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INNOVATIVE TESTING METHODS AND THEIR APPLICATION POSSIBILITIES IN TECHNICAL PRACTICE

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Abstract: Nowadays, the mission of coolants used for internal combustion engines is complex: the primary task is to perform the cooling and additional corrosion preventing, furthermore to keep the impact on the environment to a negligible level is also a basic requirement. It is in the common interest of manufacturers and users alike for this mission to be fully realised. As university lecturer, researcher, engineer and student, we are working together and turning with curiosity on a topic of interest to both industry and society. In the present paper, keeping in mind the previous ideas but taking advantage of the researcher's freedom, the basic objective of the research work is the dielectric study of various engine coolants (Glicosam Z, Prelix P, Prelix Z, Sheron K, Sheron P) using the DAK-3.5 (Dielectric Assessment Kit) measuring system. The tests were performed in the microwave range (limited to the frequency range 200–2400 MHz) and at specific temperatures (20℃, 30℃, 40℃, 50℃) and at the manufacturer's recommended dilution ratio (with deionized water). The electromagnetic behaviour of the selected coolant samples pointed to different compositions of the engine coolants, production technology and the material quality characteristics attributable to the different concentrations. Actually, the behavioural characteristics of the coolants complete the list of physical and chemical parameters in the product data sheet and safety data sheet of the coolants, providing users with more and more complete information. Among the test results of the coolant samples, the measurement results are presented at 900 MHz and 2400 MHz, namely the relationship between the imaginary part of the complex permittivity (ε") and the antifreeze capacity (t). An additional objective was to determine the (energy) electricity demand of the tests, using the Energy Logger 4000 meter.

Keywords: coolant, dielectric characteristics, energy requirements for tests

1. INTRODUCTION

Protecting the engine from freezing is an important requirement during the use of coolants for internal combustion engines, but overheating of the engine must also be avoided. Because the corrosion protection is another main function of engine coolants, the careful selection of coolants is one of many prerequisites of an engine's reliable operation. Ethylene glycol (melting point / freezing point: –12.9 °C, boiling point: 197.3 °C, flash point: 111 °C) provides an anti-freezing effect for most commercial coolants. The concentrated ethylene glycol therefore "freezes" at temperatures around –13 °C, although this freezing point can be reduced to some extent, by dilution with deionized water. This is can be explained by the strong hydrogen bonding with water molecules that prevents the formation of ice crystals. Corrosion protection can be achieved with various additives and determine the manufacturing technology. Their categorization by technologies [URL1]:

- IAT (Inorganic Acid Technology): In essence, this is the "traditional" technology. The coolants made with this technology are based on ethylene glycol with the addition of silicates and phosphates. Corrosion protection can be provided by the addition of inhibitors that form a protective layer on the surface that prevents rusting and the corrosion of copper, brass, cast iron and aluminum parts. While the protective film forms, the amount of the inhibitors continuously decreases until tehese finally dissipate from the liquid. Therefore, it is recommended to replace the coolant according to the manufacturer's recommendation, even though the antifreeze reliability is still adequate.
- OAT (Organic Acid Technology): Propylene glycol based silicate-free coolants provide the same metal wear protection as IAT coolants. Otherwise, propylene glycol based coolants are less toxic and safer for the environment, and provide longer protection than the ethylene glycol based ones and they are also free of borate, nitrite, nitrate, phosphate, silicate and amine chemicals. In this case, the corrosion protection is provided by neutralized salts prepared from organic acids and carboxylates. (Dex-Cool technology is also an OAT that is nitrite-, borate-, phosphate-, nitrate-, amine-, and silicate-free with the same metal wear protection as an IAT.)
- HOAT (Hybrid Organic Acid Technology): These coolants made with this hybrid additive technology, similar to IAT coolantsalso contain silicates (silicate-containing inhibitors (approximately 400-500 mg/litre)) complementing the protective effect of the salts of organic acids providing more durability and a longer service life to the aluminum, than the IAT coolants. It is free of nitrite, phosphate and amine chemicals.
- NOAT (Nitrited Organic Acid Technology): OAT type coolant containing nitrite.

- SHOAT (Silicate-Enhanced Hybrid Organic Acid Technology): Coolants made with silicate enriched and hybrid technology protect from freezing with a long service life of up to five years or one hundred thousand kilometres.
- SOAT (Silicate-Enhanced Organic Acid Technology): Coolants made with silicate enriched organic acid technology, protect from freezing with a long service life of up to five years or two hundred and fifty thousand kilometres.
- POAT (Phosphate Organic Acid Technology): Phosphate-containing, long service life coolants, which may have service life of seven years or four hundred thousand kilometres.

It should be noted, for these technologies, to decrease the unfavourable environmental impact, the use of propylene glycol based (non-toxic) coolants are preferred.

In regards to the freezing point rising above the desired value and the depletion of anti-corrosion additives make the changing of the engine coolant necessary. In addition to understanding the engine coolants' physical and chemical properties, the investigation of coolants in an electromagnetic field may also be of interest.According to our hypothesis, behavioural characteristics of the engine coolants' anti-freezing effect may be inferred from its dielectric parameters. As a precursor to these tests, it is necessary to recall some information relevant to the history of science and technology, which also provides an opportunity to place the research in a broader context. The range of the electromagnetic spectrum between frequencies of 300 MHz and 300 GHz is called microwave radiation. The principles were already established several decades prior. And the work of Michael Faraday (English physicist and chemist, 1791–1867) was decisive: he created the concept of the electromagnetic field. While the foundations of the electromagnetic theory were formulated by James Clark Maxwell (Scottish physicist, 1831–1879) in 1873 [Simonyi–Zombory 2000; Pozar 2012; URL2].

Microwave engineering is now a mature field of science. The effect of different media on the electric field can be described by a scalar quantity: the electrical permittivity or the absolute dielectric constant (ε [As/Vm]). The value of the electrical permittivity at any point in space can be determined as the product of the electrical permittivity of the vacuum ($\varepsilon_0 = 8.852 \cdot 10^{-12}$ [As/Vm]) and the relative permittivity of a material in comparison to a vacuum (dimensionless quantity, ε_r), according to the following equation (1):

$$\varepsilon = \varepsilon_0 \cdot \varepsilon_r \tag{1}$$

If we place the dielectricum (it is either a solid, a liquid or gaseous material, which functions as an electrical insulator (that is, its electrical resistivity is greater than 10^8 Ωm)), into a time-varying electromagnetic field, then two phenomena may be observed: on the one hand, the material becomes polarized due to the effect of the electromagnetic field. On the other hand, electrical conduction occurs. The polarization and conduction loss together are the dielectric loss. Complex permittivity depending on frequency, temperature, pressure and material quality has been introduced to quantitatively characterize these phenomena:

$$\varepsilon = \varepsilon' - \varepsilon'' \cdot j \tag{2}$$

The ε' is the real part of the complex permittivity shows the extent to which a given substance is able to store the energy of an electric field. While ε'' represents the imaginary part of the complex permittivity characterizes the extent of electrical energy converted to heat. The “j” is the imaginary unit [URL3], the negative sign before the imaginary unit accounts for the law of conservation of energy [Simonyi 2000].

As a confirmation for these theories, which are found in professional literature, in the first part of the research [Greznár–Kovács 2019] “pure” (previously not used for the cooling of internal combustion engines) ethylene glycol based engine coolants' (dilution according to the manufacturer's recommendations), considered as multicomponent materials, frequency-dependent and temperature-dependent dielectric behaviour were studied. After all, even today water – ethylene glycol type of mixture engine coolants are the most commonly used fluids in automotive cooling systems, however the heat transfer coefficient of such engine coolants is limited. Nevertheless, the rapid development of nanotechnology has led to the emergence of a “new” class of fluids. The application of nanofluids is promising, and may have better thermal conductivity than conventional coolants. Experimental results show that for example, silicon carbide (SiC) based homogeneous and stable nanofluids have better thermal conductivity and viscosity properties [Li et al. 2016] than that of traditional fluids. Although, both water and ethylene glycol can be used as coolants in engines, their heat transfer capacity is increased by the addition of nanoparticles. An alternative to improving thermophysical properties is therefore the production of nanofluids using metal oxides. Water and ethylene glycol based liquids – as base liquids – can also be mixed with CuO and Al_2O_3 nanoparticles. The results of the experiments, in regards to CuO, showed more effective heat transfer properties, in comparison to Al_2O_3 nanoparticles [Kimulu et al. 2018].

While the studies of the silicon-dioxide-lignin (SiO_2-L) particles’ (which dispersed in ethylene glycol with various weight fractions) dielectric properties showed, that even a small amount of SiO_2-L nanoparticle added to ethylene glycol, resulted a significant increase in permittivity. By dispersing the growing nanoparticle fraction in ethylene glycol, both the permittivity and conductivity increased in the test samples. It has also been confirmed that an increase in temperature also causes an increase in permittivity and conductivity, but the effect is less dominant than the effect of increasing mass fractions. [Żyła et al. 2018; Fal et al. 2019].

Based on the above, the objective of the research has been outlined: to shed light upon the joint effects of the different frequencies and temperature change by the tests of the dielectric behaviour of "conventional" coolants using different compositions and manufacturing technologies [URL4–URL8], in relation to the hypothesis already formulated above. Also, to provide a more complete source of information to users, beyond the already known physical and chemical parameters.

Furthermore, as an additional objective, determining the amount of electricity used during the operation of the measuring system is also included in the tests. Because the design of the experiments and measurements, conducted in a technical and engineering practice, in most cases it does not determine the energy consumption of the tests itself. Although, nowadays, almost without exception, we use such measuring systems, whose energy requirements are not negligible in terms of regular and continuous measurements.

2. MATERIAL AND METHOD

In materials which are placed into the electromagnetic field, some of the electromagnetic waves are either absorbed, pass through them or are reflected from their surface. With the help of the DAK-3.5 dielectric measuring system, installed in the Heat and Fluid Mechanics Laboratory at The University of Szeged (Faculty of Engineering), measurements can be performed between frequency of 200 MHz and 20 GHz. It has factory calibrations for various materials. As microwave radiation is used in industry, households and other areas of the economy, it is important to regulate the frequencies used in different technologies at an international level in order to avoid possible interference. The International Telecommunication Union has designated the ISM (Industrial, Science, Medical) frequency bands for industrial, research and medical electronic devices and applications. Electromagnetic radiation with a frequency of 915 ± 13 MHz can be used for higher power requirements and 2450 ± 50 MHz for lower power requirements [Jacob et al. 1995; URL9]. Accordingly, the results of the measurements conducted at 900 MHz and 2400 MHz can serve as a guide.

Dielectric parameters of tested materials can be calculated by knowing the reflection coefficient (Γ) of the signals reflected from the surface of the material (which will be discussed later), so the measurement is particularly sensitive to any condition that would change the phase, amplitude or even the reflected signals. The sensor of the measuring device is connected directly to a vector network analyzer (VNA – Vector Network Analyzer) via a coaxial cable, so the stability of the reflected signals is ensured. Calibration must be performed before starting of measurement, and in addition the probes must be cleaned of residues from the material before/after every measurement [DAK Professional Handbook 2016]. The tested materials are fluids: engine coolants with different compositions and two different manufacturing technologies (IAT and OAT) (Table 1) [Kovács et al. 2021]. Thus, to perform the measurement, the sensor, which receives signals reflected from the surface of the material, must be immersed in the liquids.

Table 1: Engine coolants main characteristics, based on [URL4–URL8]

Trade name (manufacturer)	Sample ID	Dilution rates (protection from freezing)	Manufacturing Technology
Glicosam Alu concentrated coolant (Semato Ltd.)	Glicosam Z	1:2 (–10 °C)	IAT
		1:1 (–20 °C)	
		3:2 (–28 °C)	
		2:1 (–33 °C)	
Prelix autoglycol antifreeze coolant (Medikémia Ltd.)	Prelix Z	1:2 (–10 °C)	IAT
		1:1 (–20 °C)	
		3:2 (–28 °C)	
		2:1 (–33 °C)	
SHERON antifreeze concentrate G11 (Sheron)	Sheron K	1:3 (–12 °C)	OAT Dex Cool
		1:2 (–18 °C)	
		1:1 (–36 °C)	
		1:0.8 (–46 °C)	
Prelix autoglykol antifreeze coolant concentrate (Medikémia Zrt.)	Prelix P	1:2 (–16 °C)	OAT
		1:1 (–35 °C)	
		3:2 (–40 °C)	
		2:1 (–46 °C)	
SHERON antifreeze concentrate G12++ (Sheron)	Sheron P	1:3 (–12 °C)	OAT
		1:2 (–18 °C)	
		1:1 (–36 °C)	
		1:0.8 (–46 °C)	

As a result of the measurements, the following "characteristics" (absolute and derived physical quantities) are available in order to point out the relationships between the composition, concentration (frost resistance) and production technology characteristics of the materials:

- ε – complex dielectric constant;

- ε′ – the real part of the complex permittivity;
- ε″ – the imaginary part of the complex permittivity;
- σ – conductivity;
- tgδ – dielectric loss factor (dissipation factor);
- Γ – reflection coefficient.

The dielectric properties were analysed in the case of a static medium (static measurements). Each coolant sample's measurement result is the average of 10 separate measurements' data points. These were used to graphically represent the measurement results.

3. RESULTS AND THEIR EVALUATION

During our research, we measured and investigated the dielectric parameters of the engine coolants from different manufacturers, made with different technologies, with different dilution ratios, looking for correlations between the characteristics and the properties of the engine coolants, with special regard to the anti-freezing effect (antifreeze capacity). Two of these measurement series were selected based on the following parameters. Regarding the engine cooling, the study of the imaginary part of the complex permittivity (ε″) per coolants, undoubtedly provides surplus information to understand, as accurately as possible, the behavioural characteristics of the coolant. However, it is difficult to evaluate, all together, the frequency dependence and temperature effects, at different dilution ratios, in relation to anti-freezing capacity, therefore two frequencies were selected 900 MHz and 2400 MHz. The recommendations, made by the International Telecommunication Union, already described in the 'Material and method' section, give reason to our choice. The measurement results at the average storage temperature of the coolants (20 °C) are shown between the test temperatures [based on the results of Kovács et al. 2021]. Thus, Figure 1, in accordance with the above mentioned, illustrates the connection between the anti-freezing effect (antifreeze capacity) and the imaginary part (ε″) of the complex permittivity at 900 MHz, in the case of the examined engine coolant samples. The diagram shows the existence and the strength of the relationship between the two variables for a given type of coolant. The size of bubbles indicates extent of anti-freezing capacity (t). Representation with functions proved to be suitable for characterizing the relationship and displaying trends. Our previous studies have confirmed that the relationship between anti-freezing effect (antifreeze capacity) and the imaginary part of the complex permittivity can be considered linear, and in the cases of the Glicosam Z, Prelix P and Prelix Z samples the imaginary part of the complex permittivity approaches zero (ε″⇒0), if the dilution ratios are lower. That is, for a more favourable anti-freezing effect (antifreeze capacity), the value of ε″ is one order of magnitude lower. The values of the samples of coolants made with IAT manufacturing technology (Glicosam Z and Prelix Z) show a similar trend, while the samples of coolants made with OAT manufacturing technology are also similar to each other.

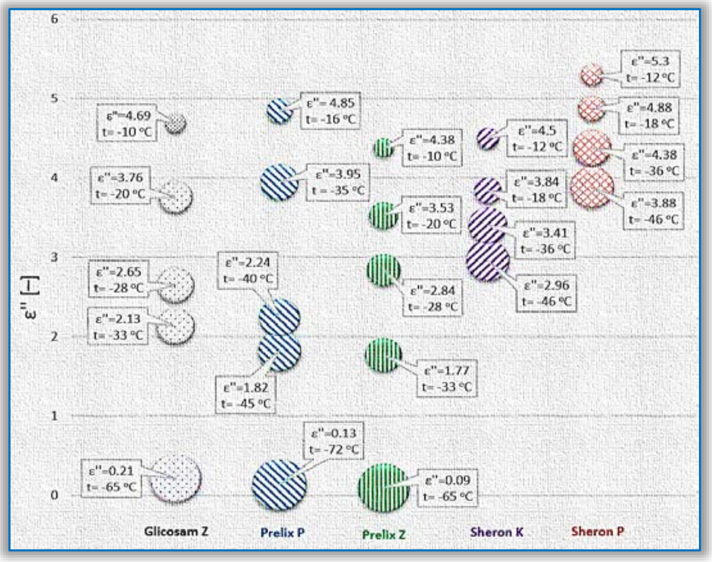

Figure 1: Relationship between anti-freezing effect (antifreeze capacity) and dielectric behaviour of different engine coolants at 900 MHz

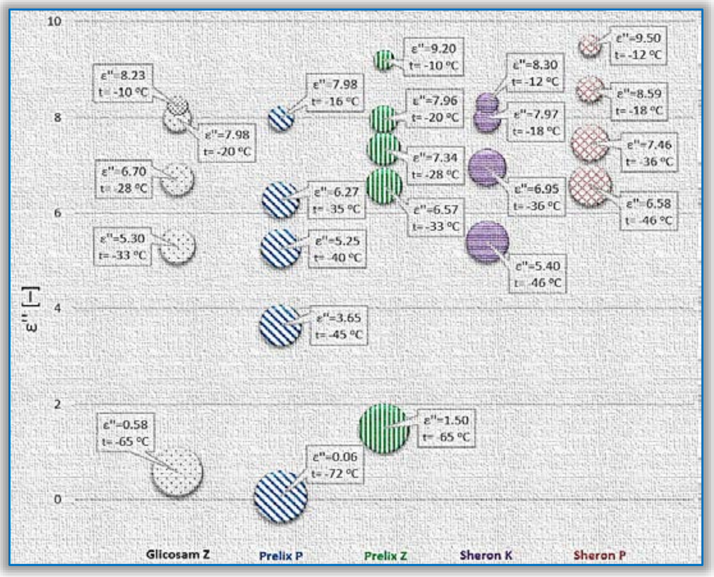

Figure 2: Relationship between anti-freezing effect (antifreeze capacity) and dielectric behaviour of different engine coolants at 2400 MHz

At the higher frequency in Figure 2, the trend of the results are better which has been confirmed by our previous studies. In the case of lower anti-freezing temperatures, in terms of the responses of ε", values above 9 also occur. This is an 80% increase compared to the results experienced at 900 MHz frequency, but not considered to be outstanding, considering that water (considered as a reference coolant in automotive engineering) has ε" is 8 (here, however, it should be noted that the temperature dependence is potent). Furthermore, the frost antifreeze capacity of the water is known, but of course, even the proximity of this state should be avoided at all costs, which means, that only the absolutely safe range may be accepted in regards to anti-freezing effect (antifreeze capacity).

However the range of ε" values "stretched" at this 2400 MHz frequency, it can be observed here as well, that both the values of the IAT samples and the values of the OAT samples show a similar trend, which can obviously be explained by the manufacturing technology characteristics.

In addition to the above written, the Vector Network Analyzer (VNA) used during the measurements determines the impedances, the reflection coefficient, the frequency-dependent values of the standing wave ratio and the analysis of other nonlinear characteristics based on the amplitude and phase information. In this way, the VNA can indicate any combination of transmission and reflection parameters (amplitude and phase), the impedance, the value of the standing wave ratio and the time domain relationships.

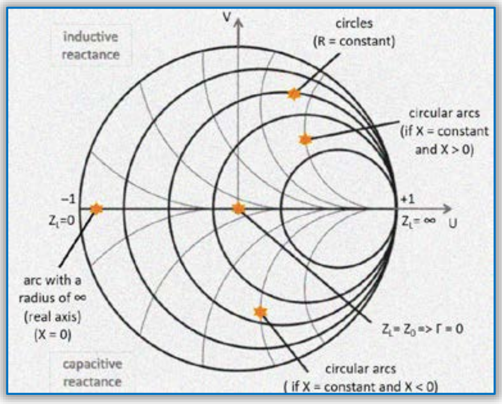

Figure 3: Simplified Smith diagram [Based on Дощич 2016 and Székely–Túrós 2020]

Given that the electromagnetic wave spreads from the source to the load (but may even be reflected). This can be characterized by a complex reflection coefficient. In addition to the illustration in a 'graphical nomogram', to help understand, the Smith diagram (Figure 3) may be used to illustrate this point. On the diagram the frequency-dependence of the load's impedance (Z_L) can be monitored, and also the $Z_L=\infty$ can be displayed. That is, on the Smith diagram on the graphical display of the measuring device [Дощич 2016; Székely–Túrós 2020] the changing values of the complex reflection coefficient (Γ) can (also) be tracked.

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0} = U + V \cdot j \tag{3}$$

The centre of the unit circle plotted in the coordinate system (U, V) is at Γ = 0, that is, at the $Z_L = Z_0$ value (when there is no reflection), given that the load (impedance value Z_L) is matched to the transmission line of the wave impedance with a value of Z_0. The reflection coefficient is actually plotted as a vector on the Smith chart, with values ranging from 0 (no reflection) to 1 (total reflection).

The periodic travelling wave and the reflected wave generate a standing wave, which is also impedance-dependent and can be characterized with the Standing Wave ratio (SWR) which can be determined with the following formula. Circles with a given standing wave ratio are located within the unit circle and are concentric with it (i.e., have the same centre). For the sake of clarity, this is not shown on the Smith diagram.

$$\mathrm{SWR} = \frac{1+|\Gamma|}{1-|\Gamma|} \tag{4}$$

However, in addition to the results and information that can be obtained with the various instrumental analytical tests, used with preference in technical and engineering practice, the energy component of the measurements is not a negligible aspect either. Not only should a series of measurements be designed technically, but also energetically. As tautology, the amount of energy depends on the performance of the instruments and equipment used during the measurements and sample preparation. As well as the time required for the given series of measurements and the time required to record/download/convert the measurement results.

Table 2: Energy requirements for dielectric measurements per series of measurements

Name of device / equipment	Energy characteristics	Time required	Amount of electricity used
DAK-3.5	P = 60.7 – 62.2 [W] cosφ = 0.55 [–]	~500 – 600 [s]	~ 30000 – 36000 [Ws]
DELL ProSupport	P = 29.3 – 37.3 [W] cosφ = 0.42 – 0.43 [–]	~ 500 – 600 [s]	~ 15000 – 20000 [Ws]
AREX heater (with magnetic stirrer)	P = 650 [W]	~ 100 – 300 [s]	~ 65000 – 195000 [Ws]
			Σ ~ 110000 – 251000 [Ws]

Regarding the energy profile of measurements, electricity demand developed statically and approximately as summarized in Table 2.

4. CONCLUSIONS

Dielectric test results of each engine coolant show that the values of the imaginary part of the complex permittivity (ε”) as a dielectric characteristic correlate with the anti-freezing effect (antifreeze capacity). A decrease in ε” values means an improvement in anti-freezing effect (antifreeze capacity). Namely, the higher dilution ratio for each sample was logically associated with a lower anti-freezing effect (antifreeze capacity) and the dielectric behaviour was characterized by higher ε” values. The measurement results tend to be similar at both 900 MHz and 2400 MHz. However, with increasing frequency, the range of the dielectric parameter ε” widened. The coolant samples showed a sudden increase in ε” with the higher dilution samples, regardless of frequency and technology.

The examined coolant samples show similar behaviour, however, the effect of the dilution ratio is clearly visible. It is justified to continue the research, specifically to analyse the effect of temperature steps for a given frequency in order to show the temperature dependence more accurately. That is, for a clear characterization of coolants' behaviour in an electromagnetic field, multidimensional analysis (examination based on the coexistence of several variables) leads to complex (it can be used both in scientific life and in practical life) results. According to Goldbach's conjecture, all physical examinations help to make fragmentary information coherent.

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