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Intake valve and combustion chamber deposits formation – the engine and fuel related factors that impacts their growth

Deposit forming tendency on the internal surfaces of spark ignition engines parts including IVD (Intake Valve Deposits) and CCD (Combustion Chamber Deposits) is one relevant parameter which causes driveability problems, affects engine durability and is of increasing concern in the automobile industry. The paper summarizes knowledge concerning the impact of engine operating conditions and fuel composition on the formation of IVD and CCD. On the basis of literature reviews and one's own research results, some interesting issues involved in the engine deposit accumulation and factors that influence their growth has been discussed. Until now at the Oil and Gas Institute (INiG) about 380 engine tests in compliance with CEC F-05-93 procedure, and about 220 in accordance with CEC F-20-98 procedure have been performed. This paper also covers description of the effects of deposits build-up on engine performance and its operational properties.

Key words: Piston Internal Combustion Engines, Intake Valve Deposits, Combustion Chambers Deposits.

Tworzenie osadów na zaworach dolotowych i w komorach spalania silników – czynniki wpływające na wzrost osadów związane z silnikiem i paliwem

Skłonność do tworzenia osadów na powierzchniach wewnętrznych części silników z zapłonem iskrowym, w tym osadów na zaworach dolotowych (IVD) i w komorach spalania (CCD), jest jednym z najistotniejszych czynników pogarszających właściwości użytkowo-eksploatacyjne pojazdu, oddziałujących na trwałość silnika i wywołujących zaniepokojenie w przemyśle motoryzacyjnym. Artykuł podsumowuje, w skrócie, wiedzę dotyczącą wpływu warunków eksploatacji silnika i składu paliwa na tworzenie IVD i CCD. W oparciu o przegląd literatury i wyniki badań własnych omówiono wiele interesujących zagadnień związanych z narastaniem w silniku osadów i czynnikami wpływającymi na ich wzrost. Dotychczas w INiG wykonano około 380 testów silnikowych zgodnie z procedurą CEC F-05-93 i około 220 zgodnie z procedurą CEC F-20-98. W artykule opisano także skutki tworzenia osadów na osiągi i właściwości eksploatacyjne silnika biorąc pod uwagę mechanizm oddziaływania osadów.

Słowa kluczowe: tłokowe silniki wewnętrznego spalania, osady na zaworach dolotowych, osady w komorach spalania.

Introduction

It is commonly known that conventional petroleum fuels like gasoline contain a complex mixture of a great amount of hydrocarbons. The hydrocarbons can be divided into classes such as paraffins, olefins and aromatics. These fuels contain also multifunctional fuel additive package designed for different specific purposes. To meet regular stringent emissions standard and performance requirements of modern engine technology, it is essential to improve fuel quality [20]. Generally speaking, molecular composition of fuels determines their physical properties, engine performances and thermal stability characteristics which is typically described in terms of the fuels tendency to form deposits inside engines. All commercial gasolines produce deposits on engine parts like: on intake valves and in combustion chambers. Carbonaceous deposits are derived primarily from the incomplete combustion of fuels and to a certain extend from lube oil contamination in the combustion chambers. These deposits can cause driveability problems, increase fuel consumption, emissions and also reduce power output and durability. Multifunctional additives containing mainly detergents of different chemistry added to fuel inhibit intake valves deposits but simultaneously provokes increase of combustion chamber deposits. It is important to underline that as engine fuel injection and management systems have become more complex, the effect of deposits has become an issue with the operation of modern engines. In spite of significant progress which has been made by many research workers toward understanding the nature and complex mechanism by which engine IVD (Intake Valve Deposits) and CCD (Combustion Chamber Deposits) are formed, a high number of factors that influence the formation and growth of these deposits makes prediction of problems in new engines families or modified engines extremely difficult and require extensive knowledge. That is why IVD and CCD in modern engines are causing increasing concern in the automobile industry.

Test methods for research and evaluation of IVD and CCD

For researching and next solving the problems in the field of deposit formation, simulation of the critical engine operation conditions and other factors affects deposit growth must be performed on a test bench. The most popular, recognized European test methods for evaluation of deposits forming tendency on intake valves and in engine combustion chambers and detergent effectiveness, focusing on CEC (Coordinating European Council for the Development of Performance Tests for Transportation Fuels, Lubricants and Other Fluids) are test methods using the Mercedes M102E (CEC F-05-93 – *Inlet Valve Cleanliness in the MB M102E Engine*) and M111 engines (CEC F-20-98 – *Deposit Forming Tendency on Intake Valves and in Combustion Chambers*) [11]. These CEC test methods have been approved both by fuel and engine producers as well as vehicle manufacturers which is noted e.g. in the World Wide Fuel Charter. For many years representatives of the Oil and Gas Institute (INiG) (earlier Petroleum Processing Institute) participated actively in both of these Groups [20]. To date at INiG about 380 engine tests in compliance with CEC F-05-93 procedure, and about 220 in accordance with CEC F-20-98 procedure have been performed. So, a lot of the observations presented below have been based on results of our own tests which were carried out on Mercedes Benz M102E and M111 engines in order to evaluate performance related to IVD and CCD forming tendency using base gasoline with varying compositions and treated gasoline with different treat rate of various additives (Fig. 1).

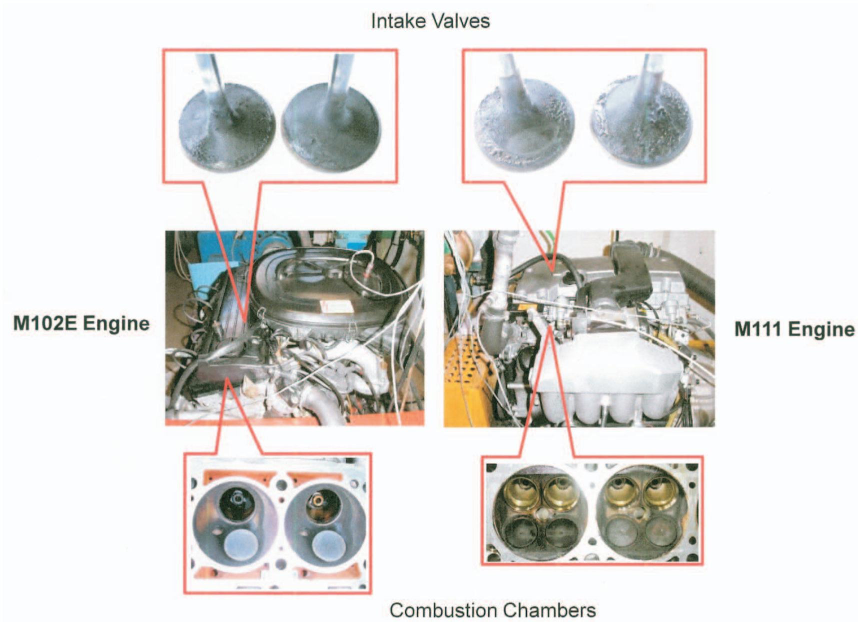

Fig. 1. Appearance of IVD and CCD in Mercedes M102E, PFI, OHC 2-VPC test engine and in Mercedes M111, PFI, DOHC, 4-VPC test engine

With the aim of gaining an insight into the deposit formation and growth process, the deposits were sometimes evaluated and measured not only at the end of the test, but also at intervals i.e. 10 hr, 30 hr and 50 hr. Furthermore, an experimental study was performed to investigate the effects of intake valves and combustion chamber temperature on deposit formation and growth in a spark ignition engine. Formed deposits were subjected to physical and chemical analysis.

Factors which influence deposit formation

Fuel composition, fuel additives, lubricating oil and engine design parameters and its operating conditions (exhaust gas, blow-by, temperature) are potential sources for formation of deposits like IVD and CCD (Fig. 2).

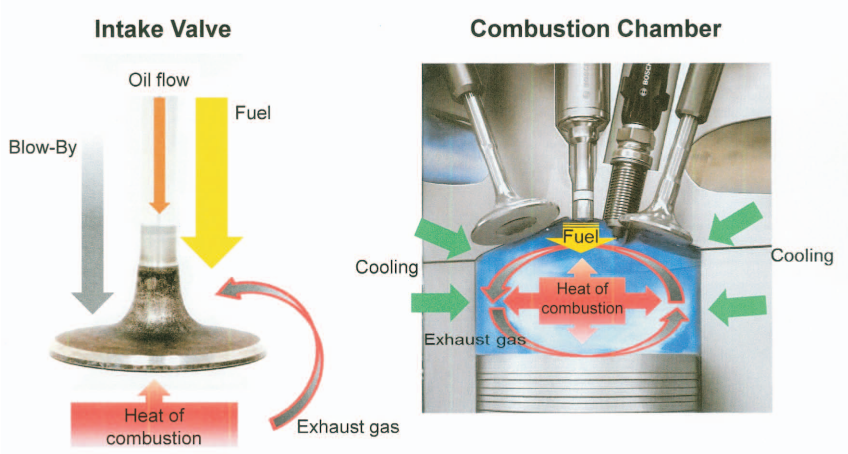

Fig. 2. Potential sources of engine deposit formation

Chemical composition of high boiling components of fuel with high deposition tendencies have immense influence regarding formation of deposits in gasoline engines. So, the most important fuel property in engine deposit formation is the boiling point and the most critical fuel components in deposit formation are those with the highest boiling point [1, 13, 16]. Taking into consideration major gasoline components, at a given boiling point, aromatic hydrocarbons are the most prone to deposit formation, olefins content of the fuel has less significant effects on deposit formation, and paraffins are the least prone to deposit formation. The important factor in deposit formation is fuel treatment by adding detergents additives into the base fuel. It was proven that all types of additives could reduce and control IVD deposit while simultaneously CCD increases. Notably, fuel treated with additives blended at an IVD control dosage, produce more CCD than the base fuel alone [2, 9, 20] – Fig. 3. Additive package components have higher boiling points compared to base fuel components and hence will cause an increase in the deposit built-up and its growth [14]. It should be stressed that while all the additives increased CCD compared to base fuel, the fully synthetic additive packages caused less of an increase than the package formulated with a mineral oil carrier fluid [20, 24]. But, currently, there are also some commercial additives which are claimed to control CCD. It was observed that CCD increase more slowly with time and take longer to stabilize in a given test engine with base fuel compared to the same base fuel treated with an additive package [11, 14, 20]. Different fuels might take different times to reach stabilization in the same test engine and it is very important to compare fuels when CCD has reached stabilized levels. So, short duration tests could be misleading if the test duration is inconsiderable compared to the time scale required to approach full stabilization. Noteworthy is also, that different fuel additives have different influence on deposits formation in different areas of the engine combustion chamber. For instance, an additive might cause a substantial increase in deposit thickness in the hotter areas and a little increase in total deposit weight but can effectively control deposits in the cooler squish areas.

Engine lubricating oil contributes to deposit formation (especially CCD) but to a slight degree in typical modern engines because of their low oil consumption. Frequently, deposits contain small quantities of Ca, Zn and Mg deriving from lubricant additives. Concentration of these elements is usually a few times higher in deposits formed on the piston top thus suggesting that oil plays a bigger role in forming piston deposits in the area of engine head.

One of the most important parameter that controls deposit formation is the surface temperature which itself changes as deposits grow because of their insulating properties.

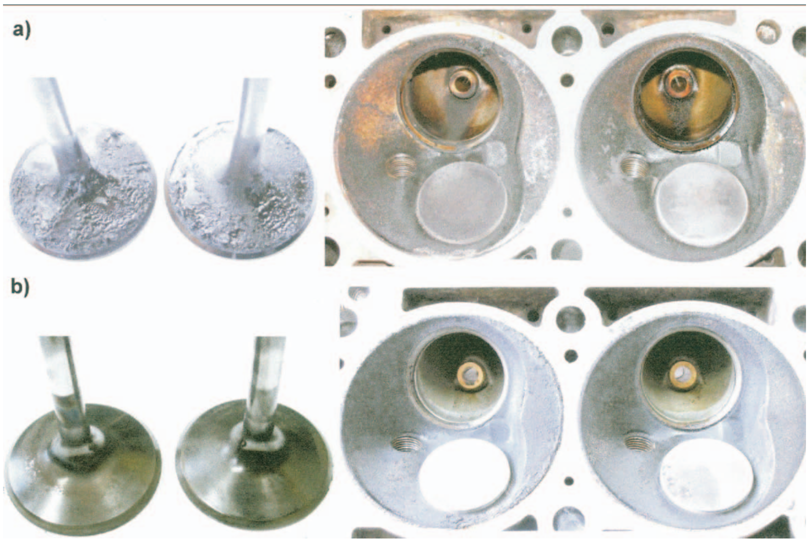

Fig. 3. Comparison of IVD and CCD for base fuel (a) and additized fuel (b)

Although both IVD and CCD are carbon deposits there are significant differences between them because of the conditions under which these deposits are formed. As stated earlier, temperature has a great impact on the formation and subsequent growth of deposits [8, 9, 12, 13, 17, 24]. For a given fuel, there will be a maximum surface temperature above which a small amount of deposit will form. During engine operation, the temperature through the engine varies in a very broad range. While the temperature inside the combustion chamber can be as high as 1700÷1750°C due to combustion of a charge, the average internal surface temperature is much lower and varies widely across the combustion chamber, from around 120°C in the cooler areas, on the surface of the intake valve to about 150÷230°C on the piston top surface, 300÷320°C at the exhaust valve seats to over 800°C at the exhaust valves, and up to 400°C in the less cooler surface of the combustion chamber [13]. Then, different internal parts of an engine have different temperature regimes and different exposure to fuel, and it is expected that deposits formed on these parts have differing chemical and physical properties. Therefore, this widely varying surface temperature causes a very large difference both in the weight as in the thickness and properties of deposits from different parts of the combustion chamber including intake and exhaust valves. As a consequence IVD are amorphous porous carbon, with a significant content of oxygen and nitrogen, and additionally contain elements such as calcium, zinc and phosphorus coming from the lubricating oil [23, 26]. As was found, the possibility for carbon deposit formation on the back of the tulip of the intake valves is increased in engines with port fuel injection system (like in M111 test engine) as the fuel is injected into the incoming engine air stream in the inlet port, which cause increased amount of fuel to have direct contact with the relatively hot valve tulip. In turn, CCD are amorphous carbonaceous material with porous structure, characterized by a heterogenous granular morphology. They are mainly composed of unburnt hydrocarbon chains, varying amounts of oxygen, phosphorus and calcium and also oxidation products derived from fuel and lubricating oil as carboxylic acids, metal carboxylates, esters, ketones aldehydes and so on [23, 26]. Generally, for any given engine thermal condition, it is the highest boiling fractions of the fuel and additives induced that contribute most to deposit formation. For a given fuel, there will be a maximum surface temperature above which deposit will form.

Considering the influence of engine design on deposit build-up it is generally agreed that typically 4-valves per cylinder engines run on much lower intake valve temperatures than 2-valves per cylinder engines. This observation was made when the M111 engine was chosen for the IVD/CCD test method CEC F-020-98, which had replaced the older CEC F-005-93 test method which made use of M102E (2-valves) engine. It was noticed that, in the M111 engine, the intake valve temperatures are up to 150°C lower than in M102E, under the same operating conditions [11, 20].

Taking into consideration that in the case of GDI (Gasoline Direct Injection) engines no fuel is injected into the intake manifold, so no fuel spray is directed on the intake valves tulip, lubricating oil is seen to be a significant factor in the amount of IVD formed in the GDI engine. In GDI engines, lubricating oil has direct paths to the intake valves through the valve guides and PCV (Positive Crankcase Ventilation) system, while fuel must be considered to interact with the intake valves in only a secondary fashion, such as through blowback upon intake valve opening. At the same time in the case of GDI engines lubricating oil flowing to the intake valves through the valve guides without washing by the fuel, in consequence quite often formed IVD in GDI engines which is higher than in the PFI [4]. In both GDI and PFI engines, operation conditions have a very significant effect on the level CCD formation. Lean cycle operation forms significantly more deposits than rich cycle in the GDI engines. When GDI engine operates in a stratified-charge mode, the overall fuel-air ratio will be very lean. These are favorable conditions for CCD formation because of low surface and gas temperatures with a lean mixture. Comparing both engine types GDI produce more CCD than PFI under the same conditions.

Deposits which have been formed, are also being removed through various mechanisms divided into three groups: chemical (including oxidation and gasification), physical (including desorption and evaporation of volatile and gaseous components) and mechanical like abrasion, flaking and wash-off [12, 13] – Fig. 4.

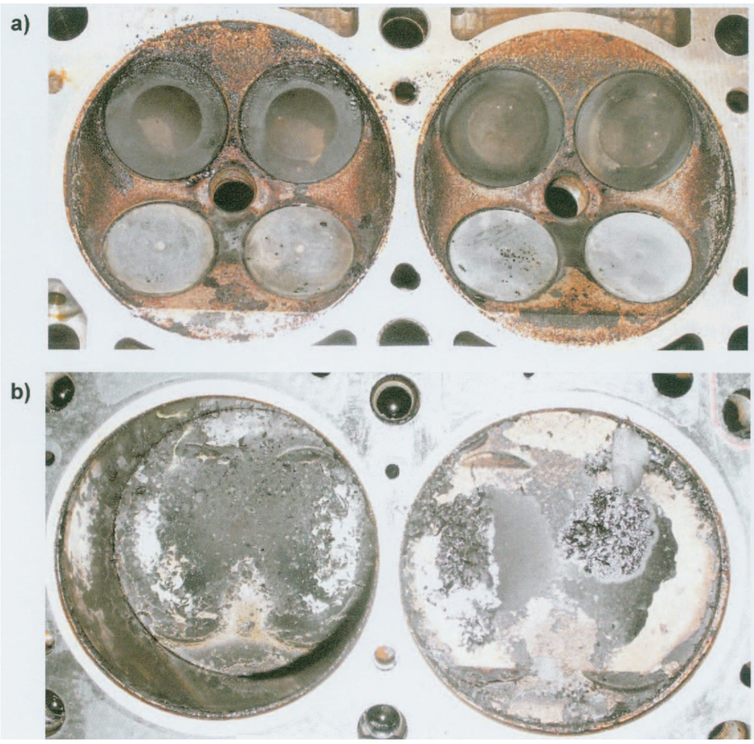

Fig. 4. Examples of deposit flaking in combustion chamber (a) and on the piston top (b)

Mechanism of deposit formation

Generally speaking it is widely assumed that deposits which accumulate on the inside surfaces of engines are derived primarily from incomplete combustion of some fuel components and fuel additives as well as lubricating oil components. The course of deposit formation and their growth is considerably influenced by engine design, its characteristics and operating conditions [1, 8, 9, 10, 14, 20, 21]. It was found that for deposit formation from gasoline, especially from aromatic compounds, two equally important processes are required, oxidation and polymerization by bonding through polar groups. When the air temperature is above 200°C, then deposit formation from gasoline must proceed under compressed atmosphere. If gasoline molecules are maintained in flames, all molecules are burnt out because they are all organic compounds. Therefore, deposits built-up from gasoline are considered to take place outside of the flame, such as in the quench zone [21]. The oxidation products generated in these reactions condense on the hot surface and next undergo pyrolysis or polymerization. The condensation of the deposit precursors on the surface is the crucial step in this process and deposit formation is strongly dependent on the surface temperature [1, 8, 9, 13, 17]. With the surface temperature increase, levels of the deposits will be reduced. As was described before, taking into consideration engine operating conditions, surface temperature increase with engine speed and load, coolant temperature and to a smaller extent with ignition advance and compression ratio (except for exhaust valve temperature) and also as the air-fuel mixture is made richer. Because of the required condensation process, more deposits will form on a cold surface, with high boiling fuel and lubricating oil constituents. Thus, GDI deposits are linked more closely to CCD of a PFI engine, because of the similarity in the physical and chemical environment [9].

Effects of deposits on engine performance and exploitation

Deposit formation in spark ignition engines is a complex phenomenon which is dependent on a number of fuel's, and engine's parameters as well as lube oil composition and its consumption quantity. Build-up, growth and accumulation of IVD and CCD lead to impaired engine performance as well as operation conditions and thus presents a significant challenge for the engine automotive industry.

In the Table 1 the most noticeable effects of deposits formation on engine performance deterioration and diminished drivability of the car are reported.

Table 1. Most significant effects of engine deposit formation

Parameters affected by deposits	Mechanism of the adverse effect	Adverse effects
Flow of air/fuel mixture into engine combustion chambers	IVD can restrict both the valve opening as well as inlet tract area, reducing the engine's volumetric efficiency.	Poor starting
		Engine stalling
		Rough running
		Hesitation when suddenly accelerating
		Engine power restriction
		Increased fuel consumption
		Increased emissions
Ignition and fuel combustion characteristics	CCD alters the designed combustion chamber features and brings about reduction of thermal efficiency manifested by reduced overall engine performance.	Reduced engine power
		Increased fuel consumption
		Increased emissions
Combustion chambers volume and thermal characteristic	CCD formed in the engine decreases the available volume and therefore a higher compression ratio of the fuel/air mixture is observed. This leads to an increase in the temperature of the end gas region and to increased propensity of the engine to knock. Build-up of CCD can produce a source of pre-ignition or detonation which can result in severe engine damage.	Serious loss of engine power
		High loads of internal engine components
		Engine overheating
		Likelihood of carbon rap between piston and head surfaces
		Increased engine noise
		Increased octane requirements
		Reduced engine durability

ect. Table 1

Parameters affected by deposits	Mechanism of the adverse effect	Adverse effects
Surface properties covered by deposits	Due to the porous nature of CCD, they are able to adsorb fuel and unburned fuel components as well as combustion products and then release them during a following cycle.	Increased HC emissions
	The presence of porous IVD when the engine is warm leads to an increase of the fuel/air mixture temperature which makes the fuel more prone to react. When the engine is cold, IVD promotes poor fuel vaporization.	Reduced engine driveability
Combustion efficiency	CCD disturb the turbulent motion of the charge intended to improve the air-fuel mixture in the cylinder.	Increased HC emissions
Deposit stability	Some engine operation conditions are favorable for deposit removal through various mechanisms. Small flakes of CCD can break lose and become trapped between the exhaust valve and seat which leads to loss of compression.	Poor starting
		Rough running
		Increased HC emissions

Conclusion

1. Deposit forming tendency is one of the most relevant parameter which causes drivability problems, increases fuel consumption and emissions as well as affects the engine durability.
2. Engine design and parameters, gasoline composition, engine operating conditions and deposit control additives are all critical factors that influence engine deposit levels.
3. Taking into consideration engine operating conditions, deposits are formed at lower speeds and loads. At higher engine speed and/or load the deposits either flake or burn off.
4. In modern PFI engines with low lubricating oil consumption, engine internal deposits are derived primarily from the fuel, and to some extent from the lubricating oil.
5. It has been established that lubricating oil is a significant factor in the amount of IVD formed in the GDI engines.
6. IVD and CCD formation in GDI engines is greater in comparison to PFI engines.
7. Engine operating conditions that tend to increase intake valves and combustion chambers surface temperature lead to a reduction of deposit formation.
8. The most important lubricating oil component for deposit formation is the base oil. Increasing the high molecular weight and low volatility content of the oil increases deposit formation.
9. The fuel treated with additives blended at an IVD control dosage produces more CCD than the base fuel alone.
10. The use of modern deposit control additives is critical to protect engines against both the intake valves and combustion chambers deposits.
11. Accumulation of IVD and CCD leads to a deterioration engine performance and vehicle drivability.
12. Different fuels might take significantly different times to reach stabilization in the same engine. Particularly long time is required for stabilization of CCD in case of base fuel. The presence of additives in fuel reduce this time significantly. So, too short duration tests could be misleading if the test duration is small compared to the time required to approach stabilization.

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