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WHITE PAPER

TRANSFORMING OIL CONDITION MONITORING: HOW THE OPS3 SENSOR ENABLES SMARTER, PREDICTIVE MAINTENANCE

EXECUTIVE SUMMARY

Modern engines demand accurate, real time insight into lubricant condition to optimize maintenance intervals, reduce operating costs, and mitigate the risk of catastrophic failure. Traditional oil monitoring methods rely on periodic sampling and laboratory analysis, which are slow, costly, and ineffective at detecting rapid degradation or contamination events.

The **OPS3 Oil Property Sensor** from TE Connectivity enables continuous, in line monitoring of engine oil condition by simultaneously measuring viscosity, density, dielectric constant, electrical resistivity, and temperature. By combining multi parametric sensing with application specific algorithms, OPS3 supports predictive maintenance, remaining oil life estimation, and intelligent oil change optimization.

This white paper presents:

- The OPS3 measurement principle based on tuning fork resonator technology
- Engine oil physical and chemical fundamentals relevant to condition monitoring
- Detection capabilities for major oil aging and contamination mechanisms
- A structured oil condition algorithm (OCA) framework for practical deployment

While the concepts and models described are broadly applicable, final algorithm calibration must be tailored to the specific oil formulation and application environment.

INTRODUCTION

Engine and lubricant manufacturers typically specify oil change intervals in terms of time or operating hours. These conservative recommendations are designed to reduce failure risk but often lead to excessive oil changes, increased maintenance cost, and unnecessary waste.

Conventional laboratory based oil analysis provides detailed information but suffers from several limitations:

- Inability to detect rapid contamination or degradation events
- Delayed feedback due to sampling and logistics
- Increased operational and environmental costs

In contrast, on board oil condition monitoring using the OPS3 sensor enables continuous assessment of oil health, rapid fault detection, and environmentally responsible maintenance management.

OIL PROPERTY SENSING

A Oil Property Sensing

The **TE Connectivity OPS3 sensor** directly and simultaneously measures the viscosity, density, dielectric constant and temperature of non-conductive oil. Relying on tuning fork technology, the sensor monitors the direct and dynamic relationship between multiple physical properties to determine the quality, condition and contaminant loading of fluids such as engine oil, fuel, transmission and brake fluid, hydraulic and gear oils, refrigerants and solvents. The multi-parametric analysis capability improves fluid characterization algorithms. The OPS3 sensor provides in-line monitoring of fluids for a wide range of OEM and aftermarket installations including fluid reservoirs, process lines and pressurized high flow conduits (e.g., engine oil gallery) for applications that include on and off highway vehicles, HVAC/R, compressors, industrial equipment and turbines. We will focus principally on the engine oil application but most of analysis can be adapted or replicated for other applications.
We will also describe the advantages for oil monitoring of a new measurement of OPS3 sensor, the fluid resistivity.

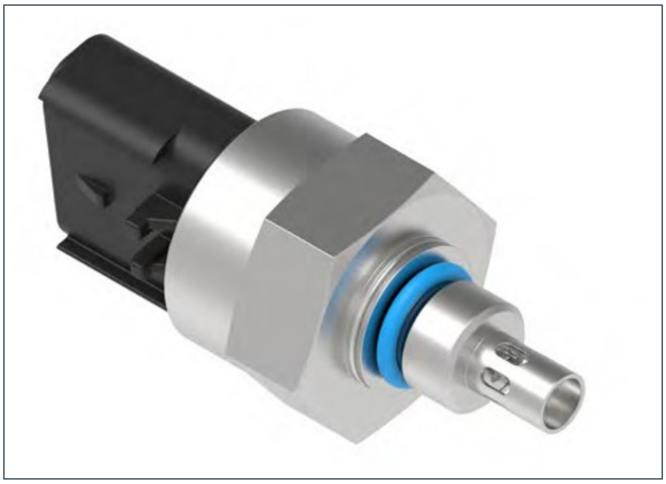

FIGURE.1.1: OPS3 OIL PROPERTY SENSOR

B Measurement Principle

OPS3 measurement is based on a tuning fork flexural resonator. This resonator is composed of quartz, a piezoelectric material capable of deformation upon application of a voltage and reciprocally electrically polarized under the action of mechanical stress. The two tines oscillate and generate a response indicative of the physicochemical and electrical properties of the fluid wherein the sensor is immersed [1,2,3].

FIGURE.1.2: TUNING FORK

A sinusoidal excitation voltage applied on thin tuning fork electrodes causes mechanical stress and periodic elastic deformation. This vibration produces a corresponding current through the electrodes. The ratio of the excitation voltage on the induced current allows measuring the impedance of the system which will be dependent on the excitation frequency, the elastic properties of the piezoelectric material and the properties of the fluid.
The quartz tuning fork impedance response in air has a sharp resonance at about 31 kHz. In a fluid, resonance frequency and amplitude are reduced due to the increased mass load and frictional forces on the system.

The calculation of fluid properties is allowed using a tuning fork equivalent electrical model.

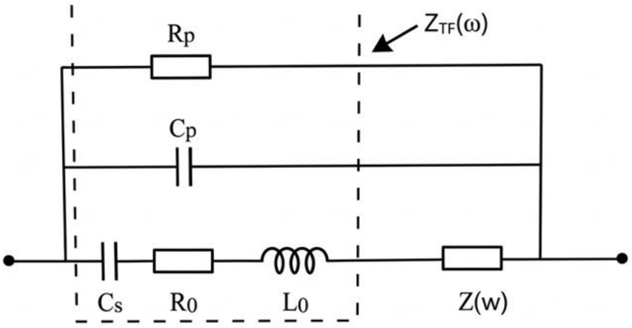

FIGURE.1.3: TUNING FORK EQUIVALENT ELECTRICAL MODEL

Tuning fork complex impedance in air is modeled by the following formula:

$$Z_{TF}(\omega)=R_P//C_P//(R_0+i\omega L_0+\frac{1}{i\omega C_s})$$

Serial capacitance Cs, resistance R0 and inductance L0 are only dependent on geometrical tuning fork parameters. Fluid impact is described by an additional term:

$$Z(\omega)=Ai\,\omega\rho+B\sqrt{\omega\rho\eta}(1+i)$$

where ω is the excitation frequency, η is the dynamic viscosity, ρ is the density, A and B are constants depending on resonator geometry.

The dielectric constant ϵ and the electrical resistivity P are measured thanks to parallel capacitance Cp and resistance Rp:

$$C_P(\varepsilon)=(\varepsilon-1)\frac{\partial C_P}{\partial \varepsilon}+C_{P,Vaccum} \qquad R_P(\mathrm{P}) = \mathrm{P}\frac{\partial(R_P)}{\partial \mathrm{P}}$$

After a necessary calibration step to calculate each parameter, the OPS3 sensor can measure dynamic viscosity, density, dielectric constant and Rp, an image of resistivity, of the unknown oil wherein it is immersed.

C Engine Oil

Engine oils are composed by paraffinic, naphthenic and aromatic hydrocarbons, mixed with different additives, and elaborated to fulfill several functions: lubrication, sealing, power transmission, engine parts cooling, cleaning and acid components neutralization.

Objective of lubrication is to reduce friction between sliding surfaces to minimize wear. Insufficient lubrication could lead to engine overheating, oil degradation acceleration and risks of engine failures. Sealing between cylinder and piston rings is necessary to avoid blow-by fuel contamination and nitrogen oxide contamination from the combustion gas. Sealing is also required between the valve and the valve steam guides to avoid unburned fuel reaching the oil. Power transmission helps ensure engine efficiency for tappet clearance and camshaft adjustments.

Proper lubrication, sealing and power transmission are ensured by appropriate oil viscosity.
Viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress. Dynamic viscosity can be defined considering a fluid trapped between a fixed plate and a second moving plate with a velocity u.

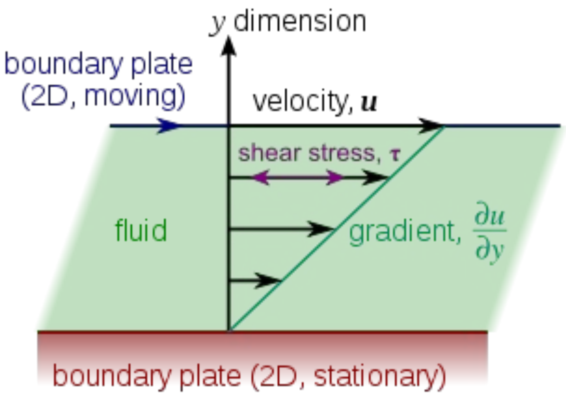

FIGURE.1.4: SHEAR STRESS OF FLUID BETWEEN TWO PLATES

Friction between each fluid layer of area A leads to a force F resisting to their relative motion.

$$F = \eta.A.\frac{\partial u}{\partial y}$$

Dynamic viscosity η represents the proportionality factor between F and the local shear velocity. Viscosity can be also expressed in other forms, the kinematic viscosity μ (cSt) which is the ratio of the dynamic viscosity η (cP) to the density ρ (gm/cc) of the fluid. Viscosity is deeply linked to fluid temperature.

Kinematic viscosity μ(T) can be modeled with the following expression (ASTM D341):

$$\log(\log(\mu + 0{,}7) = B - C.\log(T + 273{,}15)$$

where T is temperature in °C, log is base 10 log, and B and C are oil dependent constants.
Density ρ can be modeled in a simple linear form:

$$\rho = D + E.T$$

where D and E are oil dependent constants. Dynamic viscosity η(T) can be deduced from kinematic viscosity μ(T) and density ρ(T).
Base oils viscosity has naturally high temperature dependence, characterized by a low viscosity index (VI). To ensure efficient engine performance, oil viscosity should be sufficiently high at high temperature and not too thick at low temperature to provide easy engine start up. To increase VI, engine oils contain VI improver additives, composed of long–chained hydrocarbon polymers, tightly folded at low temperatures and unfolded at high temperature. Lubrication is also improved by antiwear additives which prevent friction of metallic surface during extreme operating conditions. Example of antiwear is Zinc dithiophosphate (ZDP).

Incorrect sealing could lead to functional deficiency or foam formation. Foam inhibitor additives with silicon compounds, prevent stable oil foam formation and improve air removal ability.

Oil cleaning is ensured by two types of additives: the dispersants and the detergents.

A dispersant is composed of a long nonpolar oleophilic tail and a polar head. The function of the dispersant is to maintain in suspension solid or liquid contamination particles in the oil and thus avoid any agglomeration that could lead to sludge formation. The two phenomena involved are peptization and solubilization (Moller and Nasser, 2002). Peptisation consists of wrapping solid oil contamination particles (diameter of 50-150 nm) like dust, soot and to keep them in suspension. Solubilization is the same mechanism but related to liquid contaminations like acids or condensates (inferior to 20nm).

A detergent is a colloidal metal-based additive (Klamann, 1982) and has a similar structure to the dispersant, but its tail is shorter, and the strength of its polar head is higher. The purpose of a detergent is to avoid or remove carbon, varnish or lacquer deposits and to neutralize acids created from combustion and from the oxidation and nitration processes. Indeed, contamination acids are dangerous because they can cause corrosion and increase oil degradation.

Engine oils provide an alkaline reserve to prevent acidification. The alkaline reserve can be measured by the Total Base Number (TBN) value. In the same way, acidity can be measured by the Total Acid Number (TAN). Ph value is not suited for measurement in oil because media is not aqueous. TAN and TBN measurement unit is mgKOH/g, which corresponds to the equivalent mass of potassium hydroxide required to neutralize one gram of solution. Neutralization is ensured using detergents. Some over-based detergents composed of calcium carbonate or magnesium carbonate achieve high level of protection against acidity. However, they could lead to ash formation that could be problematic for diesel particulate filter. The manufacturers tend to use relatively low ash engine oils, meaning lower TBN and alkaline reserve (Sappok and Wong, 2010), reducing chemical degradation resistance.

During oil aging, polar compounds and charge carriers' degradation products are created. In parallel, base additive compounds are depleted, decreasing protection against acidification. Electrical and chemical behaviors have a direct impact on oil dielectric constant ϵ and resistivity.

Dielectric constant ϵ or relative permittivity is the ratio of media permittivity on vacuum permittivity. Dielectric constant represents the capacity of the media to be polarized under the application of an electric field. Concretely, polarization is the consequence of the reorientation of molecular dipoles in the lubricant. During oil aging, dipole moments could change because of microscopic chemical reactions like oxidation or nitration or because of addition of polar contaminants like water (ϵ water=80) or soot. Sen et al (1992) has described and measured the dielectric constant of liquid alkanes. The study confirmed that dielectric ϵ has the following equation:

$$\varepsilon = F + G.T$$

where T is temperature in °C, F and G are oil dependent constants.

Indeed, dielectric constant ϵ could be linked with density ρ, using Clausius-Mossotti relation:

$$\frac{\varepsilon - 1}{\varepsilon + 2} = 4.\pi.\rho.Na.\frac{\alpha}{3.M}$$

where Na is Avogadro's number, α the molecular polarizability volume and M is the molar mass of the substance.

The resistivity P of a media measures the drag force encountered by free charge carriers moving through the medium under the application of an electric field. Oil resistivity is dependent on fluid viscosity, on density of free charge carriers and on specific oil chemical composition. In the first approximation, resistivity P can be modeled in a simple linear form:

$$\mathrm{P} = H + I.T$$

where T is temperature in °C, H and I are oil dependent constants.

OPS3 general measurement in temperature is presented on Fig.1.5. Two engine oil samples (15W40, new and 1000h aged) have been measured at standard engine oil application temperature range. Temperature homogeneity was maintained by mechanical stirring. The results demonstrate OPS3 capability to measure oil viscosity η, density ρ, dielectric ϵ and Rp an image of resistivity, for the entire application temperature range.

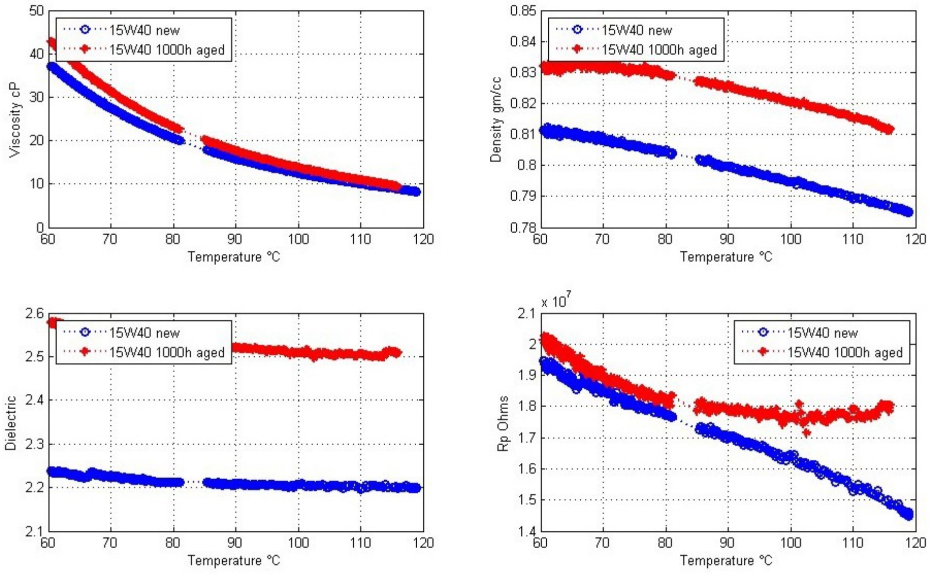

FIGURE.1.5: ENGINE OIL (15W40), NEW AND AGED MEASURED BY OPS3

Viscosity, density, and dielectric are increased during aging. Without any contamination, the increase of the three parameters can be considered normal behavior, even if we can also observe a viscosity decrease due to oil shear. The increase of resistivity at a high temperature is due to free charge carrier additives depletion. The gradients of variations will depend on oil type and application characteristics, such as temperature or contamination.

OIL AGING PROCESSES AND OPS3 SENSOR DETECTION CAPABILITIES

Throughout the lifespan of engine oil, it follows different degradation and contamination processes due to high temperature, exposition to chemically reactive combustion by-products and various contaminations. The following sections describe these processes and how each process is detectable by OPS3 sensor.

A OXIDATION

When exposed to high temperature, engine oil reacts with oxygen in the air. This reaction is called oxidation. Oil molecules chemically combine oxygen in the air to form carbonyl compounds products (C=O) such as aldehydes, ketones, esters and carboxylic acids in different concentrations. The process corresponds to two degradations: the evaporation of slight oil components and the oxygen element incorporation in oil components. This oxidation induces a polymerization of oil molecules and the formation of oil insoluble products that lead to an increase of viscosity. This oxidation induces also various formations and depletion of polar and conductive compounds that will impact oil dielectric constant and resistivity.

The oxidation process is accelerated by heat, light, metal catalysts like copper or iron and the presence of water, acids, or solid contaminants that could generate deposit formation. Oxidation is also favored by oil shear. Hydrocarbon compounds and polymer viscosity improver's additives break with shear, creating carboxylic acids, carbon active sites, which can be oxidized, and which will induce a new polymerization. Eventually oxidation is accelerated by biodiesel or ethanol due to their hygroscopic properties.

Oxidation is measured in laboratory using Fourier Transform Infrared (FTIR) spectroscopy method specified by standard test method ASTM D7418 or by ASTM D7214. The measurement is based on a quantification of the carbonyl function (C=O), corresponding to the 1700cm-1 frequency peak analysis on the absorbance spectrum. Oxidation measurement is expressed in A/cm.

Viscosity is highly increased during all oxidation processes. Resistivity is a very useful parameter because it can be directly linked to the four different phases of oil oxidation process.

During Phase 1, tested oil resistivity is increased up to 10% at 120°C. This phenomenon could be explained by the depletion of some free charge carriers' additives. Viscosity starts its continuous increase, and dielectric shows a very slight drop. Phase 1 corresponds to the predominance of a fast chemical process involving very reactive additives.

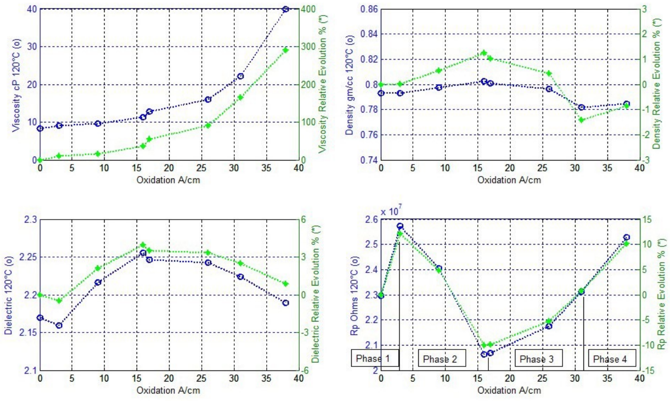

FIGURE.2.1: ENGINE OIL (15W40) OXIDATION MEASURED BY OPS3 AT 120°C

During Phase 2, tested oil resistivity decreased up to -10% at 120°C, relatively to initial value, and dielectric shows a significant increase. Phase 2 corresponds to a predominance of a slow chemical process that releases charge carriers and polar compounds.

During Phase 3, resistivity shows a new increase, linked to a new depletion of charge carriers, and dielectric is stabilized.

Phase 4 corresponds to the dramatic high viscosity increase before oil complete degradation and potential jelling.

Even if the density changes stay relatively slight, they could be linked to the four different oxidation phases.

The four different oil degradation phases and the corresponding viscosity and resistivity behaviors are described in the literature [4,5,6,7,8]. Temperature has relatively low impact on the four parameters oxidation behaviors, relative changes are similar for each temperature, except on resistivity. Phase 1 resistivity increase is amplified at high temperature and subdued at lower temperatures.

During Phase 1 and Phase 2, the level of degradation of the oil condition in phase 1 and phase 2 is low. Phase 3 corresponds to a consequent level of oil degradation. Entering Phase 3 is the appropriate timing to perform an oil change. During Phase 4, oil has already reached very high level of degradation. There is a high risk of dramatic engine failure. An oil change must be performed immediately.

The oxidation process depends on engine application characteristics and engine oil composition. OPS3 oxidation measurements of three different 15W40 engine oils are presented on Fig.2.2. The three engine oils have been stored at 150°C and regularly measured by OPS3 sensor until end of Phase 2 of oil oxidation. The results show different measurement gradients between the oils, but the general trends described above are confirmed.

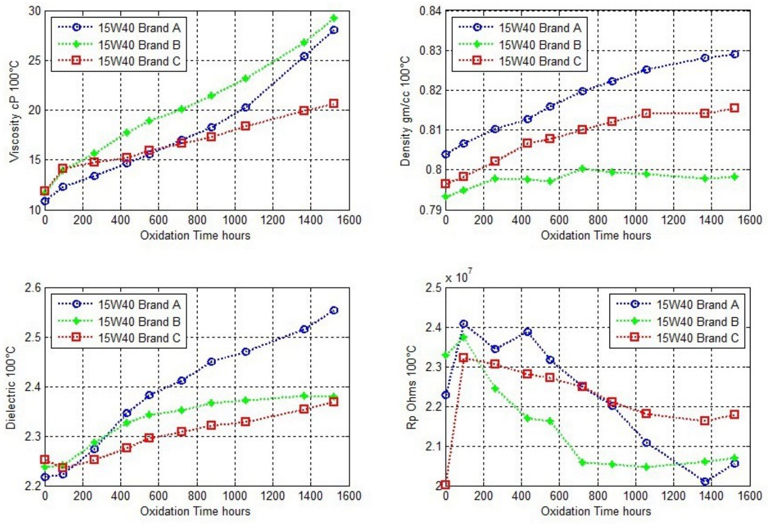

FIGURE.2.2: ENGINE OIL (15W40 BRAND A, B & C) OXIDATION MEASURED BY OPS3 AT 100°C

“Brand C” oil shows a consequent resistivity increase during Phase 1 and then relatively low increases of viscosity and dielectric during Phase 2. “Brand A” oil shows a lower resistivity increase during Phase 1 but much higher increases of viscosity and dielectric during Phase 2. These different gradients could be linked to the composition of additives. Indeed, the type and concentration of additives present in oil will favor or prevent different reactions involving oxidation and degradation products.

Since oxidation is dependent on oil composition and engine application characteristics, precise and complete oxidation modeling seems difficult. However, one can determine a typical physical change, focusing on Phase 1 and Phase 2. The solution consists of modeling Phase 1 and Phase 2 and detecting the entrance in Phase 3 linked to a consequent level of degradation. For example, 15W40 engine oil presented in Fig.2.1 could be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i.(1 + 21.10^{-3}.Ox.)$$

$$\rho_{th} = \rho_i.(1 + 0,5.10^{-3}.Ox.)$$

$$\varepsilon_{th} = \varepsilon_i.(1 + 1,5.10^{-3}.Ox.)$$

$$Rp_{th} = Rp_i.(1 - 12.10^{-3}.Ox.)$$

These models are plotted on Fig.2.3 with the related accuracy specifications in solid blue lines. The red circles represent the start of Phase 3 detection when:

$\eta \geq 1,05.\eta_{th}$ and $Rp \geq 1,05.Rp_{th}$.

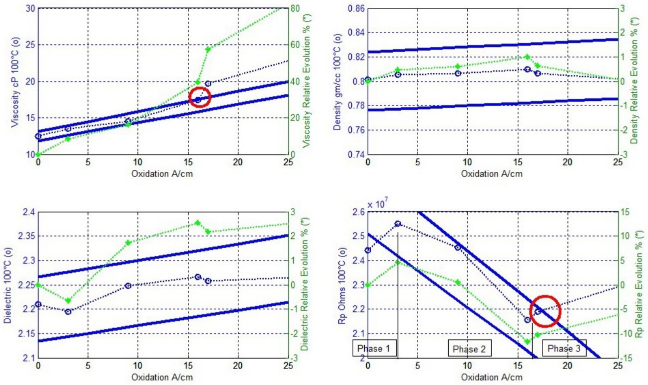

FIGURE.2.3: ENGINE OIL (15W40) OXIDATION MEASURED BY OPS3 AT 100°C

B WATER CONTAMINATION

Water contamination comes from fuel combustion processes or from exterior engine systems. Water in oil can be dangerous for the engine because it could induce excessive wear, for example by cavitation or corrosion. Water also promotes oil oxidation, acid by-products and sludge formation and thus poor engine reliability.

Water has three different states in oil: dissolved water, emulsion, and free water. Dissolved water is characterized by dispersed individual water molecules chemically linked to the oil. Above an amount called solubility, the excess water will saturate and will not be chemically linked to the oil. Free water is formed leading to a two-phase system. Because water density is higher than oil density, free water will typically accumulate at the bottom of oil pan. When mixing ratios are sufficiently high or under presence of surfactant additives, an emulsion can be formed. Emulsified water is homogeneously dispersed into the oil.

Typical water solubility and associated water states are presented in Fig.2.4.

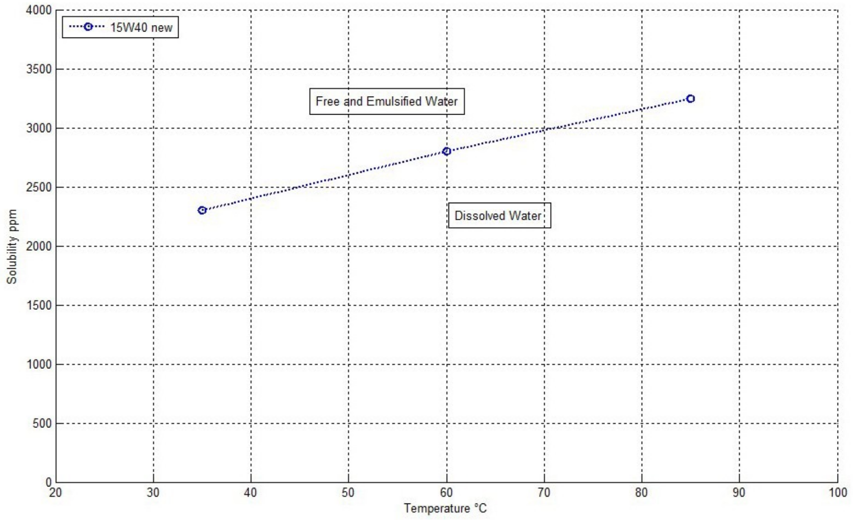

FIGURE.2.4: TYPICAL WATER SOLUBILITY IN ENGINE OIL AND ASSOCIATED WATER STATES

Solubility depends on temperature, oil additives, contamination, and oxidation [9]. Pure oils and hydraulic oils have low solubility. Typical engine oil solubility is about 2000ppm at 50°C.

The solubility of hydraulic oil, fresh and aged 15W40 engine oils, are presented in Fig.2.5.

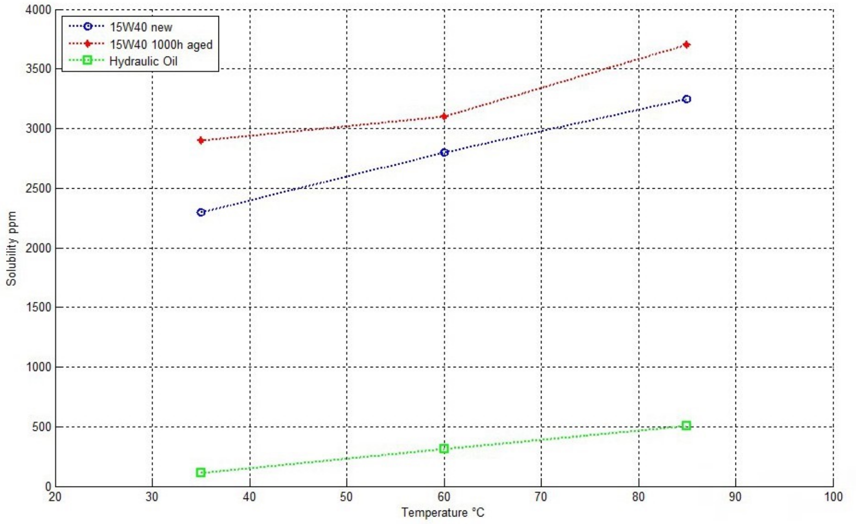

FIGURE.2.5: WATER SOLUBILITY IN HYDRAULIC AND ENGINE OIL MEASURED BY TE CONNECTIVITY WATER CONTENT SENSOR

Water in oil is typically measured in laboratory with Karl Fisher titration (ISO12937 or ASTM D1533). Karl Fisher measures total absolute water in ppm with high accuracy. However, this method is not totally appropriate with engine oil because measurement could be impacted by specific engine oil additives. Aquatest (ISO/DIS 9114 or ASTM D7358) and FTIR (ASTM D7418) are alternative methods to measure total absolute water from 100ppm with 100ppm accuracy. These three methods do not differentiate dissolved or free water. TE's water content sensor can measure water activity and then deduce solubility, independently of oil aging [19].

Water activity α Water can be defined by the following formula:

$$a_{Water} = \frac{[H_2 0]}{[H_2 0]_{Saturation}}$$

where 0< α Water <1, [H2O] is the concentration of dissolved water in oil (ppm) and [H2O]Saturation is the concentration of dissolved water in oil (ppm) at saturation point. TE's water content sensor [19] and its water activity measurement would be the relevant sensor solution to measure highest accuracy water content under saturation point.

The OPS3 water dilution measurement is presented on Fig.2.6. Engine oil (15W40) has been stabilized at 50°C and diluted with deionized water. Emulsion homogeneity was achieved by magnetic stirring. The results demonstrate OPS3's capability to detect and measure water contamination, mainly with dielectric and resistivity measurements.

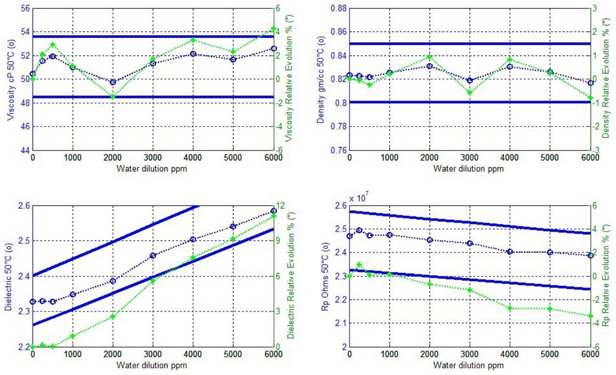

FIGURE.2.6: WATER DILUTION IN ENGINE OIL (15W40) MEASURED BY OPS3 AT 50°C

Viscosity and density do not show any changes. Dielectric is linearly increased, and resistivity is linearly decreased with water dilution. These noticeable changes have been described in the literature [3,6,10] and can be respectively explained by the high dielectric of water (εWater = 80) and the auto-ionization of water that can release free charge carriers, protons, into the oil.

OPS3 measures dissolved and emulsion water, which supports good compatibility with the application. Indeed, engine operation ensures emulsion by a high enough mixing ratio. When engine oil reaches high temperature, water may evaporate, so the detection must be performed before evaporation, preferably just after the engine starts up as the oil temperature increases.

Water in engine oil can be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i$$

$$\rho_{th} = \rho_i$$

$$\varepsilon_{th} = \varepsilon_i.(1 + 20.10^{-6}.WatDil_{(ppm)})$$

$$Rp_{th} = Rp_i.(1 - 6.10^{-6}.WatDil_{(ppm)})$$

These models are plotted on Fig.2.6 with the related accuracy specifications in solid blue lines.

C COOLANT CONTAMINATION

Engine coolant contamination comes from leakage from the engine cooling system. Coolant is composed of ethylene glycol or propylene glycol (40 to 60%), water (60 to 40%) and several additives in relative low concentrations (about 5%). Ethylene glycol and propylene glycol are miscible in water and in most organic solvents but are not miscible in oil. Common coolant additives include sodium silicate, disodium phosphate, sodium molybdate, sodium borate, and ensure the functions of lubricants, buffers and corrosion inhibitors. Coolant contamination in engine oil can be dangerous for the engine, resulting in several negative impacts. Low coolant contamination can cause heavy sludges deposits, acid compounds formation like glycolic or methanolic acids, and accelerate oil oxidation. High coolant contamination could lead to an emulsion or a gel [10] when mixed with the oil, and induces occlusions of walls and oil passageways, risks of filter blocking, reduction of oil flow and serious general decrease of lubrication efficiency.

Coolant in oil is typically measured in laboratory with FTIR (ASTM D7418) or ICP-AES spectrometry (ASTM D7151) mainly through quantification of the coolant additives elements Na, B and/or K within the oil.

OPS3 coolant (50%water) dilution measurement is presented on Fig.2.7. Engine oil (15W40) has been stabilized at 50°C and diluted with coolant. Emulsion homogeneity was achieved by magnetic stirring. The results demonstrate the OPS3 capability to detect and measure coolant contamination, mainly with dielectric and resistivity measurements.

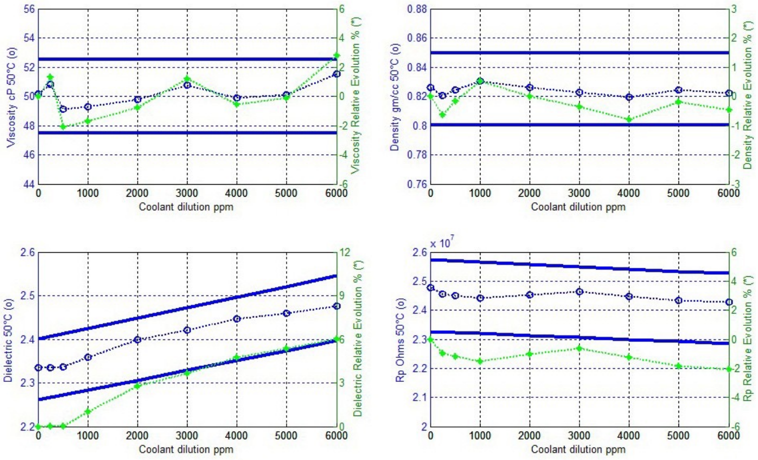

FIGURE.2.7: COOLANT DILUTION IN ENGINE OIL (15W40) MEASURED BY OPS3 AT 50°C

Viscosity and density do not show any changes. Dielectric is linearly increased, and resistivity is linearly decreased with coolant dilution. These results are fully coherent with water dilution results described in the previous section. Indeed, the tested coolant is composed of 50% water, and the dielectric and resistivity slopes are twice as low compared to the water dilution results. The changes can be respectively explained by the high dielectric of water (εWater = 80) and the auto-ionization of water that can release free charge carriers, protons, into the oil.

OPS3 measures dissolved and emulsion water coming from coolant blend, which demonstrates good compatibility with the application. Indeed, engine operation achieves emulsion by a high enough mixing ratio. When engine oil reaches high temperature, water may evaporate. Therefore, detection should be performed immediately after the engine start-up, before evaporation occurs and the oil temperature increases.

Coolant in engine oil can be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i$$

$$\rho_{th} = \rho_i$$

$$\varepsilon_{th} = \varepsilon_i.(1 + 10.10^{-6}.CoolDil_{(ppm)})$$

$$Rp_{th} = Rp_i.(1 - 3.10^{-6}.CoolDil_{(ppm)})$$

These models are plotted on Fig.2.7 with the related accuracy specifications in solid blue lines.

D FUEL CONTAMINATION

Fuel contamination within the engine is caused by imperfect fuel combustion and imperfect sealing. Unburned fuel reaches the crankcase through the space between piston and cylinder and between the piston groove and the ring. Fuel dilution can be enhanced in conditions during DPF regeneration process.

Internal combustion engines use fuels like diesel or gasoline which are mostly hydrocarbon compounds mixed with a variety of additives. Generally obtained by a specific fractional distillate of petroleum, they are nowadays increasingly blended with biofuels such as biodiesel and ethanol. Blended with petroleum diesel, biodiesel is a vegetable oil or animal fat-based fuel composed of long chain of alkyl esters. In the US, fuel standard ASTM D7467 specifies blends from B6 to B20, which corresponds to blends with 6% to 20% of biodiesel. In Europe, fuel standard EN 590 specifies blends up to B7. In gasoline fuels, ethanol is blended up to 10% (E10) in common markets and can be blended up to 85% (E85) in the flexible fuel vehicles applications (ASTM5798). In the future, the biofuel blending rates are expected to grow to fulfill environment protection rules.

Fuel physical properties can be modeled as for oil physical properties:

$$\log(\log(\mu + 0{,}7) = B - C.\log(T + 273{,}15)$$

$$\rho = D + E.T$$

$$\varepsilon = F + G.T$$

$$R_p = H + I.T$$

where T is temperature in °C; B, C, D, E, F, G, H and I are fuel dependent constants. Dynamic viscosity η(T) is deduced from kinematic viscosity μ(T) and density ρ(T).

OPS3 measurements of different fuels are presented on Fig.2.8. Fuel temperature homogeneity was achieved by magnetic stirring. The results demonstrate OPS3 capability to accurately measure fuel properties and allow robust fuel type differentiation.

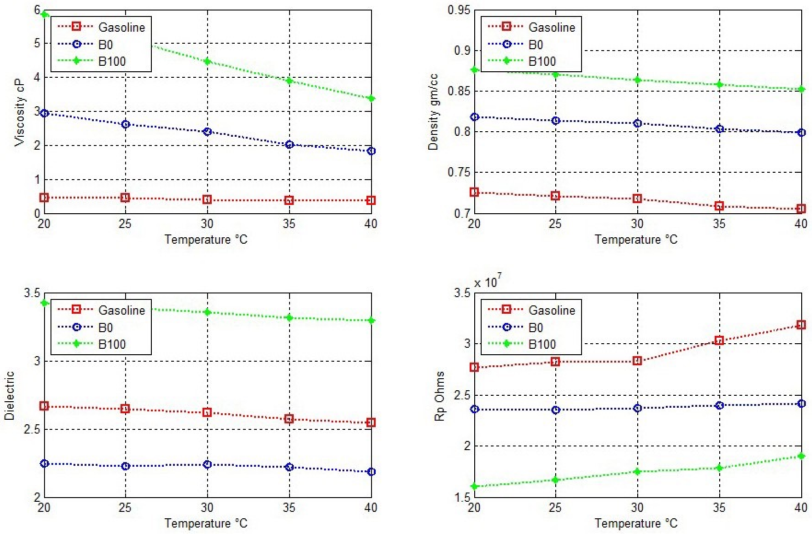

FIGURE.2.8: GASOLINE, DIESEL B0, RAPESEED B100 BIODIESEL MEASURED BY OPS3

B100 biodiesel has higher viscosity, density, and dielectric value than pure petroleum fuels. Gasoline shows a much lower viscosity than diesel fluids. Lower resistivity of biodiesel is explained by its hygroscopic characteristic. Fuel properties measurement allows fuel differentiation between gasoline, B0 and B100 but also with alternative fuels like kerosene or hydrotreated vegetable oil (HVO) [11]. More OPS3 measurements in fuels and high detection capability results are available in the literature [12]. TE Connectivity proposes also specific additional integrated algorithms to provide biodiesel concentration [20] or fuel differentiation [21].

Fuel contamination in engine oil can be dangerous for the engine because it could promote oil oxidation, acidic compounds, and soot formation. These degradations are even more increased with biofuels because of biodiesel or ethanol hygroscopic characteristics. Fuel dilution will also deteriorate oil lubrication properties and amplify risks of wear.

Fuel contamination in oil is typically estimated in laboratory with a method using flash point (ISO 2719) and viscosity measurements (ASTM D445) or with a more accurate and more expensive method using gas chromatography measurement.

OPS3 fuel dilution measurement is presented on Fig.2.9. Engine oil (15W40) has been stabilized at 100°C and diluted with diesel N°2 fuel. Blending temperature homogeneity was achieved by mechanical stirring. The results demonstrate OPS3 capability to detect and measure fuel contamination, mainly with viscosity measurement.

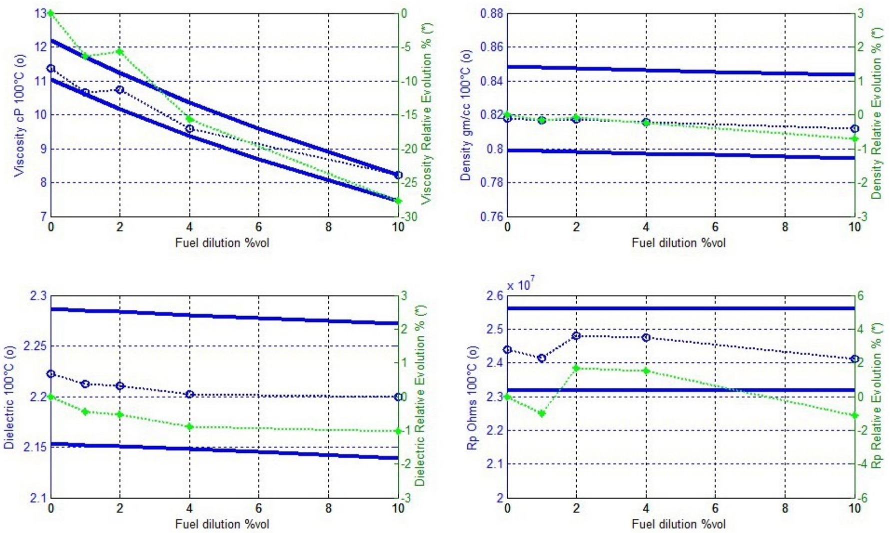

FIGURE.2.9: FUEL DILUTION IN ENGINE OIL (15W40) MEASURED BY OPS3 AT 100°C

Resistivity does not show any consequent change. Density and dielectric are linearly changed with fuel dilution. Slopes are dependent directly on density and dielectric of the two fluids (Yang et al, 2004) because they are miscible. The main change is measured with viscosity which is exponentially decreased with fuel dilution.

As engine oil and fuel are miscible fluids, the Refutas method (2000) can be used to calculate the theoretical kinematic viscosity µ of the blend. The method consists of determining a Viscosity Blending Number (VBN) for each component from their kinematic viscosity and then calculate the VBN of the blend at a fixed constant temperature [12]:

$$VBN_{Fuel} = 14{,}534 \,.\ln(\ln(\mu_{Fuel_{th}} + 0{,}8)) + 10{,}975$$

$$VBN_{Oil} = 14{,}534 \,.\ln(\ln(\mu_{Oil_{th}} + 0{,}8)) + 10{,}975$$

$$VBN_{Blend} = VBN_{Oil}.(1 - FuelDil_{(\%)}/100) + VBN_{Fuel}.FuelDil_{(\%)}/100)$$

The kinematic viscosity of the blend can then be estimated using the VBN of the blend using the following equation.

$$\mu_{Blend_{th}} = \exp(\exp(\frac{VBN_{Blend} - 10.975}{14.534})) - 0{,}8$$

Fuel contamination in engine oil can be modeled with the following equations, at constant temperature:

These models are plotted on Fig.2.9 with the related accuracy specifications in solid blue lines.

$$\eta_{Blend_{th}} = \mu_{Blend_{th}}.\rho_{Blend_{th}}$$

$$\rho_{Blend_{th}} = \rho_{Oil_t}.(1 - FuelDil_{(\%)}/100) + \rho_{Fuel_t}.FuelDil_{(\%)}/100$$

$$\varepsilon_{Blend_{th}} = \varepsilon_{Oil_t}.(1 - FuelDil_{(\%)}/100) + \varepsilon_{Fuel_t}.FuelDil_{(\%)}/100$$

$$Rp_{Blend_{th}} = Rp_{Oil_t}.(1 - FuelDil_{(\%)}/100) + Rp_{Fuel_t}.FuelDil_{(\%)}/100$$

E SOOT CONTAMINATION

Soot is composed of impure carbon particles resulting from incomplete fuel combustion.
Soot contamination in engine oil can be dangerous for the engine because soot loaded oil can cause deposits inducing further engine problems (Moller and Nassar, 2002). Soot particles can be abrasive and increase engine wear (Sato et al, 1999). Dispersant additives can manage a certain level of soot in the oil, but they cannot avoid increased viscosity with excessive soot contamination.

Soot contamination can be measured in laboratory with FTIR (ASTM D7418). Soot contamination is expressed in %. **OPS3** soot contamination measurement is presented on Fig.2.10. Engine oil (15W40) has been stabilized at 100°C and contaminated with standard diesel particulate matter (NIST2975). Oil homogeneity was achieved by magnetic stirring. The results demonstrate OPS3 capability to detect and measure soot contamination, mainly with viscosity and dielectric measurements.

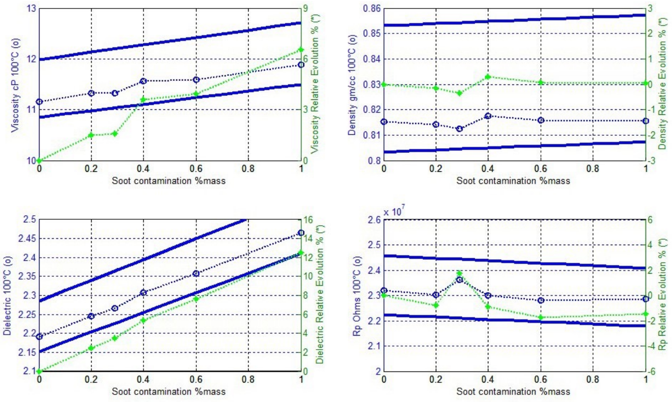

FIGURE.2.10: SOOT CONTAMINATION IN ENGINE OIL (15W40) MEASURED BY OPS3 AT 100°C

Viscosity and dielectric are high and linearly increased with soot contamination. Soot may induce slight density increase and slight resistivity decrease. These noticeable changes have been described in the literature [13] and can be respectively explained by the shape, the high polarizability and the charge characteristics of soot particles.

Soot contamination in engine oil can be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i.(1+6.10^{-2}.SootCont_{(\%mass)})$$

$$\rho_{th} = \rho_i.(1+0{,}5.10^{-2}.SootCont_{(\%mass)})$$

$$\varepsilon_{th} = \varepsilon_i.(1+12.10^{-2}.SootCont_{(\%mass)})$$

$$Rp_{th} = Rp_i.(1-2.10^{-2}.SootCont_{(\%mass)})$$

These models are plotted on Fig.2.10 with the related accuracy specifications in solid blue lines.

F METAL CONTAMINATION

Metal contamination comes from wear induced by bad lubrication and corrosion. Main metals to be monitored are Fe or Cu or Al, which are components of main engine parts.

Metal contamination is dangerous for the application because it could accelerate oil degradation. Metal contamination is above all, a sign of abnormal wear.

Metal contamination can be measured in laboratory with ICP spectrometric analysis (NFT 60 106). Metal contamination is expressed in mg/kg equivalent to ppm mass.

OPS3 iron (Fe) contamination measurement is presented on Fig.2.11. Engine oil (15W40) has been stabilized at 100°C and contaminated with <10µm Fe particles up to 10^5 ppm in mass. Oil homogeneity was achieved by magnetic stirring. The results demonstrate OPS3 capability to detect and measure extreme high levels of Fe contamination, with viscosity, density, and dielectric measurements.

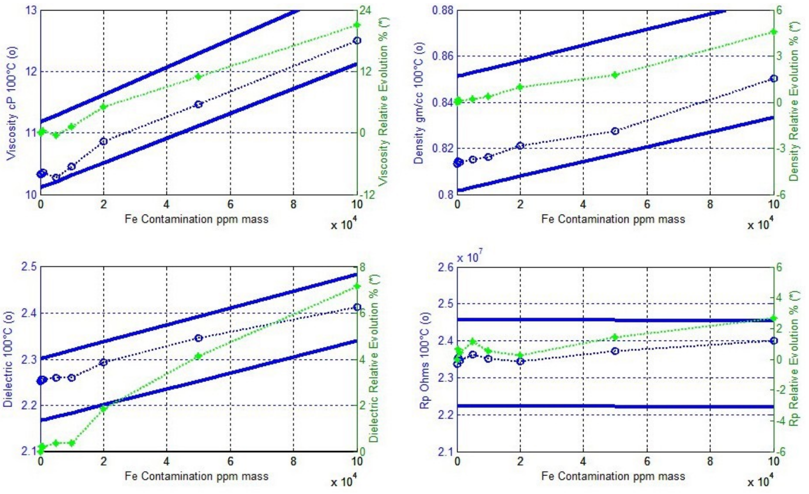

FIGURE.2.11: FE CONTAMINATION IN ENGINE OIL (15W40) MEASURED BY OPS3 AT 100°C

Viscosity, density, and dielectric are high and linearly increased with Fe contamination. Fe contamination also induces slight decreases in resistivity. These noticeable changes can be explained by the shape, the high polarizability, and charge characteristics of metal particles.

Fe contamination in engine oil can be modeled with the following equations, at constant temperature:

$$\eta_{th} = \eta_i.(1+2.10^{-6}.FeCont_{(ppm.mass)})$$

$$\rho_{th} = \rho_i.(1+0{,}4.10^{-6}.FeCont_{(ppm.mass)})$$

$$\varepsilon_{th} = \varepsilon_i.(1+0{,}8.10^{-6}.FeCont_{(ppm.mass)})$$

$$Rp_{th} = Rp_i.(1-0{,}1.10^{-7}.FeCont_{(ppm.mass)})$$

These models are plotted on Fig.2.11 with the related accuracy specifications in solid blue lines.

Similar results can be obtained with copper Cu or alternative metal contamination.

G TBN, TAN AND AGING

Regular punctual TBN and TAN measurement in reference laboratories is a method widely used to monitor oil condition externally. Aging and contamination processes induce creation of different acid compounds until complete oil degradation. These acid compounds accelerate oil degradation thanks to different chemical reactions. For example, metal contamination can be increased by corrosion produced by the acid compounds. To counter acid compounds creation and delay oil degradation, alkaline reserve is added in oil chemical composition.

Thus, fresh oil has high TBN value, typically from TBN=8 to TBN=14, and low TAN value, typically from TAN=1 to TAN =4. Then, during oil life, due to acid compounds creation, TBN is continuously decreased while TAN is continuously increased. When alkaline species are completely depleted, acid compounds are dramatically increased, and general oil degradation is highly accelerated until complete deterioration and jelling. Depending on oil composition and application characteristics, limits on TBN and TAN values could be considered to optimize oil changes. For example, some manufacturers could recommend performing an oil change when TBN=TAN, decreases the risks of dramatic oil degradation, and induced engine failure.

Typical TBN and TAN dynamic behavior is presented on Fig.2.12. TBN and TAN measurements are plotted in function of oxidation. Engine oil (15W40) has been stored at 150°C for 3000 hours and regularly sampled and analyzed until complete degradation. TBN and TAN have been measured by an external reference laboratory. The oil samples correspond to the same samples of the oxidation data presented on Fig.2.1.

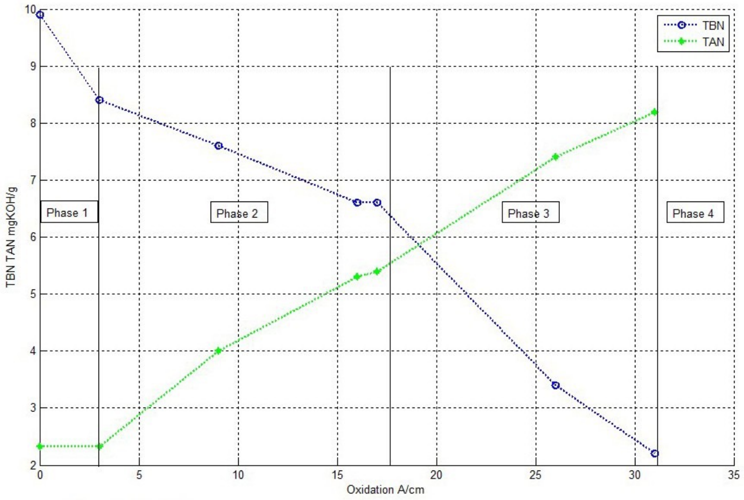

FIGURE.2.12: ENGINE OIL (15W40) TBN & TAN MEASURED BY REFERENCE LABORATORY

The results show a TBN continuous decrease and a TAN continuous increase with oxidation. The same four different phases of oil degradation described in Fig.2.1 can also be considered. During Phase 1 and Phase 2, TBN value is superior to TAN value. From the end of Phase 2, TAN value reaches TBN value and becomes superior to TBN value for the following degradation phases. TBN and TAN measurements corresponding to 38A/cm sample from Fig.2.1 were not performed because of the too high degree of oil degradation, oil was indeed completely jelled.

The correlation between absolute value of difference |TBN-TAN| and resistivity measurement is presented on Fig.2.13. The results demonstrate OPS3 capability to measure an image of TBN and TAN values thanks to resistivity measurement.

As described on Fig.2.1, resistivity is increased during Phase 1. This Phase 1 is relatively short, and the level of increase will depend on oil chemical composition and application characteristics. Then resistivity is decreased during Phase 2 until a minimum and increased again during Phase 3. |TBN-TAN| has a similar behavior, starting from a high value, because fresh oil has alkaline reserve and low acid concentration, being decreased during Phase 2 until a minimum, and then increased during Phase 3, due to acid compound creation and alkaline species neutralization. A clear correlation (R^2=0,83) is demonstrated between resistivity and |TBN-TAN|. Similar correlation has been described in the literature [17, 18].

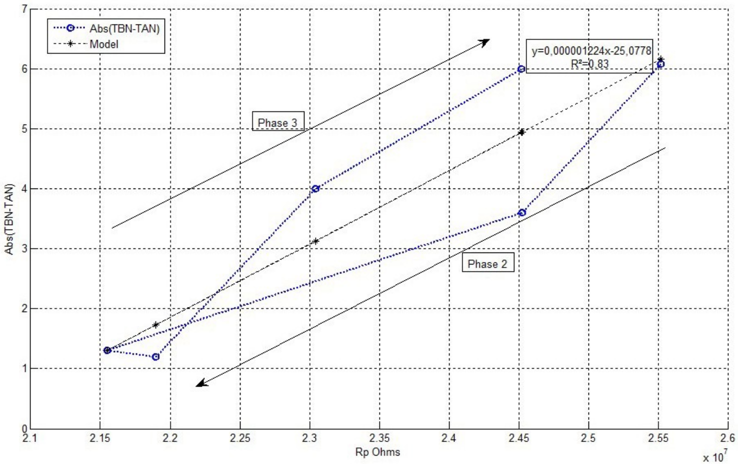

FIGURE.2.13: CORRELATION BETWEEN ABS(TBN-TAN) & OPS3 RP MEASUREMENT AT 100°C

|TBN-TAN| can be modeled with the following equation, at constant temperature:

$$\left|TBN - TAN\right| = 1{,}224.10^{-6}.R_p + 25{,}07$$

Punctual resistivity measurement will not allow a precise direct measurement of TBN and TAN values. However, resistivity monitoring will allow a prediction of |TBN-TAN| and detections of Phase 2

(when $\frac{\partial Rp}{\partial t} < 0$; TBN>TAN)

and Phase 3

(when $\frac{\partial Rp}{\partial t} > 0$; TAN>TBN)

As stated previously, Phase 3 corresponds to a consequent level of oil degradation. Entering Phase 3 is the appropriate timing to perform oil change.

H INCORRECT FLUID DETECTION

Filling fluid incorrectly could be dangerous for the engine. Indeed, engines are designed to operate with determined oil characteristics. Incorrect oil or fluid filling may degrade engine performance and could induce risks of failure.

OPS3 measurements in four different oils are presented on Fig.2.14, three engine oils 0W40, 10W30 and 15W40 and one bio ISO32 hydraulic oil. Each oil sample has been stabilized and tested at different temperatures from 50°C to 120°C. The results demonstrate OPS3 capability to detect any eventual wrong fluid, with viscosity, density, dielectric and resistivity measurements.

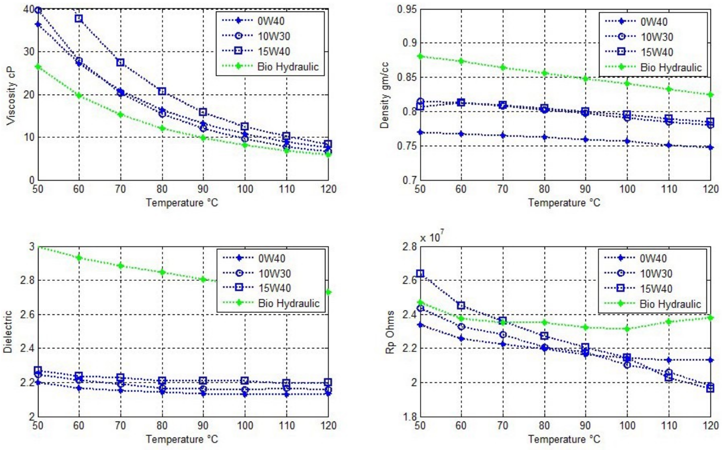

FIGURE.2.14: 0W40, 10W30, 15W40 OILS & BIO HYDRAULIC OIL MEASURED BY OPS3

OPS3 is capable of differentiating any type of engine oil or hydraulic oil with viscosity measurement. The viscosity of each sample is clearly identified, fitting with viscosity grade standard SAE J300: 15W40 has the higher viscosity; 0W40 has lower viscosity than the other engine oils at low temperature and has similar viscosity of 15W40 oil at high temperature; 10W30 has lower viscosity at high temperature than the two other engine oils. ISO32 hydraulic oil has lower viscosity than the three engine oils. Density depends on oil composition and cannot be predicted by SAE J300 grade. OPS3 clearly differentiates the oils by density. The three tested engine oils have similar dielectric ε =2,2 at 100°C, that can easily be differentiated from the tested. Bio hydraulic oil with ε =2,7 at 100°C although ISO32 hydraulic oils typically have dielectric between ε =2 and ε =2,4. Some differences between the fluids can also be observed on resistivity values.

Incorrect fluid detection could be possible, modeling the desired fluid for the considered application, and fixing some thresholds for each physical parameter. The thresholds levels will depend on the application and the different wrong fluid susceptible to being encountered.

I SYNTHESIS

The different oil contaminations and aging phenomena impacts on the four physical OPS3 sensor measurements are synthetized in the following chart. The chart demonstrates OPS3 capability to detect and measure each oil contamination and aging phenomena. Indeed, each oil contamination and aging phenomena has differentiable impacts on the four physical OPS3 sensor measurements.

	Impact on Viscosity	Impact on Density	Impact on Dielectric	Impact on Resistivity
Oxidation	+++ $\eta_t\,(1 + 21{\cdot}10^{-3} \cdot Ox)$	+ $\rho_t\,(1 + 0.5{\cdot}10^{-3} \cdot Ox)$	+ $\epsilon_t\,(1 + 1.5{\cdot}10^{-3} \cdot Ox)$	- - - $Rp_t\,(1 - 12{\cdot}10^{-3} \cdot Ox)$
Water Contamination	O η_t	O ρ_t	++ $\epsilon_t\,(1 + 20{\cdot}10^{-6} \cdot Wat(ppm))$	- - $Rp_t\,(1 - 6{\cdot}10^{-6} \cdot Wat(ppm))$
Coolant Contamination	O η_t	O ρ_t	+ $\epsilon_t\,(1 + 10{\cdot}10^{-6} \cdot Cool(ppm))$	- $Rp_t\,(1 - 3{\cdot}10^{-6} \cdot Cool(ppm))$
Fuel Contamination	- - - Function of fluid type	+ / - Function of fluid type	+ / - Function of fluid type	+ / - Function of fluid type
Soot Contamination	++ $\eta_t\,(1 + 6{\cdot}10^{-6} \cdot Soot(\%))$	+ $\rho_t\,(1 + 0.5{\cdot}10^{-2} \cdot Soot(\%))$	+++ $\epsilon_t\,(1 + 12{\cdot}10^{-2} \cdot Soot(\%))$	- $Rp_t\,(1 - 2{\cdot}10^{-2} \cdot Soot(\%))$
Metal Contamination	+ $\eta_t\,(1 + 2{\cdot}10^{-6} \cdot Fe(ppm))$	+ $\rho_t\,(1 + 0.4{\cdot}10^{-6} \cdot Fe(ppm))$	+ $\epsilon_t\,(1 + 0.8{\cdot}10^{-6} \cdot Fe(ppm))$	O $Rp_t\,(1 - 0.1{\cdot}10^{-6} \cdot Fe(ppm))$
TBN / TAN	O N/A	O N/A	O N/A	+++ / - - -
Wrong Fluid Detection	++ / - - Function of fluid type	++ / - - Function of fluid type	+ / - Function of fluid type	+ / - Function of fluid type

- Legend: +++: Strong Increase - - -: Strong Decrease
- ++ : Moderate Increase - - : Moderate Decrease
- \+ : Slight Increase - : Slight Decrease
- O : No impact +/- : Increase or Decrease
- 🟦 : High Evolution Speed 🟩 : Slow Evolution Speed

Note: Water and coolant contamination cannot be differentiated.

We can also diffentiate two evolution speeds for the different contaminations and aging phenomena. Oxidation, soot and metal contamination, and TBN / TAN evolution typically slow processes whereas water, coolant, fuel contaminations and wrong fluid filling could be very fast. Different algorithm detection strategies should then be specifically implemented for each contamination or aging item.Based on the previous measurements and on **OPS3** sensor specifications, the clearly achievable detection levels determined for each different oil contamination and aging phenomena are synthetized
in the following chart.

Presented models and analysis are highly dependent on oil type and application characteristics. Specific studies should then be performed before implementation in each application to adapt and optimize the models described.

OIL CONDITION ALGORITHM

To be as effective as possible, an Oil Condition Algorithm (OCA) should be designed for a specific application. One unique oil condition algorithm applicable for any application seems difficult to achieve. Each application would have different environmental characteristics, different application fluids, different contaminations risks, and different aging levels.

However, an effective oil condition algorithm should include some basic generic functions that could be configurable for each specific application, for example considering different thresholds or priorities. The following section describes these basic generic functions.

In the past, several solutions have been considered in the literature for oil degradation sensing with associated algorithm: classifier architectures based on linear discriminant analysis, Bayesian probabilistic models, robust fault detection and isolation, and neural networks [23, 24, 25].

The general oil condition algorithm strategy is described in bloc diagram of Fig.3.1.

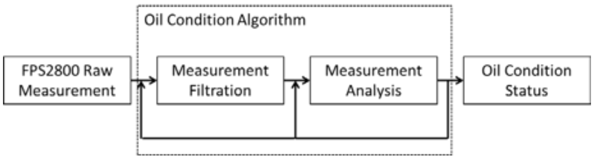

FIGURE.3.1: OIL CONDITION ALGORITHM BLOCK DIAGRAM

The oil condition algorithm described in this paper and designed to give a reliable oil condition status from **OPS3** raw measurement, will be divided into two separate steps: measurement filtration and measurement analysis.

A MEASUREMENT FILTRATION

An effective measurement filtration is needed to provide algorithm reliability and avoid any false detection. Filtration should be performed at several levels. The following basic functions should be considered as possible solutions. Each application would have specific characteristics that could induce specific adjustments.

Function A.1: Aberrant Data Filtration

Objective is to remove sensor error measurements. In some conditions, the OPS3 sensor could transmit error measurements, for example due to physical oil parameters out of specification. Sensors could transmit error measurements when immersed in fluids with higher viscosities when viscosity is specified up to 50cP. This function will only transmit correct OPS3 measurements without any error measurement.

Function A.2: Application Condition Filtration

Objective is to remove all the measurements that are not relevant for the application. For example, measurement data above 100°C would not be needed when tracking water in oil contamination because of evaporation processes.

Function A.3: Noise Filtration

Objective is to remove all measurement noise measured by the application to improve general monitoring performance.

For example, a simple infinite input response filter can be implemented. Order of filter could be adapted depending on specific application requirements (temperature gradients, etc.). Filters can be different for the various raw measurements.

Function A.4: Fresh Oil Modelling

Objective is to construct and store a temperature model of fresh engine oil for the four OPS3 sensor measurements, with the help of two temperature stabilized measurements necessary to build the models, using the equations described in Section I.C. This fresh oil modelling must be performed after an oil change. The information of the occurrence of oil change can be supplied by the user or can be detected by an additional specific function.

Function A.5: Current Oil Modelling

Objective is to construct and store a dynamic temperature model of engine oil for the four OPS3 sensor measurements and continuously update this model, with the help of two temperature stabilized measurements using the equations described in Section I.C.

Function A.6: Temperature Compensation

Objectives are to choose the adequate application analysis temperature T1, to calculate and to store the temperature compensated values thanks to Function A.4 and Function A.5 models. The four OPS3 measurements are temperature dependent and during application and it is possible that the stabilized points are not always at the same temperature. This function will allow an iso-temperature analysis with the following functions A.7 and A.8. The outputs of this function are the fresh oil physical parameters (x) at fixed temperature T1 and the current physical parameters (x) at fixed temperature T1.

Function A.7: Absolute Evolution Calculation

Objective is to calculate and store absolute evolution between fresh oil and current oil of the four parameters at the temperature T1 determined by Function A.6.

For example, absolute viscosity evolution can be calculated with the following formula:

Function A.7: Absolute Evolution Calculation

Objective is to calculate and store absolute evolution between fresh oil and current oil of the four parameters at the temperature T1 determined by Function A.6.

For example, absolute viscosity evolution can be calculated with the following formula:

$$Abs\eta_n = \eta_n - \eta_i$$

where n is viscosity of fresh oil at fixed temperature T1, and n is viscosity of current oil at fixed temperature T1.

The calculation is the same for the three other $(x)_n$ physical parameters: the density ρ, the dielectric constant ϵ and the electrical resistivity Rp.

Function A.8: Relative Evolution Calculation

Objective is to calculate and store relative evolution between fresh oil and current oil of the four parameters at the temperature T1 determined by Function A.6.

For example, relative viscosity evolution can be calculated with the following formula:

$$\mathrm{Re}l\,\eta_n(\%) = 100.\frac{\eta_n - \eta_i}{\eta_i}$$

where n is viscosity of fresh oil at fixed temperature T1, and n is viscosity of current oil at fixed temperature T1. The calculation is the same for the three other $(x)_n$ physical parameters: the density ρ, the dielectric constant ϵ and the electrical resistivity Rp.

Synthesis of Measurement Filtration

The described measurement filtration functions are synthetized in block diagram of Fig.3.2.

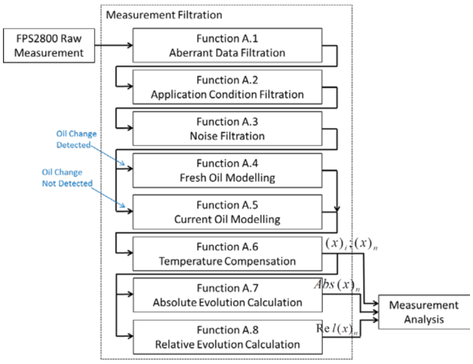

FIGURE.3.2: MEASUREMENT FILTRATION BLOCK DIAGRAM 1

The measurement filtration functions filter and pre-analyze OPS3 sensor raw measurement to determine the four following values at fixed temperature T1: fresh oil physical parameters $(x)_i$, current oil physical parameters $(x)_n$, absolute evolution $(x)_n$ and relative evolution $Rel(x)_n$. These four values will be used during the measurement analysis step and will increase aging and contamination detection capabilities.

The measurement filtration functions described should be considered as possible solutions. Each application would have specific characteristics that could induce specific adjustments.

B MEASUREMENT ANALYSIS

The following functions describe the strategy to reliably monitor oil condition and detect oil contaminations. Each formula described in Section II will be included and analyzed by the following functions.

Function B.1: High Risk Issue Detection

Objectives are to detect high levels of contamination or oil aging that can be dramatic for the application, to detect early water, coolant, fuel contaminations and to detect incorrect fluid voluntary or involuntary filling.

These contaminations are associated with high evolution speed. For example, water contamination could occur between two working engine phases and induces an increase of dielectric measurement when engine start-up, in comparison to the dielectric value before the last engine switches off. Detection algorithms should be adapted to this high evolution speed.

These contaminations have a high risk for the application but are relatively simple to manage using thresholds. For example, considering Fig.2.6, if the measurement filtration functions return the following relative evolutions at T2=50°C:

$$\mathrm{Re}\,l(\eta)_n = 0\%,\ \mathrm{Re}\,l(\rho)_n = 0\%,\ \mathrm{Re}\,l(\varepsilon)_n > 9\% \text{ and } \mathrm{Re}\,l(Rp)_n < -3\%,$$

then oil has high probability to be contaminated with more than 5000ppm water (or more than 10000ppm coolant).

Function B.2: Oxidation Trend Management

Objectives are to model and store oxidation trends and calculate relative distance to this oxidation trend. Oxidation is a particular aging process that necessarily happens during all oil life. One solution would be to consider an oxidation trend, modelled in real time and compare it to a typical oxidation trend associated with a specific application.

Example of oxidation trend tube is presented on Fig.3.3.

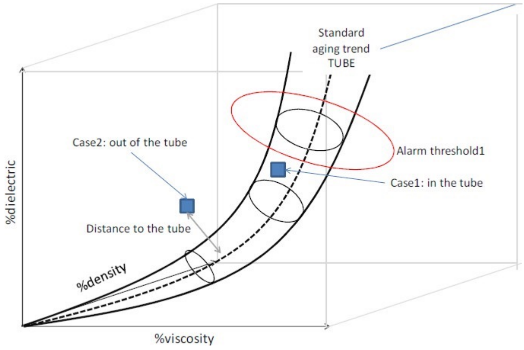

FIGURE.3.3: OXIDATION TUBE AND RELATIVE DISTANCE TO THE TUBE THRESHOLDS

Fig.3.3 is presented in three dimensions to facilitate visualization but analysis could be performed on the four different parameters to improve detection capabilities.

In Fig.3.3, the dotted line represents the average typical oxidation trend for one specific application. To consider the possible variabilities between different aging processes even in similar application conditions, the typical oxidation trend is preferably represented by a tube, in solid black lines and solid black circles. Two cases are considered for real time measurement in Fig.3.3. In Case 1, real time measurement is still inside the black typical oxidation tube, which means that oil follows expected oxidation process. Whereas in Case 2, real time measurement is out of the tube, which means that oil could be abnormally contaminated. Calculation of the distance of real time measurement to the tube will allow detection and a precise measurement of the contaminations in following function B.3.

Function B.3: Long Term Contamination Detection

Objectives are to detect contaminations with relative thresholds in comparison to oxidation trend model and to calculate absolute contamination levels.

For example, an alarm threshold is represented with a red circle in Fig.3.3. One threshold could be specifically determined for each possible long-term contamination. A precise measurement of the contamination is then possible using the models detailed in Section II.

Function B.4: Output Filtration

Objectives are to detect any algorithm default or inconsistent output and to manage noise output.

Each application will have specific characteristics and risks to the entire system. This output filtration should then prioritize and consider the raw outputs of the algorithm.

Synthesis of Measurement Analysis

The described measurement analysis functions are synthetized in block diagram of Fig.3.4.

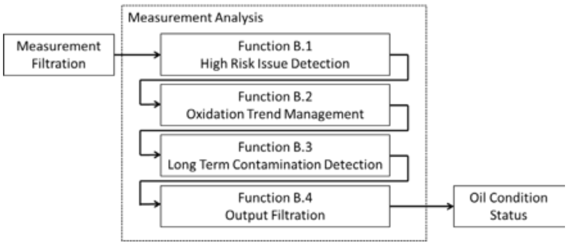

FIGURE.3.4: EXAMPLE OF MEASUREMENT ANALYSIS BLOCK DIAGRAM

The measurement analysis interprets the information from measurement filtration to determine oil condition status.

The described measurement analysis functions should be considered as possible solutions. Each application would have specific characteristics that could induce specific adjustments.

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CONCLUSION

By combining multi-property sensing with intelligent algorithms, the OPS3 Oil Property Sensor provides a powerful solution for real-time engine oil condition monitoring. OPS3 enables predictive maintenance, improved oil change intervals, reduced operating costs, and improved equipment reliability.

Successful deployment requires application-specific tuning of models and thresholds, but the foundational measurement and algorithm strategies described in this paper provide a proven and extensible framework.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

DPF: Diesel Particle Filter

ICP-AES: Inductively Coupled Plasma Atomic Emission Spectrometry

OPS: Oil Property Sensor

FTIR: Fourier Transform InfraRed HVO: Hydrotreated Vegetable Oil OCA: Oil Condition Algorithm

ROL: Remaining Oil Life

SVM: Support Vector Machine

TAN: Total Acid Number

TBN: Total Base Number

VBN: Viscosity Blending Number

VI: Viscosity Index

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OPS3 Oil Property Sensor

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