Article citation info:
GOMÓŁKA L, AUGUSTYNOWICZ A. Evaluation of applicability of dielectric constant in monitoring aging processes in engine oils. Eksploatacja i Niezawodnosc – Maintenance and Reliability 2019; 21 (2): 177–185, http://dx.doi.org/10.17531/ein.2019.2.1.

Leszek GOMÓŁKA
Andrzej AUGUSTYNOWICZ

EVALUATION OF APPLICABILITY OF DIELECTRIC CONSTANT IN MONITORING AGING PROCESSES IN ENGINE OILS

OCENA PRZYDATNOŚCI STAŁEJ DIELEKTRYCZNEJ DO MONITOROWANIA PROCESU STARZENIA OLEJU SILNIKOWEGO*

This paper reports on the study involving the development of a dependence between the selected physicochemical properties of engine oil and the variation of its dielectric constant, considered as an evaluation parameter for the degree of its exploitation. In order to get to know the selected phenomena that accompany oil aging, a decision was made to perform tests of the condition of engine oils at various stages of their exploitation. In addition to the analysis of the dielectric constant, measurements of total base number and (TBN) and infrared spectroscopy (IR) were also performed. The interdependence between the examined values is developed using the Pearson's linear correlation coefficient. As a result, the variability of TBN and IR absorbance in the context of the change in the dielectric constant were evaluated. Following the realized experimental tests, it was found that the results demonstrate a satisfactory correlation between the selected physicochemical properties of the oil, which resulted in the adoption of an assumption of a high feasibility of application of dielectric constant as a diagnostic parameter in monitoring the state of exploitation of engine oil.

***Keywords**: oil exploitation, diagnostics of engine oil, dielectric constant.*

Celem pracy było określenie związków pomiędzy wytypowanymi właściwościami fizykochemicznymi oleju silnikowego a zmianą jego stałej dielektrycznej, rozważanej jako parametr oceniający stan jego zestarzenia. W celu szczegółowego poznania wybranych zjawisk towarzyszących starzeniu się oleju zdecydowano się na przebadanie oleju w różnych stadiach jego użytkowania. Poza badaniem stałej dielektrycznej wykonano również badania całkowitej liczby zasadowej TBN oraz badania spektrometryczne w podczerwieni IR. Stopień współzależności badanych wielkości przedstawiono wykorzystując do tego współczynnik korelacji liniowej Pearsona. W efekcie oceniono zmienność całkowitej liczby zasadowej oraz absorbancji IR w kontekście zmiany stałej dielektrycznej. Po przeprowadzeniu badań eksperymentalnych, stwierdzono, że uzyskane wyniki wskazują na zadawalającą korelację pomiędzy wytypowanymi własnościami fizykochemicznymi oleju, co pozwoliło z dużą dozą pewności przyjąć, iż stała dielektryczna może być użyta w charakterze parametru diagnostycznego do monitorowania stanu oleju silnikowego.

***Słowa kluczowe**: eksploatacyjne zużycie oleju, diagnostyka oleju silnikowego, stała dielektryczna.*

1. Introduction

In the era of developing technology, ICE forms the used sources applied to drive vehicles, machines and a variety of equipment. We can assume that despite its numerous drawbacks, ICE will remain to play the role of the dominant source of power for many years [9,12]. The lubrication system forms one of the most important systems in an engine, and a lubricating oil forms its integral part. In order to adequately verify the properties of oils during operation, there is a need to easily and accurately diagnose its quality. This fact leads to the need to adequately select a representative parameter by means of which it is possible to monitor changes occurring during its exploitation. Modern engine oils consist of various components and additives, by which a number of stringent operational requirements can be achieved and realized. Therefore, it is important to adopt and select such research methods and quantities that meet the requirements of a diagnostic parameter, can be applied to analyze the quality of the oil. The assessment of oil wear in an engine currently forms one of the most dynamically developing trends in research and is of interest to many scientific institutions [7]. This subject also forms the focus of interest of private companies operating vehicles due to the practical and economic outcomes that can be valuable to them [5,6]. All mechanisms or components of equipment are subjected to the processes of aging and wear so along with aging, engine oil changes its lubricating properties, which adversely affects the characteristics of the lubrication system. Heterogeneous conditions of vehicle and machine opera-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl*** tion directly affect the intensity of changes occurring in the engine oil and; hence, individual approaches to oil quality assessment should be applied, taking into account the projected period of engine exploitation. For this reason, research was carried out with the purpose of selecting quantities that can effectively and accurately demonstrate the nature of exploitation changes and which can be easily measured and recorded.

On the basis of obtained characteristics of selected physicochemical properties of the oil and considerable level of a correlation between changes in dielectric constant and oil properties, a new methodology was proposed for the diagnostics of oil quality. To this aim, an approach to the analysis of the state of the lubricating oil was considered to be necessary.

This work focuses on demonstrating the relation between the physicochemical properties of the oil and the dielectric constant, which is an easily measurable quantity. The analysis involves the relations between the basic parameters applied to characterize the aging process of oils based on the measurements of the change in the dielectric constant of used oils in relation to the fresh ones. Due to the widespread use of electronics in vehicles, the procedures for diagnosing oil quality and methods of setting intervals of oil change were described in detail using guidelines developed by vehicle manufacturers' as well as on the basis of the logical algorithms applied for such purposes. On this basis, the development of a new method that can guide in the decisions regarding engine oil intervals was proposed as a secondary objective of the present study.

2. Initial assumptions

The review of selected service manuals shows that an oil change intervals form an ambiguous recommendation for vehicle manufacturer due to the lack of technical conditions applicable for assessing the suitability of its use in a vehicle. The advanced level of electrical and electronic measurements provides a variety of quantities and forms of control that can be applied in mechatronic systems [2,4]. However, the analysis of the state of knowledge in the area shows that the field concerned with aging of lubricating oil in internal combustion engines forms one of the challenges due to complex physicochemical processes occurring in oils. Aging processes can be delayed by adding enriching additives to oils during exploitation and such substances are known to affect anti-wear properties and increase the level of protection from engine dry running. The decrease in the value of total base number (TBN) is reported to be feasible due to the use of additives in a number of studies [10,11]. The measurements involving the total basic number belongs to routine tests as it forms a test used to determine the level of loss of alkaline reserve during operation. It can also be carried out to monitor the condition of oil additives.

The oil change intervals given by the manufacturers are often designed to occur well before engine oil starts to deteriorate its lubricating properties significantly. However, checking oil properties using analytical methods in a laboratory is expensive. In addition, the use of analytical techniques during normal exploitation can be extremely difficult. Therefore, oil is rarely diagnosed before scheduled replacement, which results in wasting huge amounts of oils.

During the exploitation of engine oil, many parameters are variable, including its kinematic viscosity, fractional composition, additive content, as well as impurity content. The kinematic viscosity test performed at 40 and 100°C demonstrates that during exploitation this value varies in a narrow range. The diagnostic parameter based on the viscosity parameter provides limited information, in particular in the conditions of varied temperatures.

Engine oil is a typical dielectric material. The study in [7] reports that dielectric spectroscopy forms one of the most powerful analytical technique applicable for measurements in dielectric materials. It can be easily used to classify oils according to their viscosity parameters. We can assume that dielectric spectroscopy can provide practical information regarding the composition and structure of the engine oil. Similarly as in [14], it was shown that the temperature coefficient of the dielectric constant of engine oils depends on whether oil is fresh or used. Therefore, an assumption was made that the measurement of the dielectric constant offers the potential to determine the condition of the engine oil.

A similar conclusion was made in [16] in which a principle of monitoring oil contamination over the Internet was proposed on the basis of the measurement of its dielectric constant. A measurement system was also developed including a capacitance sensor, a small capacitance detection circuit, as well as software applied for monitoring and data processing. The results show that the relative dielectric constant of oil can be effectively tracked and properly classified using a dedicated measuring system that can be used to determine oil change intervals.

The measurement of the dielectric constant of oils can provide valuable information regarding oil quality. A simple test dedicated to this purpose can be applied immediately to determine if the correct oil was used during a service procedure involving oil change. An increase of the dielectric constant of the oil indicates the presence of impurities or change in its chemical composition [3,15]. It was found that the rate of variation in the dielectric constant depends on the physical properties of the oil, which in turn are affected by deposition of impurities, such as density and viscosity, as well as the use of refining agents.

Synthetic and mineral oils used in engines are not perfect insulators as they are characterized by a minimal electrical conductivity. Therefore, the knowledge of dielectric properties, such as the relative electrical permittivity is important for the adequate performance of ICE engines. The monitoring of oil condition and its degradation in the online system and forecasting its replacement periods forms ones of the goals of the current automotive research [18]. Monitoring the oil condition and its degradation using an online system involving the analysis of its dielectric constant is associated with the need to get to know about its changes in the function of temperature. The reported tests [8,13] demonstrated a significant increase in the dielectric constant in the ranges of higher temperatures, which offers an easier measurement and classification of oil exploitation. The paper also analyzes the feasibility of using a capacitor sensor and its correlation with the dielectric constant. The present study found that along with the changes of the dielectric constant of the oil, its capacity changes as well.

Infrared spectrometry (IR) offers a tool that is practical in assessing oil quality and the changes occurring in it by application of spectral analysis. This is an instrumental technique based on the study of spectral analysis of electrons in chemical compounds. It is also a method used to determine the content of some chemical compounds and the measurements for such purposes are performed by application of a selected wavelength. As a result of the research, on the basis of obtained spectra and spectra of standards, the content of the compound in the tested substance can be derived. Infrared spectroscopy techniques are often applied to determine the content of undesirable components and the content of some additives [1].

Bearing the above in mind, a decision was made to design a scope of a study to include parameters such as: dielectric constant, total base number and absorbance levels.

3. Research program

For the purposes of the present study, five major steps were identified:

- identification of objects applied for extracting oil samples,
- development of sampling methodology,
- analysis of the influence of temperature on the variations in dielectric constant of oil,

– testing of samples in a laboratory,
– analysis of the results.

An important aspect was associated with the determination of an adequate representative amount of oil needed for laboratory analysis. For the purposes of comparison, tests to investigate the degradation of oil over a standard vehicle distance – 15,000 km have been determined in the first place. After each sampling (from 100 to 150 ml), the oil level was checked in the engine and it was supplemented to the level recommended by the manufacturer. A test drive was also carried out without adding oil after sampling to verify this type of operation, expecting faster oil aging. Due to the long-term duration of this type of study, a decision was made to perform only one such series on a single vehicle.

4. Objects of testing

The object applied for the testing involved six intermediate class passenger cars, normally driven in urban and non-urban environment, in particular used in everyday commute. The minimum daily distance that was covered by the cars was equal to around 40 km. The cars used petrol or operated in cycles where LPG was used alternatively with petrol and one car used diesel fuel. Each of the vehicles was used by a single driver. The vehicle engines applied semi-synthetic and synthetic oils.

The selection of objects applied for testing was also influenced by other factors, such as:
– common use of intermediate class cars in the domestic automotive market,
– varied age and mileage of vehicles,
– similar characteristics of exploitation (use in urban traffic, daily mileage, etc.),
– accessibility of vehicles for cyclic oil sampling.

Table 1 contains a summary of the basic data regarding the vehicles.

5. Laboratory testing

In addition to the assumptions adopted during the selection of test objects, the technical conditions for extraction and storing of engine oil samples for laboratory tests were defined. The program of the activities involved the following steps:
– sampling from the engine was always carried out when engine was fully heated; in cases when vehicle was parked for a longer period, sampling was preceded by a sufficient distance traveled to ensure thermal equilibrium state of the engine. This provided conditions for adequate mixing of the oil in the engine and caused water drainage from the oil,
– due to the high oil temperature at the time of the extraction, special care was taken in terms of health and safety,
– a syringe with a flexible hose was used for oil sampling,
– oil level indicator tube formed the place from which a constant, specific amount of oil was extracted for the study,
– a specific volume of oil was extracted in each case – ranging from 100 to 150 ml,

While maintaining the above guidelines, efforts were made to eliminate any errors during the sampling, in order to provide the same conditions for testing all vehicles. In order to store samples at various stages of oil exploitation, dedicated containers made of laboratory glass were purchased. They offer a very useful solution for oil storage until testing. The use of laboratory glass protects the oil from additional contamination and uncontrolled aging during storage.

Due to the selection of objects and research methodology, the analysis involved the changes of oil properties in the self-ignition (SI) and compression-ignition (CI) engines. Such an approach to the analysis had to be followed due to the actual loss of physicochemical properties, depending on the nature of use and technical condition of the vehicle, as well as progressive changes in oils following a specific mileage traveled. By conducting laboratory tests, the justification of adopting oil change intervals and the possibility of a quick and effective assessment of its state were verified on the basis of the selected diagnostic parameter.

The experimental setup comprised with the necessary equipment. Before each measurement, residual oil was cleaned from the sensor using extraction gas and it was cleaned with a paper towel and finally air-dried under pressure. This ensured reliable measurement as efforts were made to ensure that the Analexrs measuring electrodes did not contain residues of oil used in the previous tests. Another very important aspect of the research was associated with ensuring the homogeneity of the samples oil. Due to the need to store collected samples before testing, undesirable sedimentation occurred in the oils, which led to settling of residues and its delamination. Since such processes are imperceptible to the naked eye, so to ensure the homogeneity of the suspension, the oil samples were shaken gently to prevent the effect of aging before each of the test series.

The scope of research included:
– measurement of the dielectric constant using Lubri Sensor
– measurement of the dielectric constant using Analexrs sensor
– variability of the total base number (TBN),
– infrared spectrometry, variability in the level of absorbance – IR.

Table 1. Summary of data on vehicles used in the study

No.	Brand	Fuel	Engine capacity [dm^3]	Type of oil	Mileage [km]
1	Opel Astra 1.7D	Diesel	1.7	Lotos synt. 5W/40; API SN/CF, ACEA A3/B4	No available data
2	Daewoo Nexia 1.5	Petrol + LPG	1.5	Lotos synt. 5W/40;API SN/CF, ACEA A3/B4	98 400
3	Fiat Punto 1.1	Petrol	1.1	Elf Semi-Syntetic 10W/40;API SL/CF, ACEA A3/B4	81 700
4	Opel Astra 1.6 *Testing performed in two series: S1 and S2*	Petrol + LPG	1.6	Genuine GM 10W/40;API SL/CF, ACEA A3/B3	125 000
5	Volkswagen Passat 1.8	Petrol + LPG	1.8	Castrol Magnatec 10W/40;API SL /CF, ACEA A3/B3	242 038
6	Fiat Seicento 1.1 *Testing performed in two series S1 and S2*	Petrol	1.1	Mobil 1 Formula S 10W/40;API SL/SJ/CF, ACEA A3/B3	99 382

The equipment applied in the measurements oil quality by determining the oil parameters, also known as the dielectric constant, included: Analexrs mechatronic sensor and the Lubri-Sensor portable meter shown in Figs. 1 and 2. The variations in IR absorbance as a function of the course were examined by application of Specord M80 mesh spectrophotometer (Fig. 3).

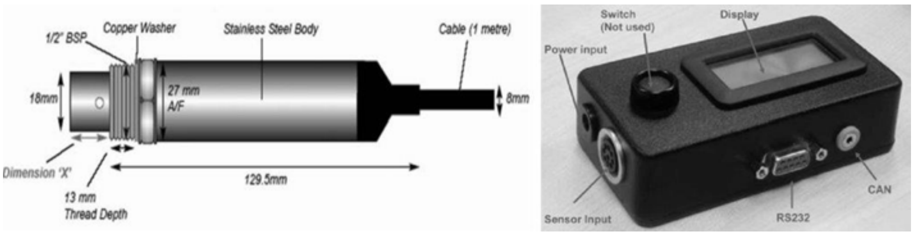

Fig.1. Analexrs sensor suite for measuring dielectric constant [19]

Fig. 2. Lubri Sensor applied for measurements of dielectric constant [20]

Fig. 3. General view of Specord M80 spectrophotometer [21]

6. Multi-aspect analysis

The essence of the concept reported in this paper involves the analysis of oil degradation based on the variations in the dielectric constant in the conditions of selected exploitation cycles. Such an assumption was connected with the necessity of a thorough study of the influence of various physicochemical properties of the aging processes in oils and determining changes in dependencies between them. Despite many studies, comprehensive insight in this area has not been gained and exiting knowledge needs to be extended, in particular due to the use of new oil components, which in principle should ensure the highest level of technical and ecological parameters while maintaining minimum production costs.

6.1. Dielectric constant

The measurement of dielectric constant was made on the basis of two sensors: Lubri and Analexrs. The characteristics of the tested parameter are outlined below.

The summary of data in charts in Fig. 4 contains the characteristic variations in dielectric constant in the particular objects used in the study. For the analysis in question, the reference was expressed as the mileage of the vehicle after which the testing of oil was carried out in individual objects.

When we analyze the diagrams representing the changes in the dielectric constant measured by two independent sensors, we found that a significant increase in the dielectric constant during use was very evident. Small differences result from the applied technique of measurement and the nominal scale of the sensors, as well as from the time intervals of the performed tests. A similar trend was observed in the characteristics of the two series of tests performed on the same Fiat Punto power unit, measured by Analex and Lubri sensors. The same applies to the function (qualitative similarity) in the two test series using Opel Astra 1.6. For the S1 series in the last car, faster oil degradation was recorded in cycles without oil refills, which resulted in earlier intervals after which values associated with the need to change oil were obtained.

This is proof that it is necessary to check the oil level in the engine during use in order to maintain the required quality of lubrication. This ensures fault-free operation of the lubrication system, and refills refresh the oil and slow down the process of the gradual oil concentration – after reaching the mileage of 25,000 km, the dielectric constant has reached the level of 65 units (Analexrs) for the Opel Astra 1.6 following oil refills. The characteristic variations of the adopted value of the diagnostic parameter are characterized by considerable levels of correlation coefficients, ranging from R^2=0.87 to 0.98.

6.2. Total base number

The measurement of the total base (TBN) number was performed by potentiometric titration according to PN–88/C-04049 standard. It is clear that the use of oil additives determines the appropriate level of the total base number during exploitation. For this reason, oils of different types cannot be mixed. This action leads to the fact that the oils in the engine can react with each other, causing a reduction in the total base number and formation of inert and even harmful chemicals for the engine. The characteristic variations in this quantity in the tested vehicles are illustrated below in Figure 5.

The results derived on the basis of the analysis of TBN in the oil during its exploitation found that the initial value of the alkaline number representing the alkaline reserve for the further period of operation forms the most important aspect. In the presented results, the initial value of TBN is in the range from 8 to 13 [mgKOH/g] and depends on the type of engine oil and its manufacturer – the higher the initial value, the longer the service life of an oil. For Fiat Punto, after comparing both series of data, a very similar loss of alkaline reserve (measured by a decrease in the base number) was observed, which most probably indicates a similar type of vehicle exploitation? For Opel Astra 1.6 (in the first test series), the effect of accelerated aging of the oil was recorded as no refills were made in this case after each oil sampling. The second test series using the Opel Astra 1.6 car served as the source of reference. During this series, the volume that was extracted was subsequently supplemented with fresh oil after each extraction.

An interesting example is offered by the course of variation in the total base number for Opel Astra 1.7 diesel. For this vehicle the lowest decrease in the alkaline reserve was recorded. Due to the fact that this was the only vehicle with a SI engine applied in the tests, it is not possible to clarify this fact more extensively.

Another interesting combination is offered by the pair of vehicles, i.e. VW Passat 1.8 running on petrol and LPG and Fiat Seicento 1.1 driving only on petrol. By comparing the courses in Fig. 5 for these two cars, wed can see a sharp decrease in the total base number for the VW vehicle in comparison to Fiat, whose total base number was lower by 0.52 mgKOH/g at the beginning of the test. The phenomenon can be explained by the fact that the vehicles differed in the engine capacity and moreover, by the fact that the VW Passat had a significantly greater mileage from Fiat Seicento at the beginning of the study (Table 1).

The variations in the value of the total base number during exploitation, i.e. the reduction of the alkaline reserve is a commonly recognized process, and this progress depends mainly on the type of exploitation and condition of the powertrain, i.e. the basic factors affecting the degradation of the oil. An initial analysis of the vehicles could as well be performed in terms of the type of applied engine oil, which is characterized by different values of the initial TBN. Bearing in mind the above, a parameter was developed for the purpose of comprising the degree of the variation in TBN between specific vehicles. Only the boundary parameters of the changes in TBN were taken into account for his purpose, i.e. TBN_{max} and TBN_{min}, after which the result was compared to the mileage traveled on a particular oil. For a broader analysis, we can consider a change in the particular periods of use.

The calculation of ΔTBN applied the formula:

$$\Delta TBN = TBN_{max} - TBN_{min} \tag{1}$$

The change in per cent was derived from the formula:

$$zTBN = 100\% - \frac{TBN_{min} \cdot 100\%}{TBN_{max}} \tag{2}$$

On the basis of a comparing of the percentage change in the total base number (representing the loss of the alkaline reserve in per cent) in relation to the vehicle mileage, we are able to compare all examined vehicles to each other (Table 2). Knowing the guidelines of the manufacturers of the particular oils as to the moment of oil change in the context of a decrease in the alkaline reserve, we are able to determine this instant in time by correlation with the course of the vehicle or time period (motohours). At this point, it is also possible to determine whether the period specified by a given manufacturer resulting from the mileage or operating hours forms a correct determinant of service operations.

The analysis demonstrates that in some cases the adopted distance is too short on the one hand for Fiat Punto and on the other hand too short when looking at the VW Passat, where the base number after the distance of 10,000 km reached the value of 3.34 [mgKOH/r], which means the loss of 60% of alkaline reserve. The result is a result for Opel Astra 1.6 in the second test series, where despite a low initial value of the total base number, a significant decrease of around 78% in the alkaline reserve was recorded for the series during which oil was supplemented with fresh oil after sampling.

The comparisons also show that an important parameter of the oil is associated with its initial TBN, which means that engines should use selected quality oils with accurately controlled initial values of TBN. The permissible TBN limits in oil are regulated by the ACEA (Association des Constructeurs Européens d'Automobiles) and depend on the type of fuel. Vehicles driving on petrol, LPG and CNG as well as ultra-low-sulfur diesel oil do not require high TBN. On the other hand, when the engine is driving on a biofuel, there is a need to select of oil with a higher TBN [17].

After a detailed analysis of the change in the total base number, the research demonstrates that it is therefore advisable to compile the measurement results with the diagnostic parameter determined using the Lubri Sensor and Analexrs index.

6.3. Distribution of spectrum radiation using infrared spectroscopy (IR)

The analysis Spectral distribution (absorbance) of infrared radiation for motor oils proves most effective in the oxygen band, i.e. in the wavenumber range around 1824-1520 [cm^{-1}]. In this range, significant changes occur during exploitation, and they can be relatively easily examined and subjected to a further analysis. The basic conditions for recording IR spectrum are: SPECORD M80 spectrophotometer, measuring range: 1860 – 1480$cm^{-1,}$ layer thickness: 0.105mm, resolution: 4cm^{-1}, fresh oil used as reference selected was selected on the basis of manufacturers' recommendations as most suitable for each vehicle. The recorded IR spectra were calculated according to the baseline based on points 1764cm^{-1} and 1516cm^{-1}, and then numerically integrated within the boundaries determined by the base points. Fig. 6 contains a summary with the variations in absorbance levels for individual vehicles and oils. Measurement and analysis of infrared spectra (IR) offers the presentation of the dynamic characteristics of thermooxidative changes in oil during exploitation, but does not meet the criteria of a diagnostic parameter. It is either very difficult or impossible to determine the boundary values to be applied for qualifying the oil for replacement (especially for the Opel Astra 1.7D), because the changes in the absorbance value do not have characteristic points in the curves that demonstrate the change in its condition.

Fig. 6 also contains information regarding the changes in the absorbance value for the Fiat Punto (in two series) that significantly deviate from the curves for other cars. The existence of the fact can be explained by the fact that calculations made for the Fiat Punto were carried out in a wider bandwidth than for other test objects.

Table 2. Variation in total base number

Vehicle	Total base number TBN_{max} [mgKOH/g]	Total base number TBN_{min} [mgKOH/g]	ΔTBN [mgKOH/g]	Percenetage change zTBN [%]	Distance [km]
Punto 1.1 series 1	12.59	7.69	4.90	38,92	18250
Punto 1.1 series 2	12.78	8.54	4.24	33,18	20000
OpelAstra 1.7D	11.58	10.45	1.13	9,76	17983
Daewoo Nexia 1.5	10.2	7.04	3.16	30,99	24259
Astra 1.6 series 1	8.22	1.94	6.28	76,40	15730
Astra 1.6 series 2	8.22	1.79	6.43	78,22	22529
VW Passat 1.8	8.36	3.34	5.02	60,05	10038
Fiat Seicento 1.1	7.84	4.70	3.14	40,05	15828

a)

b)

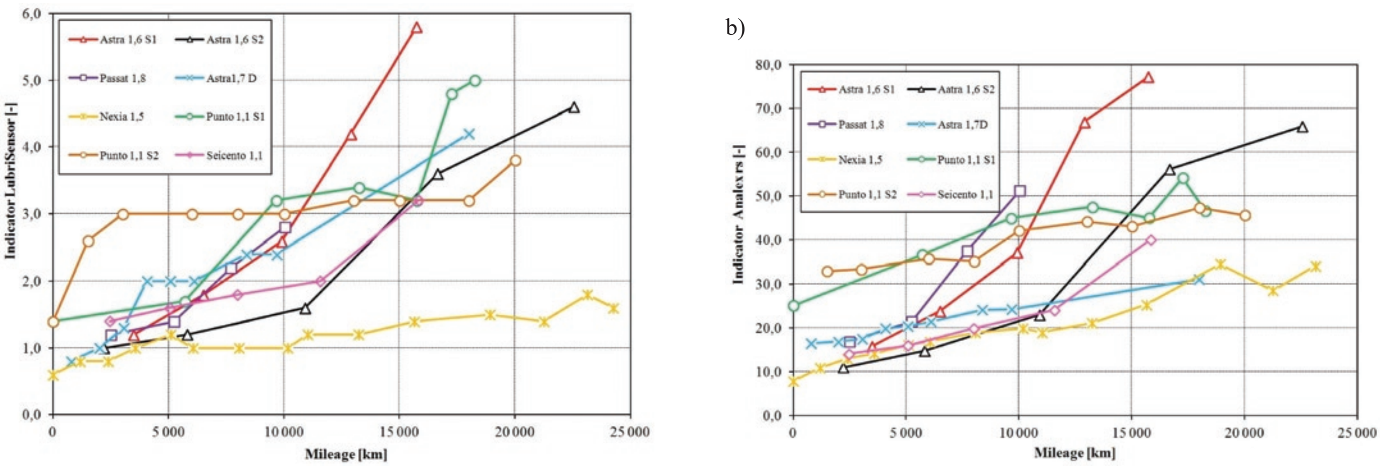

Fig. 4. Variation in dielectric constant measured by application of: a) Lubri, b) Analexrs sensors

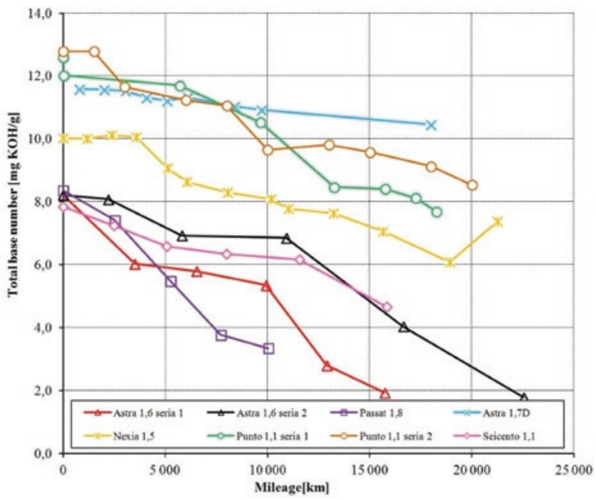

Fig. 5. Variation in total base number

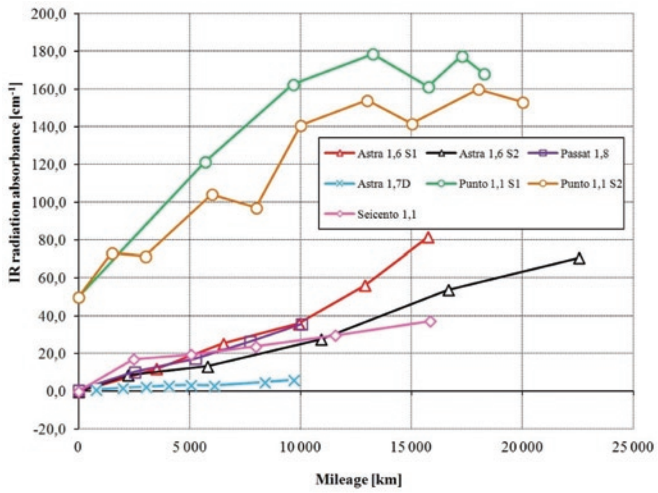

Fig. 6. Distribution of the spectrum of infrared radiation

a)

b)

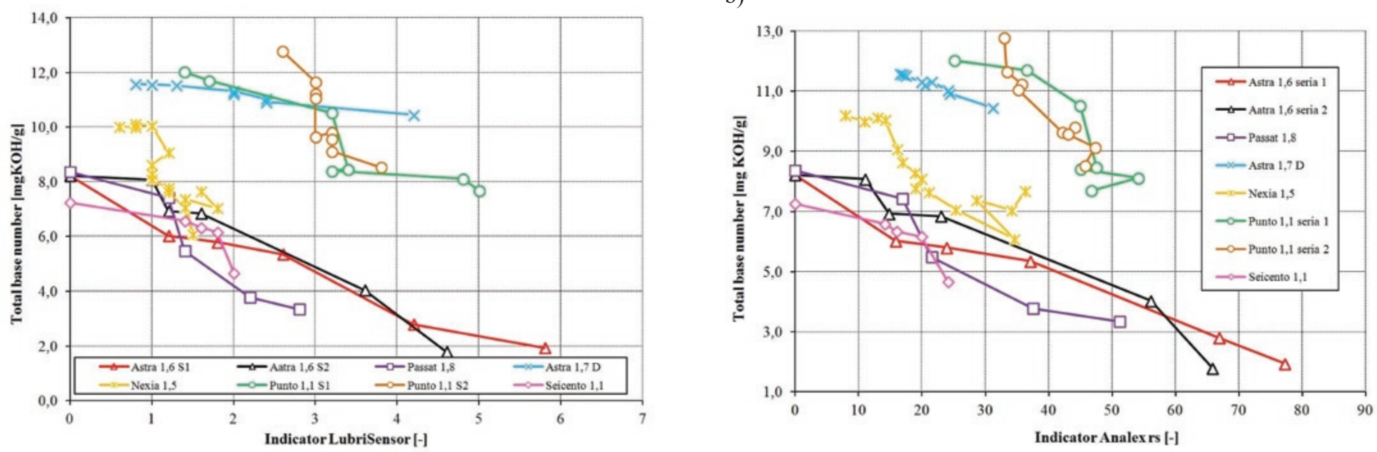

Fig. 7. Variation in dielectric constant compared to the total base number measured by application of:a) Lubri Sensor b) Analexrs

6.4. Comparative analysis

All measurements of the analyzed properties of engine oil were performed with a level of error resulting from the inaccuracy of the measurements of the applied equipment. For these reasons, it is impossible to determine the accurate value of the measured quantity and therefore it is important to assess the reliability of the results of the measurements. Therefore, in order to better visualize the variability and determine the correlation between the properties of engine oil during its exploitation, it was necessary to perform a comparative analysis. The degree of interdependence is presented using the Pear-

a) b)

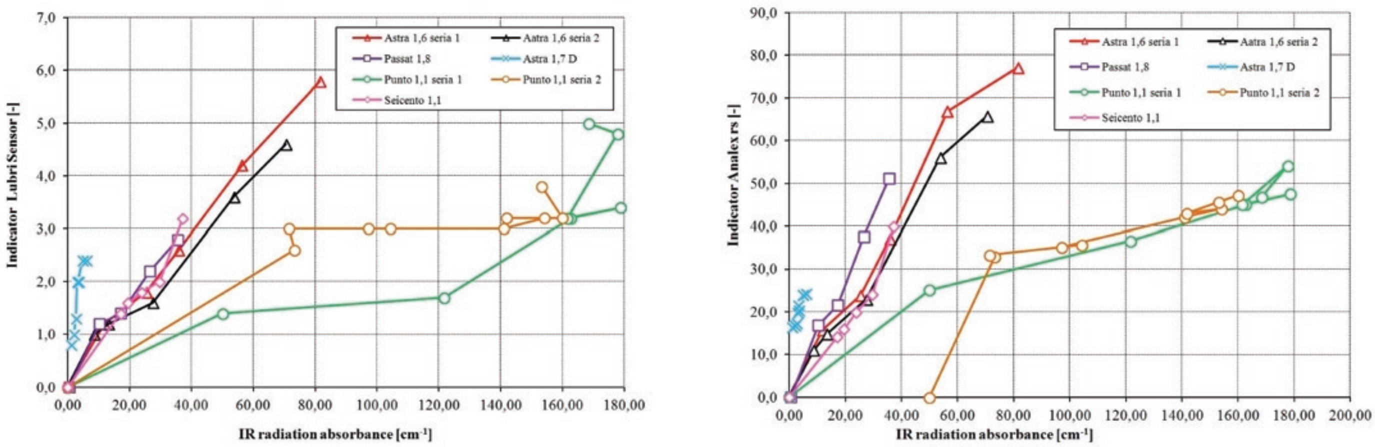

Fig . 8. Variation in infrared absorbance IR compared to the total base number measured by application of: a) Lubri Sensor b) Analexrs

son's linear correlation coefficient. For this purpose, the variations of the total base number (Fig. 7) and IR absorbance (Fig. 8) in the context of the dielectric constant were compared with the aim of its application as a diagnostic parameter.

Pearson's linear correlation coefficient forms a coefficient that defines the degree of linear dependence between random variables. A correlation was used to investigate whether there is a relationship between two variables (properties, quantities). The correlation coefficient tells us about the strength of the relation. It is defined as a value in the range from 0 to 1. The value of the coefficient tends to 1; the strength of the relationship is greater. The strength of a correlation in the range:

below 0,2– denotes a weak correlation (virtually no dependence),
0.2 ÷ 0.4 – low correlation (moderate level of dependence),
0.4 ÷ 0.6 – moderate correlation (significant level of dependence),
0.6 ÷ 0.8 – high correlation (very significant dependence),
0.8 ÷ 0.9 – very high correlation (very large level of dependence),
0.9 ÷ 1.0 – the dependence is almost full.

Pearson correlation coefficient r_{xy} was applied to the study of linear dependence of the examined variables in which an increase in the value of one of the variables results in a proportional change in the mean values of the other quantity (i.e. either increase or decrease).

This coefficient was calculated based on the formula:

$$r_{xy} = \frac{cov(x,y)}{Sd_x \cdot Sd_y} = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\Sigma\left(x_i - \overline{x_x}\right)^2 \cdot \Sigma\left(y_i - \overline{x_y}\right)^2}} . \quad (3)$$

Tables 3 to 8 present a comparison of Pearson's linear correlation coefficients for individual vehicles.

The numbers presented in the Tables indicate that a high and very high level of dependence was determined between the analyzed variables. A detailed analysis of the results obtained leads to the following conclusions:

Table 3. Summary of correlation coefficient for Fiat Punto 1.1 – series No. 1

Fiat Punto 1,1 (1)	Lubri-Sensor factor [-]	Analex rs factor [-]
Analex rs factor [-]	0.814	1.000
Total base number [mgKOH/g]	0.823	0.715
IR absorbance [cm^{-1}]	0.804	0.949

Table 4. Summary of correlation coefficient for Fiat Punto 1.1 – series No. 2

Fiat Punto 1.1 (series no. 2)	Lubri-Sensor factor [-]	Analex rs factor [-]
Analex rs factor [-]	0.888	1.000
Total base number [mgKOH/g]	0.72	0.897
IR absorbance [cm^{-1}]	0.731	0.692

Table 5. Summary of correlation coefficient for Opel Astra 1.6 – series No. 1

Opel Astra 1.6 (series no. 1)	Lubri-Sensor factor [-]	Analex rs factor [-]
Analex rs factor [-]	0.982	1.000
Total base number [mgKOH/g]	0.966	0.974
IR absorbance [cm^{-1}]	0.995	0.971

Table 6. Summary of correlation coefficient for Opel Astra 1.6 – series No. 2

Opel Astra 1.6 (series no. 2)	Lubri-Sensor factor [-]	Analex rs factor [-]
Analex rs factor [-]	0.992	1.000
Total base number [mgKOH/g]	0.960	0.953
IR absorbance [cm^{-1}]	0.984	0.988

Table 7. Summary of correlation coefficient for Volkswagen Passat 1.8

Volkswagen Passat 1.8	Lubri-Sensor factor [-]	Analex rs factor [-]
Analex rs factor [-]	0,926	1,000
Total base number [mgKOH/g]	0,903	0,916
IR absorbance [cm^{-1}]	0,974	0,990

Table 8. Summary of correlation coefficient for Fiat Seicento 1.1

Fiat Seicento 1.1	Lubri-Sensor factor [-]	Analex rs factor [-]
Analex rs factor [-]	0.982	1.000
Total base number [mgKOH/g]	0.927	0.963
IR absorbance [cm^{-1}]	0.962	0.946

– The measurement of the dielectric constant was performed by application of two sensors that differ in terms of the design. One that is known as Lubri Sensor and can be considered as a portable meter whereas Analexrs form a modern sensor that can be combined with a data acquisition system to monitor the relative permittivity in real time. Despite the different designs of the applied equipment and their measurements, a very high correlation coefficient in the range of 0.81÷0.99 was obtained.
– The methodology applying infrared spectroscopy offers the analysis of its composition and observation of the variations in quantities that occur throughout oil aging. However, selection of an unambiguous parameter characterizing the quality of oil in a given case is very difficult. Given the above and the fact that testing involves the need to apply expensive equipment, the use of this method in a vehicle is unfeasible. The calculated correlation between the values of the absorbance of radiation and the dielectric constant is in the range of 0.73÷0.99 for Lubri Sensor and 0.69÷0.99 for Analexrs, respectively.
– As we already mentioned earlier, the decrease in the alkaline reserve accompanying the exploitation of engine oil affects the degradation of oil. At the moment referred to as the point of equilibrium, the alkaline reserve is exhausted to the degree that prevents the current neutralization of acidic products of combustion and the replacement of oil with fresh oil is most desirable. The determination of the instant when oil needs to be changed with on-board diagnostic methods is very difficult. The calculated correlation between the values of the total base number and the dielectric constant is in the range of 0.72÷0.97 for Lubri sensor and 0.71÷0.97 for Analexrs sensor, respectively.
– The measurement of the dielectric constant with the Analexrs sensor or a similar sensor installed in the lubrication oil system of an ICE could provide a source of diagnostic information – to play the roles of a parameter of the condition of engine oil.

7. Concept of original method of predicting instant of oil exchange

The final stage of the study took the form of an attempt to develop a systematic methodology for forecasting oil change intervals. In this approach, it was considered to take into account all the necessary information that is needed to determine an optimal time to change the engine oil, in particular:

– parameters of fresh oil, applied or selected (quality class, viscosity class, value of TBN, etc.) that determine the starting point of the analysis,
– conditions of vehicle use and driver profile (engine speed range, engine load, coolant temperature, oil temperature and level, ambient temperature, oil pressure in various parts of the lubrication system, number of cold starts, distance traveled, etc.),
– measurements from sensors dedicated to determine oil condition (dielectric constant, TBN, viscosity or other that are applied in the market).

A control algorithm was responsible for identification of the instant corresponding to the optimal instant corresponding to the oil change. Such control algorithm would apply the available information from the data communication network with continuous data input from the vehicle and on-board sensors. This data should contain information on the level of oil degradation (and form degradation characteristic), such as:

- value of alkaline reserve loss in per cent,
- the value or level of the TBN,
- dielectric constant as a value or a percentage change,
- period of service work (kilometers, hours, etc.).

The system would take into account corrections from on-line measurements as well as given as reference parameters (commonly referred to as rough use or operation in difficult environment), by means of which oil change interval would be determined, such as:

- driver or operator profile,
- type of use,
- trend of changes in measured values,
- ambient conditions, etc.

All forecasting would be based on a real-time system that can be easily implemented in the calculation of neural networks so as to develop an artificial intelligence system. However, we can emphasize that the decisive role is taken on by the measurement of dielectric constant which, as a universal quantity, takes into account most factors affecting oil degradation (fuel, soot, sludge, lacs, gels, ferromagnetic abrasion, water, etc.) and strongly correlates with the quantities that are used for accurate laboratory measurements (spectrometry, total base number, volume of pollution produced, etc.). Any characteristic representing the changes of individual physicochemical quantities in oils derived in a correlation using a selected measured parameter can be combined in the logic of such a system.

In the age of up-to-date trends and technologies implemented in the design of lubrication systems for vehicles and machines, such as:

– oil nanotechnology – modern oil additives applied to improve not only lubricating but also capable of maintaining specific operating parameters at the projected level and rebuilding the structure of friction pairs,
– downsizing – a small volume of oil in the oil sump, high operating temperatures, high power output from small engine capacity,
– modular design of the oil system, where the used oil and filter are exchanged with an completely new module,
– on-board oil cleaning systems.

We have to realize that accurate diagnostics plays an increasing role and its role continuously gains in importance. Oil degradation depends on many factors and the proposed conceptual method is based on the analysis of several variables, which is why it is included in the proposed intelligent system. A huge amount of input data is needed for the algorithm to operate effectively. It is not enough to monitor only one of the properties of the oil and to select the oil change interval on its basis.

This concept forms a new category of vehicle use that can be only implemented in modern hybrid and autonomous vehicles. This will ensure ease of operation, effective recycling and minimization of waste as well as meeting ecological standards.

8. Conclusions

The mileage as well as the duration of the vehicle's exploitation do not offer feasible parameters for determining oil change intervals. It is necessary to establish an easy and cheap diagnostic method that can be applied with regard to engine oils. The objective during the development of such a method would involve the application of the potential information of physicochemical properties of oils to eliminate ones that have lost their lubricating properties and no longer provide engine protection. With the aim of the insight into aging of oil, an analysis concerned with selected phenomena accompanying the various stages of oil use was performed. The detailed conclusions are as follows:

– The study of IR spectra confirmed the characteristics of thermo-oxidative degradation of oil during exploitation.
– The alkaline reserve test demonstrated the tendency to decrease reserve with exploitation, and indicates the increase of the acidic environment of an aging oil.

– A change in the relative permittivity accompanies the aging of oils. The dielectric constant forms an easily measurable parameter. The measurement of the dielectric constant with a sensor installed in the lubrication oil system of ICE could provide adequate diagnostic information.
– The study of the correlation of variability in the dielectric constant with respect to variables such as the TBN and IR absorbance demonstrates a high level of dependence, which means that dielectric constant can be successfully applied as a diagnostic parameter for monitoring the condition of engine oil.
– Determination of the optimal moment of oil change requires the development of a methodology for forecasting oil change applying systematic measures.

References

1. Al-Ghouti M A, Al-Toum L. Virgin and recycled engine oil differentiation: A spectroscopic study. Journal of Environmental Management 2009; 90, https://doi.org/10.1016/j.jenvman.2007.08.018.
2. Bolognesi P, Bruno O, Landi A, Sani L, Taponecco L. Electric Machines and Drives for X-by-Wire System in Ground Vehicles 2003. 10th European Conference on Power Electronics and Application: 1-16.
3. Carey A A, Hayzen A J. The dielectric constant and oil analysis Practicing Oil Analysis Magazine 2001; 9.
4. Cheng H. Autonomous Inteligent Vehicles: Theory, Algorithms and Implementation. London Limited: Springer-Verlag, 2011, https://doi.org/10.1007/978-1-4471-2280-7.
5. Gomółka L. Ocena oleju silnikowego w eksploatacji. Praca doktorska, Wydział Mechaniczny, Politechnika Opolska, 2017.
6. Gomółka L, Augustynowicz A, Maciąg A. Analysis of the rank spreading the decline of oil in internal combustion engines. Comustion Engines 2011; 1 (144): 1-4.
7. Guan L, Feng X L, Xiong G. Engine lubricating oil classification by SAE grade and source based on dielectric spectroscopy data. Analytica Chimica Acta 2008; 628: 117-120, https://doi.org/10.1016/j.aca.2008.09.004.
8. Han Z, Wang YQing X. Characteristics Study of In-Situ Capacitive Sensor for Monitoring Lubrication Oil Debris. Sensors 2017; 17 (12) 2851: 1-13.
9. Idzior M. The development of combustion engines in the aspect of their manufacturing. Comustion Engines 2006; 1 (124): 60-70.
10. Laber A, Adamczuk K. Improving the working conditions of friction by using operation additives to lubricating oil. Tribologia 2014; 1: 27-39.
11. Laber S, Laber A. Property assessment lubricants and tribological lotos dynamic engine oil. Tribologia 2015; 3: 89-97.
12. Serrano J R. Imagining the Future of the Internal Combustion Engine for Ground Transport in the Current Context. Applied Sciences 2017; 7 (10) 1001: 1-5.
13. Stevan Junior S L, Paiter L, Galvao J R, Roque D V, Chaves E S. Sensor and Methodology for Dielectric Analysis of Vegetal Oils Submitted to Thermal Stress. Sensors 2015; 15 (10): 26457-26477, https://doi.org/10.3390/s151026457.
14. Torrents J M, Pallas-Areny R. Sensing oil condition through temperature coefficient of dielectric constant. 2003 XVII IMEKO World Congress - Metrology in the 3rd millennium, Dubrovnik, Croatia: 917-919.
15. Patch R, Kamenka D, Menzel J. Return voltage measurements Diagnostic interpretations based on the dielectric time constants. Materials Science-Poland 2009; 27 (4): 1157-1169.
16. Yang Y, Yang D, Hu Z, Zhang X. Oil Contamination Monitoring Based on Dielectric Constant Measurement. 2009 International Conference on Measuring Technology and Mechatronics Automation (ICMTMA), Zhangjiajie, Hunan, China: 245-252, https://doi.org/10.1109/ICMTMA.2009.588.
17. Zhmud B. TBN, What`s in It for me?, Lube Magazine online 2018; 4.
18. Zhu J, Yoon J M, He D W, Qu Y, Bechhoefer E. Lubrication oil condition monitoring and remaining useful life prediction with particle filtering. International Journal of Prognostics and Health Management 2013; 4 Special issue 2: 1-15.
19. kittiwake.com/online-sensors
20. pmlubricants.com.au.
21. specord-service.de

Leszek GOMÓŁKA
JAWO TECH S.R.O. Sp. z o.o., Branch in Poland
Niepodległości 67, 44-370 Pszów, Poland

Andrzej AUGUSTYNOWICZ
Faculty of Mechanical Engineering
Opole University of Technology
Mikołajczyka 5, 45-271 Opole, Poland

E-mails: leszek.gomolkaa@gmail.com,
a.augustynowicz@po.opole.pl