

Premature Flame Initiation in a Turbocharged DISI Engine - Numerical and Experimental Investigations

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ABSTRACT

This paper presents the results of experimental and numerical investigations on pre-ignition in a series-production turbocharged DISI engine. Previous studies led to the conclusion that pre-ignition can be triggered by auto-ignition of oil droplets generated in the combustion chamber. Analysis of more recent experiments shows that a modification of the engine operation parameters that promotes spray/lubricant interaction also increases pre-ignition frequency, while modifications that enhance the speed of chemical reactions (thereby favoring auto-ignition) have little or no influence. The experimental and numerical findings can be explained if we assume the existence of a substance (originating from lubricant/fuel interaction) that displays extremely short ignition delay times.

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INTRODUCTION

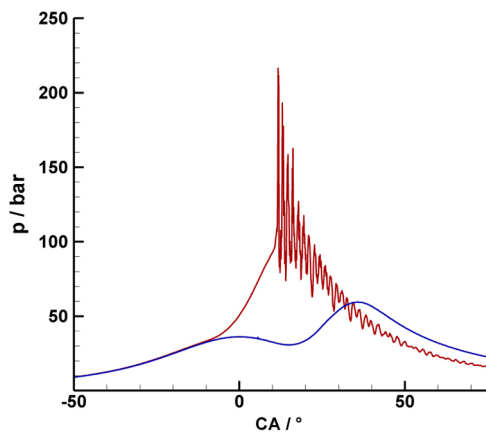


Figure 1. Comparison of an engine cycle displaying a PI (exhibiting strong engine knock) and a regular combustion cycle.

Premature and uncontrolled flame initiation, called pre-ignition (PI), has recently become a prominent issue in the development of spark-ignited engines. It is commonly assumed that this abnormal combustion mode hinders progress in engine downsizing, thus inhibiting development of more efficient engines. The phenomenon is primarily observed in highly turbocharged spark ignited (SI) engines in the full load regime at low engine speeds. Subsequent engine knock induces extremely high peak pressures, potentially

causing severe engine damage. Characteristic pressure traces for a regular cycle, and an engine cycle with PI are displayed in [Figure 1](#).

Previous investigations show that, under typical engine conditions, PI is a rare phenomenon. It appears to occur at random and often comes in intermittent series [1]. Optical investigations of the spatial distribution of the ignition spots revealed that there is no significant accumulation of PI kernels in a preferred area of the combustion chamber, as displayed in [Figure 2](#). The dots represent local ignition kernels recorded in various experiments.

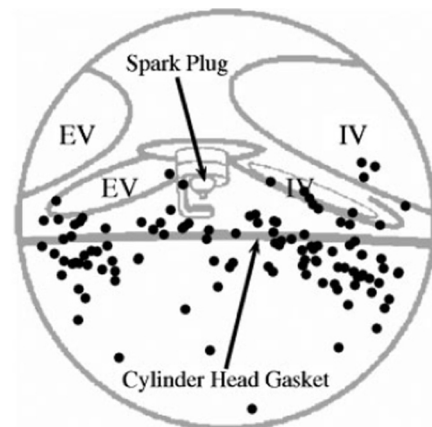


Figure 2. Spatial distribution of premature ignition kernels [2]

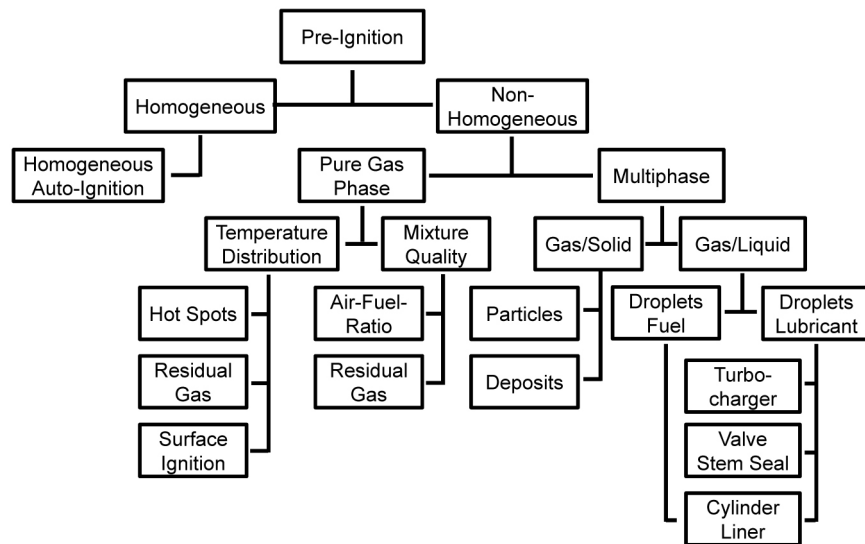


Figure 3. Logic tree for studying potential trigger mechanisms of PI

In recent years, some research has been performed in the field. Willand et al. [3] have performed experimental and numerical investigations and concluded that hot spots, deposits, lubricant droplets, residual gas, as well as auto-ignition of the fuel-air mixture are potential sources of PI. The influence of the valve timing on the indicated mean effective pressure and in particular on the occurrence of pressure waves in the intake was pointed out. The experimental analyses of Zahdeh et al. [4] indicate a correlation between the lubricant film impingement by the spray and the observed PI rate. The impact of a variety of parameters, such as fuel quality, composition of the lubricant, injection strategy and oil control ring tension was investigated. The interrelation of PI and super-knock was investigated by Bradley et al. [5], concluding that in most of the observed cases PI events entail severe engine knock. Günther et al. suggested an approach to assess the probability of PI based on the enthalpy of the mixture at top dead center derived from experiments [6]. In most of the published articles, a mechanism involving droplets released from the ring crevice due to fuel impingement is suggested.

In our previous work [1], a systematic categorization of potential PI sources was carried out, resulting in the tree structure depicted in Figure 3. In order to assess the potential of the assumed origins of PI, experimental investigations in a production engine were performed and combined with the results of numerical simulations. A detailed description of this work and its results can be found in references [1, 2, 7, 8]. For the engine investigated in these studies, it was found that the most probable mechanism leading to PI is the release of droplets from the lubricant film due to lubricant dilution by fuel.

Despite great research efforts, no conclusive answer on the causes of PI has yet been found. In fact, the cause of PI may be specific for a particular engine, so that no single generic mechanism can be identified that holds for all

engines. There-fore, in this work, theoretical considerations are combined with detailed experimental and numerical studies focusing on auto-ignition in the vicinity of droplets as a cause of PI. By these means, we investigate the sub-branches (Figure 3) associated with droplets. Physical models are applied to assess the likelihood of each scenario to occur in an IC engine. Also, the sensitivity of the PI rate with respect to changes in physical boundary conditions (e.g. cylinder pressure, gas phase and wall temperature levels, presence of droplets) is studied experimentally.

METHODOLOGY

In order to gain access to detailed knowledge about the generation of droplets and the auto-ignition of the fuel-air mixture at droplets in the test engine, the approach established earlier [1] was applied. Again, a variety of experiments were performed in conjunction with detailed numerical simulations. A few adaptations to the measurement techniques and the numerical models of the previous studies were necessary to improve the reliability and interpretability of the obtained results.

General Approach

The first step consisted of systematically identifying the governing physical and chemical processes involved in the droplet generation and the subsequent auto-ignition of the ambient fuel-air mixture. The findings of this process are summarized in Figure 4.

Assuming that oil droplets are released from the lubricant film, the probability of their existence in the combustion chamber is expected to depend on the amount of spray impingement. Thus, spray characteristics and the injector design should strongly affect the PI rate. Moreover, lubricant film temperature and the physical and chemical properties of the lubricant are expected to be a strong influence, as well. It

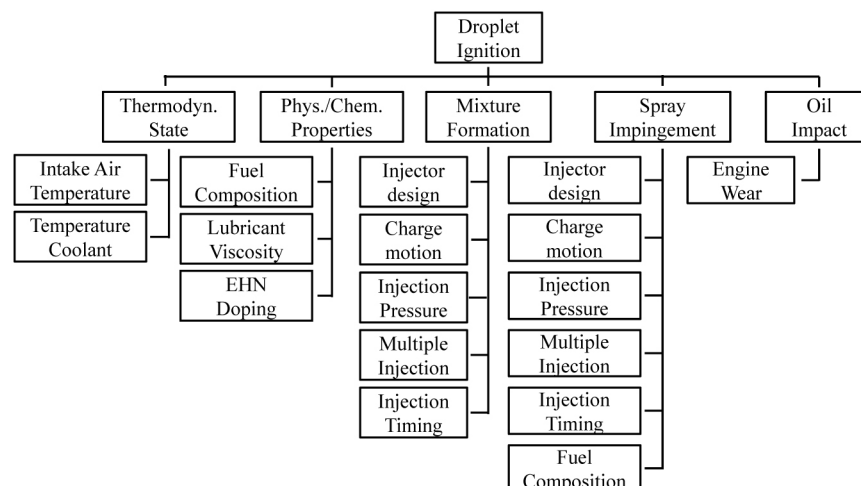


Figure 4. Governing parameters for the generation of droplets and the auto-ignition of the ambient mixture

has previously been shown that the composition of the fuel also affects the probability of PI [1].

Based on these considerations, engine experiments using fuels with varying compositions and different boiling characteristics were performed. The influence of the oil additives was analyzed. Moreover, the level of charge motion in the cylinder was varied. For all these experiments, the frequency of PI events was recorded.

Experiments

Test Engine

All experiments were performed on a four-cylinder turbo-charged DISI engine from the Volkswagen group. The stock engine data is listed in Table 1. The application of an “open” engine control unit allows the adjustment of all engine calibration parameters and maps through an interface.

To get a sufficient number of PIs, the maximal low-end torque was increased by 30% by replacing the original exhaust camshaft with a customized one. The modified cam profile is also used in the Audi AVS system of the recent engine generation [9], resulting in an increased maximal engine torque at low speed from 280 Nm to more than 350 Nm, while the content of residuals was kept at less than 1%. Furthermore, a customized, low volatile RON 95 E10 fuel was used, since the number of PIs with commercial fuels was still close to zero (cf. Figure 12). The fuel specifications are shown in Figure 15.

The camshaft drive was modified to free space for optical access in the cylinder head. However, the changes did not affect the valve timing, which was kept constant in all presented investigations, but only the path of the timing belt. The crankcase ventilation was disconnected from the intake to eliminate the influence of this source of oil droplets on the PIs frequency.

Table 1. Engine specifications

Manufacturer	Volkswagen Group
Engine Type	Based on EA113; 2.0 l TFSI
Displaced volume	1983 cc
Stroke	92.8 mm
Bore	82.5 mm
Connecting Rod	143 mm
Compression ratio	10.5:1
Mixture Formation	DI, sidewise injector position
Max. Torque	280 Nm at 1800-4700 rpm

Test Procedure

The test cycle for the investigations is shown in Figure 5. It consists of five test blocks at an engine speed of 1750 rpm and a brake torque of 360 Nm. Each block has a length of 10,000 engine cycles, corresponding to ca. 12 minutes (grey fields in Figure 5). The idle time between the blocks is needed for the cleaning of the optical access windows. The measurement procedure always follows a prescribed scheme: Before starting a new test, used oil is drained and the oil channels are cleaned with fresh oil. To prevent cold engine starts and additional oil dilution the engine coolant is preheated to 66 °C. After the coolant temperature has reached this value, the engine is started and runs at part load until the coolant temperature has reached the set value of 85 °C and intake air temperature has reached 20 °C. Both the intake air and coolant temperature are held steady for the length of the test block. Subsequently, engine load is successively increased to 360 Nm. Spark timing is fixed at 6 CAD ATDC, i.e. close to the knock limit for the worst case configuration. Global air-fuel-ratio is adjusted to $\lambda = 0.95$ for all cases. When brake torque, as well as coolant and intake air temperatures, reach steady state condition the data acquisition system is armed and the test starts. PIs are detected by event triggering on cylinder pressures with a threshold value of 120

bar. Trigger event data is recorded for all measurement channels between 6 cycles before and 14 after the PI. Since the peak pressure during regular combustion cycles does not exceed 80 bars, only cycles with knocking combustion can trigger the system. Cycles with knocking amplitudes above the threshold value, but without heat release before spark timing are distinguished from PIs and are not considered in the PI statistics. While amount of data for each experiment can differ, PI tendencies are compared in terms of PI rates, i.e. total number of PIs of all cylinders per 10,000 engine cycles. One engine cycles corresponds to two rounds of the crankshaft or four combustion cycles (4 cylinder engines). The data amount for each setting in the presented investigations was at least 100,000 engine cycles.

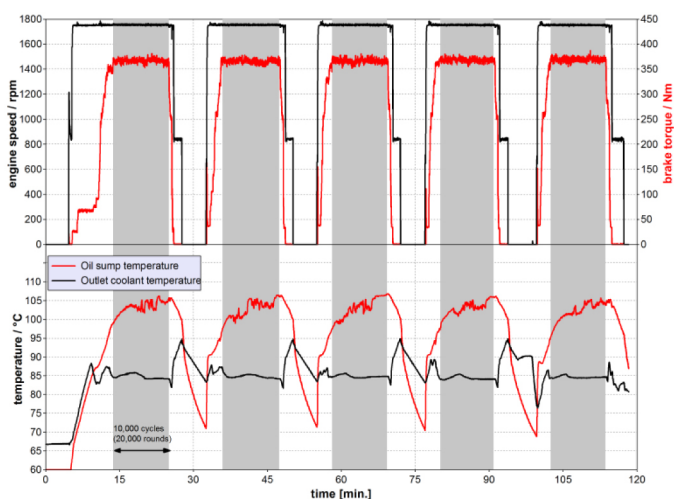


Figure 5. Test procedure

Measurement Techniques

The reliable detection of PIs requires the application of in-cylinder pressure transducers. Each cylinder was equipped with a water-cooled pressure transducer type Kistler 6061BU. These sensors have a strengthened structure, which is necessary because of the tremendous pressure peaks. The small size does not significantly influence the heat transfer from the combustion chamber. Besides the statistical evaluation of PI numbers on all cylinders, one cylinder was subject to special investigation. The intake and exhaust runners of the first cylinder were additionally equipped with piezo-resistive pressure transducers to get data for precise thermodynamic analysis. The exhaust runner of this cylinder was also equipped with an individual lambda-sensor. Besides the high-frequency data acquisition, the test engine was equipped with various low-frequency temperature and pressure sensors to monitor operating parameters.

One of the main tasks in this project is to detect positions of PI onsets in order to understand their primary origin. For this purpose, one cylinder has been equipped with three optical access points for endoscopes as shown in Figure 6. Unfortunately, only one of them, number 2 could be used.

The observation access is designed as a sleeve with an integrated sapphire window. The sleeve is screwed into the access bore and can be removed for window cleaning.

The high-speed camera system from Smetec GmbH used in the optical investigations is based on photomultiplier technology and features high temporal resolution (0.1 CAD) and high sensitivity for UV-radiation, which is of particular importance when analyzing ignition phenomena [10]. Due to its memory design with circular buffer, the camera system provides the capacity 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 PIs despite their infrequent and random appearance. The light connection between the camera system and the combustion chamber was conducted through a customized flexible endoscope with 10,000 optical fibers. The front part, which is air-cooled, has been mounted into the sleeve. The rear part, which is equipped with an eyepiece, can be fitted to the camera-system via a c-mount connector.

Because pictures deliver two-dimensional information, it is not possible to localize PI onsets by using one camera only. Initially, pictures taken from another two cameras from different angles were to be used to complete the 3D-information about flame propagation [11]. Unfortunately, this was not possible as the position of access number 3 close to the injector tip caused heavy window smearing, and number 1 did not work as the angle between it and number 2 turned out to be insufficient for 3D-reconstructions.

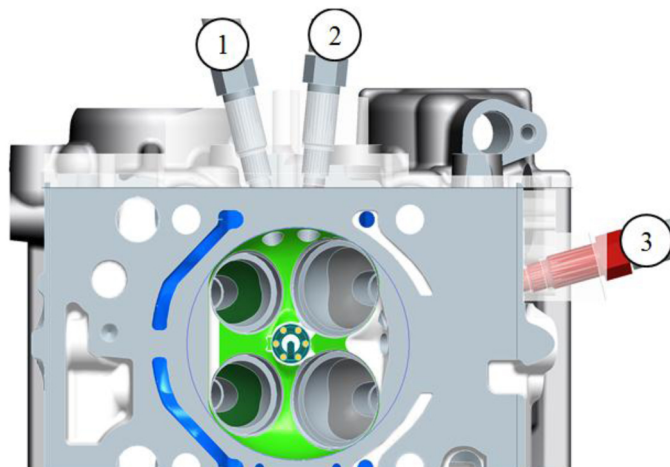


Figure 6. Arrangement of optical access positions

The complementary use of a fiber-optic-spark-plug (FOSP) appeared as a good alternative to get additional information about the flame propagation in the third dimension. Altogether 12 optical probes were installed around the circumference of the threaded portion of the spark plug. The observation fields of 8 sensors were radial in the combustion chamber and 4 were directed to the piston (axial). When the flame front reaches an observation field, flame radiation is transferred via an optical fiber to a photomultiplier which converts the detected combustion