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CHALLENGES IN THE ON-BOARD OIL CONDITION MONITORING

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Abstract: Engine oil is an essential component in modern engines and must fulfil a broad range of duties. The engine oil condition is closely related to the engine performance and to the engine reliability. Different effects during the engine operation cause the formation of contaminants reaching into the oil and degrading the oil condition. Monitoring the oil condition with an on-board sensor could provide information about the current oil status. The available sensor data and their correlation to oil contamination effects is further illustrated and examined. The major challenge to derive a reliable oil condition statement from these data is also discussed in this paper.

1. Introduction:

The aim of the automobile industry to contribute to the reduction in global warming gas emissions such as carbon dioxide (CO2) has driven the adoption of biofuels and the implementation of complex exhaust gas aftertreatment systems. The combustion of conventional fuel causes the formation of contaminants resulting in engine oil degradation. The application of biofuels, especially biodiesel, causes a significantly worse deterioration of the oil condition due to the different chemical properties. Current exhaust gas aftertreatment systems worsen the engine oil contamination although this reduces the emissions. The reason for this is that the aftertreatment requires the engine to provide some unburnt fuel in the exhaust gases causing increased oil contamination due to condensed fuel travelling down the cylinder walls into the sump. The application of an on-board oil condition sensor would be helpful in providing information about the current oil condition in order to maintain a reliable drive operation. The correlation between the major oil contamination effects and available sensor data is considered in this paper using data from the Daimler internal oil data base. This data is examined data are from a 4-cylinder diesel engine. The final discussion in this paper outlines the main challenge of oil condition monitoring.

2. Oil condition measuring principles:

Oil condition parameters obtained from current sensor technology are in terms of the physical oil condition either the kinematic or dynamic viscosity (Möller, 2001) and in terms of the chemical related oil condition parameter of relative permittivity ε_r. The following overview of the applied techniques is therefore only based on the viscosity and the relative permittivity to detect physical and chemical oil condition variations.

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2.1. Physical oil condition measuring principles:

The methods of viscosity measurement are based on the detection of oil flow properties with the help of different physical principles. The main principle of current sensors is the reaction of a crystalline quartz based electromechanical system to changes in the viscosity properties of the surrounding oil. Most of the concepts use crystalline quartz based SAW (surface acoustic wave) or the tuning fork flexural resonator technique due to practical difficulties in applying sensors in vehicles, (Dobrinski et al., 2007). The basic theory behind this measuring principle is the viscosity dependent attenuation of the initial oscillation of the quartz resonator, (Matsiev, 1998). Other approaches are based on the physical principle of heat/ thermal conduction using a cylindrical pipe and heater configuration, (Lin, 2004). The theory behind this principle using thermal conduction is very similar to the diffusion mechanism and can be derived from Fick's laws. The diffusion coefficient in liquids is inversely proportional to the viscosity, but increases with temperature, (Foth, 2005). Another possibility to determine the viscosity is the measuring of fluid dynamics with the help of a streamed cylindrical capacitor configuration. This system is theoretically based on the fluid dynamics principle according to the Hagen-Poiseulle law where the viscosity is by definition one variable in the equation, (Foth, 2005).

2.2. Chemical oil condition measuring principle:

The on-board measuring of chemical oil properties is mainly focused on the detection of polarisation effects with a capacitive element. The electrodes are separated by the engine oil as a dielectric fluid. The dielectric becomes polarised as an electric field E is applied. This results in the induction of dipoles from non-polar molecules or in the orientation of dipoles from polar molecules in the dielectric substance. The orientation of existing or induced dipoles in the opposite direction to the applied alternating electric field results in a change of the dielectric characteristic of the sensor arrangement. This change can be expressed and quantified by the relative permittivity ε_r. This value is usually displayed by the sensor and is a complex quantity:

$$\varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \quad (2.1)$$

The real part of permittivity ε_r' is a measure of how much energy from an external electric field due to the polarisation effects is stored in the dielectric material, i.e. the engine oil. The imaginary part of permittivity ε_r'' is called the loss factor and is a measure of how dissipative a material is to an externally applied electric field, (Agilent, 2006). The dissipation accompanying the polarisation effects will contribute to the dielectric losses. The relative permittivity ε_r of fresh engine oil is usually known and is typically in the range of 2.0 – 2.4. The sensor evaluation of the relative permittivity of oil therefore provides a direct measure of the increased concentration of substances from any contamination effect contributing to the overall polarisation of the dielectric.

3. Contamination effects and their influence on selected oil condition data:

The degradation of primary oil is correlated to the oil condition data of viscosity and permittivity to illustrate existing interrelations with possible sensor data. The selected datasets cover all available drive and test profiles as each profile contributes a

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different loading of contaminants that affect the oil. It should be noted that some generated data sets are from test runs that exceed normal driving applications. The approved SAE 5W-30 engine oil for this engine type is used in these plots. This should provide a realistic summary of the complete bandwidth of available load profiles covered by the plots presented here. The trade-off of the selected spectrum has caused the larger stray area of the scatterplots. The equation for the linear regression and the coefficient of determination R^2 in each plot should therefore provide a lead to indicate the tendency of the correlation.

3.1. Effect of fuel dilution on viscosity and permittivity:

A certain amount of fuel can reach the thin film of oil on the cylinder wall prior to combustion for an internal combustion engine during normal operation. The amount of fuel reaching the oil depends on the temperature, the exhaust after-treatment strategy and the load parameters. Cold temperatures of the cylinder wall will cause condensation of the fuel and thus result in higher fuel dilution, (Möller, 2001). New emission requirements for diesel engines have resulted in the adoption of aftertreatment devices including diesel particulate filters (DPFs). Particulate filters accumulate particulate matter (PM) and periodically the filters must be regenerated by oxidizing the PM at elevated temperatures. Late injections of fuel, and particularly late in-cylinder injections cause unburned hydrocarbons for DPF regeneration bearing a high risk of impingement of liquid fuel on the surfaces of the combustion chamber. Fuel may ultimately be transported down the walls and into the oil pan. Fuel dilution of oil results

firstly in a reduction of oil viscosity and increases the risk of scuffing on the cylinder walls or bearings. The kinematic viscosity of an SAE 30 oil at 100°C is between 9.3 – 12.5 mm²/s. The viscosity of the revised fuels as discussed, is significantly lower and is at temperatures of 40°C in the range of 2.00 – 5.00 mm²/s according to current standards. The oil temperature correlates to the operational, i.e. load profile of the engine. Typical boiling ranges of the type of fuel reaching into the oil are: (bio)ethanol 78.5°C (boiling end point), standard petrol 40°C-200°C, standard diesel 180°C–380°C and biodiesel 325°C-355°C, (Luther, 2008). The oil temperature in the sump of passenger cars can reach 100°C-160°C, (Reinhardt et al., 1992). Fuel dilution is thus less problematic for ethanol and petrol but is severe for diesel and especially for biodiesel. With higher oil temperatures then the low-boiling fractions of the diesel evaporate, but biodiesel remains due to the high boiling temperature of the oil. This accumulation effect is the major problem with biodiesel as it causes a permanent fuel dilution and thereby a viscosity loss. It additionally causes deposits especially on the pistons and piston rings. Stuck piston rings will then worsen the effect of fuel dilution and blow-by reaching into the oil, (Möller, 2001). The increased amount of unsaturated fatty acids from the biodiesel also affects the oxidation disposition of the oil; refer to section 3.3 in this paper. The scatterplots in figure 3.1 confirm the strong correlation between the fuel dilution in the oil samples in [weight-%] and the decrease of the kinematic viscosity at 100°C in [mm^2/s]. It is noticeable that the diesel values are typically in the range of 0-8 wt.-%. Higher values >15 wt.-% result from special test programmes such as regeneration test runs, which underline the wall impingement problem caused by DPF.

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The SAE 30 lower limit is 9.3 mm²/s and becomes violated for values >5% fuel. RME and gasoline data shows the same characteristic of viscosity as diesel. Another liquid contamination of the oil besides fuel is water and is usually caused by condensation at low oil temperatures. Water initially reduces the viscosity of the oil but it will not be examined further in this paper since small amounts of condensed water evaporate quickly with higher oil temperatures. Coolant water can also get into the oil in the case of a severe engine problem.
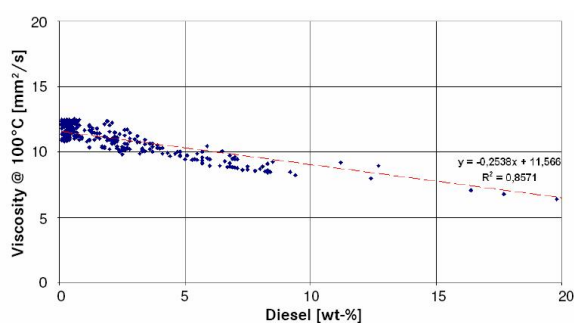

Figure 3.1.: Effect of oil dilution by Diesel fuel on kinematic viscosity

Figure 3.2 indicates that fuel dilution has no significant effect on the relative permittivity ε_e. The reason is the similarity of the permittivity number of diesel with ε_e of 2.1, compared to fresh engine oil which is in the range of 2.0-2.4. The diesel molecules are non-polar and their contribution to an electric dipole moment in the presence of an alternating field is relatively low. The relative permittivity of petrol is 2.0 and the relative dielectric constant of biodiesel (B100) is about 2.9-3.0 as the ester components cause a slightly higher dipole moment. The slight positive slope in figure 3.2 can be ascribed to scattering effects. However, in-house experiments with a 10% B100 fuel dilution in fresh oil showed no identifiable change in the dielectric

properties. The most significant dipole moment due to the polarisation effect with any fuel occurs with ethanol. The resulting relative permittivity is about 16.2, (Holdefer, 1999). An ethanol dilution in the oil from a theoretical consideration will be detectable, but this will only be possible at low oil temperatures due to the high volatility of ethanol. The effect of water in the oil is also detectable as the dipole characteristic of the polar water molecules causes a high dipole moment and thus a high relative permittivity of 80.3, (Holdefer, 1999). Data plots with water contamination of the oil were not available and are not considered in this work.
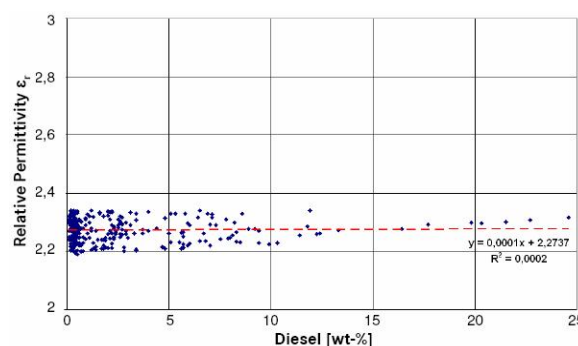

Figure 3.2.: Effect of oil dilution by Diesel fuel on relative permittivity

3.2. Effect of soot on viscosity and permittivity:

Soot is entrained in the oil usually due to blow-by of exhaust gas. Soot in the oil causes abrasion and accelerated wear in the bearing, valves and camshaft. Elevated levels of soot in the oil cause sludge and the formation of deposits. Deposits on the piston ring groves are especially harmful as they limit the freedom of movement of the piston rings and ultimately cause the piston rings to get stuck. When the freedom of movement of the piston rings becomes limited, they will not fully seal the gap between the piston

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and the cylinder wall. This causes more blow-by and more soot loading of the oil. Figure 3.3 indicates a strong viscosity increase with higher soot loading of the oil. The amount of soot in the revised oil data for the diesel engine was up to 8%-wt. It is noticeable that even an amount of 2% soot may cause the viscosity to increase >12.5 mm²/s and thus to violate the SAE 30 upper limit at 100°C. Soot formation with biodiesel is less than for standard diesel due to a higher cetane number and 11% oxygen (Schmiedel, 2004).
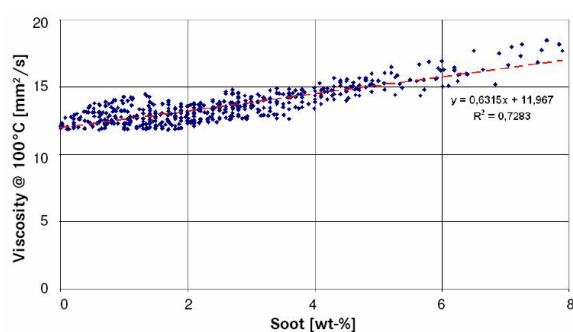

Figure 3.3.: Soot accumulation effect on kinematic viscosity

The relative permittivity of soot is 18.8 and differs considerably from the permittivity of fresh oil, (Holdefer, 1999). The high polarisability of the non-polar soot particles causes a relatively high dipole moment in the presence of an external alternating field. Figure 3.4. shows a significant correlation between the amount of soot in the engine oil and the increase in the relative permittivity.

3.3. Effect of oxidation/nitration on viscosity and permittivity:

The starting point for the oxidation process is un-burnt hydrocarbons formed in the leaner combustion flame regions where the combustion temperature is too low to ensure a complete oxidation of the fuel.
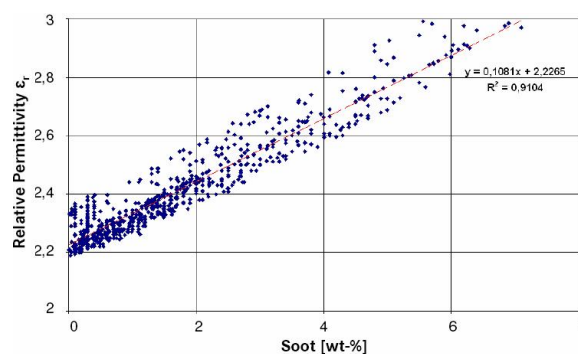

Figure 3.4.: Soot accumulation effect on relative permittivity

The unburnt hydrocarbons in the oil combined with oxygen is the starting point of the formation of radicals, (Möller, 2001). The catalytic influence of metal in the oil, e.g. from abrasion and high temperatures accelerate the formation of radicals and substantially influences thus the oxidation process. The end product of the oxidation chain is the formation of oil insoluble polymers and carbon acids. The polymers cause a severe increase in the viscosity and the carbon acids affect the engine bearings causing accelerated engine wear. The oxidation process is much more progressive with unburnt biodiesel as the unsaturated fatty acids are prone to the reaction with oxygen. The additive agents of the oil are depleted much faster and the oil lifetime is significantly reduced especially with biodiesel from less oxidation stable feedstock like SME (Soy Methyl Ester), (Schmiedel, 2004). The main difference with nitration is the starting point which is with nitrogen, i.e. NOx, compounds reaching into the oil due to blow-by gases. The chain reaction is similar to the oxidation process and the end product is sludge, causing severe deposits and nitric acids depleting the additive agents of the oil, resulting in corrosion. Figure 3.5 indicates a distinct increase of the viscosity caused by oxidation due to the formation of oil insoluble products. The IR (infra-red)

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absorption goes up to 25 cm⁻¹. The viscosity value of SAE 30 oils exceeds the allowed upper viscosity limit of 12.5 mm²/s for oxidation values of about 5 cm⁻¹.
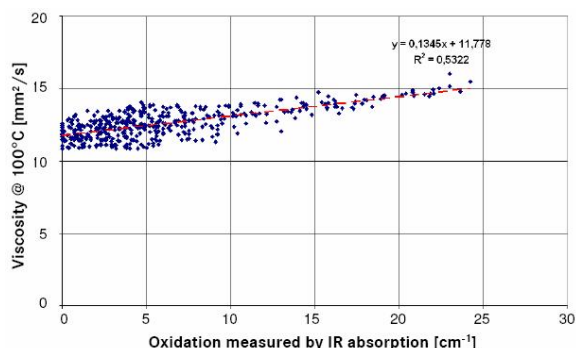

Figure 3.5.: Oxidation effect on kinematic viscosity

The carbon acids which are formed from the oxidation reaction chain and the nitric acids from the nitration process are polar molecules and have a distinct dipole characteristic providing a high dipole moment when influenced by an electric field. The relative permittivity of these acids is 57.9 for the carbon acid and 33.6 for nitric acid, (Holdefer, 1999). Despite the broad stray area in figure 3.6 there is a strong correlation between the increase in the IR absorption and the relative permittivity.
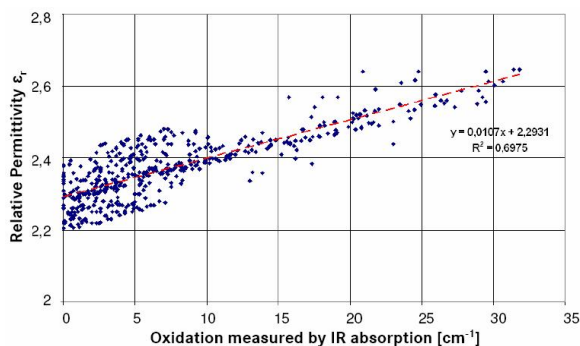

Figure 3.6.: Oxidation effect on relative permittivity

4. Discussion:

Some sensor manufacturers and potential users have published research papers where some discrete contaminations and the measured viscosity or permittivity change in the sensor output value was successfully demonstrated, usually in laboratory experiments, (Schmitigal, 2005). The observations suggest the conclusion that different contaminations are all well detectable, either with the viscosity or with the permittivity value from the sensor. This approach appears to work for discrete laboratory experiments with known levels of contamination of the oil sample. However, the crucial issue with the transfer of these correlations from laboratory experiments to vehicle applications is the inclusion of previous knowledge about the artificially doped oil samples in the laboratory. As soon as the oil is operating in a real engine under real circum-stances it must be considered as a 'black-box' where the operator is unaware of all of the processes in the oil and the oil condition is only fully known when a complete oil change occurs. Each of the contamination effects can attach value to the overall oil which is measured by the sensor. The viscosity and relative permittivity data do not provide sufficient knowledge in order to be able to distinguish which contamination influence actually contributes to the overall value. External aspects such as the initial oil quality, the fuel type and quality, the operational profile and temperature also have an influence on the progress of most of the contamination effects. The following illustration, figure 4.1 underlines the problem and will clarify the challenge with an on-board oil condition monitoring system.

The sensor data values for the available oil condition data only presents a combination of numerous and possible contamination

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mechanisms. The contaminations listed above in terms of the chemical mixture processes can be divided into homogenisation (mixing of soluble liquids), emulsification (mixing of limited soluble products) and suspension (mixing of solids in liquids).
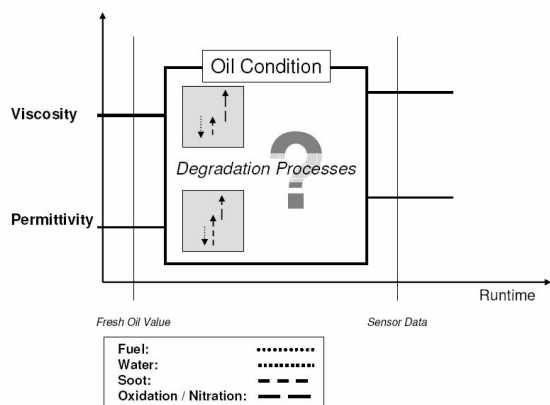

Figure 4.1.: Masking of oil degradation processes in the sump

Each blend component included in the engine oil is considered as an individual dilution and can be characterised by the individual kinematic viscosity v in [mm²/s]. (Evaporation, volatilisation losses and temperature effects are not considered here). The VBN (Viscosity Blend Number) for each substance is, (Maples, 2000):

$$VBN = 14.534 \cdot \ln\left[\ln(v + 0.8)\right] + 10.975 \quad (4.1)$$

The VBN of the final blend can be derived from the Lomonossow–Lavoisier law and is defined as:

$$VBN_{Blend} = \left[\chi_A \cdot VBN_A\right] + \left[\chi_B \cdot VBN_B\right] + \ldots + \left[\chi_{n\cdot} \cdot VBN_n\right]$$
(4.2)

where χ_A to χ_n are the mass fraction of each blend component, i.e. the oil and the contaminants. The overall kinematic viscosity is derived by solving equation 4.1 for v.

$$v = e^{e^{\frac{VBN_{Blend} - 10.975}{14.534}} - 0.8} \quad (4.3)$$

The final viscosity value v from equation 4.3 is the measured value by the on-board sensor. Any engine oil contamination examined above, except fuel dilution with conventional fuel, increases the number of polar and non-polar molecules in the oil. The presence of an alternating field causes the polarisation of these molecules, therefore forming a dipole moment μ in [C m], (Atkins, 1986). The resulting average dipole moment of the polar molecules can be expressed as:

$$\mu_{average} = \mu^2 \cdot E^* / 3 \cdot k \cdot T \quad (4.4)$$

with E* in [V m^{-1}] is the local electric field around the molecule and k is the Boltzmann-constant in [J/K] and T in [K] as temperature, (Foth, 2005). The resulting induced dipole moment of the non-polar molecules can be expressed as

$$\mu_{induced} = \alpha \cdot E^* \quad (4.5)$$

where α is the polarisability of the molecule in [J^{-1} C^2 m^{-1}]. The final polarisation P in relation to the density ρ, the number of molecules N_A and the molecular mass M_m gives

$$P = \left(\rho \cdot N_A / M_m\right)\left(\alpha + \mu^2 / 3 \cdot k \cdot T\right)E^* \quad (4.6)$$

where

$$E^* = \frac{P(\varepsilon_r + 2)}{3\varepsilon_0(\varepsilon_r - 1)} \quad (4.7)$$

which gives Debye's equation for the overall molar polarisability in relation to the permittivity

$$P = 3 \cdot \varepsilon_0 \cdot \frac{\varepsilon_r - 1}{\varepsilon_r + 2} \cdot \frac{M_m}{\rho} = N_A \cdot \left(\alpha + \frac{\mu^2}{3 \cdot k \cdot T}\right)$$
(4.8)

The measured relative permittivity ε_e using the sensor based on Debye's equation will provide a quantitative sum of all present polarisation effects in the oil. These considerations for the viscosity and the permittivity with respect to an on-board application in a vehicle, proves the

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assumption that a subsequent separation of the contamination effects is not possible with the currently available sensor data. Further research activities in the current programme are based on an evaluation of the time dependent total viscosity and relative permittivity progress as indicated in figure 4.2 for a schematic engine test run.
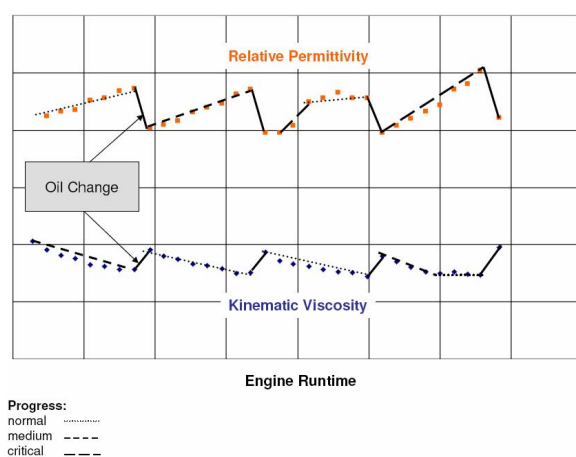

Figure 4.2: Oil condition progress regarding the engine runtime

5. Conclusion:

Current on-board oil condition sensor technology offers the viscosity and permittivity to measure the physical and chemical oil condition. Any contamination reaching into the oil, changes at least one available sensor parameter. Individual contamination effects cannot be verified and measured in the sump as a multitude of unknown effects are possible. Further research work will be focused on the analysis of available sensor data to monitor changes from fresh oil values. The intention of the present research is to know precisely whether something is happen with the engine oil instead of trying to indicate any individual effect as this is not possible using current sensor technology. An on-board oil condition sensor combined with a smart algorithm can never claim to be an oil laboratory on wheels but it will help to prevent the driver from loosing mobility caused by oil degradation.

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