Cyclic Fluctuations of Charge Motion and Mixture Formation in a DISI Engine in Stratified Operation

ABSTRACT

The processes of an internal combustion engine are subject to cyclic fluctuations, which have direct consequence on the operational and emission behavior of the engine. Direct injection gasoline engines have fluctuations that are induced and superimposed by the flow and the injection. In stratified operation they can cause serious operating problems, such as misfiring. Currently, the state of knowledge on the formation and causes of cyclic fluctuations is rather limited, which can be attributed to the complex nature of flow instabilities.

Recent analyzes of a direct injection gasoline engine's cyclic fluctuations of the in-cylinder charge motion and the mixture formation utilizes laser-optical diagnostics and numerical 3D-calculations. Individual cycles are measured using optical measurement techniques and pressure indicators for determining flow, mixture formation, and the combustion processes. Large-scale turbulence and cyclic fluctuations are modeled using 3D-calculations that are performed with a Large Eddy Simulation (LES). The results of the calculations are used to analyze the formation of cyclic fluctuations and their effect on injection and mixture formation.

The intensity of the cyclic fluctuations rises dramatically during the injection phase, because of the relationship between the cyclic fluctuating in-cylinder flow and the injection. These results are confirmed by calculations, which when combined with reproducible injection predict strongly differing mixture states at the ignition point with significant asymmetries. These asymmetries with their broad scatter range of mixture formation can explain the stochastic misfires that occur in the engine.

INTRODUCTION AND MOTIVATION

A high thermodynamic potential for lowering CO_2 emissions has been demonstrated by direct injection gasoline engines. However, a significant increase in the complexity of the combustion system is created, due to the interaction of fuel spray, charge motion, and combustion chamber geometry. Moreover, these cyclic fluctuations may results in significant limitations in the stratified operating range, due to misfiring and incomplete combustion. Typically, to achieve steady operation without misfiring, the injection and ignition timing are frequently shifted early, which is unfavorable in terms of thermodynamics.

Previously [1], it has been shown that the mixture quality at the spark plug in air-guided direct injection gasoline engines is strongly affected by the combustion chamber flow. A direct correlation was shown between the probability of misfire and the occurrence of a lean mixture at the spark plug at the point of ignition.

This study highlights the probability distribution of the relative Air/Fuel Ratio (AFR) λ measured with Laser Induced Fluorescence (LIF) at the ignition time close to the spark gap (See Figure 1). Utilization of the cyclic evaluation of the LIF results, ignited cycles and misfiring cycles have been investigated with respect to the relative AFR λ. Operating the engine without a misfire is achieved when sufficient tumble motion intensity causes a reproducible mixture state at the spark plug, as seen from the narrow probability distribution of the relative AFR λ with a closed tumble flap. Reducing the intensity of the charge motion causes the relative AFR λ probability distribution to get substantially broader and misfires will occur mainly in those cycles with a lean relative AFR at the spark gap [1].
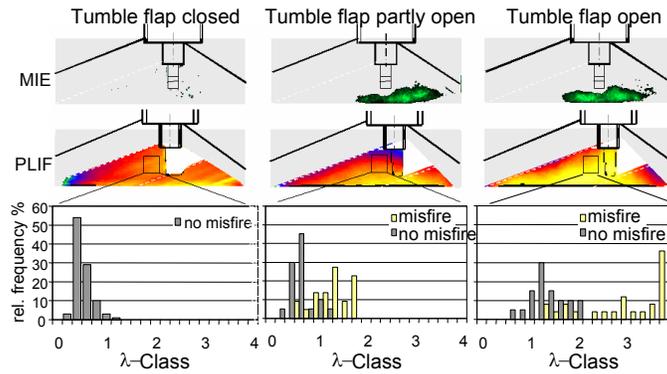
Figure 1: Mie Scattering and PLIF Measurement Results for a Variation of Charge Motion Intensity, Relative AFR λ Distribution Evaluated in the Reference Volume at the Spark Plug [1]

This analysis explains the cause of misfire. However, it does not show the relationship between cyclic fluctuations in flow and injection and the root cause of them. A combined analysis by experimental laser-optical investigation and numerical CFD computation is performed to improve the understanding as to the causes of the cyclic fluctuations.
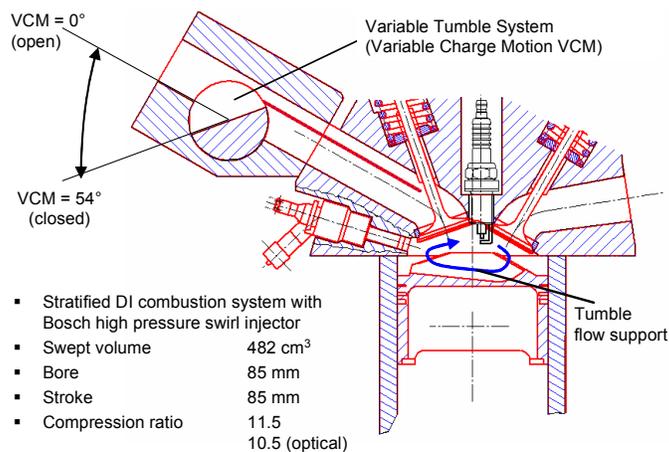
ANALYSIS METHODOLOGY

EXPERIMENTAL ANALYSIS

A single cylinder four-valve gasoline engine with high pressure gasoline direct injection is used as the test object, see Figure 2. The DISI engine features a tumble-supported, air-guided combustion system, where the required in-cylinder charge motion for stratified operation is generated by a tumble device (VCM). The injector is located below the intake ports. The test engine can be operated as a thermodynamic and as an optical version. Optical access is achieved by a glass ring that is designed to enable viewing the combustion chamber roof area.

Charge motion and mixture formation are investigated using an engine test bench employing PIV, Mie-scattering and LIEF measurements. PIV measurements during the intake and early compression stroke are performed in a motored engine test bench with a LaVision Flowmaster system. Late compression and injection are investigated by simultaneous PIV, Mie-scattering and LIEF measurements with an optical Multi-2D-technique developed by P. Wieske, S. Wissel, G. Grünefeld and S Pischinger [2].

The experimental and computational analysis is carried out in part load with a stratified mixture formation operation.

- Stratified DI combustion system with Bosch high pressure swirl injector
- Swept volume   482 cm^3
- Bore   85 mm
- Stroke   85 mm
- Compression ratio   11.5   10.5 (optical)

Figure 2: Combustion System Layout of the Single Cylinder Engine

In order to investigate the role of cyclic fluctuations of charge motion and mixture formation on engine operation stability, the injection and ignition timing is intentionally mistuned to achieve a misfiring rate of 10%. The engine settings are the following

Rotational speed / load: 2000 rpm / 2.8 bar imep

Charge motion: VCM closed

Rail pressure: 60 bar

Injection actuation end / duration: 60° CA BTDC / 1.8 ms

Ignition point: 43° CA BTDC

Misfire free ignition conditions are achieved in this operating point by the following changes to injection and ignition settings

Injection actuation end / duration: 40° CA BTDC / 1.8 ms

Ignition point: 25° CA BTDC

MULTIDIMENSIONAL NUMERICAL ANALYSIS

In order to extend the numerical analysis to cyclic fluctuations, a turbulence modeling based on the LES approach is used. The RANS approach with k,ε- or RSM model has been applied for more than two decades to study the combustion engine in-cylinder phenomena [3] and has shown its applicability to combustion engines in a large number of cases. Due to its inherent statistical averaging, the RANS approach enables prediction of the mean charge motion and mixture formation, but is limited when cyclic fluctuations shall be modeled directly. Using the LES approach, large scale turbulent structures are resolved and turbulence modeling is restricted to the sub-grid scale. For the in-cylinder flow, previous investigations have shown that LES improves the modeling of large vortex structures of the in-cylinder flow and their cyclic fluctuating behavior [4, 5].

In the current LES analysis, the program StarCD has been employed, using the LES approach according to Smagorinski [6].
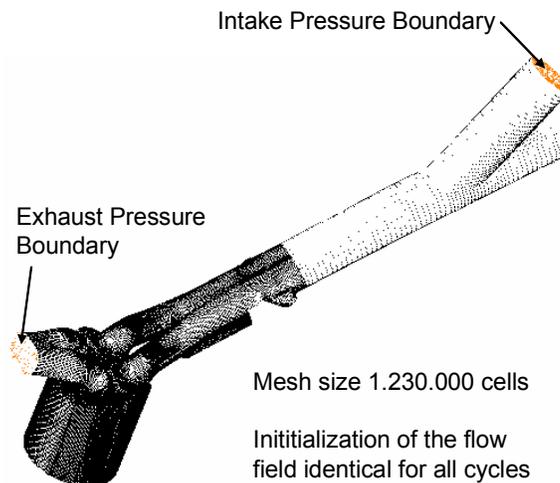

Intake Pressure Boundary

Exhaust Pressure Boundary

Mesh size 1.230.000 cells

Inititialization of the flow field identical for all cycles

Figure 3: CFD-Mesh and Boundary Conditions

Test bench measurement
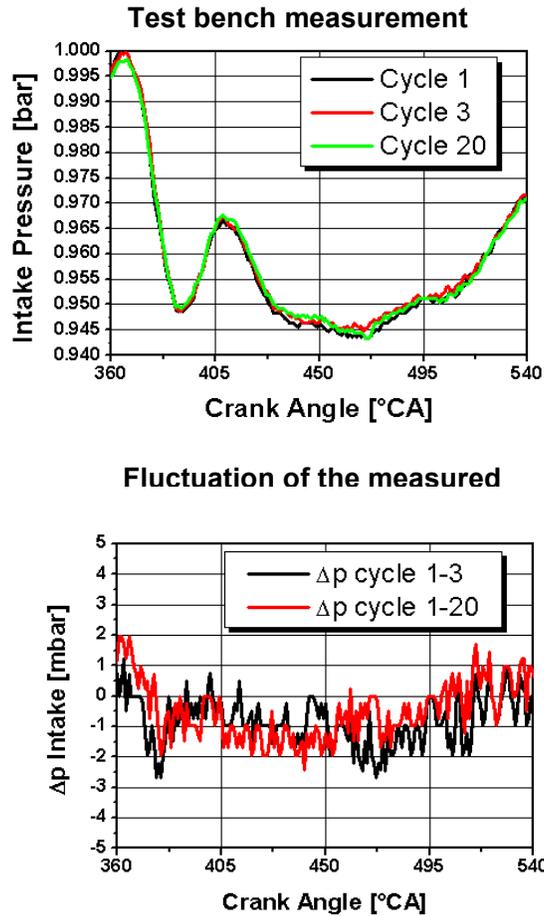

Fluctuation of the measured

Figure 4: Intake Pressure Boundary Conditions, Obtained from Experimental Low Pressure Indication

Simulations have been carried out for 10 separate cycles starting with identical initial flow fields. The pressure boundary conditions are taken from crank angle resolved test bench measurements, shown in Figure 4. The measured intake pressure traces show marginal cycle-to-cycle differences of < 3mbar.

For the simulation of the fuel injection, a two-phase Eulerian/Lagrangian coupling is used. The primary droplet break-up at the injector is modeled according to the approach of Adomeit et al. [7].

In order to separate the influence of spray and charge motion on the fluctuations, the boundary conditions for the injection are kept identical for all cycles.

RESULTS

FLOW ANALYSIS

As mentioned previously, directly measured pressure boundary conditions are used to calculate the flow of the intake and compression cycle for a total of ten cycles. As an example, Figure 5 shows a comparison between flow fields measured with PIV and calculated with LES in the symmetry plane of the combustion chamber for two individual cycles. In this comparison it is noticed that beneath the large scale tumble vortex, PIV and LES also show finer vortex structures. These are of comparable size, despite of differences in filter width. The PIV filter width is limited by the interrogation area of the PIV algorithm to approx. 2.4 mm, whereas the filter width of the LES analysis is approximately 1.0 mm, corresponding to the mean computational cell size.
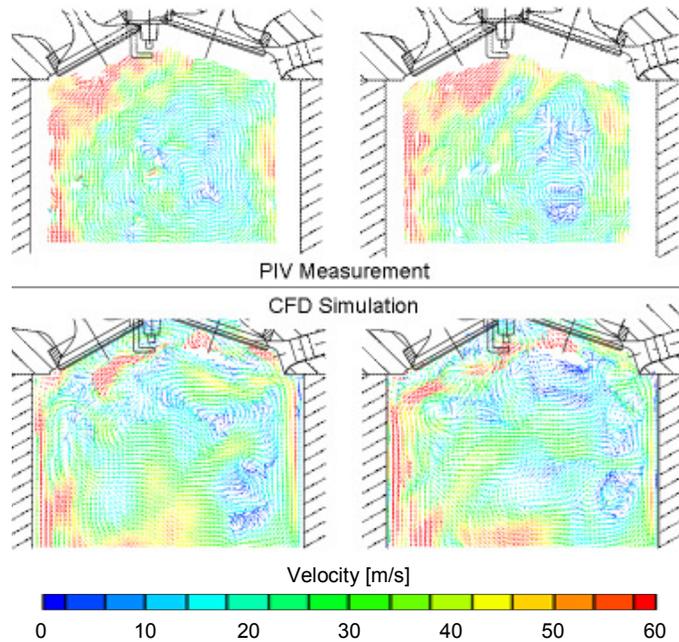
Figure 5: Comparison of Measured and Simulated Flow Field for Two Separate Cycles

In the CFD analysis it is presumed that the initial conditions for the LES computation are kept identical in the combustion chamber. Obviously, this assumption is an approximation, which neglects the properties of the remaining flow in the combustion chamber after the exhaust stroke. Nonetheless, this method is selected here, because it enables the tracking of the formation of flow differences, which finally leads to distinct cyclic fluctuations.

The simulation results show that the slightly fluctuating pressure boundary conditions cause only small variances in the port flow. There are no differences observed in the early induction period. First, distinct differences start to propagate from the volume downstream of the valve stem into the combustion chamber. From there they amplify in the outflow area at the cylinder liner. These fluctuations are subsequently transported further into the combustion chamber by the tumble motion. Finally, when the tumble transported fluctuations affect the flow in the intake duct, it can be assumed that the cyclic fluctuations are becoming self-inducing.

INJECTION ANALYSIS

The LES two-phase modeling is used in the subsequent analysis of injection and mixture formation in the combustion chamber. In the analysis, a strictly reproducible and identical injection process is fixed for all cycles regardless of the turbulence model. However, the in-cylinder flow at the start of injection exhibits the cyclic fluctuations determined by the LES simulation. Since the injection properties are strictly reproducible, the interaction of the cyclic fluctuating flow with the fuel injection can be studied in detail.

Figure 6 shows the measured and calculated flow and liquid fuel distribution in the symmetry section for two example cycles in the beginning of the injection event (9° CA ASOI). Figure 7 shows the measured and calculated flow and liquid fuel distribution after the end of injection (10° CA AEOI). Only weak variations can be recognized during early injection regarding the differences in spray shape and penetration depth of the pre-jet. However, considerable cyclical fluctuations occur after the end of injection. They are manifested by a fluctuating mixture quality, as shown by the liquid fuel distribution in the symmetry section.

In the early injection phase, shown in Figure 6, only minor differences are observed in spray penetration and shape. In the later phase and after the end of injection, considerable cyclical fluctuations can be seen in both simulation and measurement (see Figure 7).
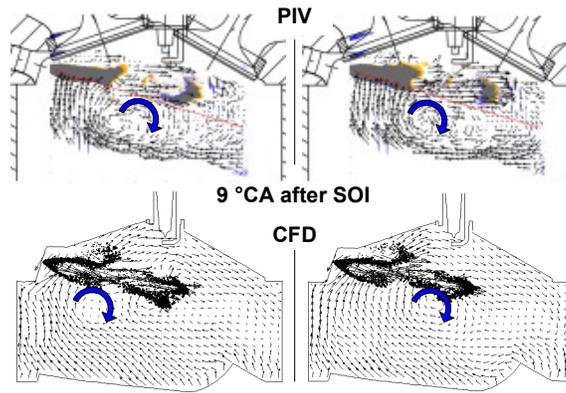
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PIV

9 °CA after SOI

CFD

Figure 6: Comparison of Measured and Simulated Injection for Two Separate Cycles, 9° CA after SOI

PIV

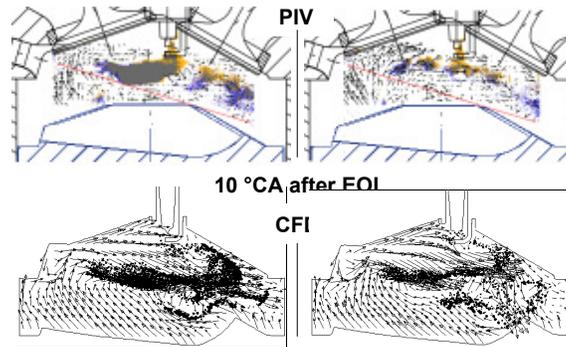**10 °CA after EOI**

CFI

Figure 7: Comparison of Measured and Simulated Injection for Two Separate Cycles, 10° CA after EOI

The effect of injection on fluctuation intensity is shown in Figure 8, which depicts the computed velocity difference of two cycles with and without injection. Apparently, the injection process causes an amplification of the cyclic variations. This observation corresponds with experimental findings, described in the following.
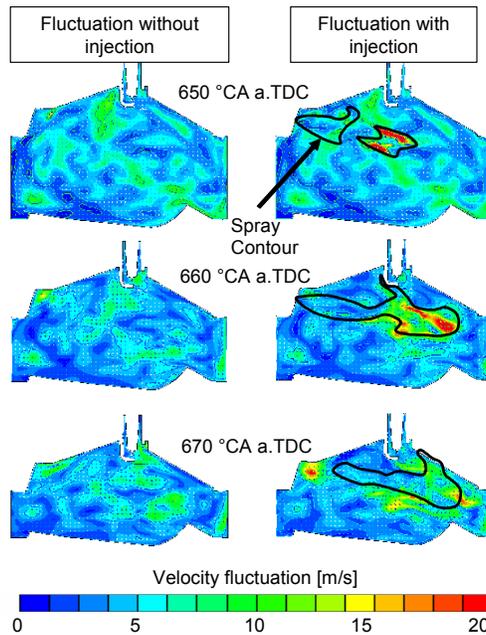

Figure 8: Development of Velocity Fluctuations with and without Injection between Two Cycles

Figure 9 shows the evaluation of PIV measurements during the compression phase with and without injection. Without fuel injection, the energy of the cyclic fluctuations remains at a fairly constant level until just before TDC, whereas there is a

6

significant increase in kinetic energy of the cyclic fluctuations with fuel injection. The kinetic energy of the cyclic fluctuations reaches a maximum at the end of injection and subsequently decreases until the ignition point is reached. However, the amount of kinetic energy is still several times higher than without injection.
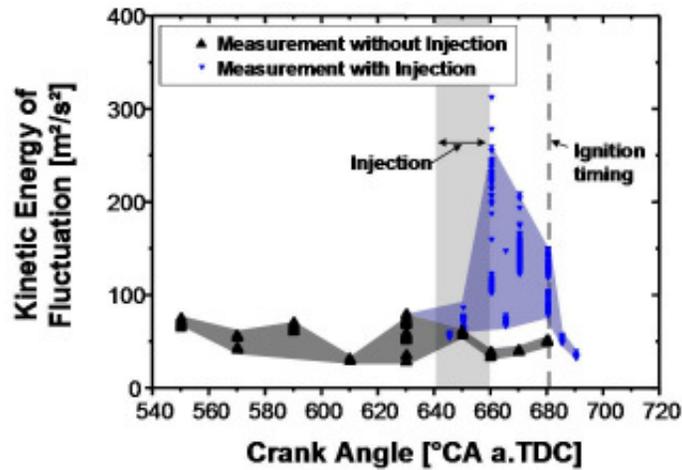

Figure 9: Kinetic Energy of Fluctuations with and without Injection

In conclusion, it can be stated that for the investigated combustion system the interaction of fluctuating flow and injection leads to substantial increase in cycle differences of the in-cylinder flow, which affects spray penetration and mixture formation. The latter is discussed in the following.

A comparison of measured and calculated fluctuations of the mixture formation is given in Figure 10. The experimental results show that the fuel vapor cloud has its upper border is at the spark plug level, and reveals noticeable cyclic fluctuations, which are observed mainly on the downstream side of the spark plug. The LES results additionally show a significant asymmetry of the fuel vapor cloud in the cross-sectional view.
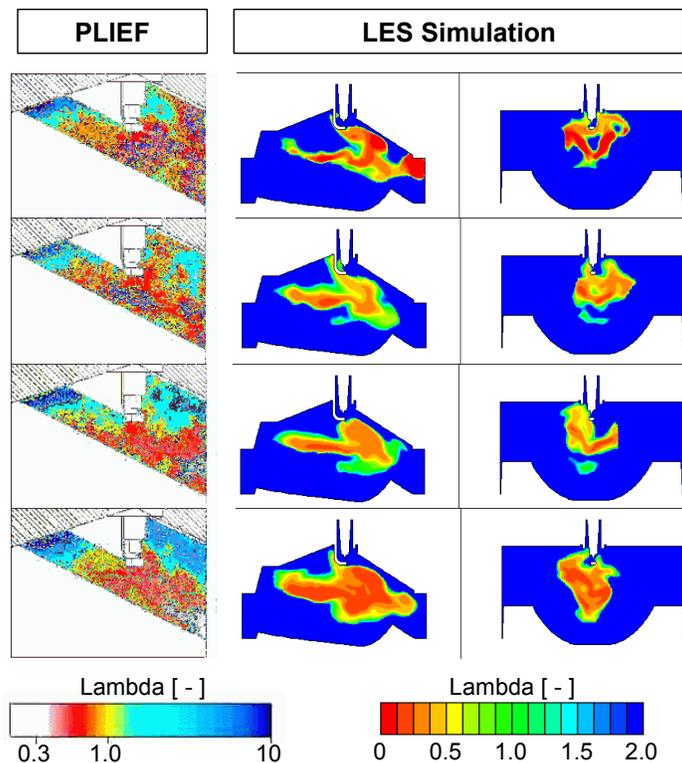

Figure 10: Comparison of Measured [8] and Simulated Fuel Vapor Distribution at the Spark Plug

7

MIXTURE STATE ANALYSIS

Although the number of 10 simulated cycles appears rather small, a statistical analysis of the mixture formation state of the 10 cycles represents a normal distribution with a good significance, while having an error probability below 0.05.

In order to quantify the cyclic fluctuations of the mixture formation state at the spark gap during the ignition event, Figure 11 shows the evaluation of the mean relative AFR during ignition in a reference volume at the spark gap for ten cycles. During the ignition duration from 678 to 690° CA, the mean relative AFR λ of four cycles is above the ignition limit of λ = 1.5. However, considering the size of the reference volume of 54 mm³ in comparison to the fine structures of the fuel distribution seen in Figure 10, it is questionable whether the mean relative AFR can be considered a reliable ignition criterion.
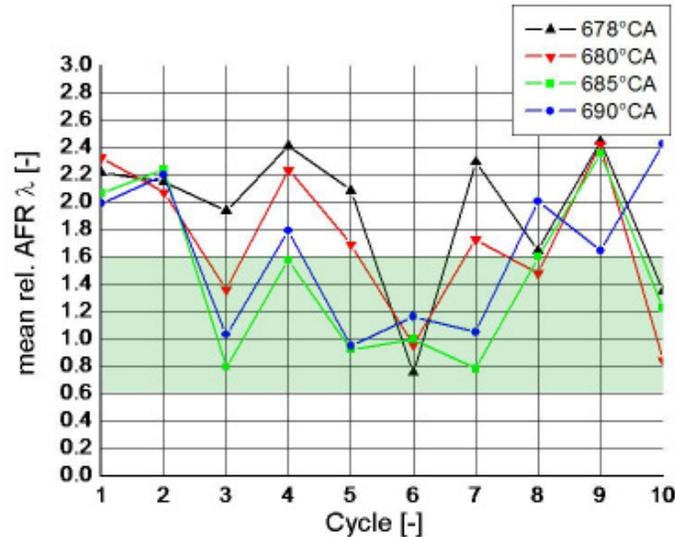
Figure 11: Evaluation of the Mean Relative AFR during Ignition for Ten Cycles

The volume fraction of the ignitable mixture within the reference volume during ignition is evaluated in Figure 12 for ten cycles. It is seen, that for most cycles the volume fraction of ignitable mixture is above 0.5, and only cycles 1 and 2 show low maximum values of around 0.25.
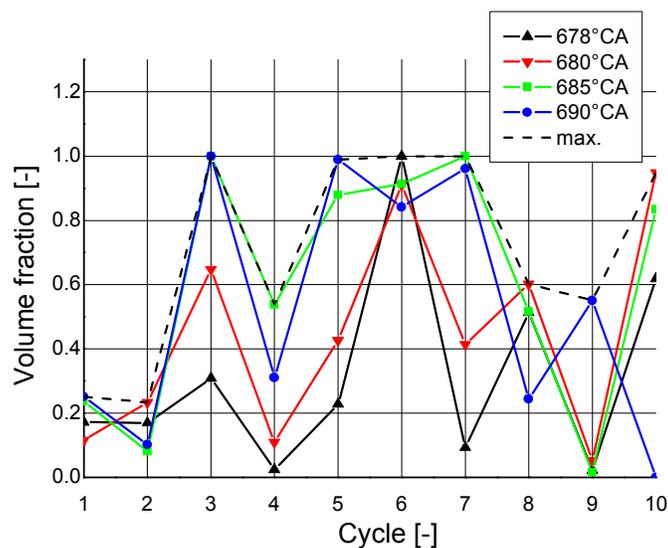
Figure 12: Evaluation of the Volume Fraction of Ignitable Mixture during Ignition for Ten Cycles

8

In order to achieve approximate information on the probability of cycles without ignitable mixture in the spark gap reference volume, a statistical fit procedure has been applied. Figure 13 shows the cumulative sum of the volume fraction of ignitable mixture and an integrated Gaussian fit function to the cycle resolved LES results. The result obtained from the statistical functional fit is a probability of 0.13 for non-ignitable mixture at the spark gap, which corresponds reasonably to the experimental result of 10% of the misfiring cycles.
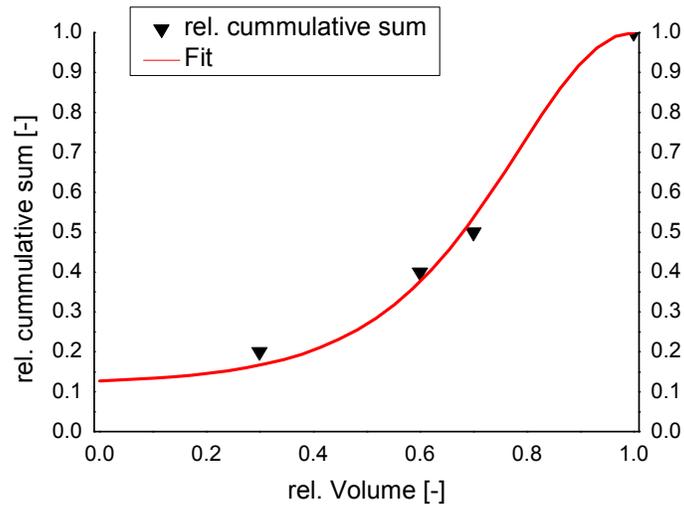

Figure 13: Relative Cumulative Sum of the Volume Fraction of Ignitable Mixture

CONCLUSIONS

It is crucial to understand the importance of cyclic fluctuations when developing direct injection gasoline engine combustion systems, due to the restriction they place on the realization of the inherent efficiency potential. Until recently, the source of cyclic fluctuations has only been vaguely identified. The primary focus of the current investigation is to obtain a better understanding of the causes of cyclic fluctuations by combining laser-optical methods and numerical analysis by Large Eddy Simulation (LES). Currently, results indicate that the key for a better understanding of the process is the knowledge about the interaction of fluctuations in charge motion and injection and their effect on mixture formation, ignition and combustion. The following conclusion can be drawn:

o   Calculations can be made using the LES simulation for cyclic fluctuations of charge motion and mixture formation. The results of the LES simulation of flow and mixture formation have been compared to PIV and LIEF measurements and show a good correlation, although simplified reproducible initial conditions and injection conditions have been assumed in the LES simulation.

o   The experiments and LES simulation illustrate that the interaction of the cyclic fluctuating flow with the direct fuel injection causes an amplification of the cyclic flow variations in the combustion system.

o   Engine misfiring can be explained by a lean mixture at the spark location. The LES calculation of 10 cycles represents a statistical significance. Application of a statistical fit procedure to the LES predictions, the probability of misfiring due to insufficient mixture formation has been obtained. It reasonably agrees with the experimental results from the engine operation.

The current investigation is limited by the application of simplified boundary conditions in order to gain a cross effect that is a free understanding of the origin of cyclic fluctuations. Later investigations can overcome this through multi-cycle simulation to properly account for the in-cylinder state at the beginning of the suction stroke and by injection models capable of accounting for the cyclic variations of the injection process itself.

Furthermore, it is required to investigate the ignition process under fluctuating flow and mixture formation conditions with high spatial gradients in sufficient detail, to obtain greater reliability in misfire prediction.

ACKNOWLEDGEMENTS

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