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SENSING OIL CONDITION THROUGH TEMPERATURE COEFFICIENT OF DIELECTRIC CONSTANT

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Abstract – Time-scheduled oil changes in internal-combustion engines are often performed well before the oil starts to significantly lose its lubricating properties. A check of oil properties using laboratory analysis methods is expensive. Using the same techniques during service would be extremely difficult. Consequently, oil is seldom analyzed before substitution, which results in oil wasting. This paper shows that in the low frequency range, the temperature coefficient of the dielectric constant of lubricating oils depends on whether the oil is fresh or it has been used. Hence, the change in dielectric constant from ambient temperature to working temperature is a possible sensing method for engine oil condition.

Keywords: oil condition sensor, oil degradation sensor, oil quality sensor, dielectric constant, temperature coefficient.

1. INTRODUCTION

Oil is a common lubricant and coolant in different motor types. Motor manufacturers establish a schedule for oil change intended to achieve optimum motor performance and extend its lifetime. But, because actual oil performance is not checked during service, the schedule for oil change and refills is based on oil condition predictions derived from engine operation parameters [1]. Therefore, depending on the ambient and use conditions, oil is often changed well before its lubricating properties are severely reduced. This results in an economic cost for the owner and an environmental cost because of the disposal of waste oil.

Car manufacturers include oil condition sensors in some of their recent models. But, actually, these sensors are mostly based on the time elapsed from the last oil change or on traveled distance, sometimes combined with motor regime data. There are certainly oil condition sensors that rely on its physical parameters: electrical conductivity [2], electrical changes on trace materials embedded in oil [3], piezoelectric changes [4], and infrared radiation absorption. None of these sensors, however, has the needed prediction repeatability and low cost to achieve broad use.

Electrical properties of materials are simple to measure at low and medium frequencies, but they strongly depend on temperature. Because ambient temperature is well below the motor working temperature, which is not constant, some oil condition sensors based on measuring electrical properties simultaneously measure the temperature in order to correct the results. This paper shows that the change experienced by the dielectric constant of oil when its temperature increases, depends on the use of that oil, hence on its condition.

2. DIELECTRIC CONSTANT OF OIL

The complex dielectric constant, which consists of the dielectric constant and the conductivity or resistivity, is the vector relationship between a sinusoidal electrical voltage and the resulting current when applied to a dielectric material such as oil [5].

Some mechanical properties of lubricating oils consisting of nonpolar molecules are intrinsically related to the complex dielectric constant [5, pp. 18, 33]. Also, the dielectric constant of mineral oils depends far less on the temperature than its conductivity [5, pp. 158, 159, 365].

Colloidal ions usually insoluble, such as oxides, condensation products, and hydrocarbons, present in deteriorated oils, change the oil dielectric constant and conductivity [5, pp. 165]. Our aim is to show that the temperature coefficient of the dielectric constant is higher for deteriorated oil than for fresh oil.

3. MATERIALS AND METHOD

The dielectric constant of lubricating oil samples has been measured with an impedance analyzer (Agilent hp4294A), by placing them inside a Liquid Dielectric Constant cell (Agilent hp16452A) connected through an 1 m lead adapter (BNC-RG58-SMA). Figure 1 shows the measurement set up. The measurement cell forms a capacitor whose impedance depends on the dielectric constant of the oil and, of course, also on the distance between electrode plates. The cell has been emptied, disassembled, cleaned, and reassembled after each set of measurements at the four selected temperatures. To ensure that the distance between plates was the same after disassembling and reassembling, the four knobs that hold the plates in place are tighten by applying the same torque using a preset torque driver. The impedance analyzer was set in precise mode acquisition, and 100 Hz to 30 MHz frequency range (20 points per decade).

The measurement cell has been immersed in a water bath (not shown in Fig. 1), whose temperature was controlled by a heater and a thermostat. The temperature was programmed to 10 °C, 20 °C, 40 °C, and 60 °C. The uncertainty in the actual cell temperature was about ±3 °C. Care was paid to ensure that no water leaked into the measurement cell because that would ruin the capacitance measurements.

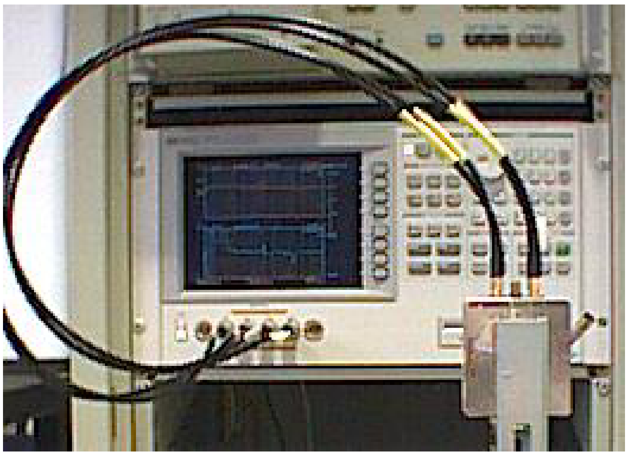

Fig. 1. Set up for the impedance analyzer (hp4294a) and cell (hp16452a) for liquid dielectric constant measurement.

We measured fresh Repsol Elite 15W40 lubricating oil and samples of the same oil obtained during a standard diesel motor endurance test. The first oil sample was obtained after 174 h of tests running, after which the oil was changed. The second sample was obtained after 174 additional hours, at which end the oil was changed again. The third sample was obtained after the last 191 h , which brought the motor close to the end of its expected life. Each test severely deteriorated the oil.

We first measured the fresh oil and successively measured oil used in later stages in the motor endurance test. At each temperature setting, the impedance analyzer performed a frequency sweep. By first measuring the cleaner oil we reduced the risk of dirty oil contaminating the cell.

4. RESULTS AND DISCUSSION

At ambient temperature (20 °C), the capacitance of the oil-filled cell is larger than the capacitance of the empty cell (C_0 = 35.5 pF). This is a consequence of the oil relative dielectric constant, which is about 2.5.

Figure 2 shows the dependence of capacitance on temperature for fresh and used oils at 100 Hz. Values between the four measured temperatures have been linearly interpolated. The capacitance of fresh oil, and hence its dielectric constant, remains practically constant up to 40 °C, and then slightly increases with temperature. Used oil always has a larger dielectric constant than fresh oil. Furthermore, its temperature coefficient is also larger than that for fresh oil. However, the temperature control was not accurate enough and the measured temperatures were so few that further tests are needed to confirm if oil used in a motor that has been running for a longer time always has a larger dielectric constant and a larger temperature coefficient than oil used in a motor that has been running for fewer hours.

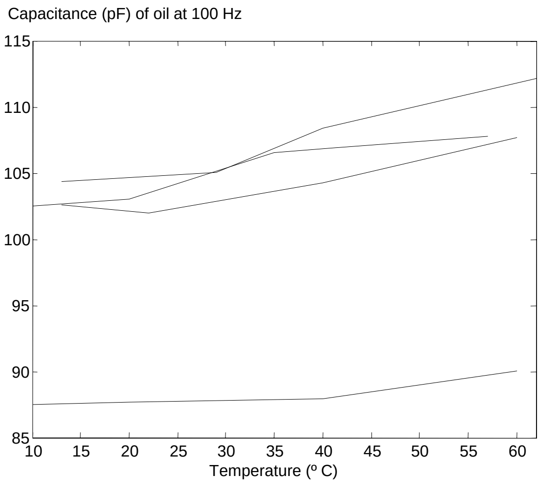

Fig. 2. Capacitance of fresh (solid line) and used Repsol Elite 15W40 oil versus temperature, at 100 Hz after:171 h (dashed line), 171 additional hours (dotted line), and 191 h more hours (dash-dotted line).

Figure 3 shows the dependence of capacitance on temperature for fresh and used oils at 1 MHz. The dielectric constant of fresh oil decreases for increasing temperature. The dielectric constant of used oil is higher than that of fresh oil and also decreases for increasing temperature. There is no definite relationship between the dielectric constant and the time the motor has been running.

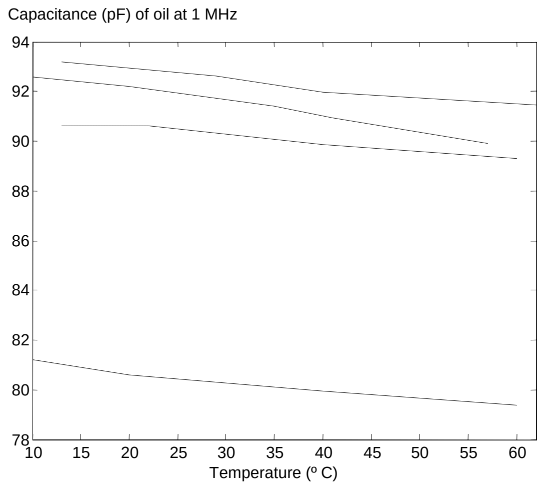

Fig. 3. Capacitance of fresh (solid line) and used Repsol Elite 15W40 oil versus temperature, at 1 MHz after:171 h (dashed line), 171 additional hours (dotted line), and 191 h more hours (dash-dotted line).

Measurements at intermediate frequencies between 100 Hz and 1 MHz displayed a behavior similar to that in figures 2 and 3. Depending on the oil sample, the average temperature coefficient for used oil ranged from 0.08 pF/°C to 0.16 pF/°C at 1 kHz. Measurements from 1 kHz to 10 kHz are convenient because at lower frequencies the cell impedance increases, thus reducing the current and, hence, the signal-to-noise ratio. At frequencies above 100 kHz, parasitic impedances become relevant and reduce the accuracy too.

By comparing figures 2 and 3 we find that at high frequency the dielectric constant and its temperature coefficient are smaller than at low frequency. In order to further investigate this frequency dependence, fig. 4 shows the cell capacitance versus frequency at 40 °C. The change in cell capacitance with frequency is larger than that observed in the 10 °C to 60 °C range measured at a given frequency. Again, that change is larger for used oil than for fresh oil. This suggests that interfacial effects are significant in oils, and become more significant in used oils, that can be contaminated carbon and metal particles resulting from motor combustion.

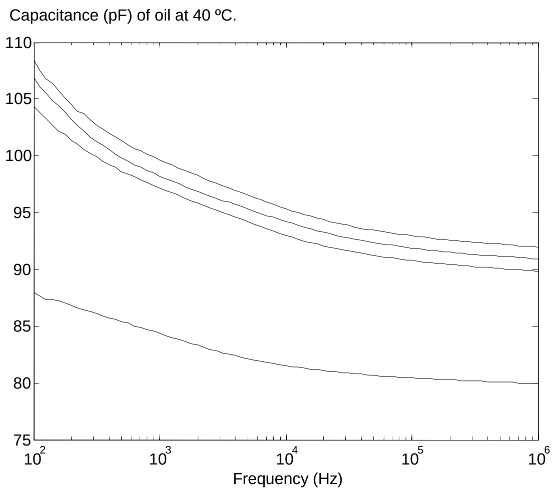

Fig. 4. Capacitance of fresh (solid line) and used Repsol Elite 15W40 oil versus frequency at 40 °C after:171 h (dashed line), 171 additional hours (dotted line), and 191 h more hours (dash-dotted line).

The actual temperature range in car engines is larger than the 10 °C to 60 °C range used here. Therefore, we should expect in practice larger capacitance changes for used oil. In fact, by introducing the cell in a climatic chamber (Climatest model CM4-25, serial number 404), operating in the range from –20 °C to 80 °C, we obtained, for fresh oil and the third used oil sample, the same qualitative behavior reported in figures 2 and 3.

These results agree with the predictions in [5, pp. 165], regardless of the mixing law considered for the mixture of oil and contaminant or degrading materials [6, 7]. Contaminated oil can have an increased viscosity depending on the contaminants. In any case, oil contaminants can reveal motor malfunctioning and excessive wear. Therefore, the temperature coefficient of oil can be applied in oil conditions sensors not only in cars but also in aircraft, locomotives, off-road vehicles, marine engines, power generators, and compressors.

5. CONCLUSIONS

The temperature coefficient of the dielectric constant of lubricating oils depends on whether the oil is fresh or it has been used. Repsol Elite 15W40 lubricating oil has a very small temperature coefficient before use and a large temperature coefficient after use in a diesel motor subjected to an endurance test. That temperature coefficient depends on the frequency. Its average value at 1 kHz is around 0.1 %/°C. This dependence can become the sensing principle for an oil condition sensor. Alternative oil condition sensor methods need a simultaneous temperature measurement in order to correct for the effect of the temperature on the measured parameters. Here, the temperature effect is the sensing basis instead.

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