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EVALUATION OF ENGINE OIL FOAMING TENDENCY UNDER URBAN DRIVING CONDITIONS

OCENA ZMIAN CHARAKTERYSTYK PIENIENIA OLEJÓW SILNIKOWYCH UŻYTKOWANYCH W WARUNKACH JAZDY MIEJSKIEJ

The purpose of the article was to analyze the foaming tendency of engine oils used under excessive operating conditions. To achieve this end, foaming characteristics were determined for 23 oil samples in three measurement sequences. Foaming tendency was measured using the ASTM D 892 standard method, which consists in assessing foaming tendency of the liquid and foam stability. The cars used in the tests were uniform in terms of brand, type and operating conditions. The relationship between the mileage of the cars tested and the volume as well as stability of foam in used engine oils were presented using scatter plots with regression lines, correlation coefficient and 95% confidence interval. Based on the obtained results it was found that foaming tendency for new oils is characterized by high variability. The strongest foaming tendency at 24°C and 93°C (Sequence I and II) was observed for two out of five oil groups. Statistically significant differences were found between mileage and foaming tendency/foam stability for individual oils tested.

Keywords: *degradation, engine oil, foam tendency, foam stability, oil condition monitoring.*

Celem opracowania była analiza zmian charakterystyk pienienia olejów silnikowych użytkowanych w warunkach jazdy miejskiej. W związku z realizacją sformułowanego celu oznaczono skłonność do pienienia oraz trwałość piany dla 23 próbek oleju, według normy ASTM D 892. Próbki oleju pochodziły z samochodów stanowiących jednolitą flotę pod względem: marki, typu oraz warunków pracy silnika. Zależności przebiegu eksploatacyjnego badanych samochodów, z ilością i trwałością piany, w przeprowadzonych olejach silnikowych sprawdzono poprzez zastosowanie wykresów rozrzutu z linią regresji, współczynnikiem korelacji oraz 95%-owym przedziałem ufności. Na podstawie uzyskanych wyników stwierdzono, że skłonność do tworzenia piany dla olejów świeżych charakteryzuje się dużym zróżnicowaniem. Największą skłonność do pienienia w temp. 24°C i 93°C (Sekwencja I i II) zaobserwowano dla dwóch (z pięciu) grup olejowych. Potwierdzono istotne statystycznie różnice pomiędzy przebiegiem badanych pojazdów a poziomami poszczególnych charakterystyk pienienia.

Słowa kluczowe: *degradacja, olej silnikowy, skłonność do pienienia, trwałość piany, monitorowanie jakości oleju.*

1. Introduction

Belonging to the group of operating fluids, engine oils are generally known to exhibit foaming tendencies. This particular property of oils may cause a number of unfavorable effects in actual use, such as: too low amount of lubricant applied to the brake assembly, increased compressibility of operating fluids (resulting from the presence of air bubbles), heat dissipation difficulties or accelerated oxidation. Moreover, foaming can result in poor system performance and can cause serious mechanical damage: disturbances in the lubrication and cooling of the cooperating elements, the decrease in the pump capacity or the discharge of the operating fluid from the tank of the machine which, in turn, can lead to an increase in maintenance costs and pollution of the environment. That is why foam resistance is considered one of the most important properties of lubricants [4, 6-8].

The foaming tendencies of engine oils represent a serious problem, especially when they are stronger than what might be deemed permissible under given operating conditions. Resistance of the operating fluids to foaming depends on many factors, including the chemical and physical properties of these fluids. The influence of viscosity, density and surface tension on this phenomenon is very significant. It is worth noting that unfavorable operating conditions and poorly structured oil circuits are particularly conducive to foam formation.

Engine oil which should create only limited amounts of foam is subjected to foaming resistance tests. Foaming characteristics are measured by the ASTM D 892 standard method, which consists in evaluating the foaming tendency of the liquid and foam stability. The lower amount of foam, the better resistance to foaming. That is why, most lubricants contain antifoam additive to break up foams [1, 10].

Attempts to determine the limit levels for engine oils, found in both subject literature and practice [5, 9-13], all come down to assessing the permissible changes of the following [2, 12]:

- one selected physicochemical property of oil,
- one selected engine parameter,
- a parameter considered to be representative of the aging process,
- a set of parameters characterizing oil quality,
- a concentration of additives,
- the value of the synthetic parameter,
- similarities in the condition of oils.

Individual oil condition indicators (viscosity, acid number, base number, etc.) are widely used; nevertheless, it is equally important to consider a more general indicator which is the oil's tendency to foam.

The purpose of this paper is to analyze the foaming tendencies of engine oils used under excessive operating conditions. To achieve this end, the foaming characteristics (foaming tendency and foam stability) were determined for 23 oil samples in three measurement sequences, as described in the subject guidelines.

2. Materials and methods

The lubricating oils selected for testing have all complied with the specifications of Mitsubishi Motors Corporation (the manufacturer of the engines used in the study). The research material comprised of engine oil samples coded as CE, MS, ME, PS and PE. The quality of engine oils used in cars of the same type, operated under the same conditions and over the same period of time, was thoroughly assessed. The cars used in the tests were uniform in terms of brand, type and operating conditions and belonged to the Driver Training Center fleet. In total, there were 23 vehicles with spark ignition engines (cylinder capacity of 1,332 cm³) and operating on fuel coming from the same producer. Detailed specifications of the engine are presented in Table 1. All of the cars were generally used for conducting driving license tests. Three out of five oils (MS, ME and PE) were applied to five cars each, whereas two out of five (CE and PS) were applied to four cars each. At the beginning of the investigation an unused/new oil sample was tested. Then, the samples were collected and examined after one year (when the oil was changed).

Table 1. Detailed specifications of the engine.

Model code	4A90
Type	DOHC MIVEC
Cylinder volume [cm ³]	1,332
Maximum power [kW@rpm]	80@6,000
Maximum torque [Nm@rpm]	145@4,000
Fuel supply	MPI
Capacity of the lubrication system	4 l.
Required engine oil specifications	Synthetic 5W-30

The engine oil specifications (grade SAE 5W-30) are presented in Table 2 together with the API and ACEA standards.

Table 2. Quality and viscosity grades of the engine oils selected for testing.

Classification	Oil				
	CE	ME	MS	PE	PS
SAE	5W-30	5W-30	5W-30	5W-30	5W-30
ACEA	A3/B3-10, C3-10	C2/C3-10	C3-10	C2-10	A3/B3-10
API	SH	SM/SN	SM/SL	-	SM

Details on the number of kilometers traveled by each car selected for testing can be found in Table 3. The sample code includes the oil code and the car code. When analyzing the results, account should be taken of "harsh" operating conditions of the vehicles, i.e. operating at varying engine load, extended idling, driving in street traffic, short distance driving causing under-heating of the engine, and frequent start-ups at low engine temperatures. It should be noted that the tests as well as the sampling procedure were planned (in agreement with the fleet owners) in such a way as to avoid topping up the oil between

Table 3. The number of kilometers traveled by the cars tested.

Sample code	Mileage - starting point [km]	The number of kilometers traveled [km]
CE 17760	12858	13220
CE 17943	14571	13907
CE 17977*	6033	9975
CE 18716	9477	12169
ME 17764	15484	14501
ME 17810	7840	8749
ME 17973	8015	9029
ME 18345	9753	9234
ME 18760	15307	14573
MS 18011	13486	9005
MS 18128	14571	10803
MS 18361	14988	14166
MS 18793**	6223	6100
MS 18817	14666	13877
PE 17939	12370	13066
PE 18024	11694	11748
PE 18207	12209	13223
PE 18591	15409	15188
PE18689	13290	15531
PS 18149	13556	14384
PS 18193*	14457	18211
PS 18784	11948	12317
PS 18799	14154	13523

* - used for different purposes/operated under different conditions,

** - significantly lower mileage

the test periods. Ultimately, all selected cars were used for examination purposes, but after the completion of the study, it turned out that two of the cars from the selected fleet were actually used for other purposes. The one with the engine oil coded PS 018193 was used by the employees of the Driver Training Center as a company car. The

second car, to which the engine oil CE 017977 was applied, was used for training purposes. Both cars practically never served the examination purposes. Such information is a great contribution to this work, as it also demonstrates the impact of the operating conditions on the properties of engine oils.

The standard method generally used is to measure the volume of foam generated by blowing air through the sample of the test oil in the period of 5 minutes (foaming tendency), followed by a measurement of the foam volume after allowing it to stand for 10 minutes or by a measurement of the total time until the foam completely disappears. The measured volume of foam after this time is called the "foam stability".

The lab set for measuring the resistance of oil to foaming (Fig. 1) consists of:

- a measuring cylinder made of glass resistant to heating, of volume 1000 cm³, and the scale interval of 10 cm³,
- a rubber stopper (fitted to the cylinder) with two holes: the central one to insert the sparger and lateral for the placement of the air discharge tube,

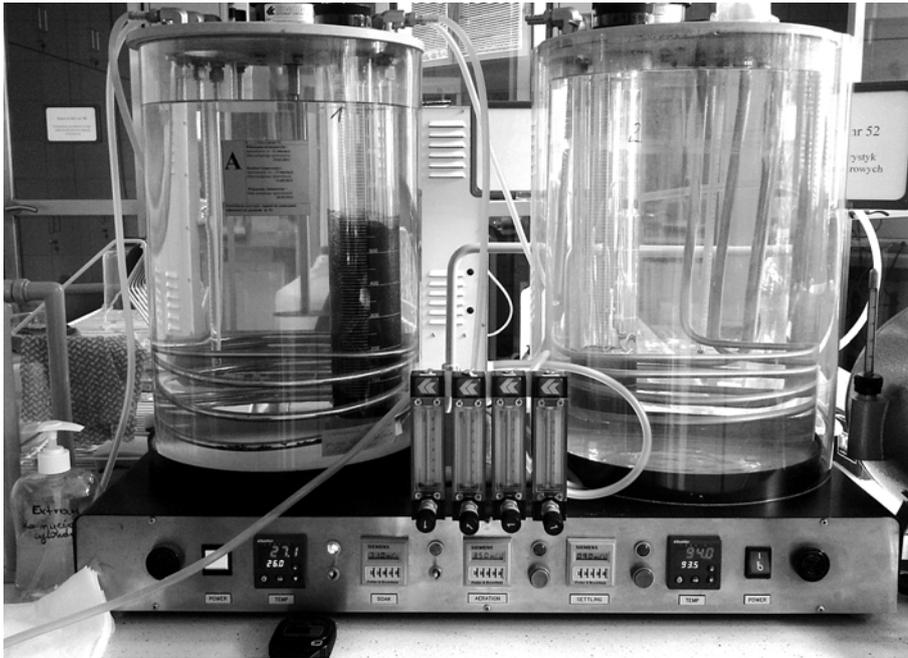


Fig. 1. The workstation where the foaming tendency of oils was measured; Department of Performance Testing, Oil and Gas Institute in Kraków

- a sparger, consisting of a brass air supply pipe and a spherical aluminum oxide membrane filter, cm^3 ,
- a lab bath, with thermo-regulators, filled with water,
- a flow meter to measure air volume flow,
- a thermometer with a measuring range of 0-100°C,
- a thermo-regulator - an electric heater with automatic temperature control.

The measurements were made in three sequences:

- sequence I – measurement at the temperature of 24°C,
- sequence II – measurement at the temperature of 93°C (a new sample),
- sequence III – measurement at the temperature of 24°C performed after the measurement at the temperature of 93°C.

The requirements regarding foaming tendency are given in the following way:

- **sequence I – no more than 50/10 [foam volume, cm^3]**, (interpretation: at the temperature of 24°C the foaming tendency is of 50 cm^3 , whereas the foam stability is of 10 cm^3),
- **sequence II – no more than 100/10 [foam volume, cm^3]**, (interpretation: at the temperature of 93°C the foaming tendency is of 100 cm^3 , whereas the foam stability is of 10 cm^3),
- **sequence III – no more than 50/10 [foam volume, cm^3]**, (interpretation: at the temperature of 24°C the foaming tendency is of 50 cm^3 , whereas the foam stability is of 10 cm^3) – measurement at the temperature of 24°C performed for the sample after the measurement at the temperature of 93°C.

The first figure represents the requirements for the foaming tendency and the second for foam stability.

The results obtained were statistically analyzed using the STATISTICA software (StatSoft Inc., USA). To investigate the relationship between the mileage of the cars tested and the volume as well as stability of foam in used engine oils, scatter plots with regression lines, correlation coefficient and 95% confidence interval were used. Shapiro-Wilk test was applied to assess whether data are normally distributed.

3. Results and discussion

Detailed results for each sample tested are shown in Table 4. The results for sequence I, II, and III measurements are summarized in each column. In sequence I, at the temperature of 24°C the strongest foaming tendency was observed in three samples from the MS oil group (MS 018011, MS 018361, MS 018128 with the following values – 680, 670, and 650 cm^3 , respectively) and in two oil samples from the ME group (ME 018345, ME 017973 with the values of 640 and 630 cm^3). The same samples showed the highest foam stability measured at the temperature of 24°C. It was on the level of 490 cm^3 (an average for the three MS oil group samples) and 345 cm^3 (an average for the two ME oil group samples). In sequence II, at the temperature of 93°C, the oil samples from the MS group (MS 018011, MS 018361, MS 018128 – an average: 570 cm^3), continued to exhibit the strongest foaming tendency. Other samples with relatively high foaming tendency were those from the ME oil group (ME018345 and ME 017973 – an average: 395 cm^3) and from the PS oil group (PS 018149, PS 018784 and PS 018799 – an average: 370 cm^3). It is worth noting that in spite of various amounts of

foam in samples at 93°C, in all analyzed cases, the foam stability 10 minutes after discontinuing the air blow was at zero level. In sequence III, the foaming tendency and foam stability were measured again at the temperature of 24°C; the difference was that it was a measurement of the samples that had been tested at 93°C before. The results are consistent with those obtained in sequence I. In the PS oil group, it is worth analyzing further the oil sample PS 018193 and in the CE group – the oil CE 017977, which despite the large number of kilometers traveled have retained the lowest levels of foam volume and stability. This clearly proves that unfavorable operating conditions increase the foaming tendency of oils.

When analyzing the results of the foaming tendency tests (Table 4) for new oils (before application to the engine) it can be observed that only one oil type (CE) did not exhibit foaming tendency in any of the three sequences, the MS oil showed some foaming tendency in sequence II, whereas the remaining oils exhibited foaming tendencies in all three sequences. The strongest foaming tendency was observed for the PE oil (SI-150 cm^3 , SII-50 cm^3 and SIII-90 cm^3), yet after the service life ended, the average foaming tendency of this oil was similar to that of the CE oil group and significantly lower than in the other three groups (which actually had much lower foaming tendency and foam stability for new oil than the PE oil).

Figures 2 and 3 illustrate the results of the foaming tendency measurements. The symbols (in boxes) indicate the average values of the individual parameters, while the upward and downward whiskers depict the distribution of individual measurements around the mean (standard deviation).

The strongest foaming tendency in sequence I was observed for the ME oil group samples ($\bar{x} = 600 \text{ cm}^3$, $s = 33 \text{ cm}^3$), in sequence II for the MS oils ($\bar{x} = 458 \text{ cm}^3$, $s = 149 \text{ cm}^3$) and in sequence III for the ME oil group again ($\bar{x} = 600 \text{ cm}^3$, $s = 6 \text{ cm}^3$). The lowest mean values were found in all three sequences for the CE oil group samples – in SI ($\bar{x} = 295 \text{ cm}^3$, $s = 166 \text{ cm}^3$), in SII ($\bar{x} = 255 \text{ cm}^3$, $s = 11 \text{ cm}^3$) and in SIII ($\bar{x} = 403 \text{ cm}^3$, $s = 52 \text{ cm}^3$). High values of standard deviation in the CE, MS and PS oil groups are caused by different operating conditions under which the oils PS 018193 and CE 017977 were used and a relatively low mileage of the car with the oil MS 018793. Excluding these three

Table 4. The foaming tendency and foam stability of the oil samples tested

Sample code	Sequence 1 (SI)	Sequence 2 (SII)	Sequence 3 (SIII)
CE0K	0/0	0/0	0/0
CE 017760	420/170	250/0	480/200
CE 017943	360/180	270/0	360/150
CE 017977*	10/0	240/0	350/0
CE 018716	390/170	260/0	420/180
ME0K	10/0	60/0	20/0
ME 017764	600/430	340/0	600/400
ME 017810	550/300	310/0	590/290
ME 017973	630/340	390/0	600/310
ME 018345	640/350	400/0	610/330
ME 018760	580/320	330/0	600/310
MS0K	0/0	20/0	0/0
MS 018011	680/460	580/0	620/450
MS 018128	650/490	570/0	620/460
MS 018361	670/520	550/0	610/510
MS 018793**	30/0	190/0	340/30
MS 018817	520/330	400/0	570/470
PE0K	150/0	50/0	90/0
PE 017939	490/70	170/0	460/60
PE 018207	340/50	160/0	360/40
PE 018024	480/80	190/0	440/50
PE 018591	490/100	240/0	500/60
PE 018689	510/110	230/0	520/70
PS0K	50/0	70/0	30/0
PS 018149	550/180	380/0	480/170
PS 018193*	20/0	270/0	340/20
PS 018784	510/90	370/0	500/170
PS 018799	540/160	360/0	470/160

* - used for different purposes/ operated under different conditions

** - significantly lower mileage

samples from the mean and standard deviation, the following results are obtained: in SI for the CE oils ($\bar{x} = 390 \text{ cm}^3$, $s = 24 \text{ cm}^3$), for the MS oil group ($\bar{x} = 630 \text{ cm}^3$, $s = 64 \text{ cm}^3$) and for the PS oil group ($\bar{x} = 533 \text{ cm}^3$, $s = 17 \text{ cm}^3$). In SII for the CE oils ($\bar{x} = 260 \text{ cm}^3$, $s = 8 \text{ cm}^3$), for the MS oils ($\bar{x} = 525 \text{ cm}^3$, $s = 73 \text{ cm}^3$) and for the PS oil group ($\bar{x} = 370 \text{ cm}^3$, $s = 8 \text{ cm}^3$). In SIII for the CE oil samples ($\bar{x} = 420 \text{ cm}^3$, $s = 49 \text{ cm}^3$), for the MS oil group ($\bar{x} = 605 \text{ cm}^3$, $s = 21 \text{ cm}^3$) and for the PS oil group ($\bar{x} = 483 \text{ cm}^3$, $s = 12 \text{ cm}^3$).

The highest mean value of foam stability in sequence I and in sequence II was observed for the MS group of oils. It was ($\bar{x} = 360 \text{ cm}^3$, $s = 191 \text{ cm}^3$) and ($\bar{x} = 384 \text{ cm}^3$, $s = 178 \text{ cm}^3$), respectively. Slightly lower values (ca. 12 cm^3 lower in sequence I and ca. 56 cm^3 lower in sequence III) were observed for the MS oil group. The lowest mean values were noted for the PE oil group – in SI ($\bar{x} = 82 \text{ cm}^3$, $s = 21 \text{ cm}^3$)

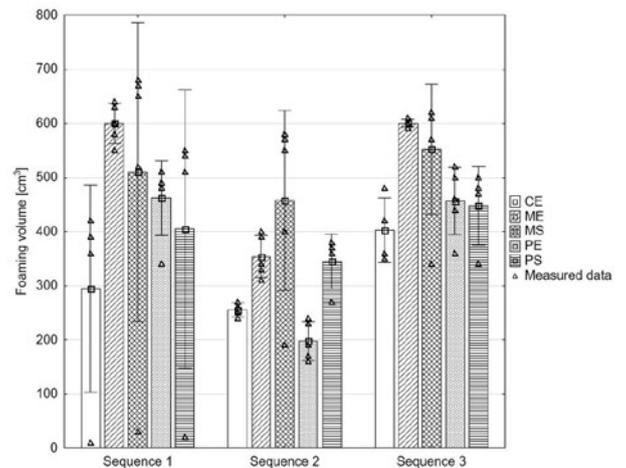


Fig. 2. The foaming tendency of engine oils measured after their service life ended (with mean values and standard deviations)

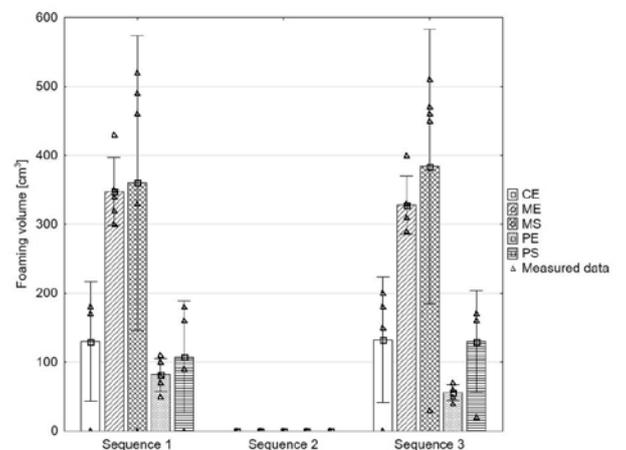


Fig. 3. The foam stability of engine oils measured after their service life ended (with mean values and standard deviations)

and in SIII ($\bar{x} = 56 \text{ cm}^3$, $s = 10 \text{ cm}^3$). Similar tendencies were observed for CE and PS oil groups (the mean foam stability in both sequences for these groups is 125 cm^3). Also, with regard to foam stability, particularly high standard deviations are noticeable in CE, MS and PS oil groups due to different operating conditions of some of the oils (PS 018193 and CE 017977) and relatively low mileage of the car with the MS 018793 oil. Excluding these three samples from the mean and standard deviation calculation, the following results are obtained: in SI for the CE oil group ($\bar{x} = 173 \text{ cm}^3$, $s = 5 \text{ cm}^3$), for the MS oil group ($\bar{x} = 450 \text{ cm}^3$, $s = 72 \text{ cm}^3$) and for the PS oil group ($\bar{x} = 143 \text{ cm}^3$, $s = 39 \text{ cm}^3$). In SII for the CE oil group ($\bar{x} = 177 \text{ cm}^3$, $s = 21 \text{ cm}^3$), for the MS oil group ($\bar{x} = 473 \text{ cm}^3$, $s = 23 \text{ cm}^3$) and for the PS oil group ($\bar{x} = 167 \text{ cm}^3$, $s = 5 \text{ cm}^3$).

The test results for engine oils operated under similar driving conditions show that the samples from the PE oil group exhibit lower foaming tendency at the temperature of 93°C , or are characterized by a greater ability to eliminate foam. On the other hand, the MS oil group samples are also worth mentioning. In their case, when analyzing the results in sequence II, a large number of emerging air bubbles can significantly reduce not only the lubrication capacity due to the presence of air but also the efficiency of the pumping systems. It should also be noted that the impact of car use and operating conditions on the foaming tendency of oils is significant. As it has been previously mentioned, two of the cars in the test were used in urban driving conditions, whereas the other ones were operated under “harsh” conditions (short distance driving, under-heating of the engine etc.)

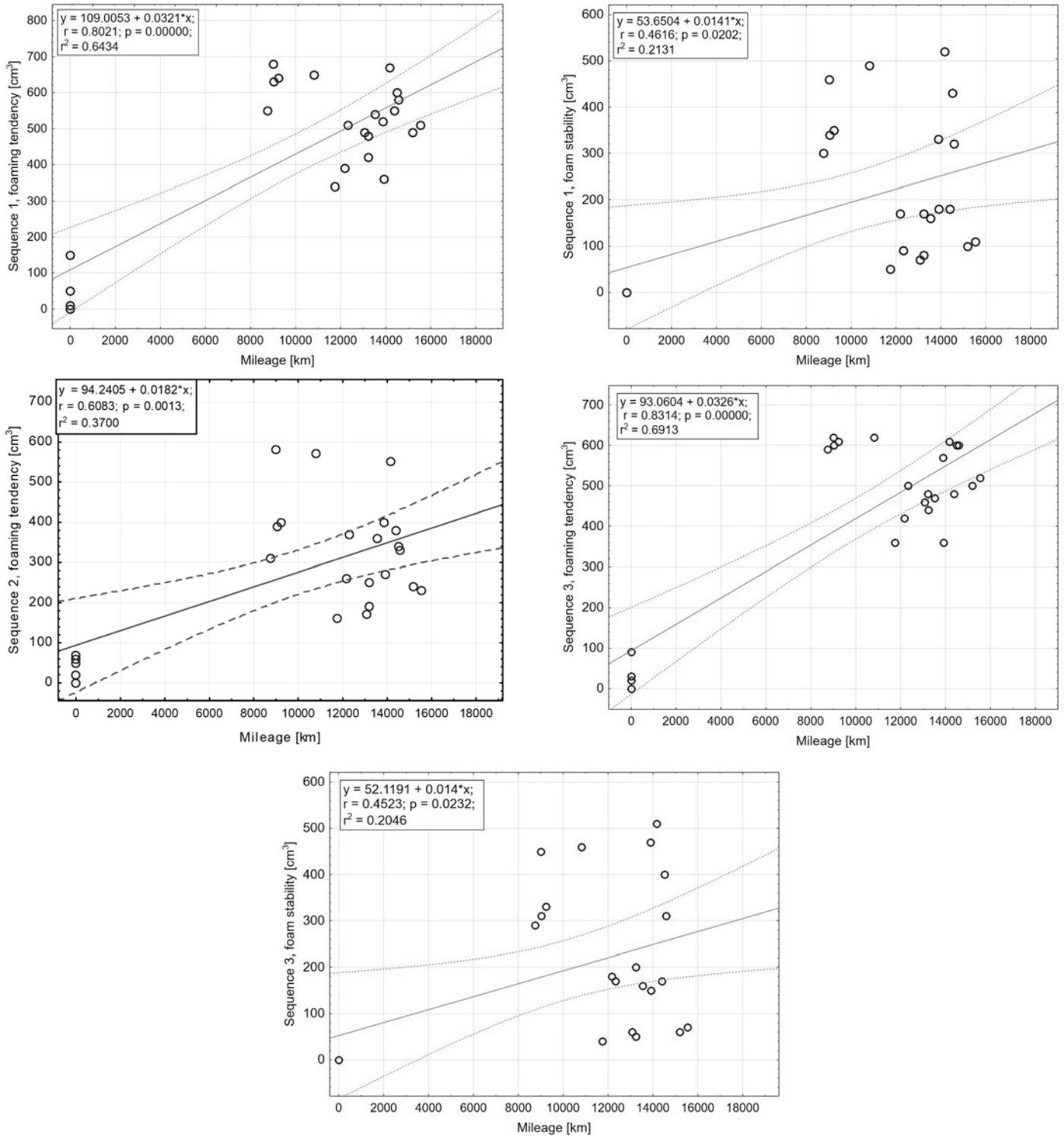


Fig 4. Scatter plots with regression lines, correlation coefficients, and 95% confidence intervals

because they were generally used for conducting driving license tests. The study results indicate that for the two vehicles operated differently, both the foaming tendency and foam stability significantly differ from the properties of the other oils tested. It is particularly noticeable in the foam stability for sequence I and III, which remains stable on the zero level, whereas it exceeds the value of 100 cm³ in all other oils. This may be related to the fact that more severe operating conditions accelerate the degradation of oil. According to Duncanson [3], water, solid impurities and oxidation products can contribute to the creation of foam in lubricating oils.

At the same time, it can be observed that also the service-life of oil may affect its foaming tendency – the higher the mileage, the stronger foaming tendency and foam stability. This trend is visible for groups of vehicles operated under similar driving conditions. With prolonged engine oil use, the products that result from the oxidation of oils become the dominant influence on the foaming tendency. After some period of oil use, a large amount of oxidation products is formed which settle on the particles and convert them into a colloidal suspension. Such colloidal suspension has solid particles surrounded

by compounds such as: resins, asphaltenes and macromolecular acidic substances, which become foam stabilizers.

Assuming similar operating conditions (and excluding the following oils: PS 018193 and CE 017977), such significant differences in the foaming tendency as observed for individual oil groups may be explained by differences in the amount of antifoam additives or by the type of additives used by manufacturers.

According to expert tests [9], the critical value for the foam volume at 93°C is 200 cm³, whereas for foam stability it is max. 30 cm³. Upon analyzing the results obtained for the limit values, it should be noted that while the foam stability remains at zero level, in the case of the amount of foam accumulated as a result of blowing air through the test oil sample in the period of 5 minutes, there are significant differences observed. The PE oils, for which the average value remains at the permissible limit, are definitely the best performers. The other oils tested exhibit very strong foaming tendencies with the highest values achieved by the ME and MS oils.

In order to check whether there is any statistical relationship between the mileage and the foaming tendency/foam stability, scatter plots with regression line and correlation coefficient were used (Fig. 4). It should be noted that three samples (PS 018193, CE 017977, MS 018793) have been left out in statistical analyzes due to their not meeting the prerequisite of being operated under similar conditions.

When analyzing the received significance levels (0.0000; 0.0202; 0.0013; 0.0232), it was found that all of them are below the limit value (0.05), so they should be considered statistically significant. It may be therefore concluded that there are also statistically significant differences between the mileages of the cars tested and the individual foaming characteristics (except for SII, foam stability). The obtained correlation coefficients show that in all five analyzed cases positive correlation was obtained. This, in turn, suggests that an increase in the foam volume and stability measured at the temperatures of 24 and 93°C (SI and SII) is related to the vehicle's service life, expressed in the number of kilometers traveled. The highest correlation coefficient was obtained for the foaming tendency at 24/93°C (SIII, $r = 0.8314$). Using J. Guilford's terminology, it is indeed a high correlation. Scatter plots with regression lines and correlation coefficients also show strong outliers. These are PS 018193 and CE017977 oils that have been used in cars operated under different conditions.

The observed increase in foaming tendency mainly results from gradual depletion of anti-foaming agents in oil. It may also be affected by physicochemical properties of oil. In order to obtain the full picture parameters such as: kinematic viscosity, HTHS, CCS, TAN, oxidation, nitration, water content, wear debris content were also measured. However, the research material obtained is very extensive and the changes in the abovementioned parameters have become the subject of other papers that have already been published [11, 12] or are currently in print.

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4. Conclusions

The creation of foam in engine oils negatively affects the entire lubrication system and may increase the wear of engine elements thus contributing to reduced engine life. Engine oils should have high foam resistance and low foam stability. This is achieved by the selection of suitable oil components and anti-foam additives. However, there are several factors that may change the characteristics of oil foaming during operation. The conducted research on a fleet of 23 vehicles operated under similar conditions allowed us to compare the foaming characteristics of oils after their service life ended. Based on the results obtained, it was found that:

- Foaming tendency for new oils is characterized by high variability. Only new oil from the CE group did not exhibit foaming tendencies in any of the sequences. The MS oil exhibited foaming tendency in sequence II, whereas the other oils showed foaming tendencies in all three sequences. The PE oil showed the strongest foaming tendency among new oils tested (SI – 150 cm³, SII – 50 cm³ and SIII – 90 cm³).
- The results of in-service research carried out under similar conditions show that the PE oils are either less likely to exhibit foaming tendency or have a higher foam elimination capacity. An inverse relationship was obtained, compared to new oils.
- The strongest foaming tendency at 24°C (SI) was observed for three samples from the MS oil group (MS 018011, MS 018361, MS 018128 and these were the following values – 680, 670, and 650 cm³, respectively) and for two samples from the ME oil group (ME 018345 and ME 017973 with the respective values of 640 and 630 cm³).
- The same samples showed the highest foam stability measured at 24°C (SI) - on the level of 490 cm³ (an average for three MS oils) and 345 cm³ (an average for two ME oils).
- The strongest foaming tendency at 93°C (SII) was observed for the MS oil group (MS 018011, MS 018361, MS 018128 – average 570 cm³), for the ME oil group (ME 018345 and ME 017973 – average 395 cm³), and for the PS oils (PS 018149, PS 018784 and PS 018799 – average 370 cm³).
- In all analyzed oil samples, the foam stability for sequence II (10 minutes after the air blow was discontinued) remains at zero level.
- Statistically significant differences were found between the mileage and the levels of individual foaming characteristics ($p < 0.05$).
- Positive correlation coefficients were obtained, thus proving that an increase in the foam volume and stability measured at the temperatures of 24 and 93°C (SI, SII and SIII) is related to the vehicle's service life and expressed in the number of kilometers traveled.

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