applied sciences

Article

Evaluation of the Potential Use of Thermal Conductivity and Breakdown Voltage to Determine the Degree of Lubricating Oil Dilution with Diesel Oil

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Abstract

The dilution of lubricating oil with diesel oil (DO) is a significant operational problem in piston combustion engines, as it degrades lubrication conditions and may accelerate the wear of interacting components. This study aimed to evaluate the usefulness of selected thermophysical and electrical properties of lubricating oil for determining the degree of its dilution with diesel oil. The tests were conducted on mixtures of SAE 30 or SAE 40 lubricating oil with diesel oil over a concentration range of 0–100% m/m of the latter material. Changes in thermal conductivity, thermal effusivity, and breakdown voltage were examined as a function of the mixture's fuel content. The thermal conductivity and effusivity of the tested oils were measured using the MTPS (Modified Transient Plane Source) transient method, while the breakdown voltage of the tested oils was measured at mains frequency using an apparatus in which the oil sample was exposed to an increasing electric field by gradually increasing the alternating voltage at a constant frequency until electrical breakdown occurred. An increase in the proportion of diesel oil caused a systematic linear decrease in thermal conductivity and thermal effusivity. A decreasing trend was also observed for breakdown voltage; however, this parameter exhibited significantly greater variation in results. The results indicate that thermal conductivity and thermal effusivity are more useful for assessing the degree of dilution of lubricating oil with DO than breakdown voltage.

Keywords: marine enegine; lubricating oil; fuel dilution; diesel oil; thermal conductivity; thermal effusivity; breakdown voltage

Academic Editors: Robert E. Hayes and Joe Mmbaga

Received: 13 May 2026
Revised: 26 May 2026
Accepted: 30 May 2026
Published: 2 June 2026

1. Introduction

During the operation of marine piston combustion engines, a significant tribological issue is the degradation of lubrication conditions in friction zones, resulting from the combined effects of mechanical loads, temperature, oil aging products, and contaminants originating from the combustion process and the fuel system. These phenomena are influenced by both the engine's design characteristics and its current wear state, as well as by the viscosity–temperature, detergent-dispersant, antiwear, and oxidation properties of the lubricating oil used. A particularly undesirable phenomenon is the dilution of

https://doi.org/10.3390/app16115512

lubricating oil with fuel, which reduces viscosity, decreases the thickness of the lubricating film, shifts lubrication characteristics toward mixed or boundary conditions, and degrades wear protection for interacting components. In the case of marine engines, this problem is of operational significance, particularly due to prolonged operation under load, high reliability requirements, and the possible use of fuels with varying compositions and properties. The literature on the subject, therefore, extensively analyzes the impact of fuel contamination/dilution by diesel oil (from both distillate fractions and heavier fuels) in circulating oil on tribological wear, the stability of the oil's physicochemical properties, and the effectiveness of operational diagnostics based on oil analysis methods [1,2].

Operational analyses and research results confirm that the presence of fuel in lubricating oil adversely affects engine operation, leading to decreased engine efficiency, shortened oil service life, and reduced operational reliability and safety [3,4]. Prolonged and progressive dilution of lubricating oil with fuel can result in the accelerated wear of mechanical components and, in extreme cases, lead to serious failures, including an explosion in the crankcase [5,6]. Castrol technical materials published by Castrol indicate that the significant dilution of lubricating oil with fuel may be one of the causes of such a risk.

Given the significant operational importance of fuel dilution of lubricating oil, its early detection and quantitative assessment remain critical. In diagnostic practice, both macroanalytical and microanalytical techniques are used, with the choice of method depending on the engine type, fuel type, lubrication system design, and the required accuracy of the determination [2,7]. In the routine monitoring of circulating oil condition, indirect methods predominate, primarily the measurement of kinematic viscosity and the determination of the flash point of samples periodically collected from the lubrication system [3,7].

These parameters serve as useful screening indicators, as the presence of fuel in the oil typically leads to a decrease in viscosity and a drop in flash point; however, interpreting these changes requires the simultaneous consideration of the effects of oxidation, the presence of soot and wear products, and changes occurring in the additive package [7–9]. For this reason, direct methods are used in advanced diagnostics, particularly gas chromatography, which enables the quantitative determination of the fuel content in lubricating oil with high selectivity and repeatability [10].

Complementary spectroscopic techniques, including FTIR, and sensor-based solutions designed for the rapid identification of changes in sample composition are also used; however, their effectiveness depends on the oil matrix type, the fuel type, and the calibration procedure [9,11]. The most important methods for identifying and assessing the degree of lubricating oil dilution with fuel, along with possible applications, are presented in Figure 1. In daily operation, however, viscosity analysis and flash point determination remain the basis for assessment, while instrumental methods are used primarily to confirm the diagnosis, quantitatively assess the scale of the phenomenon, and interpret ambiguous cases [10,12,13].

The primary and widely used methods for detecting fuel dilution in lubricating oil are measurements of flash point and viscosity, and indirectly also monitoring the lubricating oil level in the crankcase. However, these methods provide only indirect information on changes in oil composition and often require complex laboratory equipment or specialized measurement systems.

Therefore, the authors have attempted to explore alternative approaches for assessing changes in lubricating oil composition beyond standard methods. In particular, the focus has been placed on methods based on thermal and electrical properties, which may enable rapid oil diagnostics. The proposed approach may potentially be applied both in continuous condition monitoring systems for lubricating oil and as a supplementary method to currently used diagnostic techniques.

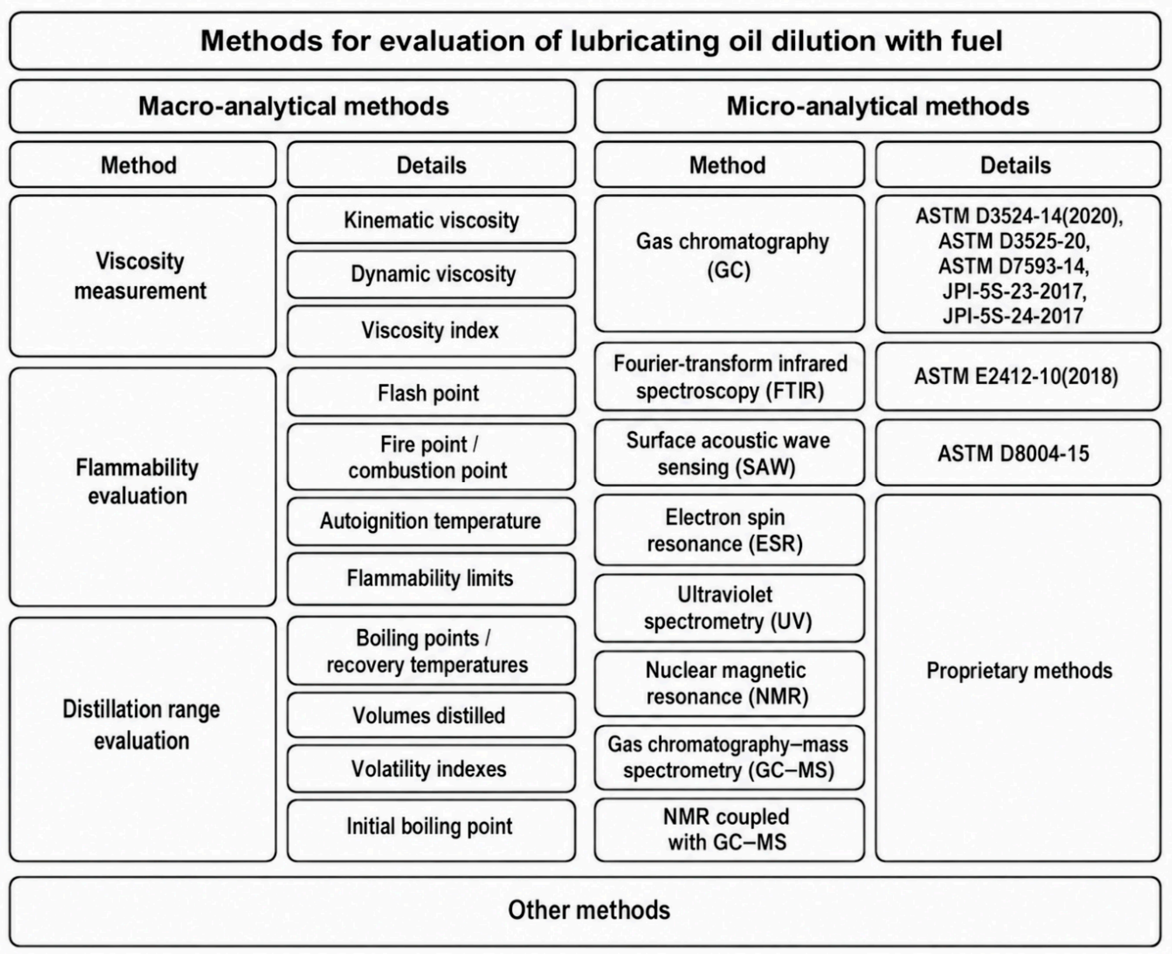

Figure 1. Overview of methods for detecting and determining the degree of fuel dilution in engine lubricating oils [14].

The proposed methods represent a novel approach which, to the best of the authors' knowledge, has not previously been considered in the literature for this specific application. The evaluation criteria were focused on achieving a high correlation between the measured characteristic parameter and the degree of lubricant oil dilution with diesel fuel, as well as on measurement speed, cost, potential for automation, and applicability under industrial conditions.

Following an in-depth analysis of the topic, the authors concluded that physical parameters related to the thermal and electrical properties of lubricating oil can serve as a complement to traditional in-service methods for assessing fuel contamination.

Of particular note are thermal conductivity and thermal effusivity, which describe the oil's ability to conduct and exchange heat with its surroundings. The dilution of lubricating oil with diesel oil, which has different thermophysical properties, can lead to measurable changes in these parameters. Analysis of these values, therefore, offers a potential means of indirectly assessing the degree of degradation in lubricating properties resulting from the presence of fuel [15].

The electrical parameters of the oil may also be of significant importance, particularly the breakdown voltage, which is a measure of its dielectric strength. The introduction of fuel fractions into lubricating oil affects its structure and physicochemical properties, which may result in a change in electrical breakdown resistance [16]. Monitoring the breakdown voltage can therefore serve as an additional diagnostic tool to assess the degree of dilution and the overall condition of the lubricating oil.

In this article, the authors sought to determine the usefulness of selected thermal parameters (thermal conductivity and thermal effusivity) and electrical parameters (breakdown voltage) for assessing the degree of dilution of lubricating oil with diesel oil. The study aimed to determine whether changes in these parameters can serve as a reliable and practically useful indicator of the presence of fuel in lubricating oil and whether they can supplement or expand upon the diagnostic methods currently in use.

2. Materials and Methods

2.1. Mixtures of Lubricating Oil and Diesel Fuel Used in the Experiment

The study utilized Orlen Efecta Diesel Bio (designation CN27102011D ORLEN S.A. Płock, Poland) [17], which meets the requirements of the Regulation of the Minister of Climate and Environment for liquid fuels (RMG) [18] and the ZN-ORLEN-5:2019 standard [19]. This fuel also meets the requirements for DMX-category marine diesel oils specified in ISO 8217:2017 [20] (Attachment C). The nominal parameters of this diesel fuel (DO) are presented in Table 1. The lubricating oils used in the tests were single-grade Agip/Eni Cladium 120 SAE 30 CD/CF and Agip/Eni Cladium 120 SAE 40 CD/CF oils (Eni S.p.A., Rome, Italy, whose characteristics are presented in Table 2.

Table 1. Physicochemical properties of Orlen Efecta Diesel Bio as declared by the manufacturer [17].

Specification	Parameter
Cetane index	≤51
Initial boiling point	75–180 °C
Boiling temperature range	95% vol. distills below 360 °C
Flash point (determined in a closed crucible)	>56 °C
Autoignition temperature (according to DIN 51794:2003-05 [21])	up to 240 °C
Kinematic viscosity (according to PN-EN ISO 3104:2021 [22])	1.5–4.5 mm^2/s (2.549 mm^2/s) at 40 °C approx. 2.151 mm^2/s at 50 °C
Density	820–845 kg/m^3 at 15 °C
Relative vapor density	approx. 6 (air = 1)
Cloud point	−7 °C
Cold filter plugging point	−28 °C

Table 2. Manufacturer-declared physicochemical properties of Agip/Eni Cladium 120 CD/CF lubricating oils (supplied by Eni S.p.A. (Rome, Italy) and used in tests [23–25].

Specification	Parameter	
Lubricating oil	Agip/Eni Cladium 120 SAE 30 CD/CF	Agip/Eni Cladium 120 SAE 40 CD/CF
Kinematic viscosity (according to PN-EN ISO 3104:2021 [22])	108 mm^2/s at 40 °C 12.0 mm^2/s at 100 °C	160 mm^2/s at 40 °C 15.7 mm^2/s at 100 °C
Viscosity index	100	100
Base number	12 mg KOH/g	12 mg KOH/g
Flash point (determined in an open crucible)	225 °C	235 °C
Pour point	−18 °C	−15 °C
Density	895 kg/m^3 at 15 °C	900 kg/m^3 at 15 °C

Agip/Eni Cladium SAE 30 CD/CF and Agip/Eni Cladium SAE 40 CD/CF are API CD/CF (Series III) engine oils designed for the lubrication of naturally aspirated and highly turbocharged compression-ignition engines used in marine, rail, and industrial applications. Their formulation and additive package provide appropriate detergent-dispersant, antiwear, antioxidant, and anticorrosion properties, allowing them to be used in circulating systems of engines powered by both light diesel oils and heavier fuels, including residual marine fuels and fuels with an elevated sulfur content. These properties determine the oil's ability to limit deposit formation, keep contaminants in a dispersed state, and maintain the required lubricating properties under varied engine operating conditions [23,24].

The lubricating oils used in the experiment belong to the two viscosity grades most commonly used in stationary industrial engines and marine engines, and they also meet the specifications of manufacturers of marine and industrial engines such as Deutz MWM, Dorman Diesel, Fincantieri—Divisione Grandi Motori, Isotta Fraschini, MAN B&W, Mirrlees, MTU marine oil, New Sulzer Diesel, NOHAB, S.E.M.T.—Pielstick, SKL, VM, and Wärtsilä.

In the tests conducted, the dilution ratios of DO and lubricating oil were defined in terms of mass fractions to relate the results to the actual amounts of substance in the sample, independent of temperature changes. Samples were prepared using a RADWAG WPs 510/C/2 precision laboratory balance (RADWAG Wagi Elektroniczne, Radom, Poland) with a resolution of 0.001 g. According to the calibration certificate, the maximum deviation of the readings was 0.002 g (for a 400 g standard). In each series of experiments, samples with a nominal mass of 200 g were prepared.

Mixtures of lubricating oil with DO at a specified fuel mass fraction $C = [m_{DO}/(m_{DO} + m_{LO})] \cdot 100\%$ were prepared according to the following procedure. Firstly, a clean glass vessel was placed on the balance and tared. Then, using a precise laboratory pipette, the required mass of lubricating oil, m_{LO}, was dispensed. After taring the balance again, the mass of DO, m_{DO}, was measured. The resulting mixture was homogenized using a magnetic stirrer for 15 min.

The repeatability of the instrument readings was checked before each measurement using a standard mass. The standard type B uncertainty for the mass fraction of DO in the mixture was determined based on the mass measurement uncertainty specified in accordance with the guidelines of the Joint Committee for Guides in Metrology [26]. The uncertainty of the mass determination was 0.0023 g. Calculations of the uncertainty of the mass fraction showed that, for the analyzed fuel concentrations, it was: 1% (m/m)–0.026%, 2–0.010%, 5–0.002%, and for concentrations above 10–0.001% [11].

Thermal conductivity and effusivity were measured for samples with diesel oil content of 0, 1, 2, 5, 10, 15, 20, 50, and 100% m/m, respectively, while breakdown voltage was measured for 0, 1, 2, 5, 10, 20, 30, 40, 50, 75, and 100% m/m.

2.2. Research Methodology

2.2.1. Thermal Conductivity and Effusivity Measurement

The thermal conductivity of the tested oils was measured using the MTPS (Modified Transient Plane Source) transient method, with a C-Therm TCi Thermal Conductivity Analyzer (C-Therm Technologies Ltd., 40, Fredericton, NB, Canada) which is an extension of the classic TPS method [27]. MTPS was developed specifically for heat transfer fluids (transfer oils, silicone oils, etc.). Classical methods, such as TPS and others, are susceptible to convection and require long measurement times [27–29]. Studies [27–30] show that MTPS enables repeatable and accurate measurements of λ for various liquids over a wide temperature range, typically with an error of <5–6% relative to literature values or reference methods. This method is based on the analysis of transient heat conduction in a semi-infinite medium, in which the thin-film measuring element simultaneously serves as a heat flux source and a resistive temperature sensor [27–31]. In this approach, the sample surrounding the sensor is assumed to be sufficiently large such that boundary effects are negligible during the measurement time scale, allowing heat propagation to be modeled as diffusion in a semi-infinite domain. In the case of the tested lubricating oils, this assumption is satisfied due to the relatively small thermal penetration depth compared to the sample volume and the short duration of the measurement. Additionally, the measurement system used in this study is specifically designed to ensure reliable operation for oils and heterogeneous liquids, enabling accurate determination of thermal properties under such conditions.

The Modified Transient Plane Source (MTPS) method uses a single-sided interfacial heater/sensor surrounded by an integrated heated guard ring. The heater/sensor generates a transient heat pulse that is applied to the sample. The guard ring acts as a thermal barrier around the sensing area, minimizing lateral heat flow at the sensor–sample interface. This configuration enables a short-time transient measurement in which the sensor response is used to determine thermal conductivity and thermal effusivity of the tested liquid. The theoretical basis of the method is the heat conduction equation in differential form [27–31]:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{1}$$

where T denotes temperature, t denotes time, and α denotes thermal diffusivity, defined as [27–31]:

$$\alpha = \frac{\lambda}{\rho c_p} \tag{2}$$

where λ is thermal conductivity [W/(m·K)], ρ is density [kg/m^3], c_p is specific heat capacity [J/(kg·K)], and α is thermal diffusivity [m^2/s] [27–31].

A material's thermal effusivity, also known as thermal responsivity, is a measure of its ability to exchange energy with its surroundings. Thermal effusivity e is a combination of material thermal conductivity, density, and specific heat capacity:

$$e = \sqrt{\lambda \rho c_p} \tag{3}$$

In the MTPS method, the sensor surface temperature response is analyzed after applying a transient heat pulse of known power. The change in the electrical resistance of the sensor is converted into a temperature response, and the resulting voltage change is evaluated as a function of the square root of time. According to the MTPS calibration procedure, the slope m of the voltage change versus $\sqrt{t}$ relationship is used to determine the effusivity of the tested sample [31]:

$$\frac{1}{m} = Me_2 + C \tag{4}$$

where m is the slope of the voltage response versus square root of time, M is the slope of the effusivity calibration curve, C is the calibration intercept, and e_2 is the thermal effusivity of the tested sample. Thus, the sample effusivity is obtained as [31]:

$$e_2 = \frac{1/m - C}{M} \tag{5}$$

This approach allows thermal effusivity to be obtained directly from the calibrated MTPS response, without calculating thermal diffusivity from thermal conductivity, density, and specific heat capacity [31].

This means that the temperature curve is inversely proportional to the thermal conductivity of the tested medium, which forms the basis for its determination by fitting the model to experimental data [27–31].

Measurements were performed using the MTPS system, in which a sensor with known geometric and electrical characteristics generated a controlled heat pulse, and the change in its resistance was converted into a change in temperature. The recorded temperature signal as a function of time was subjected to numerical analysis, in which the solution of the heat conduction equation was fitted to the experimental data, yielding the coefficient value [31].

The studies were conducted under conditions ensuring compliance with the assumptions of the theoretical model, in particular, maintaining an isothermal state at the start of the measurement. Temperature stability was defined as a variation not exceeding 0.5 °C over a period of 10 min. Oil samples were prepared to ensure homogeneity and continuous thermal contact with the sensor surface, which is crucial for the correct implementation of the heat conduction model's boundary conditions [31].

The measurements during the experiment were performed at a temperature of 23 °C. Temperature control was carried out using an external thermometer. According to the calibration certificate for the reference liquid manufactured by Sigma-Aldrich, at a measurement temperature of 20.6 °C, the instrument accuracy was as follows:

- For conductivity: expected value 0.609 W/mK, measured value 0.605 W/mK, accuracy −0.58%;
- For effusivity: expected value 1595.0 $\left(W\cdot s^{0.5}/\left(\mathrm{m}^2\cdot\mathrm{K}\right)\right)$, measured value 1588.1 $\left(W\cdot s^{0.5}/\left(\mathrm{m}^2\cdot\mathrm{K}\right)\right)$, accuracy −0.43%.

The reference measurement confirmed the validity of both thermal conductivity and thermal effusivity readings obtained using the MTPS configuration [31].

The measurement procedure included applying the sample to the sensor surface, stabilizing the system, generating a thermal pulse, and recording the temperature response as a function of time. A series of measurements was performed for each sample, and the obtained data were subjected to statistical analysis. The relative standard deviation and the model fit coefficient were adopted as quality criteria, ensuring a high degree of agreement between the experimental data and the theoretical model [31].

The study was conducted at the Maritime University of Szczecin using C-Therm's TRIDENT system. In the C-Therm MTPS design, the heater/sensor and guard ring are integrated into a single assembly mounted on an insulating backing material, ensuring that almost all heat transfer during the measurement occurs between the sensor assembly and the sample. In operation, the sensor is placed in intimate contact with a sample, as illustrated in Figure 2. The testing apparatus is shown in Figure 3.

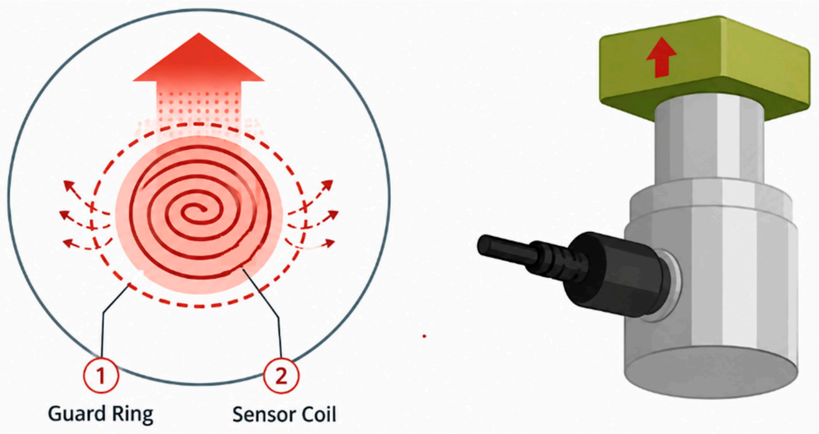

Figure 2. Conducting the thermal conductivity measurement. The red arrow indicates the direction of transient heat flow from the sensor toward the tested oil sample [31].

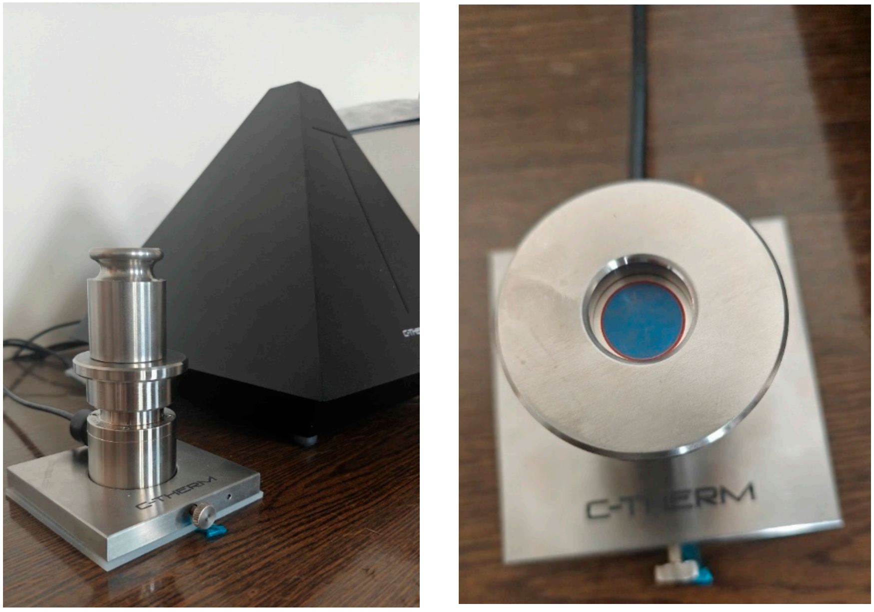

Figure 3. Apparatus used to measure thermal conductivity.

The methodology used corresponds to an approach widely employed in research [27–29]. This research includes studies of the thermophysical properties of liquids [27–30], where transient response analysis enables rapid and precise determination of thermal conductivity with a small sample volume. It is crucial that the experimental conditions align with the assumptions of the mathematical model, particularly regarding sample homogeneity, the absence of contact discontinuities, and the stability of initial conditions, all of which were ensured in the experiments conducted.

2.2.2. Breakdown Voltage Measurement

A BA100 Breakdown Analyzer for Oil Testing (b2 electronics GmbH, Klaus, Austria) was used to measure breakdown voltage. This is a highly specialized laboratory device designed to evaluate the dielectric properties of electrical insulating liquids, particularly transformer oils used in high-voltage equipment. This test enables a quantitative assessment of a material's ability to resist electrical breakdown, which is one of the key operational parameters of power systems.

The device operates by applying a controlled alternating voltage at mains frequency (50 Hz) to a system of electrodes immersed in the liquid sample under test. During the measurement, the voltage increases automatically and linearly at a fixed rate until a critical value is reached, at which point dielectric breakdown occurs. This phenomenon is identified by a sudden drop in electrical resistance and the formation of a conductive channel between the electrodes. The recorded voltage value at the moment of breakdown constitutes the result of a single measurement.

The measurement was performed up to 100 kV (AC rms), enabling analysis of a wide spectrum of electrical insulating liquids with diverse properties. The measurement system was equipped with a set of measuring electrodes with defined geometry (most commonly spherical or hemispherical), whose spacing and surface parameters complied with regulatory requirements. The liquid sample was placed in a special measurement chamber made of an electrically insulating material, ensuring repeatable test conditions and minimizing the influence of external factors.

The test procedure was conducted in accordance with the requirements of the PN-EN 60156:2008 standard [32], which specifies detailed conditions for sample preparation, electrode geometry, voltage rise rate, and the number of measurement repetitions. In accordance with the standard's guidelines, a series of consecutive measurements was performed for each sample, with a sufficient relaxation time for the system and thorough mixing of the liquid ensured between consecutive tests to eliminate the products of previous discharges. The final result was determined as the arithmetic mean of the obtained breakdown voltage values, with simultaneous analysis of standard deviations to assess the repeatability of the results.

PN-EN 60156:2008 standard corresponds to the European IEC 60156 standard. In this case, the gap width between the electrodes was 2.5 mm, and the voltage ramp rate was 2 kV/s. Twelve breakdown voltage measurements were performed for each sample.

The use of the BA100 analyzer (Figure 4) enabled high measurement accuracy and repeatability, thanks to full process automation and the elimination of human influence on the test procedure. The obtained results serve as the basis for assessing the quality of the electrical insulating oil, its degree of degradation, and its suitability for continued use in electrical power equipment.

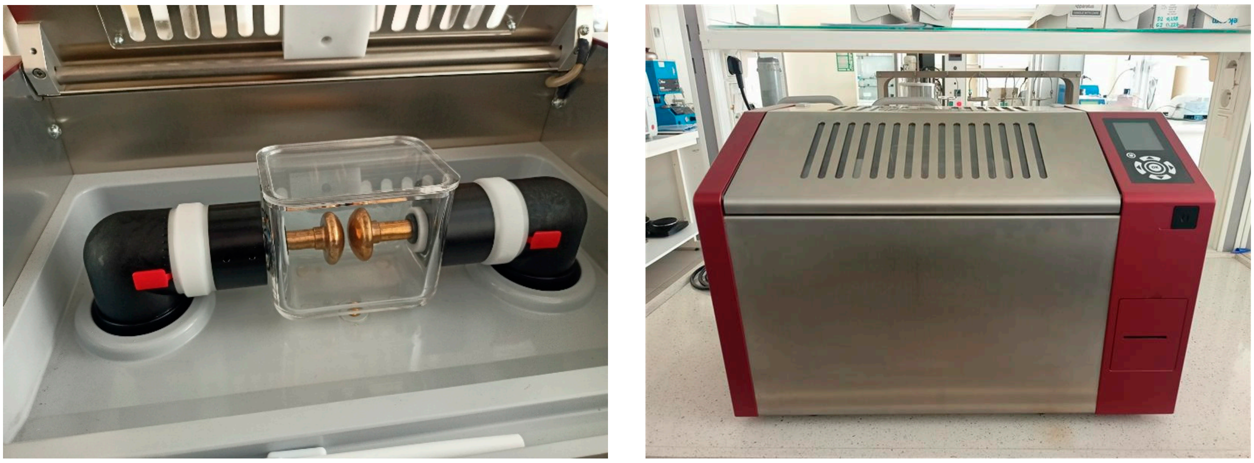

Figure 4. Equipment used to measure breakdown voltage.

An important element of the methodology was ensuring appropriate sample preparation conditions, including filtration, degassing, and temperature stabilization, which directly helped eliminate interfering factors such as moisture, solid particles, and dissolved gases. Environmental parameters, in particular ambient temperature and humidity, were monitored and maintained at levels compliant with regulatory requirements.

3. Results and Discussion

3.1. Thermal Conductivity

Figure 5 shows the measured thermal conductivity of the tested lubricating oil–diesel oil mixtures as a function of the mass fraction of diesel oil (DO) in the mixture. As the diesel oil content in the lubricating oil increased, thermal conductivity decreased.

The thermal conductivity of the tested pure lubricating oils was 150.0$\left(\mathrm{W}\cdot s^{0.5}/\left(\mathrm{m}^2\cdot\mathrm{K}\right)\right)$ for SAE 30 oil and 152.6 $\left(W\cdot\frac{s^{0.5}}{\mathrm{m}^2\cdot\mathrm{K}}\right)$ for SAE 40, while the thermal conductivity of pure DO was 140.1 $\left(\mathrm{W}\cdot s^{0.5}/\left(\mathrm{m}^2\cdot\mathrm{K}\right)\right)$. The standard deviation, σ, and the statistical measurement uncertainty, u, for a population of 30 measurements performed for each sample are presented in Table 3.

The functional relationship between thermal conductivity, κ, and the mass percentage of diesel oil, C, in a mixture with lubricating oil was linear (dotted lines in Figure 5) and can be described by the function:

$$\kappa = a_1 C + a_2, \tag{6}$$

where $a_1\left(\frac{\mathrm{mW}}{\mathrm{K\cdot m\cdot(\%}m/m)}\right)$ and $a_2\left(\frac{\mathrm{mW}}{\mathrm{K\cdot m}}\right)$ are empirical coefficients dependent on the types of lubricating oils and diesel oil used in the experiment.

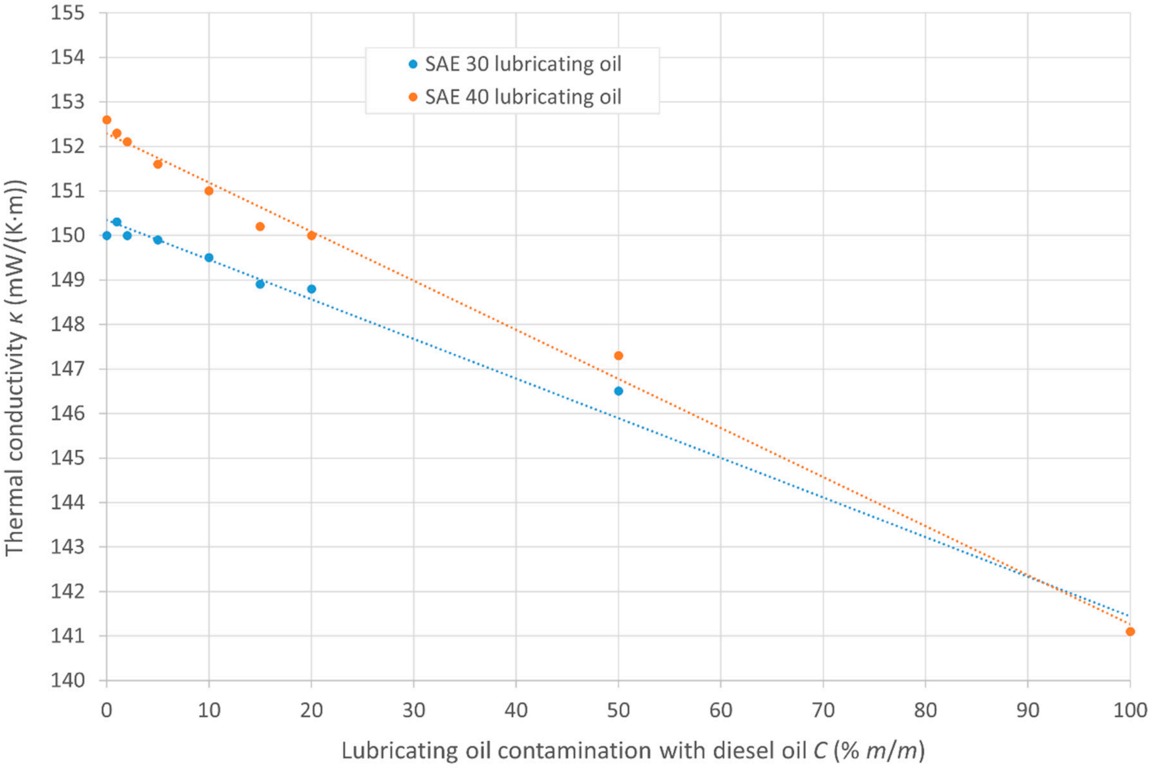

Figure 5. Thermal conductivity of the tested lubricating oil–DO mixtures.

Table 3. Standard deviation and measurement uncertainty of thermal conductivity.

Base Oil for Preparing Blends		**Mass Fraction of DO in the Blend with Lubricating Oil C (% m/m)**								
		0	**1**	**2**	**5**	**10**	**15**	**20**	**50**	**100**
Viscosity Class		**Statistical Factor (W·s$^{0.5}$/(m^2·K))**								
SAE 30	Standard deviation σ	0.4	0.5	0.4	0.7	0.5	0.4	0.5	0.4	0.7
	measurement uncertainty u	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
SAE 40	Standard deviation σ	0.5	0.6	0.6	0.5	0.6	0.6	0.6	0.6	0.7
	measurement uncertainty u	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Table 4 presents a summary of the values of the coefficients a_1 and a_2, along with the coefficient of determination (R^2), root mean squared error (RMSE) and mean absolute error (MAE) for the mixtures used.

Model (1), along with the coefficients presented in Table 4, could be applied in further studies. The high values of the coefficient of determination, $R^2 \geq 0.9899$, indicated an excellent fit of the model to the empirical data. The observed trend stemmed primarily from the package of performance additives contained in the lubricating oils, including compounds with a thermal conductivity coefficient higher than that of the base oil. Thus, the thermal conductivity of the lubricating oil was higher than that of pure DO. The estimated error values (RMSE and MAE) are relatively low, which indicates that the model is useful, especially for high values of lubricating oil dilution by fuel.

Table 4. Coefficients characterizing the linear thermal conductivity model of the tested mixtures.

Base Oil for Preparing Blends	**Slope Coefficient a_1**	**Displacement Coefficient a_2**	**Determination Coefficient R^2**	**RMSE**	**MAE**
Viscosity class	mW/(m·K·wt.%)	mW/(m·K)	–	mW/(m·K)	mW/(m·K)
SAE 30	–0.0890	150.340	0.9899	3.1404	2.3732
SAE 40	–0.1103	152.290	0.9938	2.4618	2.005

3.2. Thermal Effusivity

Figure 6 shows the measured thermal effusivity values of the tested lubricating oil-DO mixtures as a function of the mass fraction of DO in the mixture. As the DO content in the lubricating oil increased, a decrease in thermal effusivity was observed, similar to the thermal conductivity.

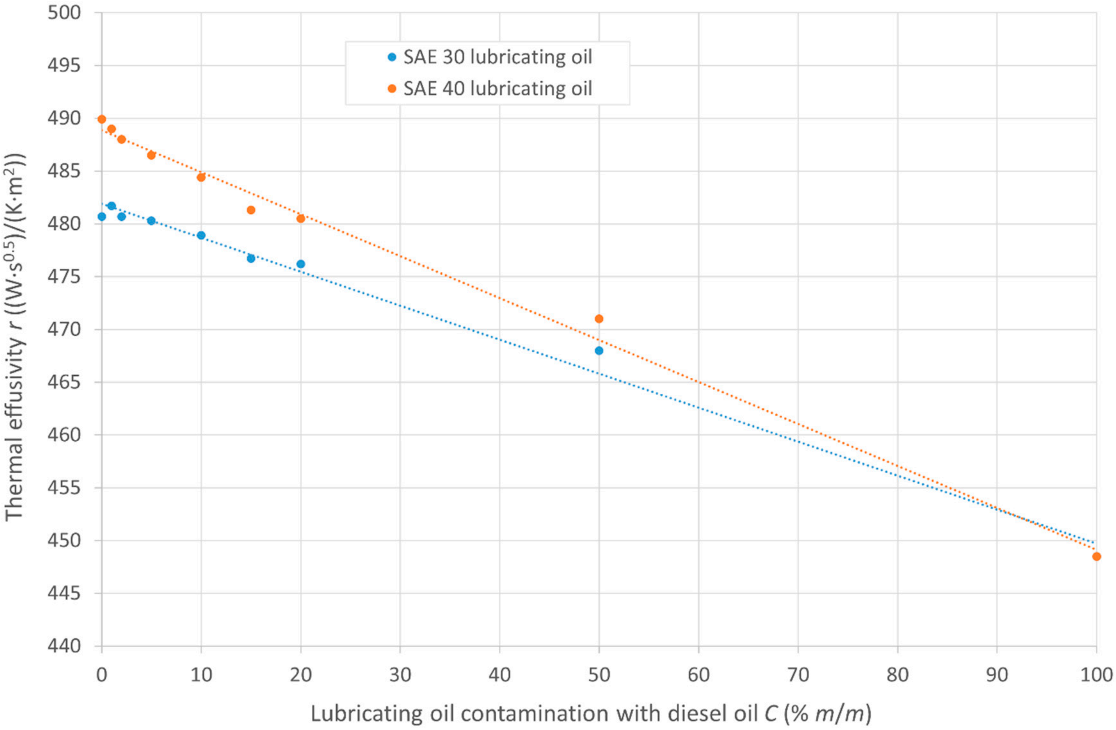

Figure 6. Thermal effusivity of the tested lubricating oil–DO mixtures.

The thermal effusivity of the tested pure lubricating oils was 480.7 (W·$s^{0.5}$/(m^2·K)for SAE 30 oil and 489.9 (W·$s^{0.5}$/(m^2·K)) for SAE 40, while the thermal effusivity of pure DO was 488.5 (W·$s^{0.5}$/(m^2·K)). The standard deviation, σ, and the statistical measurement uncertainty, u, for a population of 30 measurements performed for each sample are presented in Table 5.

The functional relationship between thermal effusivity, r, and the mass percentage of DO, C, in a mixture with lubricating oil was linear (dotted lines in Figure 6) and can be described by the function:

$$r = b_1 C + b_2, \tag{7}$$

where b_1 (W·$s^{0.5}$/(m^2·K) (% m/m)) and b_2 (W·$s^{0.5}$/(m^2·K)) are empirical coefficients dependent on the types of lubricating oils and DO used in the experiment.

Table 5. Standard deviation and measurement uncertainty of thermal effusivity.

Base Oil for Preparing Blends		**Mass Fraction of DO in the Blend with Lubricating Oil C (% m/m)**								
		0	**1**	**2**	**5**	**10**	**15**	**20**	**50**	**100**
Viscosity Class		**Statistical Factor ($W\cdot s^{0.5}/(m^2\cdot K)$)**								
SAE 30	Standard deviation σ	1.4	1.9	1.6	2.4	1.8	1.6	1.7	1.6	2.6
	measurement uncertainty u	0.3	0.3	0.3	0.4	0.3	0.3	0.3	0.3	0.5
SAE 40	Standard deviation σ	1.8	2.2	2.0	1.9	2.1	2.0	2.0	2.1	2.6
	measurement uncertainty u	0.3	0.4	0.4	0.3	0.4	0.4	0.4	0.4	0.5

Table 6 presents a summary of the values of the coefficients b_1 and b_2, along with the coefficient of determination (R^2), root mean squared error (RMSE) and mean absolute error (MAE) for the mixtures used.

Table 6. Coefficients characterizing the linear model of thermal effusivity for the tested mixtures.

Base Oil for Preparing Blends	**Slope Coefficient b_1**	**Displacement Coefficient b_2**	**Determination Coefficient R^2**	**RMSE**	**MAE**
Viscosity class	$W\cdot s^{0.5}/(m^2\cdot K)(\%m/m)$	$W\cdot s^{0.5}/(m^2\cdot K)$	–	$W\cdot s^{0.5}/(m^2\cdot K)$	$W\cdot s^{0.5}/(m^2\cdot K)$
SAE 30	−0.3219	481.980	0.9903	3.0783	2.3064
SAE 40	−0.3975	488.970	0.9935	2.5155	2.0859

Model (2), together with the coefficients presented in Table 6, can be applied in further research. High values of the coefficient of determination, $R^2 \geq 0.9903$, indicated an excellent fit of the models to the empirical data. Similarly to the case of thermal conductivity, the observed trend resulted primarily from the package of performance additives contained in the lubricating oils, including compounds that positively influenced the efficiency of heat exchange between the lubricating oil and the environment. The estimated error values (RMSE and MAE) are relatively low, which indicates that the model is useful, especially for high values of lubricating oil dilution by fuel.

3.3. Breakdown Voltage

Figures 7 and 8 present the measured breakdown voltage values for the tested lubricating oil blends with viscosities SAE 30 and SAE 40, respectively, with DO, as a function of the mass fraction of diesel fuel in the blend. As the DO content in the lubricating oil increased, the breakdown voltage decreased.

The breakdown voltage of the tested pure lubricating oils was 66.8 V for SAE 30 oil and 58.1 V for SAE 40, while the breakdown voltage of pure DO was 35.1 V. However, the measurement results showed significant fluctuations, presumably due to heterogeneity in the oils' composition and thus differences in the obtained breakdown voltage values. The standard deviation, σ, and the statistical measurement uncertainty, u, for a population of 12 measurements per sample are presented in Table 7.

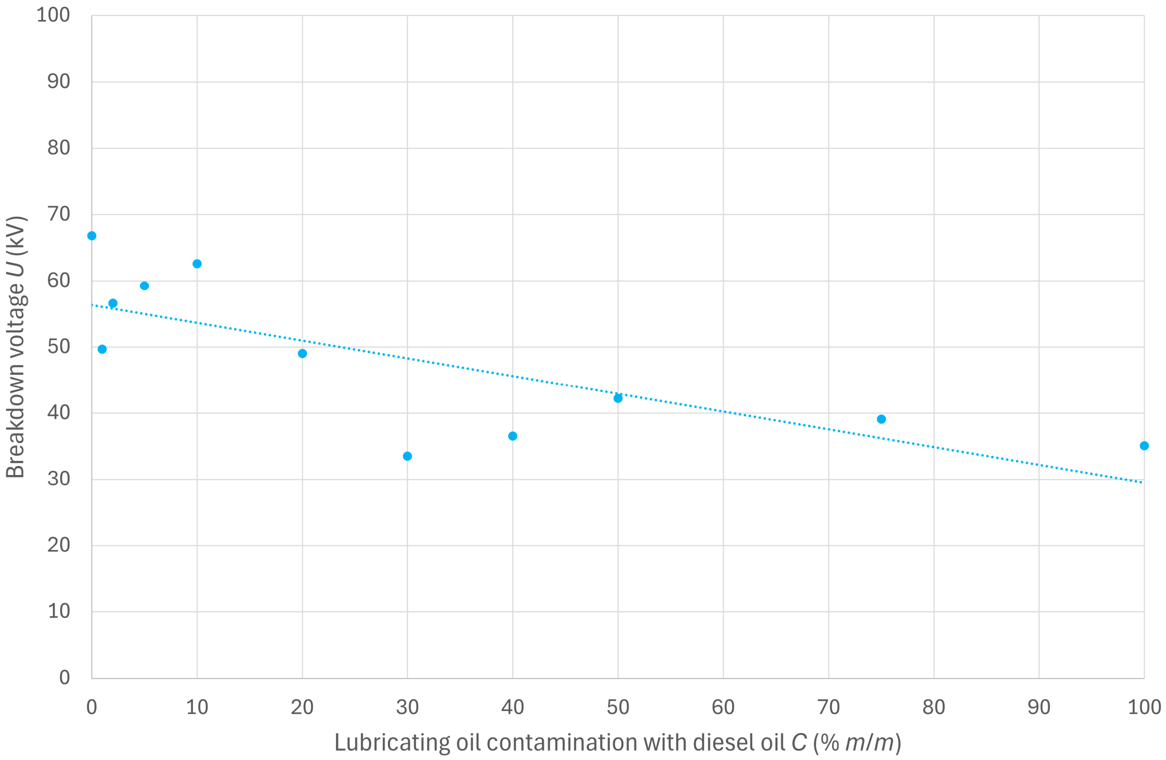

Figure 7. Breakdown voltage of the tested lubricating oil mixtures of SAE 30 viscosity grade with DO.

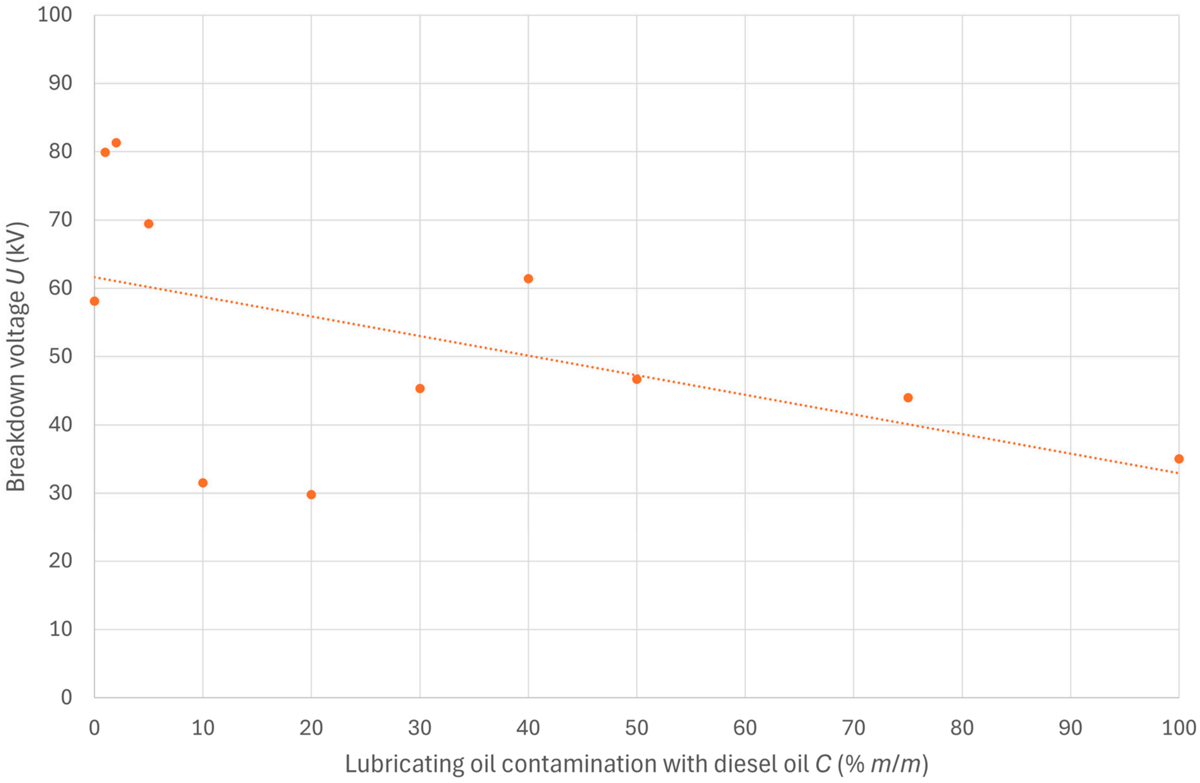

Figure 8. Breakdown voltage of the tested lubricating oil mixtures of SAE 40 viscosity grade with DO.

Table 7. Standard deviation and measurement uncertainty of breakdown voltage for the tested lubricating oil–DO mixtures.

Base Oil Viscosity Grade	DO Mass Fraction, C (% m/m)	Standard Deviation, σ (V)	Measurement Uncertainty, u (V)
SAE 30	0	8.7	2.5
SAE 30	1	8.9	2.5
SAE 30	2	5.2	1.5
SAE 30	5	12.1	3.4
SAE 30	10	2.5	0.7
SAE 30	20	4.5	1.3
SAE 30	30	7.2	2.1
SAE 30	40	8.4	2.4
SAE 30	50	8.0	2.3
SAE 30	75	5.3	1.5
SAE 30	100	7.7	2.2
SAE 40	0	9.8	2.8
SAE 40	1	8.5	2.4
SAE 40	2	9.9	2.8
SAE 40	5	10.5	3.0
SAE 40	10	8.8	2.5
SAE 40	20	8.7	2.5
SAE 40	30	8.6	2.4
SAE 40	40	4.9	1.4
SAE 40	50	5.7	1.6
SAE 40	75	7.9	2.3
SAE 40	100	7.7	2.2

The functional relationship between breakdown voltage, U, and the mass percentage of DO, C, in the mixture with lubricating oil was linear (dotted lines in Figures 7 and 8) and can be described by the function:

$$U = c_1 C + c_2, \tag{8}$$

where $c_1 \left(\frac{\mathrm{V}}{\% m/m}\right)$ and c_2 (V) were empirical coefficients dependent on the types of lubricating oils and diesel oil used in the experiment.

Table 8 presents a summary of the values of the coefficients c_1 and c_2, along with the coefficient of determination (R^2), root mean squared error (RMSE) and mean absolute error (MAE) for the mixtures used.

Table 8. Coefficients characterizing the linear breakdown voltage model for the tested mixtures.

Base Oil for Preparing Blends	Slope Coefficient c_1	Displacement Coefficient c_2	Determination Coefficient R^2	RMSE	MAE
Viscosity class	V/wt.%	V	–	V	V
SAE 30	−0.2684	56.315	0.5740	42.7277	35.6203
SAE 40	−0.2872	61.651	0.2692	48.6668	39.1324

Model (3), together with the coefficients presented in Table 8, may be used in further research. Nevertheless, the obtained values of the coefficient of determination, R^2, in the range of ~0.27 to ~0.57 indicated an average fit of the models to the empirical data. The estimated error values (RMSE and MAE) are relatively high, which indicates the limited usefulness of the model in question.

4. Conclusions

This study aimed to evaluate the potential of using selected thermophysical and electrical properties of lubricating oil as indicators of its dilution with DO. The analysis was performed on mixtures of SAE 30 and SAE 40 viscosity grade lubricating oils with DO over a fuel content range of 0 to 100% m/m.

The results indicated that thermal conductivity and thermal effusivity showed a clear, reproducible dependence on the fuel content of the lubricating oil. As the mass fraction of DO increased, a systematic decrease in the values of both parameters was observed. These relationships were well described by linear models, for which very high values of the coefficient of determination were obtained ($R^2 \geq 0.9899$ for thermal conductivity and $R^2 \geq 0.9903$ for thermal effusivity). The results indicate that thermal conductivity and thermal effusivity are highly sensitive to changes in mixture composition, making them quantitative indicators of the degree of dilution of lubricating oil with diesel oil, provided that reference characteristics for a given oil–fuel system are determined beforehand.

The low standard deviations and measurement uncertainties obtained during the tests confirm the good repeatability and stability of the measurement method. This indicates that the analyzed thermophysical parameters can serve as a useful supplement to classical diagnostic methods used in assessing the condition of lubricating oil, particularly in laboratory analyses.

A different pattern of results was observed for breakdown voltage. Despite the observed general trend of decreasing values with increasing diesel content in the lubricating oil, the measurement results exhibited significant variation. Consequently, the obtained regression models showed relatively low coefficients of determination ($R^2 \approx 0.27$–0.57), indicating the limited usefulness of breakdown voltage as a parameter for quantitatively assessing the degree of lubricating oil dilution in fuel. This variability may result from the high sensitivity of liquid dielectric properties to local compositional inhomogeneities and the presence of additives in lubricating oils.

From the perspective of diagnostic applications, the results indicate that thermal conductivity and thermal effusivity are the most promising parameters for the indirect assessment of fuel content in lubricating oil, whereas breakdown voltage serves only a supplementary function due to greater variability in the results.

The presented study serves as an introduction to further work on the use of the thermophysical properties of lubricating oils in the operational diagnostics of internal combustion engines. Future studies plan to analyze the influence of additional operational factors. Possible directions for future research include incorporating operational factors such as oil aging, carbon deposits, moisture, and wear particles, which are commonly present in engine oil during service, and evaluating their influence on the measured results. In the present study, these factors were not analyzed, as the primary objective was to provide a general assessment of the applicability of the proposed methods, which was carried out under controlled reference conditions.

It should also be noted that thermal conductivity may be used not only for the quantitative assessment of fuel dilution but also for evaluating the degree of oil degradation relative to a reference condition.

Furthermore, investigating specific factors affecting the results, such as additive polarity, moisture content, and electrode contamination, as well as potential methods for controlling them, is considered a worthwhile direction for future research.

Author Contributions: Conceptualization, L.C.; methodology, L.C. and K.B.; software, L.C., M.S., K.B. and M.K.; validation, L.C., M.S. and K.B.; formal analysis, L.C., M.S. and K.B.; investigation, L.C., M.S., K.B. and M.K.; resources, L.C., M.S., K.B. and M.K.; data curation, L.C. and K.B.; writing—

original draft preparation, L.C., M.S. and K.B.; writing—review and editing, L.C., M.S., K.B. and M.K.; visualization, L.C., M.S. and K.B.; supervision, L.C.; project administration, L.C.; funding acquisition, L.C., M.S. and K.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Ministry of Science and Higher Education of Poland, grants number 1/S/KSO/26; 1/S/KE/26; 1/S/KTiTWM/26.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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https://doi.org/10.3390/app16115512