

Influence of the Mixture Formation on the Lubrication Oil Emission of Combustion Engines

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ABSTRACT

Partly competing objectives, as low fuel consumption, low friction, long oil maintenance rate, and at the same time lowest exhaust emissions have to be fulfilled. Diminishing resources, continuously reduced development periods, and shortened product cycles yield detailed knowledge about oil consumption mechanisms in combustion engines to be essential. There are different ways for the lubricating oil to enter the combustion chamber: for example as blow-by gas, leakage past valve stem seals, piston rings (reverse blow-by) and evaporation from the cylinder liner wall and the combustion chamber. For a further reduction of oil

consumption the investigation of these mechanisms has become more and more important. In this paper the influence of the mixture formation and the resulting fuel content in the cylinder liner wall film on the lubricant oil emission was examined. The oil emission behavior was investigated in a single cylinder spark ignition engine under different mixture formation conditions with Direct Injection (DI) and with Port Fuel Injection (PFI). The oil film thickness and the fuel content in the film were observed using the Light Induced Fluorescence (LIF) technique. The light accessed the cylinder liner through a silica glass window at significant locations which were determined by CFD-simulation. Moreover in-cylinder experiments have been carried out to measure the

composition of the oil film and the hydrocarbon emissions by online mass spectrometry. Further numerical simulation results and fundamental laboratory experiments contributed to a more detailed understanding of the interrelation between mixture formation and oil emission.

INTRODUCTION

The purpose of the research project “Lubricating oil emission and Mixture formation” is to determine the influence of the mixture formation and the combustion process in respect to the emissions caused by the lubricating oil thus by the SI-engine oil balance. The oil film on the cylinder liner wall is of great importance for the analysis of such correlations. Therefore the composition of the oil film is the prime objective of this research. [Figure 1](#) shows the active mechanism which contributes to the oil emission of SI-engines. Differences in the mixture formation lead to a different fuel entrainment to the wall film. Such mixture formation can be influenced by the parameters rail pressure (P_{rail}), end of fuel injection and injection pulse timing (EOI, ID), the air ratio λ and the charge motion, which can be controlled on the test engine with a tumble flap (VCM roller). Measurements are performed for fuel and oil film thickness (d_{Fuel} and d_{Oil}), as well as the concentration of fuel within the wall film (x_{Fuel}) and the oil emissions in the exhaust gas ($b_{\text{e-Oil}}$). For reference measurements the lateral swirl injector is placed into the inlet manifold for an external mixture formation.

analysis of the influence of the flow behavior on the fuel deposition on the cylinder liner wall and determines the resultant fuel concentrations and mixture viscosity in the wall film as input quantities for the oil emission simulation. In order to determine the film thickness of the cylinder liner wall a newly developed optical measurement technique is integrated into the cylinder liner. This allows the film thickness measurement of fuel layers and oil layers in the wall film on the basis of light-induced fluorescence (LIF). Furthermore a new sampling technology is integrated, which takes samples of the wall film during engine operation. Afterwards these wall film samples are analyzed for fuel concentration using a mass spectrometer. Furthermore the oil emissions are determined by direct measurement in the exhaust gas.

The existing simulation program for the calculation of oil emissions (based on the work of Lechtape-Grüter [8]) shows good correspondence for an engine with port fuel injection (PFI) [9]. As the market share for engines with direct injection increases and the oil evaporation changes with the kind of the mixture formation, these effects must be considered in the simulation of oil emissions. It is for this reason that the existing simulation program and the calculation process are reworked to account for the results of the experiments of this research. The newest extension of the program is also introduced in this paper.

FUNDAMENTAL EXPERIMENT

The purpose of the experiment is to show the correlation of fuel concentration within a mixture of oil and fuel, in respect to oil evaporation. Thus the same processes which one supposes to occur in the liner wall film. As of now evaporation of oil is determined by the measurement of the evaporation loss after the NOACK method [1]. This method is based on a slow heating-up of the oil over equilibria states. However this reproduces the highly dynamic processes in the combustion chamber insufficiently. The main focus and the challenge of this experiment are to demonstrate the highly dynamic heat introduction over non-equilibria states during the combustion.

The heat transfer from the combustion to the cylinder liner wall film is dominated by convection [2]. In order to heat load a sample in a reproducible and stable manner the transition from heat transfer to heat radiation yields good results for the fundamental experiment. Yet due to effects specific for radiation (e.g., reflexion) realistic film-thicknesses cannot be covered. However, with this fundamental analysis of the influence of fuel on the oil evaporation it is negligible. For the technical implementation of the experiment the following requirements exist for the set-up:

- Highly dynamic, controllable and reproducible heat loading of the sample

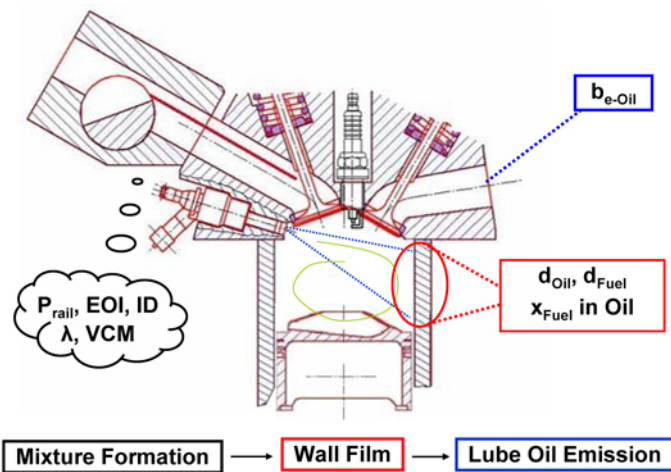


Figure 1. Influence of Mixture Formation on the Oil Emission

For a comprehensive approach of the problem, first of all a fundamental experiment is carried out. The purpose of the experiment is to show the influence of fuel within a mixture of oil and fuel for the oil evaporation. Furthermore CFD simulation supports the preparation of the engine tests to define the measurement positions. CFD also allows for the

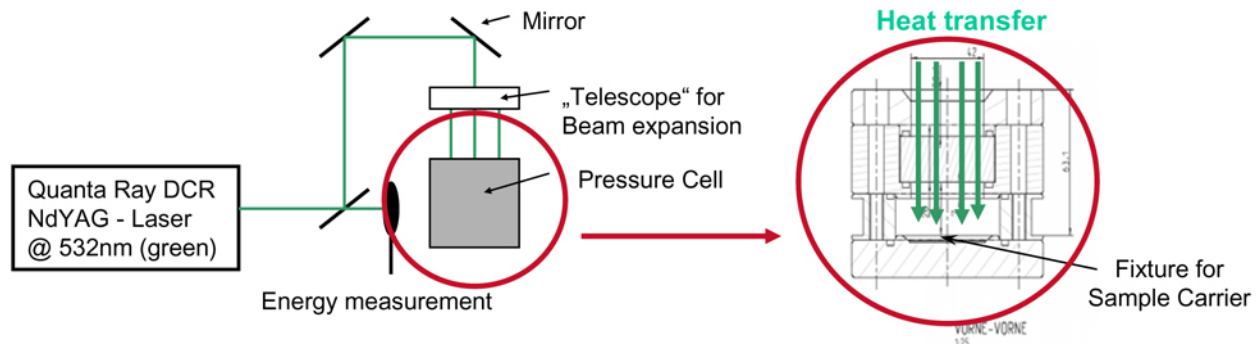


Figure 2. Setup and Procedure of the Fundamental Experiment

- Defined initial state of the sample (fuel concentration)
- Account for specifics of the motor, such as combustion chamber geometry and pressure
- No chemical influence of the evaporation effects of the pressurizing gas ($\Rightarrow$ nitrogen)
- Variability of cylinder pressure and cylinder temperature

The following figure describes the implementation and the set-up of the fundamental experiment which meets the above referenced requirements:

<figure 2 here>

A precisely defined sample can be inserted on a sample carrier into the container. By means of a pulsed laser it is then exposed using an optical path as well as the silica windows integrated into the pressurizable container.

Below you find the strictly timed and reproducible test procedure:

1. Produce a sample in a chemical laboratory: exact mixture in concentration of oil and fuel
2. Insert the 5-mm-high sample into the tempered container, then seal and pressurize the container with nitrogen
3. Controlled heat loading of the sample with 200 pulses of stabilized laser light, evaporation of the sample material, as can be observed through the silica window, as well as continuous capture of number and energy of the laser pulses
4. Expansion of the container pressure to ambient condition
5. Extraction and analysis of the vapor by means of mass spectrometry
6. Determination of the oil evaporation relative to the fuel concentration in the oil

Figure 3 shows the main results. The first measurement (0% fuel content) is calibrated to 100% of oil signal from mass spectrometry. The considerable distribution of the oil signal

as a result of clear shot-to-shot-dispersion of the laser power could be significantly reduced by a standardization of the oil evaporation signal to the nominal laser energy. Figure 3 shows the widely distributed measurement values with increase of higher fuel concentrations.

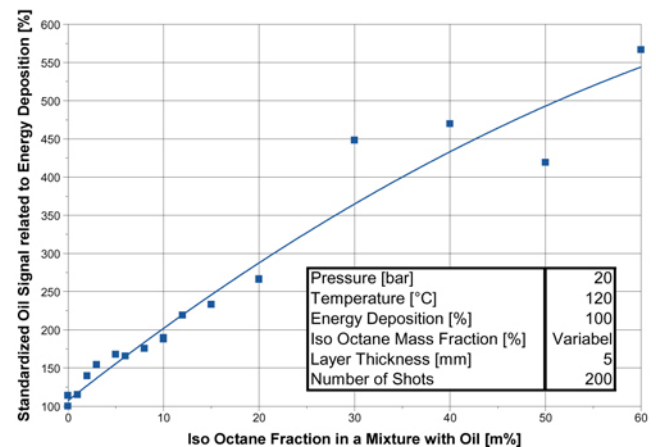


Figure 3. Results of the Fundamental Experiment: Impact of the Fuel Concentration on Oil Emission

Reason for this increasing distribution of measurement results is the higher volatility of the fuel. For normal engine operation lower fuel concentrations are relevant. Therefore this correlation offers a reliable basis for the use of the test results in the simulation of the oil emissions as described in the chapter "oil emission simulation". The fuel used during the experiment was ASTM Isooktan. Texaco Havoline Energy 5W30, a fully synthetic series engine multi grade oil was used for the oil. It is identical with the oil planned to be used for the oil film thickness measurement with the engine tests described later in this document. During testing fuel concentration, container temperature, container pressure and the film coating thickness were varied.

In the course of the experiment it showed that beside the temperature primarily the fuel concentration has a significant influence on the oil evaporation. Container pressure and film coating thickness showed no noticeable influence on the oil

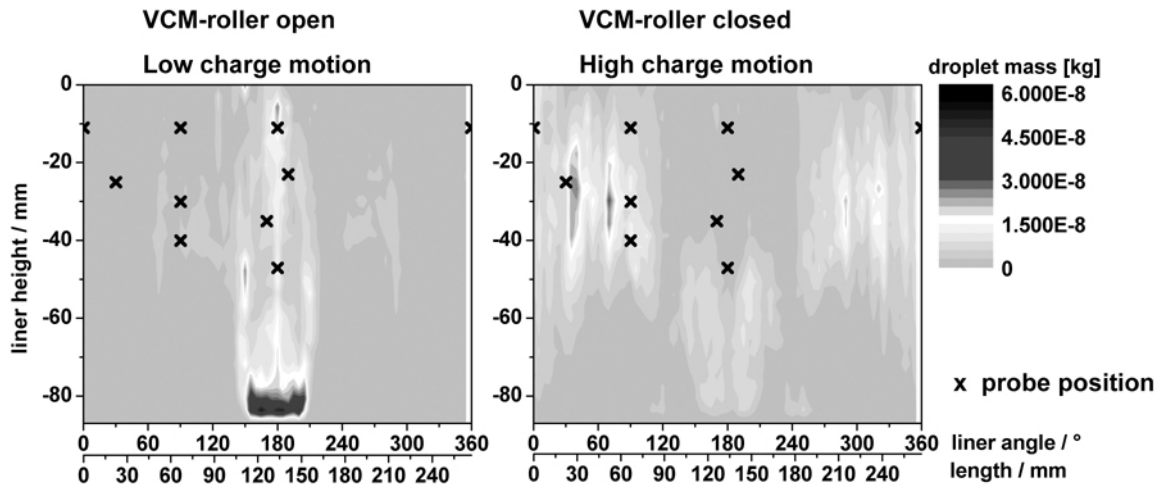


Figure 4. Accumulated Droplet masses for different VCM Positions

evaporation. The fundamental experiment clearly demonstrated that the fuel concentration in the oil film has a considerable influence on the evaporation of oil. This correlation is transferred into the models of the oil emission simulation.

SIMULATION OF INJECTION AND WALL FILM FORMATION

CFD simulations of the inside cylinder flow were carried out to determine the positions of the optical probes in the first step. In the second step the wall film forming process was simulated and the mixing viscosity in the oil film was determined as input parameters in the oil emission simulation.

The intake and exhaust port, as well as the combustion chamber, formed by cylinder head, piston and liner were simulated with the software ES-ICE 2.02.054 as a moving grid. For the simulations software STAR CD v3.26 and k , ϵ -Turbulence-Model for high Reynold Numbers was used. The modeling of the injection occurred with a primary break-up model for swirl injectors (based on the work of Han et al. [3]).

To determine the exact position for the optical probes, intake and compression stroke of the test engine with intake-synchronous direct injection for a homogeneous mixture formation were simulated on the basis of existing data. The operating point was set to 2000 rpm with 10 bar pmi. The simulation was performed prior to the initial operation of the engine test stand. The liquid phase was evaluated in liner wall proximity, because at that time only insufficient research had been undertaken on the droplet wall-interaction model.

Figure 4 shows the cumulated fuel-droplet masses in wall proximity for one cycle each, and for a single operating point

with a high and low charge motion. Because it can be assumed from the fact that a high fuel amount in liner proximity causes a high fuel entrainment into the liner wall film, the probe positions were selected accordingly (black mark-up in figure 4).

<figure 4 here>

For the determination of the mixing viscosity and concentrations of fuel in the oil film, intake and compression stroke were simulated using the boundary conditions determined during the test bench run. The “Bai” model implemented in STAR CD was used for the modeling of the drop wall interaction, based on the work of Bai and Gosman with respect to the drop wall interaction and wall film formation in diesel engines and SI-engines [4, 5]. Because the simulation of the oil film is not possible with the in-cylinder simulation on account of the moving grid, the mixing viscosity and concentrations of fuel in oil was calculated, spatiotemporal resolved using the fuel-wall film formation of the injection simulation and the oil film height from the simulation of the piston ring dynamics as described in the chapter “oil emission simulation”.

The simulated fuel-wall film formation is in good agreement of the results shown by the LIF measurements. This is both true in the spatial distribution and temporal sequence of fuel injection start, to wall film formation, as well as end of fuel injection to the termination of the drop film interaction. The clear differences of the absolute fuel wall thicknesses result from the evaporation behavior of the tracer used in the LIF measurements as described in the following chapter