

Investigations on Pre-Ignition in Highly Supercharged SI Engines

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ABSTRACT

This paper presents the results of a study on reasons for the occurrence of pre-ignition in highly supercharged spark ignition engines. During the study, the phenomena to be taken into account were foremost structured into a decision tree according to their physical working principles. Using this decision tree all conceivable single mechanisms to be considered as reasons for pre-ignition could be derived. In order to judge each of them with respect to their ability to promote pre-ignition in a test engine, experimental investigations as well as numerical simulations were carried out.

The interdependence between engine operating conditions and pre-ignition frequency was examined experimentally by varying specific parameters. Additionally, optical measurements using an UV sensitive high-speed camera system were performed to obtain information about the spatial distribution of pre-ignition origins and their progress.

The numerical simulations included the analysis of the general auto-ignition behavior of air/fuel mixtures depending on the thermodynamic conditions, mixture composition and other factors by taking into account detailed reaction kinetics. Furthermore, 3D CFD simulations were conducted in order to determine the predominant conditions within the combustion chamber.

By combining the results of the experimental and numerical investigations, many of the identified mechanisms could be ruled out. Others were classified to be very improbable. The release of lubricant oil droplets from the cylinder liner turned out to be the most probable explanation for the occurrence of

pre-ignition. As a main factor influencing the amount of droplets released and hence the pre-ignition frequency, oil dilution caused by spray impingement due to the lateral injector position was identified.

INTRODUCTION

Downsizing is an important concept to reduce fuel consumption as well as emissions of spark ignition engines. Engine displacement is reduced in order to shift operating points from lower part load into regions of the operating map with higher efficiency and thus lower specific fuel consumption. Since maximum power in full load operation decreases due to the reduction of displacement, engines are supercharged, which leads to a higher specific loading of the engines. Hence, new combustion phenomena can be observed especially at full load and low engine speed, which are not yet known from naturally aspirated engines.

The most important phenomenon is referred to as “pre-ignition”. Due to its large potential of engine damage this phenomenon is actually deemed the most important limiting factor for further downsizing [1]. In cycles with pre-ignition, air/fuel mixture ignites before the spark plug fires which results in a much higher pressure rise than in a regular combustion (see [Figure 1](#)). Due to the elevated pressure level and the frequently disadvantageous spatial position of the auto-ignition origin, combustion can pass into heavy knock which may cause severe engine damage.

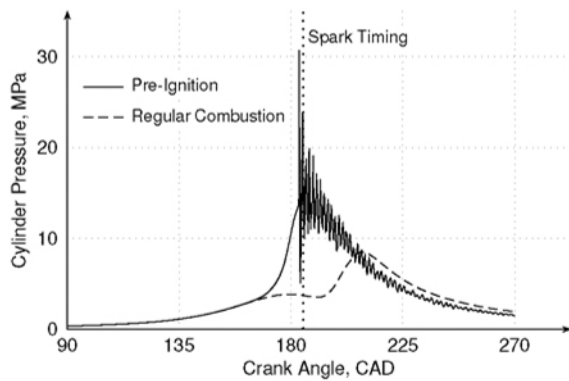


Figure 1. Pressure traces for regular combustion and pre-ignition

Thus, pre-ignition is a subject of extensive research work trying to determine reasons for its occurrence in order to derive measures to avoid it. This paper presents the results of a study carried out for this purpose using a highly supercharged production engine with direct injection.

METHODOLOGY

In order to assess possible causes for pre-ignition, experimental investigations using a test engine were carried out which were accompanied by numerical simulations. The results of both methods were combined during the evaluation process.

EXPERIMENTS

Test Engine

The test engine used for the experimental investigations was a direct injection spark ignition engine with four-cylinder in-line design and turbocharger. All testing was conducted using a slightly modified production engine with specification as shown in [Table 1](#) unless otherwise noted.

Table 1. Test engine specifications

Manufacturer	Volkswagen AG
Engine Type	2.0 l T-FSI
Displacement	1983 cm ³
Bore	82.5 mm
Stroke	92.8 mm
Compression Ratio	10.5 : 1
Max. Power	147 kW at 5700 rpm
Max. Torque	280 Nm at 1800-4700 rpm
Fuel Quality	RON 98
Mixture Formation	DI, lateral injector position

Charging-air pressure could be raised beyond the production-model level by manual override of parameters in the engine control unit. Additionally, a modified exhaust cam shaft was

applied, which enabled engine operation at considerably higher torque. Thus, the load conditions required to produce a sufficient number of pre-ignition events in a reproducible manner could be reached.

For all investigations described in this paper, the engine was run in full load operation at 1750 rpm with a brake torque of 360 Nm. Spark timing was fixed close to the knock limit for the worst case configuration during each of the parameter variations, global air/fuel ratio was adjusted to $\lambda = 0.95$ for all cases.

Measurement Techniques

The test engine was equipped with various temperature and pressure sensors to monitor operating parameters and with three optical accesses for the endoscopic combustion visualization.

In each of the four cylinders a pressure transducer was employed to measure cylinder pressures with a high temporal resolution. For this purpose, water-cooled piezoelectric pressure sensors of the type 6061BU by Kistler were used, which were able to resist the high pressure peaks resulting from pre-ignition.

For the endoscopic visualization of the flame front propagation in the combustion chamber, a high-speed camera system based on photomultiplier technology was applied to one of the cylinders featuring high temporal resolution (0.1 CAD) and having its highest sensitivity in a wavelength band between 250 nm and 450 nm, a range of particular importance for analysis of ignition phenomena. With its memory design using circular data storage, the camera system provides the facility to save data from cycles not only after but also before a predefined trigger event. Thus, it was possible to record a large number of pre-ignitions despite their infrequent and random appearance. The arrangement of the optical probes in the cylinder head can be seen in [Figure 2](#).

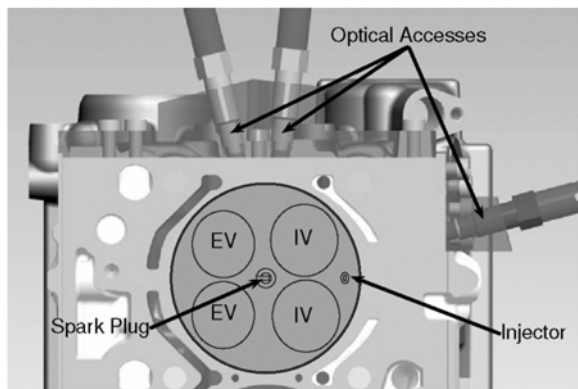


Figure 2. Arrangement of components at the cylinder head

NUMERICAL SIMULATIONS

Besides these experimental investigations, numerical simulations were carried out, which can be divided into two groups: on the one hand, 3D CFD simulations using the commercial CFD code STAR-CD by CD-adapco gave information about the conditions within the combustion chamber, including pressure, temperature distribution and local mixture composition. On the other hand, simulations of the detailed chemical kinetics were conducted for multiple scenarios.

During the investigations concerning the inflammability of air/fuel mixtures under the conditions determined by CFD computations and experimental measurements, two approaches with different levels of detail were used. The influence of thermodynamic parameters such as pressure and temperature and of mixture composition factors such as air/fuel ratio and exhaust gas fraction on auto-ignition properties in general was analyzed using the model of a homogeneous reactor [2]. By means of a one-dimensional combustion model, the influence of spatial inhomogeneities (i.e. hot spots, droplets and particles) could be investigated [3].

Simulations were conducted taking into account detailed reaction kinetics. For zero-dimensional computations, a "Toluene Reference Fuel" (TRF) mechanism by Andrae et al. [4] was used which contains the "Primary Reference Fuel" (PRF) mechanism by Curran et al. [5, 6] describing the combustion of iso-octane/n-heptane mixtures, extended by oxidation reactions for toluene. The TRF mechanism provides the advantage of being a more accurate model of the real multi-component fuel used for the experiments. For one-dimensional simulations, a reduced mechanism by Andrae and Head [7] was used to reduce computational effort.

PROCEDURE

In order to investigate the causes for pre-ignition, at first all mechanisms to be considered were identified systematically.

For this purpose, the possible mechanisms were arranged into a tree structure according to their physical working principles (see Figure 3).

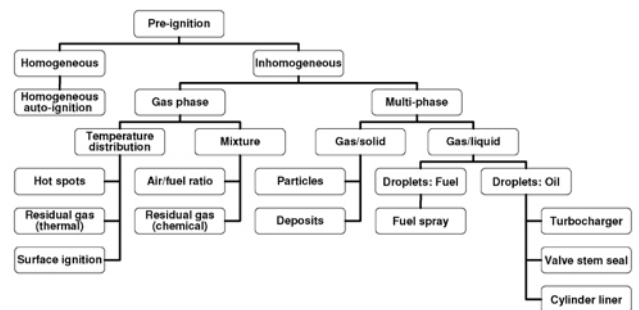


Figure 3. Possible mechanisms leading to pre-ignition

At first, homogeneous and inhomogeneous phenomena can be distinguished. Whereas for the homogeneous case there are no variations, inhomogeneous effects can be divided into pure gas phase and multi-phase phenomena. For the gas phase phenomena, inhomogeneity can consist in the spatial distribution of temperature and mixture composition. Multi-phase mechanisms can be subdivided according to the second phase involved besides the gas phase: solid phase and liquid phase. The detailed classification is illustrated in Figure 3.

RESULTS

During the evaluation process, some key experiments turned out to be particularly selective regarding the possible mechanisms leading to pre-ignition. The results of these experiments will be shortly presented below. Afterwards, a brief description of the results of the numerical simulations is given. At the end of this section, some general results about the characteristics of pre-ignition are presented.

EXPERIMENTAL RESULTS

Starting at the predefined reference operating point, multiple parameter variations were carried out. To produce comparable results, the most important operating parameters such as torque, air/fuel ratio and spark timing were maintained during the variations.

Temperature Variation

During the investigations of the temperature dependence of pre-ignition frequency, the coolant temperature (measured at the engine block outlet) was varied between 75 °C and 95 °C. The results can be seen in Figure 4. Pre-ignition frequency is plotted against coolant temperature, normalized to 10,000 engine cycles. The results shown in the diagram are based on a total of 100,000 cycles for each data point.

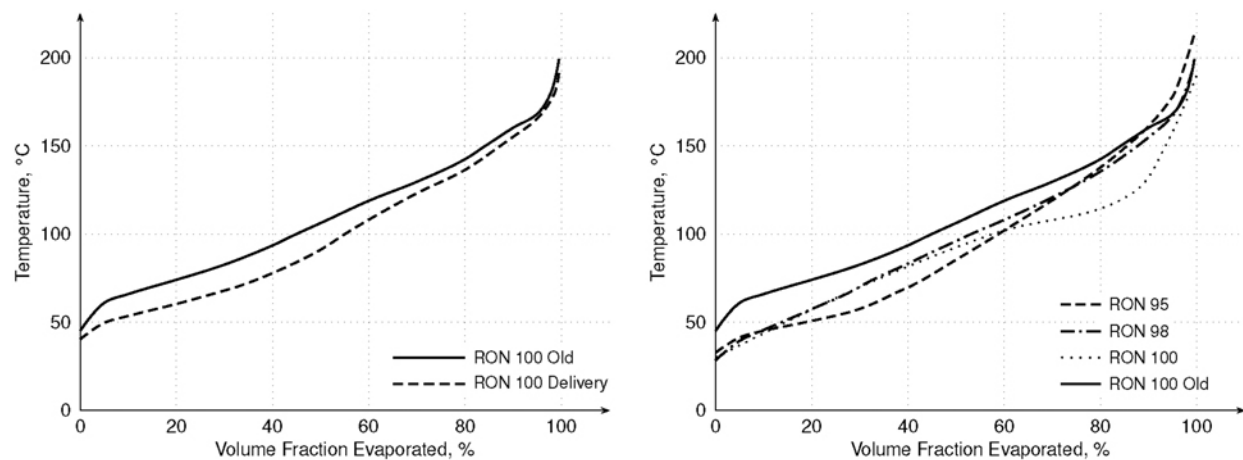


Figure 6. Boiling curves of fuels used during fuel variations

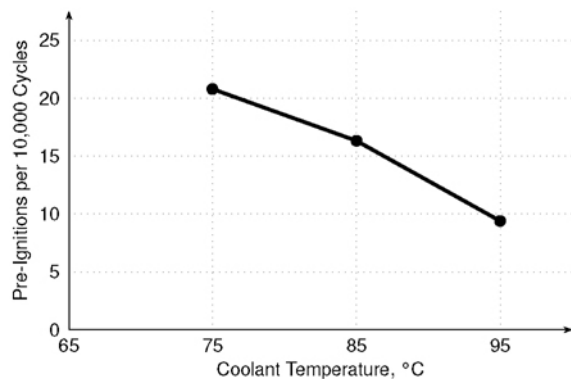


Figure 4. Effect of coolant temperature on pre-ignition frequency

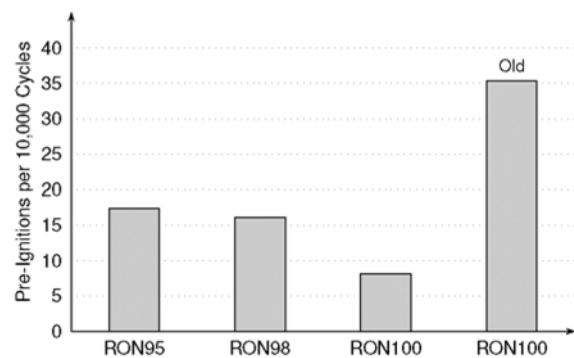


Figure 5. Pre-ignition frequency for different fuels

The most remarkable aspect concerning the result is the fact that pre-ignition frequency does not increase for higher coolant temperatures, but decreases even significantly. This firstly surprising observation is an important indication for the assessment of multiple pre-ignition mechanisms.

Fuel Variation

In addition, the influence of the fuel used in the test engine on pre-ignition frequency was investigated. The results are presented in [Figure 5](#). For the fuel variations, commercial fuels exhibiting research octane numbers (RON) 95, 98 and 100 were used. Additionally, the engine was run on an “old” RON 100 fuel which had formerly been stored for several years. This old fuel showed minor differences concerning its knock characteristics compared to the new RON 100 fuel, but a significantly higher pre-ignition frequency. This is strong evidence of the octane number being inadequate to draw conclusions about pre-ignition tendency for a given fuel. For the other fuels, pre-ignition rate tended to decrease with increasing octane number.

Supposing that the increase of pre-ignition frequency can be ascribed to the long-lasting storage, there remain two different explanations: The effect can rely either on a raised inflammability due to the preferential evaporation of low-boiling, knock resistant components or on a change of physical properties during the storage time. As the knock characteristics, which are directly coupled with the inflammability, were apparently not influenced by the storage time, the latter hypothesis appears more probable.

The influence of storage on the boiling characteristics of the fuel can be seen in [Figure 6](#) on the left. The diagram indicates the boiling curve after several years of storage compared to the curve measured just after delivery. The comparison shows that the boiling curve has shifted towards higher temperatures due to evaporation of volatile components. The diagram on the right side of [Figure 6](#) provides a survey of the boiling curves of all fuels used for the investigations presented in this paper (RON 100 curve based on data from a data sheet holding considerable uncertainties).

<[figure 6](#) here>