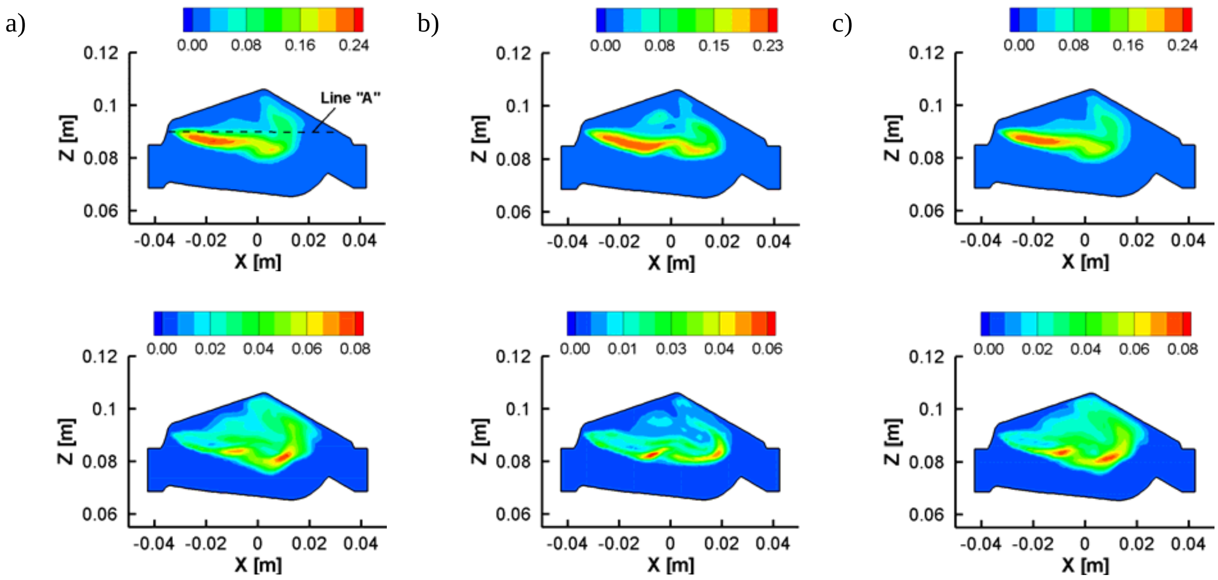

Figure 2. Mean mass fraction (top) and rms of mass fraction (bottom) at CA = 315°. (a) Two-phase flow with constant spray boundary conditions. (b) Two-phase flow with variable spray boundary conditions. (c) Two-phase flow with the joint effect of both velocity cyclic fluctuations and variable spray boundary conditions.

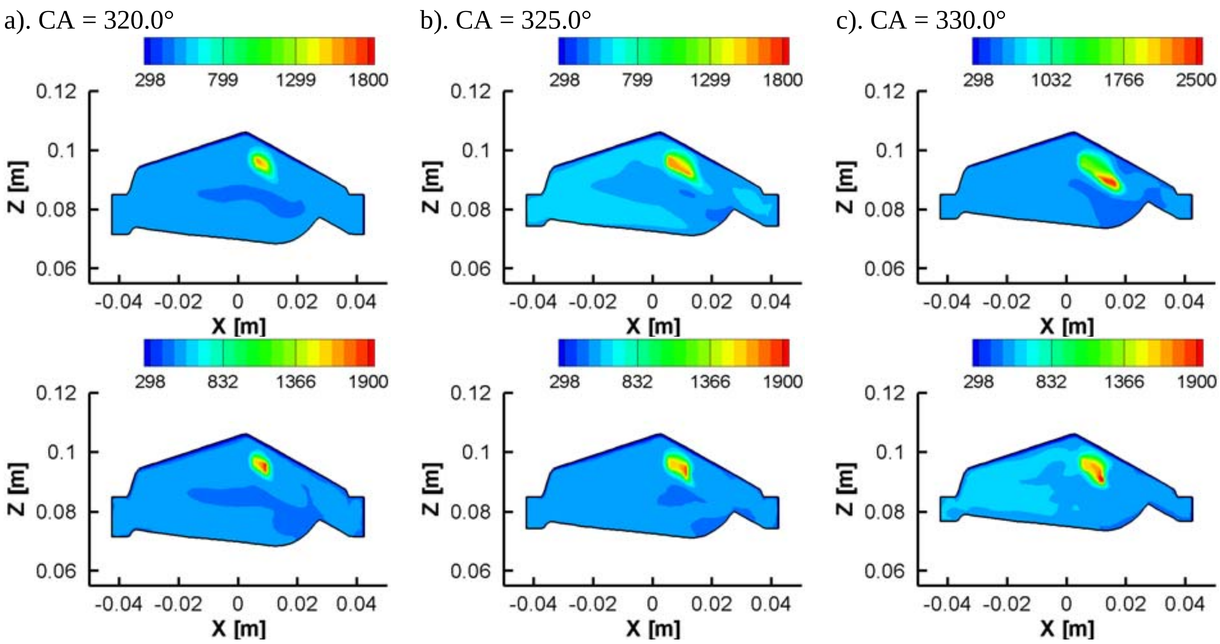

Figure 3. Evolution of ignition processes. Instantaneous temperature field in the cross section of a combustion chamber for different crank angles, results obtained with RANS (top) and LES (bottom).

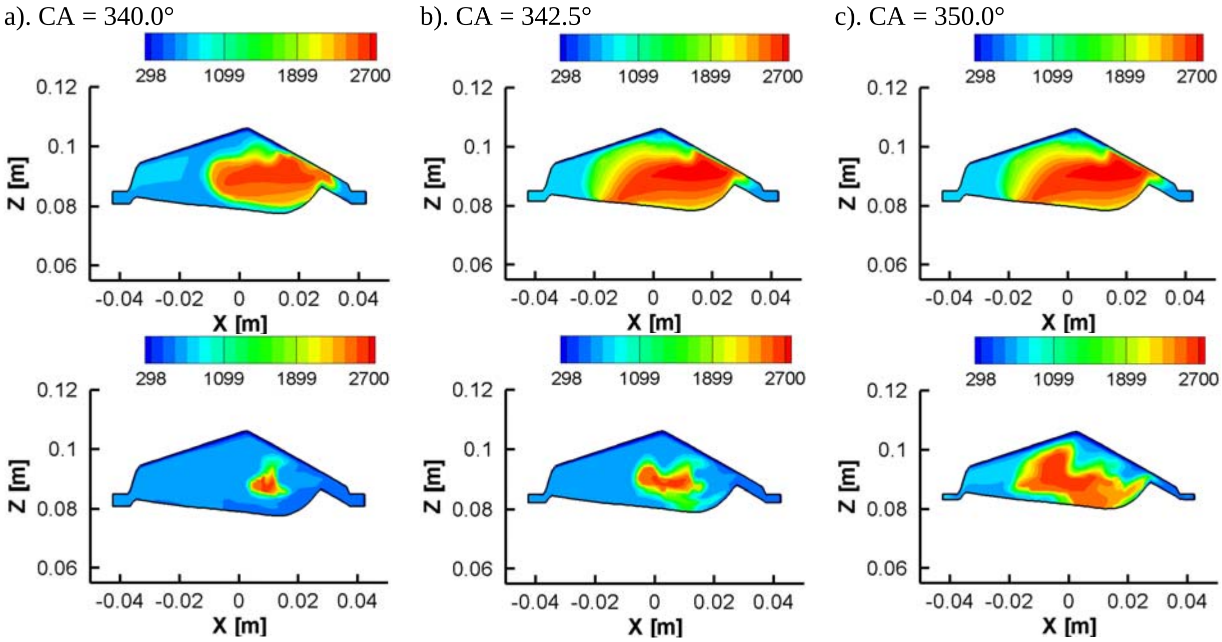

Figure 4. Evolution of combustion processes. Instantaneous temperature field in the cross section of a combustion chamber for different crank angles, results obtained with RANS (top) and LES (bottom).