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ANALYSIS OF THE EFFECT OF SELECTED ADDITIVES OF AVIATION LUBRICANTS ON THEIR PERFORMANCE PROPERTIES

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Abstract

The article presents typical lubricants used in aviation and examples of operational problems resulting from, among other things, the introduction of lubricant replacements for old aviation technology or new additives to improve the lubricity of common aviation fuel. A selected aviation fuel additive (DCI-4A) was then analyzed and its effect on a selected engine was studied. FTIR spectrum analysis was also carried on the presence of water using the TN-699 oil as an example. In conclusion, conclusions and recommendation are presented – the implementation of new lubricants and additives requires, in each case, a series of laboratory and bench tests and monitoring of tribological processes in the operation of machinery and equipment.

Introduction

Friction is one of the resistances to motion that occurs when two bodies move relative to each other (external friction) or deform fragments of a given material (internal friction). During friction there is energy dissipation and heat release (LARSSON et al. 2021), which is consciously used in braking systems

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and friction welding, among others. Friction can also be a negative phenomenon, causing increased energy consumption in drive/power systems, changes in material microstructure or accelerated wearing of both machine and equipment components (BOBZIN et al. 2021).

The parameters and effects of external friction are derived from the value of the coefficient of friction – a dimension that depends on the (KARUPPASAMY et al. 2021):

– material and surface quality of the kinematic pair (friction node);

– quality of lubrication, including the correct choice of lubricant for the operating conditions of the machine;

– the technical condition of the lubricant, including viscosity level, cleanliness, and chemical degradation;

– the influence of external factors such as temperature and acceleration.

The purpose of a lubricant is to reduce the coefficient of friction and to dissipate heat with the wear products from the friction node (GOTI et al. 2023). The right lubrication reduces both the risk of accelerated machine degradation and failure, and the costs of unplanned repairs with downtimes. For this reason, is used for example the tribological diagnostics of machines and technological processes, which can be carried out in real time or periodic non-destructive testing based on certified laboratories and standards. In both cases, the selection of test methods, apparatus and methods for interpreting test results are based on modern measurement and analytical capabilities and the many years of experience of tribology – an interdisciplinary scientific field that includes (FESRI et al. 2024):

– tribological research – mechanics, mechanical engineering, chemistry and physics, surface engineering, materials engineering including lubricants;

– triboengineering – economics, law regulations, risk management, operational organization and working methodologies.

Reliability of tribological knowledge and research methods are key to (MILER et al. 2019):

– select appropriate lubrication and diagnostic criteria;

– ensure the required service life of the machine at the assumed exploitation costs;

– provide reliable monitoring and prediction of degradation of friction nodes.

The emergence of new materials of construction, lubricants, and additives, as well as new metrological and analytical capabilities, requires tribological knowledge to be supplemented.

The aim of this paper is to present selected operational problems for two major groups of lubricants (fuels and oils), considering the influence of additives and water. Incorrect selection of oil additives can accelerate the wear of parts working in the engine. When water is present in the fuel, it not only leads to corrosion, but also to the growth of both bacteria and fungi, the presence of which may change the composition of the fuel which significantly degrade its operational parameters (GÓMEZ-BOLIVAR et al. 2024). Therefore, it is so important to choose a suitable method to identify the change in fuel composition. For this reason, it will be proven the analysis of the FTIR spectrum for the detection of water in a selected aviation fuel (TN-699), which has not been fully tested for this aspect. Layout of the work:

– a brief characterization of lubricants used in military aviation technology and selected operational problems;

– research on the effect of DCI-4A additive in JP-8 fuel on the durability of diesel engine components;

– identification of the water content of synthetic oil containing polyol esters and other additives not shown by manufacturers in the product specification with the help of FTIR method;

– description of the research methods used and apparatus;

– presentation of selected results of laboratory and stand tests for the above-mentioned operational problems.

Materials

The requirements for the parameters that lubricating oils for gas turbine engines must achieve are defined by the SAE AS5780D standard. The performance limitations specified in the engine certificate are most often listed as brand names of specific oil formulations. Similarly, a conventional lubricating oil for SI reciprocating engines typically meets SAE J1899 or SAE J1966 with performance limitations listed as brand names of specific oil formulations. The acceptance of a particular oil for a turbine engine becomes binding if the engine manufacturer demonstrates that an oil with properties within the range of criteria in the specification is acceptable for adaptation in the engine in question according to the criteria described in the above three standards. Among the aviation fuels that have found application in turbine engines are JP-8 and Jet A-1 oils (NIDZGORSKA et al. 2023). There are also appearing oils that are used for aircraft engines of Eastern European production. Here in the world, a wide range is offered by the French company Turbonycoil, which has TN-699, as a replacement for Russian B-3V oil. More details of these oils are put in the Table 1.

Table 1

Details of selected oils used in NATO Air Forces

Name of oil	NATO Code	Standards	
		American	British
Jet A-1	F-35 (1978)	MIL-DTL-83133	DEF STAN 91-091
JP-8	F-34 (1990)		DEF STAN 91-87
TN-699	O-160 (1996)	MIL-PRF-23699G	DEF STAN 91-100

It is worth noting here that the additives in JP-8 fuel and in JET-A1 can neutralize each other or generate dangers. They can simultaneously change the effect of friction and, at the same time, have a very aggressive effect on the zinc coatings found on the fuel installations of old types of aircraft engines and on airport installations and military bases that have not undergone retrofit work to accommodate JP-8 fuel. Additives in JP-8 fuel can also act aggressively on some types of seals and gaskets. In addition, the level of aggression and danger increases in the presence of water in the fuel, because of the concentration of additives and increased surface tension. Examples of operational problems of lubricants can be found:

– during with NATO's accession of Central and Southern European countries, the new members had to change their aviation fuels to JP-8 for Soviet-made engines, which negatively affected this type of engines;

– Dissolution of elastomers during qualification testing of the helicopter SW-4. The central flexible fuel tank, air-certified for Jet A1 fuel, was detected dissolving in JP-8 fuel. The accompanying symptom was the blockage of the fuel filters and the spontaneous shutdown of the engine during the ground test;

– it was found mixing Jet A1 fuel with JP-8 (Jet A1 + additives), in the visually inspecting for being water in the EC-135 helicopter, what in result led to pronounced stratification of fuel. An example of the effect of water particles on TN-669 oil can be seen in Figure 1 (NIDZGORSKA et al. 2023);

– JP-8 fuel causes difficulties in diesel engines with low compression ratios (about 14:1 and below) during cold start and idling due to low compression temperatures and subsequent ignition delay. The cetane index is not specified in MIL-DTL-83133 to 40 or higher. Lubricity is not specified in MIL-DTL-83133 too, due to which modern common rail diesel engines may experience wear problems with high-pressure fuel pumps and injectors.

Fig. 1. TN-669 oil without water molecules (left) and containing water molecules (right)
Source: based on NIDZGORSKA et al. (2023).

Methods

The standard test method for evaluating new turbine fuels and aviation fuel additives is practice ASTMD4054-19. It covers and provides a framework for evaluating and the original equipment manufacturer (OEM) approval of new fuels and new fuel additives for use in commercial and military aviation gas turbine engines. The OEMs are solely responsible for approving the fuel or additive in their engines and airframes. Standards organizations and the USA military list only those fuels and additives that are mutually acceptable to all OEMs. ASTM International and OEM participation in the evaluation procedure does not constitute approval of the fuel or additive. Only after the OEM approval and industry review and vote can a fuel or fuel additive be listed in fuel specifications, such as British DEF STAN 91-091, American standards MIL-DTL-83133 (for aviation) and MIL-DTL-5624W (for the Navy). This OEM evaluation and approval process has been coordinated with airworthiness and certification groups within each company, the Federal Aviation Administration (FAA) and the European Aviation Safety Agency (EASA).

DCI-4A is an additive designed to both protect the fuel system from corrosion and reduce engine wear. It can be used in aviation gasoline, motor gasoline, jet fuel and other distillate fuels. It is widely used in fuel storage and distribution systems and in pipeline equipment protection. In aviation, it has been approved in MIL-DTL-5624W specifications as a corrosion inhibitor and under Stanag 2754 for JP-8 oil.

A research method used to analyze the condition of fuels and oils, as well as to study changes in their chemical composition, is the Fourier-transform infrared spectroscopy (FTIR) (LEKŠE et al. 2024). This method is very sensitive to molecular movements and reconstructions of the structural units that make up the local structure of water at different temperatures. This method allows the study of the behavior of molecules in their own environment. Therefore, it can be used to observe any structural changes in the object under study that can be clearly detected by transforming IR spectra (VASYLIEVA et al. 2018). In theory, the spectrum of liquid water absorbs at bands in the interval from 1,700 cm^{-1} to 1,400 cm^{-1} and from 3,800 cm^{-1} to 3,000 cm^{-1}. Absorption at about 1,650 cm^{-1} is due to bending of the H_2O molecule, and the 3,400 cm^{-1} band consists of symmetric stretching absorption at about 3350 cm^{-1} and asymmetric stretching absorption at about 2,500 cm^{-1}. Absorptions at higher wavelengths are due to linear combinations and multiples of fundamental vibrations. Absorption in the region from 3,800 cm^{-1} to 3,000 cm^{-1} is typical of OH group stretching vibrations, and its presence is the first indication that hydrogen and, by extension, water are present in the sample (SANGUINITO et al. 2020). The structural dynamics of water molecules can be studied by transforming the spectrum in the region of OH stretching vibrations, since the frequencies of these vibrations are in good correlation with the strength of hydrogen bonding (DOKTER et al. 2006, KYUEUN et al. 2019). All types of vibrations on water molecules in FTIR analysis are included in Figure 2.

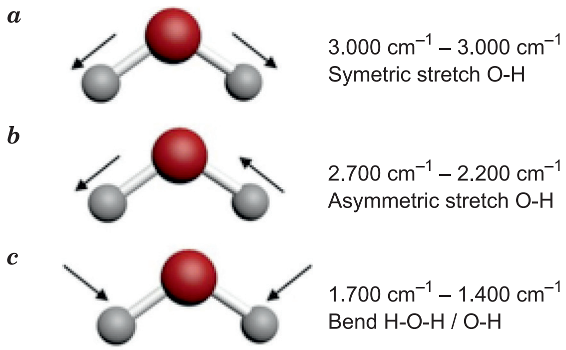

Fig. 2. Vibrations of a H_2O molecule during with the FTIR analysis:
a – symmetrical, *b* – asymmetrical, *c* – bending
Source: based on KYUEUN et al. (2019).

Standards describing the methodology of testing fuels and oils give freedom in the selection of additives in oils. On this basis, the laboratory testing a given sample in accordance with the above standards issues the results of the tests performed and its own opinion on the results. The final decision and responsibility in the matter of responding to the results performed and allowing the oil to be used belongs to the user.

FTIR spectrum analysis of TN-699 oil samples

It was used to analyze the FTIR spectrum the Thermo Scientific™ Nicolet iS 10 FTIR spectrometer extended with an autosampler (Fig. 3). The measurement range: from 4,000 cm^{-1} to 500 cm^{-1}. To operate the instrument itself was based on OMNIC Integra software. Both tests were carried out at approximately 23°C and in according with the defense standard NO-91-A258-1:2011.

To see what effect water content has on the FTIR spectral characteristics, FTIR spectral analysis was performed for the following TN-699 oil samples:

– without added water (TN699-0PPM);
– with the addition of 100 ppm of water (TN699-100PPM);
– with the addition of 200 ppm of water (TN699-200PPM);
– with the addition of 1,000 ppm of water (TN699-1000PPM).

Testing of TN-699 oil samples was carried out at a room temperature of about 23°C and in accordance with the standard ASTM D7066-4.

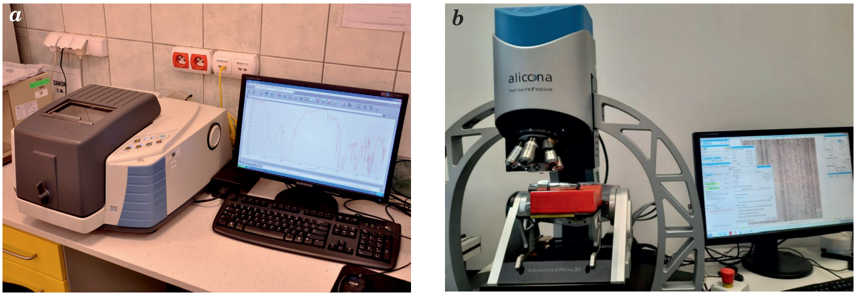

Fig. 3. Measuring equipment: *a* – Thermo Scientific™ Nicolet iS 10 FTIR spectrometer expanded with autosampler, *b* – the Alicona Infinite Focus G5 Plus scanner

Analysis of the impact of the DCI-4A additive

The experiments checked the effect of DCI-4A additive on the example of AVL engine – common rail (CR) type as a comparison of diesel, JP-8 oil, and JP-8 oil with DCI-4A additive. Details from the high-pressure pump were analyzed after a stall period of 600 hours using the Alicona Infinite Focus G5 Plus scanner (Fig. 3), with which the surface roughness of the shaft R_a and R_z will be examined after a stall period on the above-mentioned oils.

Results

The DCI-4A additive

The condition of the shaft from the high-pressure pump changed significantly after testing the DCI-4A additive to JP-8 oil after 300 hours of engine operation comparing with the same shaft after 300 hours of operation but using ordinary diesel fuel or JP-8 oil (Fig. 4). Based on this, graphs of the change in surface roughness of the shaft relative to the position on this shaft was developed using the Alicona Infinite Focus G5 Plus scanner (Fig. 5).

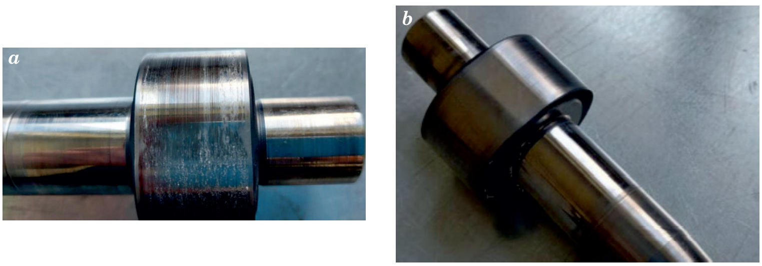

Fig. 4. Conditions of the shaft after 300 hours of operation using JP-8 oil with DCI-4A additive (*a*) and without DCI-4A additive (*b*)

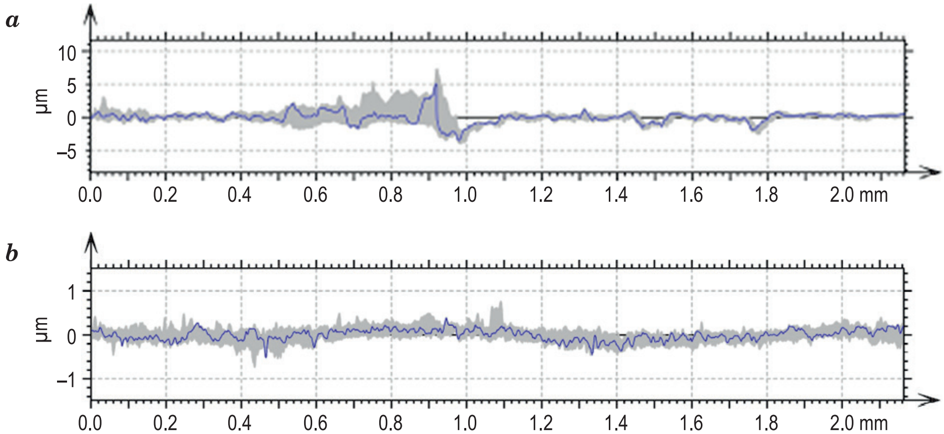

Fig. 5. Diagrams of the dependence of roughness versus position on the roller surface after 300 hours of operation using JP-8 oil: *a* – with the additive DCI-4A, *b* – without DCI-4A

Using the Alicona Infinite Focus G5 scanner, the roughness of the roller surface was examined after testing on all three oils tested. The results of the performed measurements are presented due to the tested roughness parameter when comparing all oils. The values of the R_a and R_z parameters of the shaft for the tested oils are included in Figure 6.

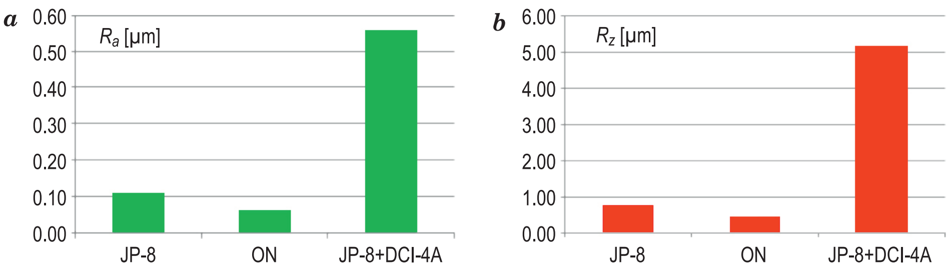

Fig. 6. Surface roughness values R_a (*a*) and R_z (*b*) of the roller after 300 hours of operation with the tested oils

FTIR spectrums for TN-699 oil samples

Analysis of the FTIR spectrum for TN-699 oil samples with different water contents is included in Figure 7. Only the spectral range from 3,100 cm^{-1} to 3,700 cm^{-1}, characteristic of radiation absorption by water molecules (both O-H bond vibrations and typical of hydrogen bonds), was considered. The spectral range from 1,500 cm^{-1} to 1,700 cm^{-1} was not considered, because in this range there are much smaller spectral deviations which makes this interval much more difficult to analyze.

In the spectrum contained in Figure 7 the apex of the spectrum for each sample at a bandwidth value of about 3,390 cm^{-1} can be easily identified, the above maximum signal values have been collected and based on them can be described by the relation contained in Figure 8.

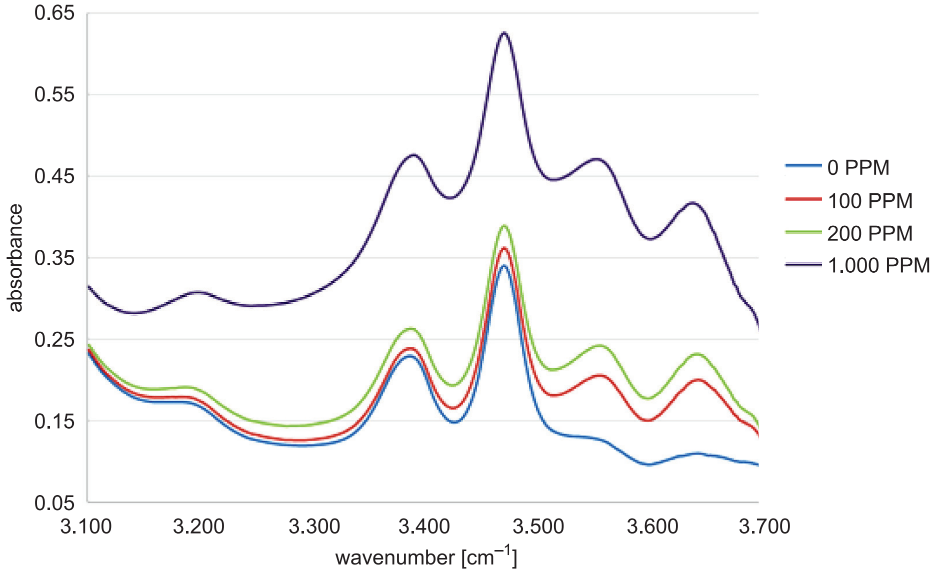

Fig. 7. FTIR spectrum for TN-699 oil samples in the range from 3,100 cm^{-1} to 3,700 cm^{-1}

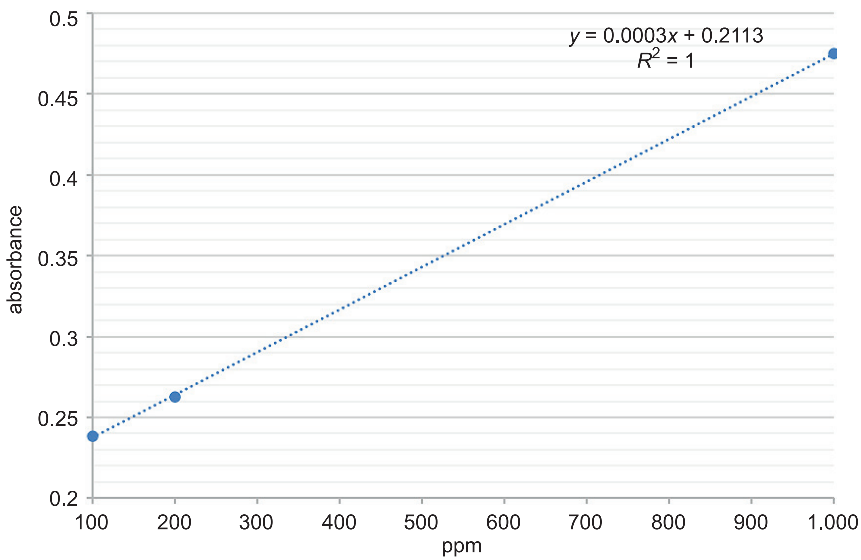

Fig. 8. Relationship of water content in TN-699 oil (using FTIR technique)

Discussion

The DCI-4A additive

The addition of DCI-4A in the amount indicated in the standard and manufacturer's specifications significantly worsened the lubricity of the CR engine kinematic pairs tested and accelerated their galling. The shafts show a more than fivefold increase in surface roughness after 300 hours of operation compared to their counterparts in which the DCI-4A additive does not appear. It is worth noting here that the DCI-4A oil additive adopts an EP (Extreme pressure) type character, which can be compared to chemical polishing of the metal surface. Additives of this type react with the roughness of the metallic workpiece above the high-energy threshold. They prevent the transfer of microchips on the surface and the formation of build-up on the "abrasive grain". It does not reflect the characteristics of Anti Wear type additives, which are characterized by the reduction of excessive abrasive wear between metal surfaces, as well as the formation of deformable reaction layers and improvement of the adhesion trace.

The producer of DCI-4A indicates that the above additive is a corrosion inhibitor and increases the lubricating properties of aircraft engine fuels. Meanwhile, there is an increase in surface roughness and an increase in surface abrasiveness, which is the opposite of what was originally intended. This is particularly evident on the surfaces of the shaft cooperation, where the graph illustrates a significant increase in the distribution of roughness (see Fig. 4). It is possible to get the impression here that the DCI-4A additive has begun to interact badly with the JP-8 base fuel additives, which were introduced in accordance with NATO requirements, resulting in a significant deterioration of the shafts instead of improving the lubricating properties of the oil.

It is also worth noting that the DCI-4A additive has a specific intended use for fuel tanks and its main purpose is to prevent leaks from storage tanks and pipelines, to prevent particulate fuel contamination, and to reduce to a minimum the risk of blockage of filters and screens by corrosion material. It follows that the oil does not perform well under classical operating conditions as a jet fuel additive, which is indicative of the not enough thorough research carried out in the past.

FTIR spectrums for TN-699 oil samples

The first significant absorption of the FTIR spectrum for TN-699 oil samples containing water appears in the band from 3,700 to 3,400 cm^{-1}, where signal maxima can be observed at 3,630 cm^{-1}, 3,550 cm^{-1} and 3,450 cm^{-1}. It may also be observed in this range that the intensity increases directly proportional to the water content of the sample. This result coincides with theoretical assumptions, since in this band there are typical stretching vibrations of the OH group, which is also found in the water molecule. As one looks at the graph of the FTIR spectrum of pure TN-669 oil, the maximum value of absorbance is located at a band of the order of 3,450 cm^{-1}, which increases in the test sample in direct proportion to the water content. The second significant peak of the FTIR spectrum graph appears at a band of the order of 1,630 cm^{-1}, and it is also higher if the water content of the test sample increases. This result also coincides with theoretical assumptions, i.e. the process of radiation absorption in ranges characteristic of water molecules is more intense when the amount of water molecules increases. It should also be noted here that the changes in absorption in samples containing water relative to the sample without water are very small, slightly exceeding the value of 0.3 with a sample containing 1,000 ppm of water while with a sample of 100 ppm the deviation is three times smaller. These are small deviations that can be relatively easily disturbed if light metals or alcohols are included in the oil composition.

By analyzing the peaks on the absorbance graphs of TN-669 oil samples due to water content, a graph can be drawn showing the dependence of absorption on the water content of the sample. Based on the samples in hand, this relationship can be described by the linear function $f(x) = 0.0003x + 0.2113$; where the variable x is the water content. This graph very nearly describes the relationship compared to the actual values of the samples with a relative error of a maximum of 7%. However, this characterization made from four samples with values of 0 ppm; 100 ppm; 200 ppm and 1,000 ppm of water seems questionable. A very likely scenario is that based on samples with values of 400 ppm; 700 ppm or even 1,200 ppm the relationship will not have linear characteristics which gives a great area for further research.

Conclusions

Various lubricants are used in aviation, based on petroleum products, mineral and synthetic oils, to which various additives are added, selected by the manufacturer of critical components considering their design features and expected operating conditions. Improper selection of the type and quantity of additives can:

– negatively change the physical and chemical parameters of lubricants;
– significantly deteriorate the lubrication of friction nodes;
– intensify corrosion processes in fuel, oil, or hydraulic systems;
– intensify chemical reactions with seals;
– shorten the life of the lubricant;
– increase the level of risk of failure or accident;
– increase operating costs.

To ensure the safe operation of machinery and equipment, it is advisable to monitor the quality of lubricants, both before they are applied to the facility and during periodic condition inspections.

Analysis of the FTIR spectrum provides the opportunity to analyze oils and lubricants for the presence of water. It is worth noting, however, that the amplitudes of vibrations at water content have small values, and at the same time the method itself is very sensitive to changes in the properties of the oil under study, which are affected by such factors as temperature or even the type and material of the plates on which the sample under analysis is placed. The tests are also problematic because in the composition of oils there are also O-H bonds from compounds other than water, such as traces of hydroxyl groups of alcohols, phenols or carboxylic acids, with an increase in the intensity of each band being more indicative of water. In addition, oil tends to become cloudy when exposed to water (see Fig. 1), which caused the intensity of the bands and baseline to increase by scattering, making it difficult to analyze aviation oils by FTIR.

It is also worth using aviation experience here, such as the implementation of new lubricants and additives for the operation of machinery and equipment in various industries should be verified by the user too.

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