Oil Condition Monitoring Using a Thermal Conductivity Sensor

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In recent years, the monitoring of oil-based liquids has gained increasing importance in various branches of the industry. In this contribution we discuss the application of a miniaturized thermal conductivity sensor for the monitoring of water contamination and deterioration processes in mineral oil. The sensor, which utilizes the hot film principle, features a molybdenum resistive structure simultaneously serving as heater and sensing element. The experimental results show that both, water contamination and deterioration processes in mineral oil lead to an increased thermal conductivity, indicating the potential of thermal conductivity sensors in the field of oil condition monitoring. Finally we analyzed the sensor's performance numerically in order to further evaluate its applicability and possible design modifications.

Introduction

In recent years, the monitoring of oil-based liquids has gained increasing importance in various branches of the industry. A prominent example is the condition monitoring of lubrication and insulating oils. In both cases the water contamination of oil often cannot be avoided which seriously influences its performance if certain levels are exceeded. In the case of lubrication oil, excessive water content leads to insufficient lubrication and subsequently to abrasive wear and corrosion. In case of insulation oils, increased water content results in a considerable reduction of the breakdown voltage. Thus, the detection of water content in the oil is of major importance.

Comparing the thermal transport properties of mineral oil and water, it turns out that the latter features a five times higher thermal conductivity. This indicates that thermal conductivity is a potential parameter for the detection of water content in mineral oils. In this contribution we investigate the thermal transport properties of W/O emulsions and artificially aged oils using a resistive hot film microsensor.

	ϑ	ρ	c_p	λ
	°C	$\frac{kg}{m^3}$	$\frac{J}{kgK}$	$\frac{W}{mK}$
Water	20.0	998	4183	0.598
Engine Oil	60.0	868	2010	0.140
Insulation Oil	60.0	842	2090	0.120

Table 1: Thermal properties of selected liquids [1].

Theory

During the last four decades many different techniques for measuring the thermal conductivity of liquids, solids, and gases have been developed. For the characterization of the thermal transport properties of fluids, in particular the transient hot-wire method is widely-used (see, e.g., [2]). This technique is based on a thin metal wire, mostly made of platinum, simultaneously serving as both, heater and sensing element. By applying a transient electrical current, the wire and the surrounding medium under investigation start heating up. Recording the corresponding temperature response of the wire enables the determination of the thermal conductivity and diffusivity of the surrounding fluid. Instead of a wire, other heater geometries have also been utilized. In case of the classical transient hot-strip technique a thin metal sheet is used (see e.g., [3]). In micro technology, this sheet is replaced by a thin film structure deposited on a substrate. In order to minimize the influence of this substrate on the sensor's performance various geometries like thin membranes, cantilevers, or micro-bridges can be utilized. However, regarding the applicability in harsh industrial environments, a trade-off has to be found between sensitivity and mechanical robustness. In this contribution we consider a hot film microsensor, which is operated using an adapted transient method.

Considering the small dimensions of the sensor compared to the used sample volumes (15 ml) of the investigated liquids, the corresponding temperature field in some distance from the sensor can be approximated by solving the heat diffusion equation for a thermal point source switched on at $t = 0$:

$$\vartheta(r,t) = \frac{\Phi}{4\pi\lambda\, r}\, \mathrm{erfc}\left(\frac{r}{\sqrt{4at}}\right) \tag{1}$$

Here Φ denotes the heating power, λ the thermal conductivity, a the thermal diffusivity, and r the radial distance from the point source [1]. Note that for small r, this approximation becomes inaccurate and even yields a non-physical singularity for $r = 0$. The diffusivity is related to the heat capacity c_p by

$$a = \frac{\lambda}{\rho \cdot c_p}, \tag{2}$$

where ρ denotes the mass density. For $t \to \infty$ the complementary error function erfc in Eq. (1) approaches unity such that in the steady state, the temperature distribution depends on the thermal conductivity and the heating power only:

$$\vartheta(r)\Big|_{t\to\infty} = \frac{\Phi}{4\pi\lambda\, r} \tag{3}$$

Sensor Design and Fabrication

Figure 1 shows the basic layout of the thin film microsensor. The device consists of a glass substrate (5 mm x 2.6 mm x 0.4 mm) with a resistive loop made of molybdenum as resistive sensing and heating element. Molybdenum is known for its linear resistance characteristics, which is valid over a wide temperature range. The shape of the resistive loop is especially designed to allow digital laser trimming. To avoid any chemical interaction between the resistor and the fluid, the molybdenum is covered with a silicon nitride protective layer. The bonding pad area is additionally coated with a nickel chromium adhesive layer and a gold layer. All films have been deposited by RF-sputtering in a Perkin Elmer 4400 diode system. The system allows the deposition of the nickel chromium and gold films without a vacuum interruption, which ensures the production of solderable contacts.

The film patterning has been carried out by lift off photolithography techniques. The connecting wires are bonded to the contact pads by soldering. The temperature coefficient of the resistive loop was measured to be $0.956 \times 10^{-3}/°C$ and its resistance was 112.55 Ω at 22.1°C.
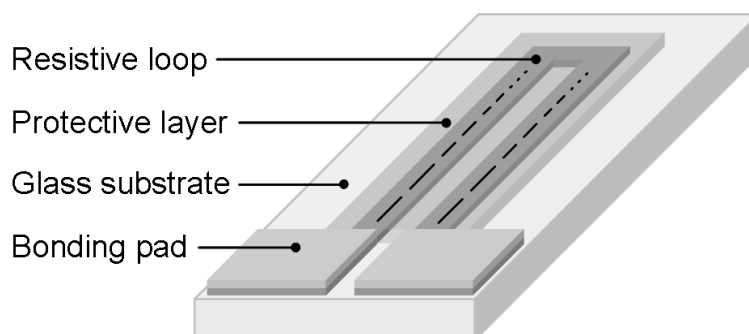

Fig. 1: Design of the hot film sensor.

Measurement Setup

The sensor was inserted into a beaker containing the sample liquid and was electrically connected to a measurement bridge as shown in Fig. 2. The differential bridge output voltage is amplified by an instrumentation amplifier (gain = 25) and recorded by means of a digital oscilloscope. By switching on the power supply (12 V), the heater current is turned on and the temporal evolution of the resistance (and thus the sensor temperature) can be monitored by recording the bridge output voltage. As long as the temperature at the walls of the beaker does not increase significantly, the assumption of an infinitely extended medium, which is also underlying Eq. (1), is approximately valid. In this case the sensor response is basically determined by the thermal material parameters of the surrounding liquid.
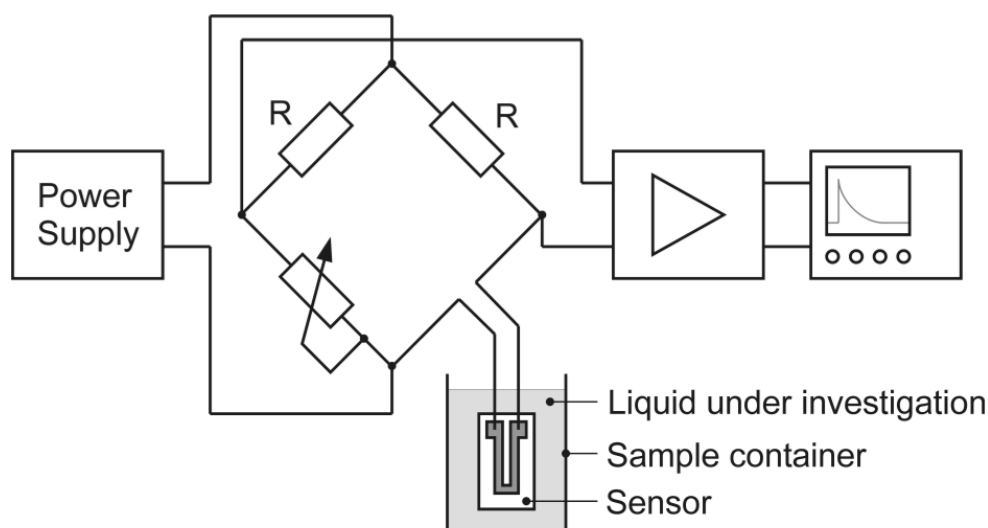

Fig. 2: Measurement Setup (R=470 Ω).

Results and Discussion

First we investigated water contamination in engine oils, where we deliberately contaminated a standard engine oil (SAE 15W40) with DI water, which leads to the formation of an emulsion. Figure 3 shows the resulting temperature rise $\Delta\vartheta$ above ambient (room) temperature versus the time t after switching on, for emulsions featuring a water content of 7%, 15% and 18% by volume compared to the pure oil sample. After the initial transient, the excess temperature becomes essentially determined by the thermal conductivity (see also Eq. (1)). It can thus be seen, that for increasing water contents the thermal conductivity of the emulsions increases, which leads to lower excess temperatures. Compared to pure oil, the excess temperature at $t = 20$ seconds is reduced by 4.7%, 10.5%, and 13.6%, for the W/O emulsions containing 7%, 15%, and 18% of water by volume, respectively.
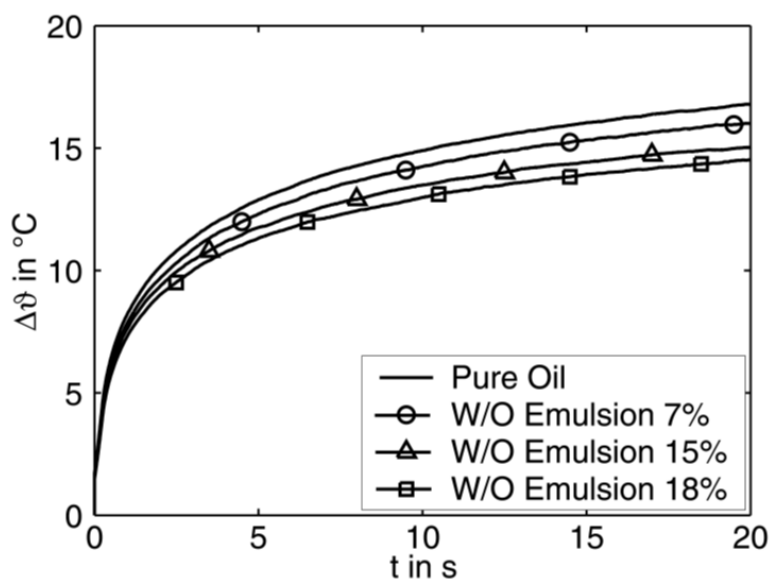
Fig. 3: Temperature rise $\Delta\vartheta$ vs. time t for W/O emulsions of 7%, 15%, 18% b.v. and the corresponding pure oil (SAE 15W40).
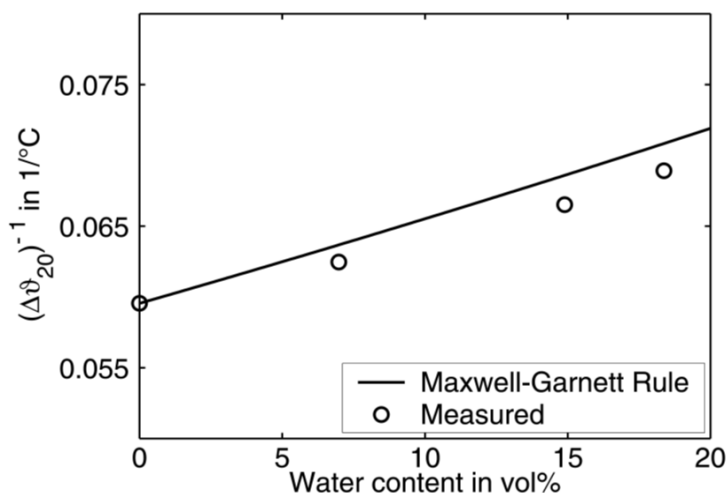
Fig. 4: Inverse of $\Delta\vartheta$ @ $t=20$ seconds (which is approximately proportional to λ) vs. water content in % b.v.

Figure 4 shows the inverse of the excess temperature, $1/\Delta\vartheta$, at $t = 20$ seconds versus the water content. At this time the disturbing influence of the boundary is still negligible and the excess temperature has virtually reached its steady state. Thus we can assume that $1/\Delta\vartheta$ will be approximately proportional to the thermal conductivity λ (see also Equ. (1) for $t \rightarrow \infty$).

In further experiments we investigated the effect of oxidative deterioration. Figure 5 shows the resulting temperature rise $\Delta\vartheta$ above ambient (room) temperature versus the time t after switching on, for engine oil (SAE 15W40) which was artificially aged at 160°C for 7 days according to a standardized method. It can be observed that the deteriorated oil features an increased thermal conductivity which could be related to water formation due to thermal oxidation processes in the engine oil. We observed a total increase of about 3.4% for the above mentioned ageing conditions.
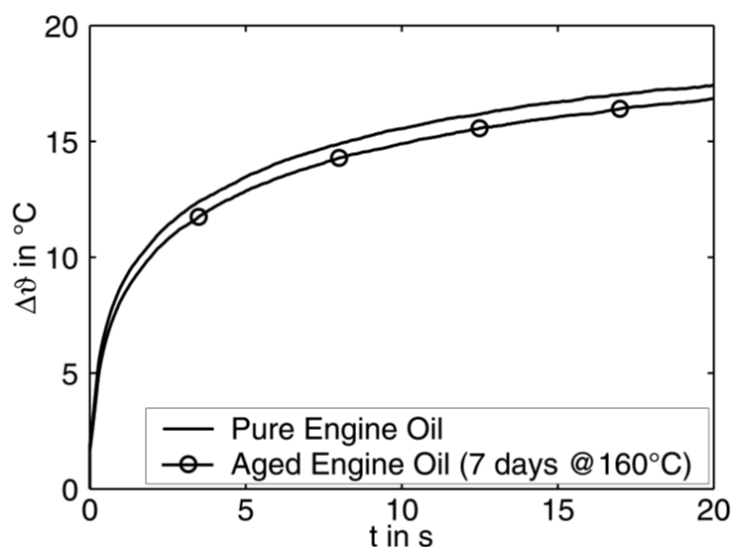

Fig. 5: Temperature rise $\Delta\vartheta$ vs. time t for pure engine oil (SAE 15W40) and artificially aged engine oil (7 days @ 160°C).

According to theoretical considerations, for the steady state the excess temperature of the sensor becomes essentially determined by the thermal conductivity of the surrounding fluid. This mechanism allows to clearly detect water deterioration in mineral oil, but underlies the restriction of a maximum measuring time that must not be exceeded to avoid the disturbing influence of the liquid boundary. To overcome this problem a transient measurement lasting several hundred milliseconds could be utilized, which would correspond to the concept of the above-mentioned hot-wire and hot-strip methods. However, as can be seen, e.g., from the measurement shown in Fig. 3, within this time frame a deviation between different samples can hardly be observed. By considering the sensor design, we find that the initial transient to a certain extent will be determined by the specific heat of the sensor substrate and the liquid. Glass features a specific heat comparable to that of mineral oil and moreover shows a very high thermal conductivity (typically 10 times higher than that of oil). Hence it can be assumed that due to the relatively thick glass substrate, the sensitivity in the initial transient regime is decreased accordingly. However, at the same time the thickness of the sensor increases its physical robustness.

To further investigate on these assumptions, a Finite Element (FE) simulation has been conducted. Figure 6 (a) depicts the simulated temperature rise $\Delta\vartheta$ within the initial transient of 500 milliseconds for an emulsion featuring a water content of 20% by volume compared to the pure oil sample. In order to evaluate the impact of the substrate thick-

ness on the initial temperature slope, we calculated the initial transient for the same sample liquids but for a sensor structure with a reduced thickness of 5 microns instead of 400 microns. Figure 6 (b) shows the resulting excess temperature and the initial temperature slope. As expected reducing the thermal mass of the sensor results in a steeper slope and in an increased sensitivity with respect to water contamination of the oil. Compared to the pure oil sample, the initial transient slope, $d\Delta\vartheta/dt$, for the emulsion was -13.0% and -24.5% smaller for the thick and the thin glass substrate, respectively. This indicates the increase in sensitivity for the transient measurement method that can be obtained by reducing the influence of the glass substrate by making it thinner. Thus the sensitivity generally increases if a thinner glass substrate is used. In practical applications, the mechanical robustness of the sensor has to be considered as well, which accordingly requires a trade-off in choosing the thickness.
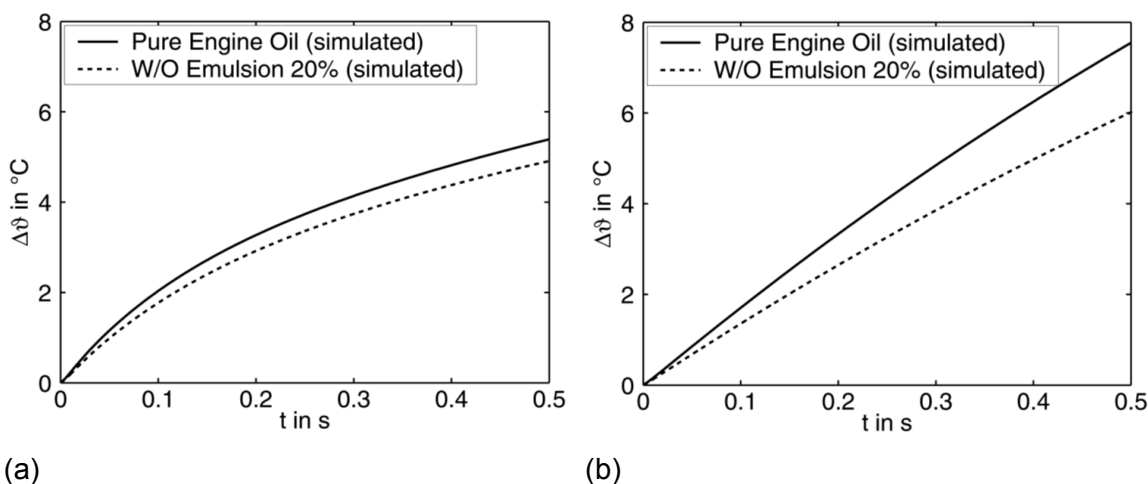

(a)   (b)

Fig. 6: (a) Simulated temperature rise $\Delta\vartheta$ vs. time t of the initial transient for W/O emulsions of 20% b.v. and the pure oil. (b) Simulated temperature rise $\Delta\vartheta$ vs. time t for a glass substrate with a reduced thickness of 5 µm.

Conclusion

In this contribution we discussed the applicability of thermal conductivity sensing for liquid condition monitoring. As sample applications we considered the water contamination and the deterioration of mineral oils. For this purpose we performed experiments with a hot film sensor using a resistive thin-film molybdenum structure on a glass substrate. It could be shown that not only water-in-oil emulsions but also aged oils feature increased thermal conductivities compared to the base oils, which indicates that monitoring the thermal conductivity by means of miniaturized sensors could be utilized in oil condition monitoring systems. By means of numerical simulations it was furthermore found that the sensitivity of the sensing approach in the transient regime could be significantly increased by utilizing a thinner substrate, which, however, would reduce the mechanical robustness of the sensor.

Acknowledgements

References

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