The Optical Spark Plug: Window–related issues

M. Lackner[1]*, H. Kofler[1], H. Ranner[1], F. Winter[1],
J. Klausner[2], G. Herdin[2]

[1]Institute of Chemical Engineering, Vienna University of Technology,
Getreidemarkt 9/166, A-1060 Wien, Austria

[2]GE Jenbacher GmbH & Co OHG, Achenseestraße 1-3,
A-6200 Jenbach, Austria

Abstract

By focusing a sufficiently strong, pulsed laser beam one can obtain breakdown and a plasma in air, which is quite similar to the one generated by an electric spark plug as it is used in Otto engines. Such "optical spark plugs" have several advantages like the unrestricted choice of the ignition location. A key element in a future laser-ignited engine is the optical window. Experiments were carried out in a small engine with windows made of quartz, sapphire, ZnSe and Alon™. Strategies of how to prevent fouling of optical windows in combustion chambers are presented. The authors consider laser ignition a superior technique that, due to advancements in laser technology, has come close to practical utilization.

Introduction

Internal combustion engines play a dominant role in transportation and energy production. Even a slight improvement will translate into considerable reductions in pollutant emissions and impact on the environment. The two major types of internal combustion engines are the Otto and the Diesel engine. The former relies on an ignition source to start combustion, the latter works in autoignition mode. Ignition is a complex phenomonon known to strongly affect the subsequent combustion. It is especially the early stages that have strong implications on pollutant formation, flame propagation and quenching. The spark ignited Otto engine has a widespread use and has been subject to continuous, sophisticated improvements. The ignition source, however, changed little in the last 100 years. An electrical spark plug essentially consists of two electrodes with a gap in between where, upon application of a high voltage, an electrical breakdown occurs.

Soon after the invention of the laser it was discovered that the focusing of a sufficiently strong, pulsed laser could yield a breakdown and plasma in air, quite similar to the one generated by electric spark plugs. The idea to use lasers for ignition was soon put into practice [1] starting with laboratory experiments. Numerous potential advantages of such "optical spark plugs" like unrestricted choice of ignition location were discovered [2], [3]. In [4], laser ignition is compared to conventional spark plug ignition. [5] reviews different alternative ignition systems.

However, within more than 40 years, no laser-based ignition system has made its way to a real world application.

One constraint has come from the laser itself; although lasers have become more compact and less expensive over the years, they are not yet quite suitable for the construction of a commercial ignition system.

Another unresolved issue is the optical window. Evidently, it is a key element in a future laser-ignited engine. The window(s) must withstand the harsh and transient conditions in the combustion chamber and also show a low propensity to deterioration and fouling. So-called combustion chamber deposits (CCD) may rapidly lower and eventually destroy the transparency of the window, hence inhibiting optical access and reliable ignition.

Specific objectives

Laser-induced ignition has interested numerous research groups, however, the scientific literature is very scarce when it comes to the optical window.

This work is about the experimental investigation of different window substrates for use in combustion environments, especially in combustion chambers. A small internal combustion engine running on liquid fuels was used. The window was mounted in the cylinder head next to the spark plug. The infrared-transparent media quartz, sapphire, ZnSe and Alon were compared according to how prone they are to the formation of CCD under various conditions. Strategies of how to prevent fouling of optical windows in combustion chambers were to be elaborated and explained. Strategies of how to keep windows in combustion environments clean is not only needed for laser ignition, but also relevant to windows used for diagnostic purposes in combustion applications in general.

Combustion chamber deposits

A laser ignition system or "optical spark plug", in contrast to a conventional electric spark plug ignition type system is located entirely outside the combustion chamber. The energy necessary for ignition is delivered to the engine purely optically. This implies a window to couple in the laser light. The window is hence a key element in a future laser ignition system. Several concepts are viable; One might think of a single central laser source from where optical fibers deliver the laser pulses to the individual cylinders. At the cylinders, only a focusing optics in needed. Another possibility would be to equip each cylinder with its own laser plus focusing unit. The latter concept has more similarity with today's spark plugs.

In any case, a window is indispensable.

That window has to meet three basic criteria: It must, for long term operation:

- withstand the thermal and mechanical stresses from the engine
- withstand the high laser power necessary for ignition
- exhibit a low propensity to fouling

The first and second demands are met by the window substrate. Since pulsed lasers often operate at infrared wavelengths (1064 nm for Nd:YAG lasers), infrared transparent media are favourable. Here, experiments with quartz, sapphire, Alon™ and ZnSe were carried out. [6] presents an overview of infrared transparent window materials (see also Table 2).

The third requirement, a low inclination to the formation of window deposits, is addressed in this work. The literature does not contain much information on the prevention of window fouling in particular [7]. Combustion chamber deposit (CCD) formation is treated e.g. in [8]-[11].

Apart from trouble they cause particularly in optical diagnostics, CCD are generally unwanted, since they influence the combustion process in engines in an unfavourable way. Major problems are the CCD-generated "hot spots" that may lead to engine knock and higher emissions in unburned hydrocarbons and NO_x [9]. With respect to CCD, a 4 stroke Otto engine running on gasoline was studied in [8] and [9]. A two stroke Otto engine was investigated in [10], and a Diesel engine in [11]. The two stroke engine is a particular case, since lubricating oil and fuel are supplied together to the engine. The focus of these studies was on the influence of fuel additives ([8], [9]), lubricating oil ([10]) and the fuel itself [11]. In [12] it was concluded that the CCD in Otto engines stemmed primarily from the fuel and only to a limited extent from impurities in the lubricating oil. The aromatic hydrocarbons and those with high boiling points in the fuel were found to account for the formation of CCD [13], [14], which, in those studies, were found to be polymers from the oxidative coupling of their precursors [14], [15]. In test runs with a two stroke engine [10], it was discovered that the influence of the lubricating oil outweighed the unsaturated hydrocarbons in the fuel in the contribution to CCD formation.

Lubricating oil additives on the basis of calcium sulfonate were found to have a stronger effect on the CCD formation than derivates of succinimide. The chemical composition of CCD can be regarded as very complex. It results from the formation of particulates from incomplete combustion and the aging and thermal stressing processes on the surface of the combustion chamber in a hot, oxidative environment [9].

If one studies the formation of CCD, one will find that initially, material with comparatively low boiling point and high carbon content will be deposited at the cold combustor walls [16]. As the layer of CCD continuously grows, the thermal insulation gets better, hence the temperature rises, which leads to less volatile CCD at the surface. In [9], the influence of fuel additives on the microstructure and porosity of CCD was investigated. Generally speaking, CCD constitute a significant problem in gasoline and diesel engines. In gas engines that deploy clean fuels like natural gas, the issue of CCD is not as important.

Experimental

In this work, experiments concerning the formation and prevention of CCD formation on a window for laser ignition in an engine were carried out. A single cylinder, 4 stroke Otto engine with a displacement volume of 150 cm^3 was used for that purpose (see Table 1 for technical data).

Engine for window testing	
Type: Two valves, 4 stroke, spark plug ignited	
Fuels: gasoline, isooctane, toluene, ethanol, MTBE	
Cylinder head thermo stated 70-350°C	
Bore	10 mm
Stroke	10 mm
Displacement volume	150 cm^3
Compression ratio ε	~10

Table 1: Engine for the window testing. The windows (19 mmx5 mm) were mounted next to the spark plug. The spark plug was located centrally in the cylinder head.

The window was mounted in the engine using two copper rings (see Fig. 1). These rings worked as a sealing. The diameter of the free window was 14 mm. For better thermal insulation of the window, in some tests the window was contained between two rings of inorganic material with low thermal conductivity such as mica. This sealing method also provided adequate tightness for the whole test duration, which normally was 2 hours (5 minutes up to 10 hours of uninterrupted engine operation). The temperature was measured during the engine rest runs in two locations. A special surface thermocouple (type K) was used to measure the temperature at the back of the window (i.e. the outer side). Another thermocouple (type K, 1 mm diameter) was placed inside the cylinder head close to the window.

As fuels, gasoline (RON 95, petrol station grade), methyl tertiary butyl ether (MTBE), toluene, isooctane (2,2,4-Trimethylpentane) and ethanol (all in technical purity) were used. Synthetic oil (OMV SYN SAE 40/W) was used for lubrication. The engine was operated at a stoichiometric air/fuel equivalence ratio (lambda = 1.0). The difference in weight of the window (dried at 150°C for 2 hours) before and after each test run was taken as the CCD mass accumulated for gravimetric analysis. The relevant parts of the engine are shown schematically in Fig. 1.

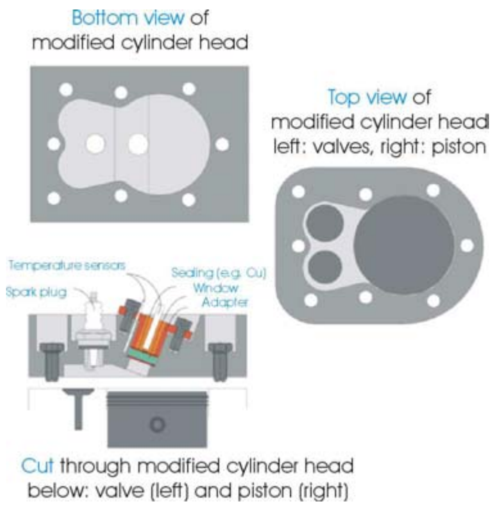

Fig. 1: Depiction of the experimental setup.

In the pertinent literature, CCD samples were washed in e.g. toluene or acetone prior to weighing in order to remove volatile constituents such as trapped fuel residues. This procedure was intentionally not adopted in this work. The term “deposits”, within the scope of this work, denotes the sum of all non-volatile, liquid-viscous to solid material from the combustion process that was collected on the window. Prior to the test runs, the windows were cleaned mechanically and in concentrated HNO_3. After the tests, they were dried for 2 hours at 150°C. The window substrates quartz, sapphire, Alon™ and ZnSe were investigated. Alon™, aluminum oxynitride spinel, is a ceramic material that with good transparency and strength. The substrates are compared in Table 2.

Material	Tensile Strength	Melting point	Thermal conductivity	Hardness (Knoop)	Coefficient of thermal expansion
	[MPa]	[°C]	[W/mK]	[kg/mm²]	[10^{-6}/K]
Sapphire	800	2000	42	2000	5
AlON™	380	2150	12.6	1950	7.5
ZnSe	100	1850	18	105	7.3
Quartz	80	1550	1.4	600	0.13

Table 2: Properties of the window materials (taken from [6]). All windows in this work were 5 mm thick and 19 mm in diameter.

Results and Discussion

The window tests were conducted in order to develop strategies to prevent the CCD formation on the window necessary for laser ignition. Basic testing was done regarding the influence of the window temperature, window substrate, lubricating oil and fuel type. Also, the cold start phase was investigated.

Influence of the temperature

The temperature on the window inside the combustion chamber is influenced by its mounting position, the engine speed, the thermal conductivity of the window itself and the sealing material.

The mounting position and the engine speed were held constant. The window and sealing materials were varied in this study. Apart from copper sealing rings with a very high thermal conductivity, an insulation material was used (Klingersil ™, thermal conductivity of 0.2-0.42 W/mK).

The temperature of the cylinder head could be varied by air and water cooling between 70°C and 350°C (measured in the bulk). The temperature at the outer window surface was approximately 23 °C higher than the temperature of the cylinder head block. Fig. 2 depicts the dependence of the window CCD formation on the temperature. All experiments in Fig. 2 were carried out with sapphire, the temperature of the cylinder block was set between 70°C and 350°C. The test duration was 2 hours each. The experiments were started with a cold engine. The warm up phase took approximately 15 minutes.

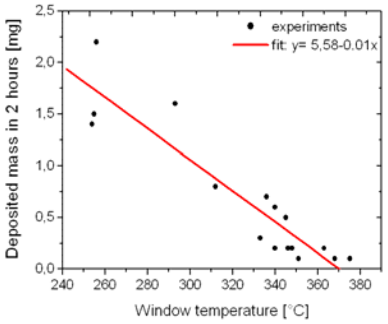

Fig. 2: Influence of the temperature (thermo stated cylinder head) on the rate of deposit formation on the window. (Window substrate: sapphire; Test duration: 2 hours for each setting).

As it can be seen from Fig. 2, the mass of the CCD formed during the 2-hour-interval decreases with rising temperature.

The thermal conductivity of the window material also influences the temperature at the surface. Experiments with different window substrates at constant cylinder head temperature (350°C) are depicted below in Fig. 3.

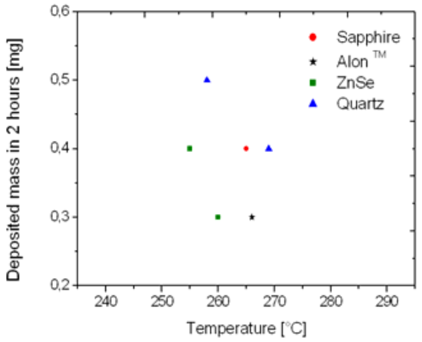

Fig. 3: Influence of the window material on the rate of CCD deposition (temperature of the cylinder head: 350°C; test duration: 2 hours).

The heat conductivity of the window governs the surface temperature and hence the amount of CCD.

As it is expected and can be seen in Fig. 3, the mass of the CCD increases with decreasing thermal conductivity of the substrates. The lower the thermal conductivity, the lower the heat losses are. It was found out that the material as such does not have a strong influence on the deposited mass. The different materials, due to different heat conductivities, lead to different temperatures. It is only the temperature differences that lead the observed differences.

In order to exploit and further investigate the positive effect of high temperatures on low CCD mass, the window sealing was optimized. Suitable materials with low thermal conductivities were tested. The results are shown in Fig. 4.

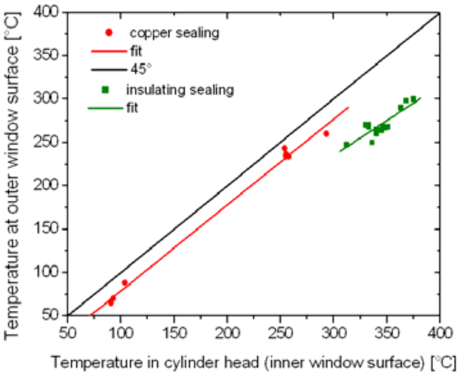

Fig. 4: Influence of the window sealing material on the rate of CCD deposition (temperature of the cylinder head: 350°C; test duration: 2 hours). The heat conductivity of the sealing influences the surface temperature of the window and hence the amount of CCD deposited there.

Another interesting question is whether window deposits formed in the still cold engine are reversible or irreversible. CCD initially show a steady growth and finally reach a constant thickness. In the engine investigated in [9], the steady state was observed after approximately 10,000 miles of engine operation.

Fig. 5 shows the temporal evolution of CCD on sapphire. 2 sealings (copper and insulating material) were used.

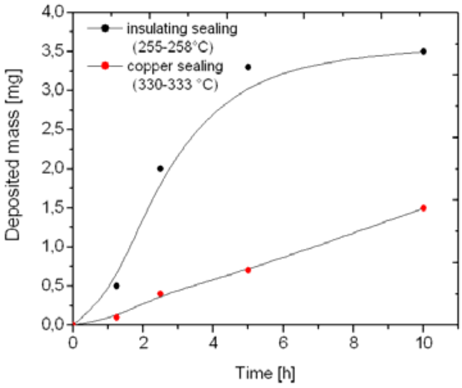

Fig. 5: Cold start behaviour.

Influence of the lubricating oil

The CCD are partly organic and partly inorganic. They stem from the fuel, but also from the lubricating oil. Carbonaceous deposits on the windows could be observed at temperatures up to approximately 300 °C.

At higher temperatures, a white powder-like layer was formed on the window. Mechanically it was hard to remove. A similar layer was observed on the windows from test runs below 300°C and subsequent treatment in a muffle furnace (400°C, 3 hours). The powder was composed of almost pure CaSO4, which seemingly originates from the calcium sulfonate in the lubricating oil. After an oil change of the engine, it was observed that the window became apparently soiled stronger at the same operating conditions. This behaviour first seemed to be paradox, but can be explained as follows:

Lubricating oil is composed of a variety of constituents with different boiling points. Fresh engine oil contains many rather volatile components that escape, decompose, burn and subsequently lead to deposits. With increasing residence time and thermal stressing of the engine oil, the volatile fraction is reduced, and the influence of the oil on CCD formation goes down.

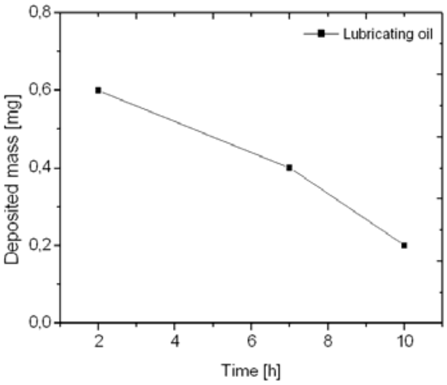

Fig. 6: The more thermally stressed the lubricating oil is, the less it contributes to window deposits.

Influence of the fuel

The influence of various fuels on the formation of CCD on the window was studied. The base fuel in this work was petrol station grade gasoline (RON 95). Fig. 7 shows the results.

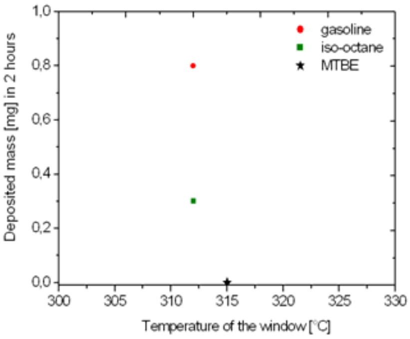

Fig. 7: Influence of the fuel type on the CCD formation. The temperature was roughly the same. MTBE produced virtually no deposits, gasoline more of them than iso-octane.

The engine ran well with all of these fuels.

The influence of the fuel type on CCD formation was also studied in [10] and [11]. In [10], CCD from gasoline an isooctane were directly compared. [11] the influence of attrition from engine components on the composition of CCD was studied.

In that study, two fuels, conventional diesel and biodiesel, were used in two separate engines that were operated for 70,000 km each. The CCD were evaluated for heavy elements from attrition. Attrition, according to these authors, is a function of engine lubrication which, in turn, is influenced by the interaction of the oil with the fuel used.

Influence of the laser: ablation effects

When the laser beam passes a soiled window, an effect called “ablation” occurs. The high intensity laser pulse is partly absorbed by the (black) contaminations. These are quickly heated up so that they evaporate. This is shown below in Fig. 8 for a Nd:YAG laser beam of 5 ns duration and 10 mJ energy.

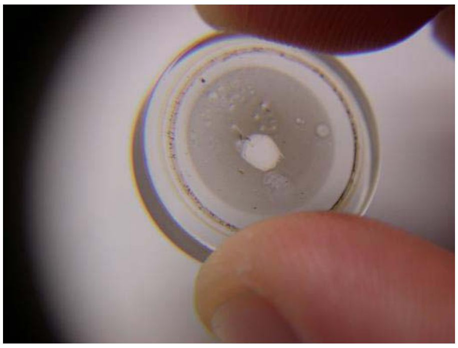

Fig. 8: Ablation: Nd:YAG laser, 5 ns, 10 mJ

Ablation is ineffective with non-absorbing materials (e.g. mineral deposits). It was found to work very well with carbonaceous deposits. A Nd:YAG laser has a wavelength of 1064 nm; By frequency-doubling, one can obtain 532 nm. Nd:YAG lasers are frequently used for laser ignition experiments.

Fig. 9 shows the transmission of the engine-derived deposits of light of 1064 nm and 532 nm.

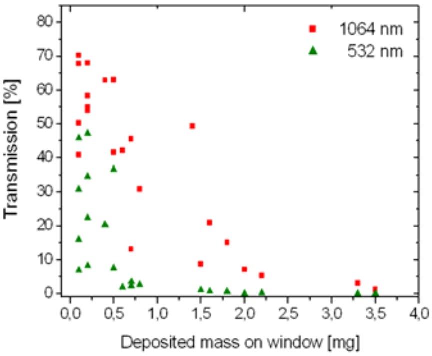

Fig. 9: Influence of the laser on the CCD formation (ablation).

Strategies to keep the window clean

In order to reduce the formation of CCD in internal combustion engines, the fuels usually contain surfactant additives. Typical additives are polyether amines and polybutene amines [9]. Due to the high temperatures, the effectiveness of the surfactants is not as high as intended.

Also, purging of the window region with clean gas can hinder the formation of CCD.

Based on the present study and the experiments presented above, one can conclude:

Strategies to reduce the CCD formation on windows should aim at keeping the window at high temperatures.

One of the easiest measures in this respect would be the choice of a window substrate with low thermal conductivity. Also, a window sealing with low thermal conductivity can aid in preventing heat losses of the window.

Conclusions

Otto engines rely on an ignition source. For that purpose, conventionally electric spark plugs are used. “Optical spark plugs”, that is laser ignition systems, have been envisaged for a considerable period of time. A major benefit of providing the ignition energy in an optical way only is the free and unrestricted choice of the location of ignition.

Experiments were performed to determine a suitable window configuration with low propensity to fouling for long term system operation.

Tests with windows made of sapphire, quartz, ZnSe and Alon™ were conducted. The windows were mounted in a single cylinder, 4 stroke Otto engine run on gasoline (RON 95), methyl tertiary butyl ether (MTBE), toluene, isooctane and ethanol. The influence of the window surface temperature was investigated. The cold start phase was studied, too. Gravimetric analysis, transmission spectroscopy, elementary analysis of the deposits and surface analysis of the deposits were conducted. It was found that the temperature of the inner window surface had a very strong influence on the formation rate of the combustion chamber deposits (CCD). Carbonaceous deposits were found to exist up to approximately 300°C. CaSO4 originating from the lubricating oil was identified as the most prominent inorganic constituent of the deposits. Strategies to reduce the CCD formation on windows should aim at keeping the window at high temperatures.

The authors consider laser ignition an advanced method of igniting engines that has come close to practical realization. This work is a contribution to an element which has not yet been considered extensively, the optical window.

Acknowledgements

We are indebted to Prof. Ernst Wintner from the Institute of Photonics, Vienna University of Technology, Austria, for fruitful discussions. This work was supported by the Austrian Industrial Research Promotion Fund (FFF) under Grant FFF 803050 and by the A3 project number 806238/7782. The authors also want to thank Prof. Avinash Agarwal from the Department of Mechanical Engineering, Indian Institute of Technology Kanpur, India, for valuable discussions.

References

[1] H. Kopecek, E. Wintner, H. Pischinger, G. Herdin, and J. Klausner, Basics for a future laser ignition system for gas engines, ICE-Vol.35-2, Paper No. 2000-ICE-316, ICE Fall Technical Conference ASME 2000, Peoria USA (2000).

[2] Kopecek, M. Lackner, F. Winter, and E. Wintner, Laser ignition of methane-air mixtures at pressures up to 4 MPa, J. Laser Phys. 13, 1365 (2003).

[3] M. Lackner, S. Charareh, F. Winter, K. F. Iskra, D. Rüdisser, T. Neger, H. Kopecek, and E. Wintner, Investigation of the early stages in laser-induced ignition by Schlieren photography and laser-induced fluorescence spectroscopy, Opt. Express 12, 4546-4557 (2004).

[4] Ronney P.D., Laser versus conventional ignition of flames, Optical Engineering 33(2), 510 (1994).

[5] J. D. Dale, M. D. Checkel, P. R. Smy, Application of High Energy Ignition Systems to Engines, Prog. Energy Combust. Sci. 23, 379-398 (1997).

[6] Daniel C. Harris, Durable 3–5 μm transmitting infrared window materials, Infrared Physics & Technology, Volume 39 (4) 185-201 (1998).

[7] H. Kofler, M. Lackner, F. Winter, Fenster zur Verbrennungsdiagnostik, to be submitted to Flammentag 2005, Braunschweig, Deutschland (2005).

[8] Art J. Nelson, John G. Reynolds and Joseph W. Roos, Comprehensive characterization of engine deposits from fuel containing MMT®, The Science of The Total Environment 295 (1-3), 183-205 (2002).

[9] T. W. Zerda, X. Yuan and S. M. Moore, Effects of fuel additives on the microstructure of combustion engine deposits, Carbon 39(10), 1589-1597 (2001).

[10] Masato Fukui, Tadafumi Sato, Naotake Fujita and Michio Kitano, Examination of lubricant oil components affecting the formation of combustion chamber deposit in a two stroke engine, JSAE Review, 22(3), 281-285 (2001).

[11] P. Tarkowski, J. Sarzynski, P. Budzynski, R. Paluch, M. Wiertel, Influence of the kind of fuel oil on the deposit composition in the diesel engine combustion chamber, Fuel 80, 1399-1403 (2001).

[12] J. C. Edwards, P. J. Choate, Average molecular structure of gasoline engine combustion chamber deposits obtained by solid state ^{13}C, ^{31}P and ^{1}H nuclear magnetic resonance spectroscopy, SAE paper 932811 (1993).

[13] T. Uehara et al., Study on combustion chamber deposit formation, SAE Transactions 106(4), 741-759 (1997).

[14] R. J. Prince et al., A laboratory simulation and mechanism for the fuel dependence of SI combustion chamber deposit formation, SAE Transactions 104(4), 1364-1379 (1995).

[15] S. R. Kelemen et al., Fuel lubricant and additive effects on combustion chamber deposits, SAE paper 982715 (1998).

[16] G. T. Kalghati, Deposits in gasoline engines, SAE paper 902105 (1990).

[17] K. M. Adams, R. E. Baker in: L. B. Ebert (editor), Chemistry of engine combustion deposits, New York: Plenum Press, p 19 (1985).