Physical Sensors for Fluid Media in Industrial and Automotive Applications

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Abstract

In this contribution, selected recent approaches and results concerning the application of sensors for physical properties of fluids are discussed. The sensor principles are illustrated using examples including oil condition sensors and other automotive applications.

Introduction

Fluids play a primary role in many industrial processes but also other equipment and machines such as automobiles. It is often useful or even essential to monitor the actual state of the fluids in order to determine required maintenance (refill or replacement) of a working liquid or to indirectly obtain information about the state of the machine or plant. Examples in automotive applications would be gearbox and engine-oils, hydraulic fluids, and fuel.

Most often the required information has a chemical character, e.g., the oxidation of the fluid needs to be monitored or the concentration of a certain (contaminating) substance needs to be evaluated. These tasks seem to call for dedicated chemical sensors. A typical chemical sensor uses an interface material that the transforms the chemical information into a physical quantity that can be sensed by a corresponding physical sensor. At the interface, chemical reactions are taking place which often leads to issues in terms of reproducibility, reversibility of the associated reactions and poisoning. Moreover the interface materials themselves are often prone to degradation such that the accuracy, particularly in harsher environments, cannot be maintained. Thus in many (often industrial) applications one adopts the concept of "physical chemosensors", where a purely physical sensor is used to obtain information on the state of the liquid [1]. If, for instance, the monitored process is well understood, physical parameters can be used to indirectly determine the chemical state of the fluid. A simple example for this approach is the determination of the alcohol content of a brew by means of a density measurement. Alternatively, for more complex processes, physical sensor arrays can be employed, which are related to the sought chemical parameters by means of a calibration procedure.

Suitable physical fluid parameters include viscosity, density, sound velocity, electric and thermal conductivity, and permittivity. In this contribution, as an example, electric conductivity/permittivity sensing and viscosity as well as associated applications are briefly reviewed. Since the monitoring of engine oil will serve as a prominent example, just a few words on the motivation. Monitoring the condition of engine oil can on the one hand lead to increased oil drain intervals but can at the same time provide increased insight in the current state of the engine and thus may help to prevent potential malfunction or even engine breakdown. Lubricating oil is exposed to various strains depending on the operating conditions, the fuel quality, the ambient conditions, and operating parameters. In order to determine the optimum oil change interval reliably, the actual physical and/or chemical condition of the oil should be monitored either by using dedicated sensors immersed in the oil or by estimating the condition of the engine oil by means of indirect methods mainly relying on operating parameters like engine speed, performance and temperature. Major chemical indicators of oil deterioration are for instance the acidity of the oil, its oxidation, contamination (e.g., by soot), and the consumption of additives.

Even though this paper has a certain review character, its scope and format as well as the vast material that is available in the application fields discussed does not allow to provide comprehensive references to

related works. All citations given are therefore examples (mainly of our own work), which may serve as starting points for further literature research.

Sensing of Electric Fluid Parameters – Conductivity and Permittivity

The determination of electric fluid properties is near at hand and can – at first sight – be easily implemented by inserting electrodes into the fluid under test and investigating current-voltage relations. In particular, methods involving electrochemical reactions at the electrodes (such as in voltammetry, see, e.g., [2], [3]) and methods aiming at the determination of bulk fluid properties can be distinguished. In electrochemical impedance spectroscopy or EIS for short (see, e.g., [4] for an example on applications to engine oil), electrode effects are most often considered in a detailed equivalent circuit, which also contains components representing the electric bulk properties of the liquid, i.e., conductivity and permittivity. Using EIS, the frequency spectra of the latter are investigated. While the measurement of these parameters is comparatively straightforward (if electrode effects are properly taken into account), the interpretation of the results, depending on the application, can be difficult. For engine oil condition monitoring, commercial sensors aiming at the prediction of oil quality have been introduced by Temic (permittivity) and Delphi (conductivity), where the underlying investigations are reported, e.g., in [5] and [2], respectively. In short it can be stated, that the specific conductance as well as the permittivity are related to a number of relevant oil parameters (in particular acidity), however, the derivation of a simple correlation can be difficult. In case of fuel sensing, interesting applications lie in the detection of alcohol content in fuels ("flex fuel" sensors) and to sense the content of biodiesel (rapeseed oil methyl ester, RME) in diesel. Both applications are enabled by the different permittivity of the fuels [6].

Due to the high permittivity of water, permittivity measurements seem ideal to detect the water content in a mixture. However, for immiscible components, the microstructure of the mixture needs to be considered, e.g., the structure of an emulsion. Unless the underlying geometry of the mixture is specified, only limiting bounds for the macroscopically apparent, so-called effective permittivity can be provided. Considering purely dielectric media (i.e. neglecting a potentially present conductivity, see also further remarks below), a simple pair of bounds are the so-called Wiener bounds [7], which correspond to a particular geometry of the surfaces between the aqueous and oil phase as shown in Fig. 1. If all surfaces between the phases were in parallel with the applied electric field, the effective permittivity would assume a maximum value, whereas it would correspond to a minimum, if all surfaces were orthogonal to the field. These structures can be considered analogous to capacitors, which are connected in parallel and series, respectively. Obviously these extreme cases represent anisotropic media such that the associated maximum and minimum values for the effective permittivity will never be assumed for a macroscopically isotropic mixture like an emulsion.
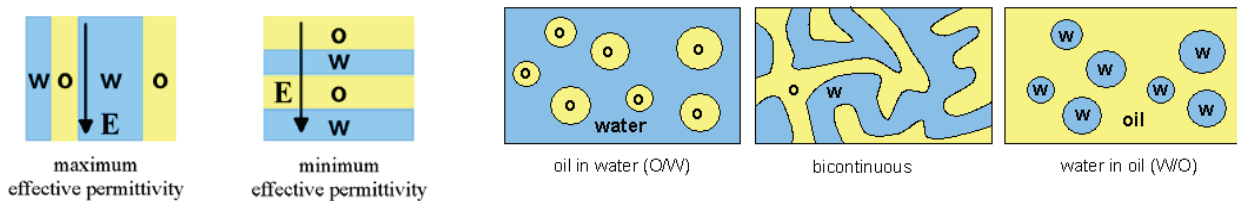

Fig. 1: Inter-phase geometries associated with the Wiener bounds (left, the arrow denotes the direction of the applied electric field $\mathbf{E}$) and microstructure of emulsions (right).

Apart from theories providing limiting bounds for the effective permittivity of a two phase mixture, there are a number of mixing formulas referring to specific inter-phase geometries. In [8] we confirmed that for water-in-oil (W/O) emulsions, the so-called Maxwell-Garnett mixing formula [7], which provides an approximation of the effective permittivity of a medium with spherical inclusions, can be applied successfully. For W/O emulsions, the Maxwell-Garnett (MG) rule reads [7]

$$\frac{\varepsilon_{r,m}}{\varepsilon_{r,o}} = 1 + 3f \frac{\varepsilon_{r,w} - \varepsilon_{r,o}}{\varepsilon_{r,w} + 2\varepsilon_{r,o} - f(\varepsilon_{r,w} - \varepsilon_{r,o})}, \tag{1}$$

where $\varepsilon_{r,m}$, $\varepsilon_{r,w}$, and $\varepsilon_{r,o}$ denote the permittivities of the mixture, water, and the oil, respectively, and f denotes the water fraction by volume. To apply (1) to oil-in-water (O/W) emulsions, the permittivities of water and oil have to be interchanged. Assuming $\varepsilon_{r,w} > \varepsilon_{r,o}$, at a given water fraction f, the MG-rule for O/W

emulsions will generally yield larger permittivities than that for W/O emulsions. In practice, for a given f, a macroemulsion will only exist in one of the two manifestations. For low water fractions, commonly W/O emulsions are obtained, while for high water fractions, O/W emulsions will emerge. For some intermediate value of f, a transition from one into the other phase structure will appear. For microemulsions, i.e. emulsions where the droplet size is in the submicron range due to special surfactants, this transition does not necessarily occur abruptly, but intermediate dispersion structures ("bicontiniuous" structures) may appear [10], see Fig. 1.

Considering the case of water contamination in oil (and assuming that the water fraction that is soluble in oil is negligible), for low volume fractions of water, (1) can be further approximated by considering that the permittivity of water-phase, $\varepsilon_{r,w}$, is commonly much larger than that of the oil phase [8]:

$$\varepsilon_{r,m} \cong \varepsilon_{r,o}(1+3f). \tag{2}$$

This rule simply states that water contamination approximately leads to a percentual increase of the oil's permittivity given by three times the water content in percent (by volume). This is much lower than one might expect in view of the high permittivity of water and is basically caused by the fact that the water phase is concentrated in tiny droplets rather than being continuously mixed with the oil.

Viscosity Sensing

Viscosity is a major physical parameter characterizing liquids and often provides an indication about the state of the liquid to be monitored. The viscosity (more precisely the "shear viscosity") η can be defined in terms of a simple experimental arrangement, where the liquid under test is sheared between two laterally moving plates. η is then defined as the ratio between the applied shear stress (maintaining the movement) and the resulting gradient of the flow velocity (i.e. the so-called shear rate) of the liquid sheared between the plates. The so defined viscosity (as already proposed by Newton) can be measured in a straightforward manner by laboratory instruments, which in some manner impress a shear deformation on the liquid and measure the associated externally applied shear forces. Most often, rotational movements are utilized, e.g., by immersing a rotating cylinder in a viscous liquid. The ratio of applied torque and the resulting angular rate is then a measure for η. As an alternative to continuous rotation, also rotational harmonic oscillations can be applied. For so-called non-Newtonian liquids, the ratio of torque and angular rate (or equivalently, shear stress to velocity gradient) depends on the measurement parameters used. For example, the viscosity may drop for increasing shear rates (so called shear-thinning behavior). In case of rotational oscillations, the obtained viscosity may depend on the frequency and furthermore frequency-depending phase shifts between torque and angular rate can occur, which can be represented as an imaginary part in the viscosity when using complex notation for time-harmonic signals. The latter effect is associated with so called viscoelastic behavior. These two examples represent non-linear and linear distortions of the ideal Newtonian behavior.

The miniaturization of suitable viscosity measurement principles on the one hand facilitates the implementation of these devices online. On the other hand, scaling effects have to be taken into account, which lead to issues when it comes to applications in complex liquids such as suspensions featuring non-Newtonian behavior, which, as mentioned above, yields a dependence of the measured viscosity on the measurement parameters. This has led us to the investigation of different device designs, see, e.g., [9]. Examples for our own work illustrating monitoring processes utilizing viscosity sensors are the monitoring of transitions in emulsions [10], of zeolite synthesis [11], and of engine oil deterioration [12].

Sticking to the example of engine oil deterioration, viscosity is one of the major parameters characterizing the state of engine oil. Other indicators are permittivity and conductivity (see also above). Most often oil condition sensors are devised as multifunctional sensors, see for example [13] and [14] where permittivity sensors are combined with microacoustic sensors. As viscosity is a strongly temperature-dependent parameter, a temperature sensor has to be included in these multifunctional sensors. Viscosity is a good parameter for engine oil deterioration as it increases with the oil's oxidation, the aggregation of insoluble components but also with increasing soot content. The latter can also be clearly detected in the permittivity signal [15]. The viscosity reduces in the case of fuel dilution [15], thus deterioriation is not necessarily connected with an increase in viscosity, which makes the interpretation of the signal more difficult. A major issue is also the applied vibration frequency associated with microacoustic devices. Nonlinear behavior and viscoelastic effects, or more generally, non-Newtonian behavior may occur. As

the major interaction with the viscous fluid is by means of shear displacements in the liquid, one has to keep in mind that, due to the small penetration depth δ of shear waves in liquids, a "thin film viscosity" is measured, which does not necessarily correspond to the "macroscopic" viscosity value as it is obtained by a standard laboratory viscometer. The penetration depth is given by [16]

$$\delta = \sqrt{\frac{2\eta}{\rho\omega}} \qquad\qquad\qquad (2)$$

where ρ and ω denote the mass density and radian frequency, respectively. Depending on the frequency and the viscosity, it can be in the micron to submicron range. This can lead to the effect that in case of water in oil emulsions, e.g., for significant water contamination of the oil, the presence of water droplets is not detected as an increase in the viscosity (as it appears macroscopically) if the droplet diameters are larger than δ as they do appear in the thin film sensed by the sensor. However, if a droplet occasionally adheres to the sensor surface, a reduced viscosity is measured by the sensor [17].

Similar effects have been observed with the deterioration of additives, which is differently sensed by microacoustic sensors and laboratory equipment. This leads to the conclusion that the correlation coefficients between sensor signal and laboratory viscometer readings depend on the additives and thus on the oil type [18], see the example in Fig. 2. As a simple statement it can be said that these "high frequency devices" tend to measure the viscosity of the base oils and changes thereof. In [18] thermally aged base oils have been investigated, where a correlation with the acidity of the oil (described by the total acid number TAN), which in case of thermal ageing is intimately linked to oxidation processes, has been achieved.
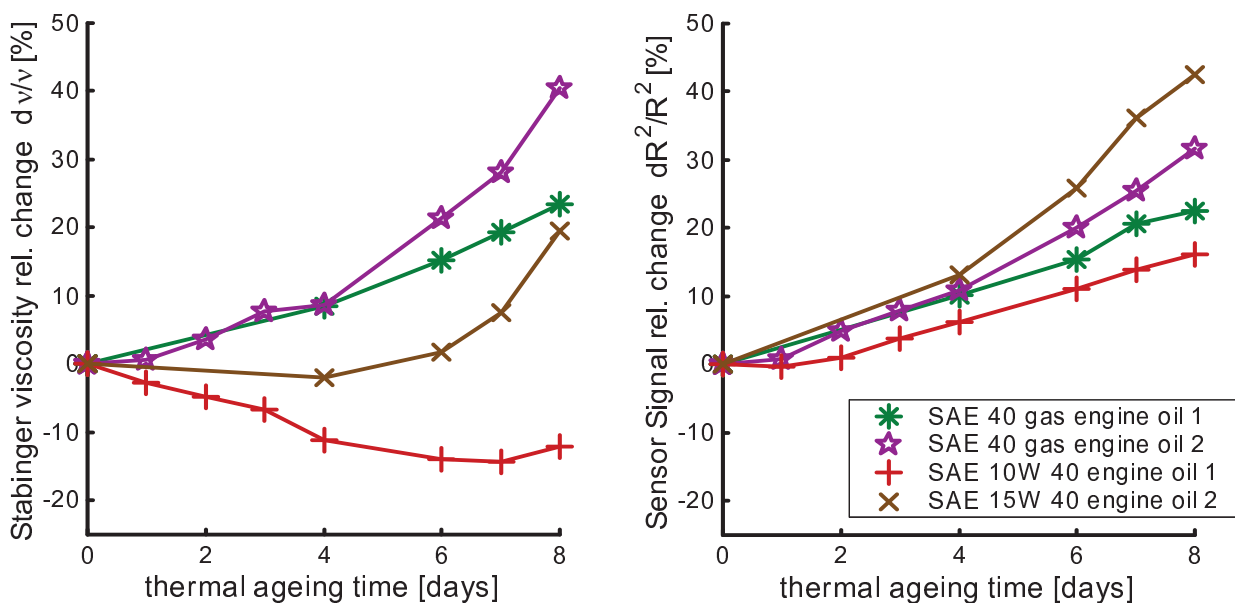

Fig. 2: Relative changes in the measured viscosities for base oils (gas engine oils) and heavily additivated automotive engine oils as a function of the duration of thermal ageing. The left plot shows the values measured by a laboratory viscometer (Stabinger viscometer) while the right plot shows values obtained by a thickness shear mode (TSM) resonator. The differences – in particular for the additivated oils – are attributed to the different rheological domain probed and the fact that a TSM sensor determines a thin film viscosity (see also [18]).

Thus the viscosity signal provided by these sensors cannot be interpreted easily and in particularly it cannot necessarily be correlated to readings from laboratory viscometers. However, changes in these viscosities can indicate oil deterioration equally well as measurements with traditional viscometers. Also for conventional lab viscometers it is well known that different methods may yield different measurements. An example is the High-Temperature-High-Shear viscosity [19] where the measurement parameters lead to operation in a regime similar to that in bearings in combustion engines. It would thus significantly help

to promote microacoustic viscosity sensors for oil condition monitoring applications if an associated standard (for a "microacoustic viscosity") were established.

Conclusion

Miniaturization technologies allow the implementation of sensors for physical fluid parameters in online applications leading to many new opportunities in the field of condition monitoring. When scaling down known measurement principles as well as when implementing new methods at the microscale, it has to be considered that the obtained measurement results are not necessarily comparable to that of macroscopic measurement equipment. This fact can be nicely demonstrated using the case of viscosity sensing. Moreover, when using the concept of physical chemosensors (i.e. using physical sensors to indirectly determine a targeted chemical property), clear and reproducible relations between sensor output and sought parameter need to be established. Thus the associated research involves not only work on the sensor technology but also on the physical interaction of the sensor mechanism with the process observed.

Acknowledgments

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