

Experimental Studies on the Occurrence of Low-Speed Pre-Ignition in Turbocharged GDI Engines

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ABSTRACT

In the present paper the results of a set of experimental investigations on LSPI are discussed. The ignition system of a test engine was modified to enable random spark advance in one of the four cylinders. LSPI sequences were successfully triggered and exhibited similar characteristics compared to regularly occurring pre-ignition. Optical investigations applying a high speed camera system enabling a visualization of the combustion process were performed. In a second engine the influence of the physical properties of the considered lubricant on the LSPI frequency was analyzed. In addition different piston ring assemblies have been tested. Moreover an online acquisition of the unburned hydrocarbon emissions in the exhaust gas was performed.

The combination of these experimental techniques in the present study provided further insights on the development of LSPI sequences. In particular strong evidence enabling the identification of the fundamental trigger of premature, local auto-ignitions has been found. The results of the optical investigations reveal that pre-ignition is initiated in the immediate vicinity of glowing solid particles. The particles either result from the flaking of deposits or as a consequence of the contamination of the combustion chamber subsequent to a pre-ignition event.

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INTRODUCTION

Downsizing is a promising concept to increase the efficiency of SI engines. A reduction of the engine's displacement provides a shift of the operating range towards higher loads. The loss of power output in the full load regime related to the reduction of the displacement is compensated by applying a boosting strategy. The resulting increase of the pressure provoking elevated temperatures in the combustion chamber promotes the occurrence of abnormal combustion events.

In addition to the "regular" knocking combustion low speed pre-ignition (LSPI) has recently become a rather prominent issue in the development of SI engines. LSPI refers to uncontrolled and stochastically appearing auto-ignition events that are observed before spark timing. LSPI is typically observed in highly boosted SI engines at high load and low speed conditions. LSPI often occurs as intermittent series of several events, although singular events are also observed depending on the operating conditions. The extreme knock generally induced by a pre-ignition event potentially causes severe engine damage.

Despite the strong efforts spent on the investigation of this undesirable abnormal combustion phenomenon in recent years a general theory explaining its occurrence is not yet available. Dahnz et al. have performed an extensive study dedicated to the identification of the fundamental sources of pre-ignition [1]. The authors managed to exclude several potential causes and concluded that the auto-ignition at either lubricant/fuel droplets ejected from the piston crevice or glowing solid particles represent the most promising agents for pre-ignition. The hypothesis of lubricant induced pre-ignition received particular attention in the research community.

The studies of Palaveev et al. revealed a substantial impact of the spray impingement on the pre-ignition frequency [2]. Increasing the impingement generally entailed significantly higher pre-ignition frequencies. According to Wang et al. a split injection strategy with appropriate injection timings preventing fuel impingement represents a promising means of preventing LSPI [3]. Amann et al. managed to avoid pre-ignition almost completely using different piston crevice and piston crown geometries [4]. The study showed that only deep and shallow crevices mitigate pre-ignition. From these results one can

come to the conclusion, that the extent of the liquid reservoir consisting of a mixture of fuel and lubricant in the piston ring crevices exhibits a dominant impact on the occurrence of LSPI.

The investigations of Takeuchi et al. demonstrated a considerable impact of the lubricant oil composition on the pre-ignition frequency [5]. In particular a significant correlation of the auto-ignition temperature at high pressures determined by differential scanning calorimetry and the LSPI frequency was observed. In addition the authors provide evidence that additives containing calcium promote the occurrence of pre-ignition events. Experiments performed by Werler et al. yield that the introduction of liquid lubricant in the combustion chamber of a rapid compression machine accelerates the auto-ignition of fuel/air mixtures considerably under certain conditions [6]. Welling et al. determined the propensity to auto-ignition of various lubricant base stocks and mixtures of base stocks with different additives in a production engine [7]. Their test engine was operated with port fuel injection. An additional direct injection system was implemented to introduce either pure lubricant or mixtures of lubricant with fuel into the combustion chamber. Port fuel and direct injection of mixtures of fuel and lubricant did not provoke higher auto-ignition frequencies compared to regular PFI fueling. In contrast the direct injection of pure lubricant caused a considerable increase of the auto-ignition frequency. The authors concluded that a strongly non-homogeneous distribution of the lubricant in the combustion chamber represents a prerequisite for LSPI. Their studies revealed strong disparities in the ignition tendency between base stocks from the different API classes and even between the different representatives within a specific API category. The authors identified a petrochemical diester base stock as the least reactive of all the tested formulations. In addition they found a correlation between the physical properties of the lubricant (density and kinematic viscosity) and the propensity to auto-ignition. An increase in the density as well as in the kinematic viscosity of the lubricant caused a substantial drop in the observed ignition frequencies. Dingle et al. performed studies on lubricant induced pre-ignition in a research mono-cylinder engine featuring a large optical access enabling the visualization of the onset of auto-ignition [8]. The engine was operated with port fuel injection and liquid lubricant (PAO API Group IV) was directly injected into the combustion chamber immediately after the intake valves closed. After a single injection of lubricant during a specific cycle a pre-ignition event was observed. In addition the cycles subsequent to the injection of the lubricant exhibited a series of alternating regular and pre-ignition cycles, similar to naturally occurring LSPI. Luef et al. performed an extensive study on the tendency of the lubricant oils to auto-ignite [9]. Their results yield a major influence of the base oil quality and the viscosity of the formulated lubricant. In particular aliphatic, paraffinic hydrocarbons featuring high molecular weights (18 to 32 carbon atoms) were identified as promoting agents for pre-ignition. In addition they were able to demonstrate that synthetic lubricants mitigate LSPI.

The above mentioned studies provide significant evidence for a direct contribution of the lubricant in the development of pre-ignition. In addition evidence suggesting that pre-ignition results from auto-ignition at solid particles can be found in the literature. Okada et al. performed experiments applying a high speed camera system to

enable a visualization of the pre-ignition process [10]. The authors detected glowing particles during the compression stroke of the cycles exhibiting pre-ignition. Sudden changes of the direction of particle trajectories probably resulting from the rebound of the considered particles at the cylinder walls were observed. Thus the authors concluded that these particles are likely to be of solid nature. In a further study the authors artificially introduced solid particles featuring different physical and chemical properties directly into the combustion chamber. The results yield that combustible particles featuring a sufficient size provoke LSPI.

The exact triggering mechanism and the role of the lubricant within are not fully understood yet. The experimental evidence admits two distinct hypotheses: Either the lubricant directly triggers pre-ignition or it has a promoting effect on the formation of particles or deposits, representing a source of particles, potentially causing pre-ignition. In addition no satisfactory explanation for the typical pattern of LSPI events, occurring in sequences of alternating pre-ignition and regular combustion, has yet been found. Further studies on the impact of the lubricant and the sequential behavior are mandatory to promote a fundamental understanding of pre-ignition.

The present paper presents a summary of the latest experimental research on LSPI. The results of optical investigations applying a high speed camera system to enable a visualization of artificially generated LSPI events are discussed. In addition studies on the impact of lubricant formulation and the sealing effect of the piston rings on the frequency of LSPI events are presented. Furthermore a determination of fuel and lubricant emissions in the exhaust gas subsequent to LSPI events was performed.

The aim of the present study is to verify the assumption that the liquid reservoir in the piston crevice is involved in the development of pre-ignition. Moreover the influence of the lubricant and in particular of the lubricant properties shall be further illuminated.

METHODOLOGY

Optical Investigations

The present work is based on experiments performed in a modified four-cylinder turbocharged DISI production engine (Audi EA113 series) equipped with an endoscopic access enabling high speed visualization of the combustion. The detailed specifications of the engine are available in Palaveev et al. [2]. The lubricant oil features the following characteristics: SAE viscosity class = 5W-30, kinematic viscosity $KV_{100} = 12.33 \text{ mm}^2\text{s}^{-1}$, viscosity index $VI = 163$ and a standard additive package. A RON 95 E10 standard gasoline fuel was employed. More specifications, such as the corresponding boiling curves and the additive content, can be obtained from Palaveev et al. [2]. A high speed camera system (HSS6, LaVision) and an engine-mounted borescope (diameter = 6.5 mm) was applied to visualize the combustion process. In order to ensure a precise correlation between the frame timing and the engine crank angle, the camera-setup is extended by a high-speed controller (HSCv2), which is connected to the crank angle encoder. The resulting hyper-sampling system represents a time-based high-speed set-up able to capture the dynamics of fluctuations in the engine speed. Considering the

recorded intensity of soot luminosity in preliminary calibration tests, the accomplishable maximum temporary resolution is limited to 12.5 kHz. Thus an angular resolution of 1 deg. CA at 1750 rpm is achieved. The visualization is performed in a CA-range between 180 deg. CA before top dead center (bTDC) and 180 deg. CA after top dead center (aTDC).

A systematic investigation of LSPI is hindered by the stochastic and sporadic occurrence of pre-ignition events. An unreasonably high experimental effort is required to gather sufficient data for a detailed evaluation. The number of necessary engine tests can be reduced if pre-ignition events are triggered artificially. The suggested approach cannot provide any information on the fundamental origins of a LSPI sequence. However valuable insights in the processes involved in the development of a pre-ignition sequence out of an initial event can be obtained. For instance the hypothesis assuming that a sequence of alternating pre-ignition and regular combustion events occurs as a consequence of the initial pre-ignition event can be verified.

In this paper an experimental approach is presented enabling an artificial initiation of pre-ignition events based on premature spark timing. Optical and thermodynamic analyses of LSPI events reveal that pre-ignition typically emerges from local auto-ignition kernels provoking a regular flame front propagation, generally followed by heavy knock. In previous studies on the same engine the observed mean LSPI timing was 12 deg. CA bTDC (18 deg. CA before the knock limit) at a brake mean effective pressure (BMEP) of 22.6 bar (360 Nm) and an engine speed of 1750 rpm. The premature heat release causes a rise in pressure and temperature in the end-gas, provoking detonations leading to the propagation of high amplitude and high frequency pressure waves in the combustion chamber. This phenomenon is also referred to as “super-knock” [11]. The described phenomenon of flame propagation followed by an end-gas detonation can be also modeled by a single-cycle spark-ignition well before the knock-limit. The existing ignition system was modified to enable a spark timing advance on cylinder number four. The adapted setup is depicted in Figure 1.

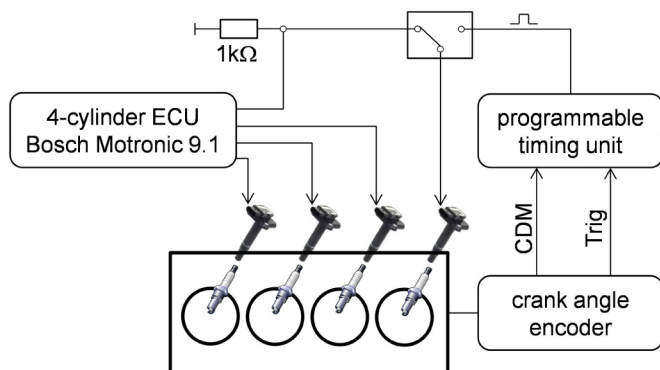


Figure 1. Modified ignition system enabling manual triggering of the spark.

Lubricant Related Experiments

Additional experimental work on the impact of the lubricant on the occurrence of LSPI was performed in a four-cylinder turbocharged DISI engine featuring a displacement of two liters differing from the engine used in the previously discussed experiments. The previous

engine suffered from severe damage as a consequence of the critical operating conditions and required substantial maintenance. The new engine was operated under full load and 2.000 rpm. A boost pressure in the range of 2.6 bar to 2.8 bar was applied. Commercial lubricant oil featuring an SAE viscosity of 0W-40 and the corresponding standard additive content was used. The engine was fueled with a RON 95 fuel station gasoline. In the experiments the physical properties of the commercial lubricant were altered by adding different additives and the effect on the pre-ignition rate was verified. At first a reference test was performed using the original lubricant. In a next test a blend of the lubricant and a commercially available viscosity index improver was applied. Another test run using a blend of the lubricant with an additive that increases wettability and thus reduces the surface tension was conducted. To conclude the experimental investigations the reference test run with original lubricant was repeated. Every individual test run covers a total number of 50.000 cycles. The presented investigations were performed in collaboration with an OEM. A more precise description of the experimental approach cannot be provided since the details are protected by a non-disclosure agreement.

The experimental approach was complemented with online unburnt hydrocarbon emission monitoring. The concentration of the exhaust gas components from the lubricating oil of modern combustion engines is in the range of a few parts per million (ppm). For this reason a measurement system with high selectivity and a low detection limit is essential for dynamic oil emission measurements. Mass spectrometers meet these requirements and have been optimized during the last years particularly for this application [13].

A quick transfer of the exhaust gas from the test bench to the detector is necessary for rapid online measurements of oil components. Using a heated transfer line the exhaust gas is conducted under avoidance of condensation effects into the pre-vacuum chamber. A schematic of the experimental setup is depicted in Figure 2.

A small amount of sampling gas is extracted continuously from the exhaust gas and transported into the ion source. This technique enables an extremely high time resolution with a sampling rate up to 250 Hertz. Hence even crank angle resolved measurements inside the cylinder are feasible. The hexapole transports the ions into the high vacuum area of the mass spectrometer. Three quadrupole mass filters permit the selection of certain components from the exhaust gas which are delivered to the detector.

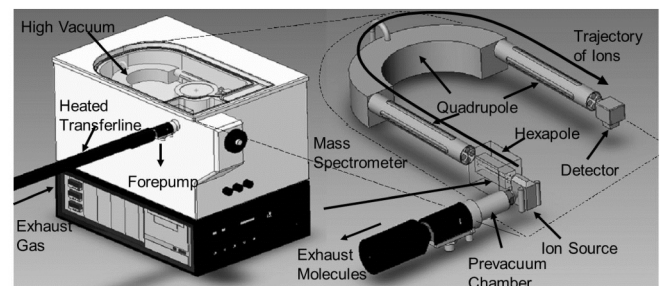


Figure 2. Schematic of the oil sampling setup.