A NOVEL SENSOR FOR DETECTION OF OIL CONDITION AND CONTAMINATION BASED ON A THERMAL APPROACH

Sridhar V.* and Chana K. S.
*Author for correspondence
Osney Thermo-Fluids Laboratory
Department of Engineering Science,
University of Oxford,
Oxford, OX1 3PJ,
United Kingdom,
E-mail: vikram.sridhar@eng.ox.ac.uk

ABSTRACT

Oil condition and contamination can be a major issue in lubrication systems such as aircraft, automobiles etc. Lubricating or cooling oil contamination occurs when metallic or non-metallic particles are produced due to wear of machine components and these are not captured by the filter system. Furthermore, thermal stressing causes oxidation and thereby degradation of the oil. Liquid contamination can occur from water condensation or fuel from heat exchangers. These can cause degradation of the oil and reduce the lubricating properties and clogg oil paths and accelerate the wear of moving parts. On-line oil condition monitoring systems are important for preventive maintenance especially for aircraft engine bearings, aviation gearboxes etc. Current on-line oil condition monitoring sensors are mainly eddy current, optical based. These sensors have a major drawback that they are prone to surface contamination and non-linearity. The gauges are also not sensitive enough to detect extremely small particulates or are prone to false detection such as trapped bubbles. A new sensor has been developed using thin film heat transfer sensors that can detect any form of contamination in oil such as metal, non-metals, oxidation, liquids etc. The sensor works on the principle of measuring the thermal product of the material, as the composition of the material in contact with the sensor changes the thermal product changes and can be detected. The sensor can be used for both on-line and in-line condition monitoring and has been demonstrated to be robust. Initially, lab based tests were carried out to optimise the system for sensitivity and signal to noise ratio. The sensor has been demonstrated to detect 0.25% of contaminants by mass. Experiments were carried out by seeding metallic and non-metallic particles of various sizes to an engine oil system to validate its performance.

NOMENCLATURE

c	[J/kgK]	Heat capacity
k	[W/mK]	Thermal conductivity
q	$[W/m^2]$	Heat flux
ρ	$[kg/m^3]$	Density
t	[s]	Time
T	[K]	Temperature
x	[m]	Cartesian axis direction
y	[m]	Cartesian axis direction

Subscripts

wall	Conditions at the wall
0	Initial condition

INTRODUCTION

Oil condition monitoring has become a necessity in Aerospace and Mechanical industry. The techniques to measure oil contamination is becoming an established method to predict and avoid breakdowns of gas turbine engines, automotive engines, manufacturing machines etc. The monitoring can be performed off-line in a laboratory which is time consuming or can be performed on-line. In an on-line monitoring system, samples are taken and analysed in real time and warns the user of the contamination level present in the oil.

Over the years, many sensors have been developed for oil condition monitoring. Some of the real time sensors operate based on monitoring the dielectric constant [1] [2] of the liquid. The dielectric constant is a measure of the ability of a fluid to resist an electrical field. These sensors work well in detecting water contamination as oil and water have very different dielectric values. However, a major drawback is that they are temperature dependant. Another method used in monitoring is based on various optical techniques, such as infrared spectrometry or particle sizing. These however have a limitation of contamination of optics. Hall effect sensors have also been deployed where ferrous particles are identified and quantified [3], but again they are unable to work on non-ferrous particles. This approach is advantageous in that it makes it possible to track the progress of debris contamination. Acoustic sensors have also been developed to measure the changes in viscosity using micro acoustics [4] or by measuring the shear motion of a piezoelectric resonator immersed in oil [5].

The main aim of this work is to develop a new sensor based on measuring the thermal product of the material that is in contact with the sensor and its application in the detection of contamination in oil, fuel etc for real-time applications.

WORKING PRINCIPLE AND THEORY

The sensor's working principle is based on measuring the thermal product of a material in contact with the sensor. The sensor basically contains thin film platinum gauges. When an electrical square pulse of certain amplitude and duration is passed through the sensor, the sensor's temperature increases as some of the heat is dissipated in the sensor's bottom and some is dissipated in the surrounding material and a certain temperature is recorded by the sensor. As the surrounding material composition changes, the dissipated heat between the sensor substrate and surrounding material changes. The change can be correlated to the change in thermal product of the material. In the case of contamination of oil, the thermal product will be different for the contaminants compared to the oil (Thermal product $\sqrt{\rho c k}$ for oil is 500 and metals is 22,000) and hence the heat transfer will be different.

The relation between heat transfer and thermal product is derived as follows:

The heat transfer equation is given as

$$\frac{\partial^2 T(x,t)}{\partial x^2} = \frac{1}{\alpha(x)} \frac{\partial T(x,t)}{\partial t} \tag{1}$$

where T is temperature, x is distance in the substrate, t is time and

$$\alpha = \frac{\rho}{kc} \tag{2}$$

The analytical solution for a step function in temperature of this equation is evaluated as:

$$\dot{q}_{wall} = (T_{wall} - T_0) \frac{\sqrt{\pi}}{2} \frac{\sqrt{\rho c k}}{\sqrt{t}} \tag{3}$$

where $\dot{q}_{wall}$ is heat transfer rate, T_{wall} is wall temperature, T_0 initial conditions.

$$q_{wall} \propto \sqrt{\rho c k} \tag{4}$$

This shows that the heat transfer to a material is directly proportional to the thermal product of that material.

EXPERIMENTAL SETUP

The experimental setup consists of thin film heat transfer gauges painted on a Macor® disc and placed in the bottom of a cylindrical steel container as shown in figure 1. Two thin film gauges were used and an average reading was taken from the two. An electronic circuit was built to generate the variable amplitude and duration pulse and another circuit to measure the change in resistance of the sensor. The data was recorded using National Instruments DAQ card NI USB-6361 and LabVIEW® software. MATLAB® was used in post processing of the data.

Figure 1: Setup for measuring contamination

The data was sampled at 100 kSPS and for each sample, eight tests were carried out to ensure repeatability without removing the sample and subsequently the samples were averaged to give the final reading. The tests were performed at constant temperature.

PRELIMINARY TESTS ON SENSOR

Once the sensor was built, it was decided to check the repeatability, accuracy and linearity of the sensor. For these preliminary tests, acetone and distilled water were used.

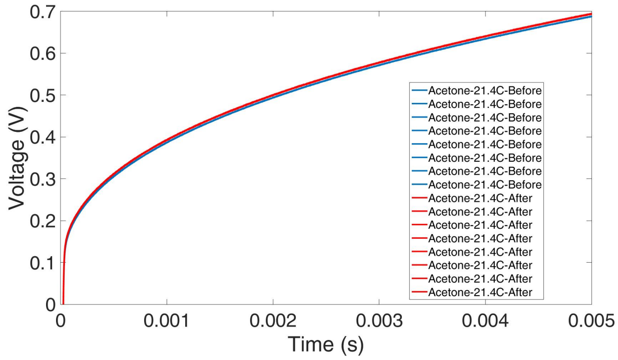
REPEATABILITY

One of the important characteristic of a sensor is the repeatability of the measurements. To check the repeatability of the sensor, two tests were carried out using acetone. In the first test, eight readings were taken without removing the sample in the container and in the second test the acetone was removed and refilled in the container to the same temperature. Notably, the readings in both cases as shown in figure 2a and 2b are very consistent which shows that good repeatability is achieved with the sensor.

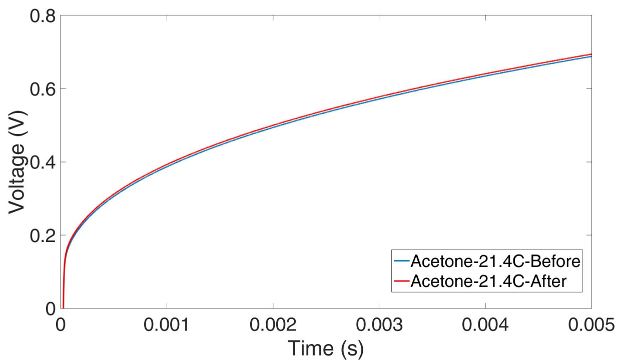
EFFECT OF TEMPERATURE

A well known fact about heat transfer measurement is that it is temperature dependent. Since this sensor has to be incorporated into various application where the temperatures will not be constant, it has to be shown that the variation with temperature is linear so that temperature correction can be incorporated in the electronics.

In the previous section, it has already been shown that the sensor is reproducible at constant temperature. Tests were conducted at three different temperatures using acetone. Figure 3a shows that as the temperature increases, the curve shifts upwards.

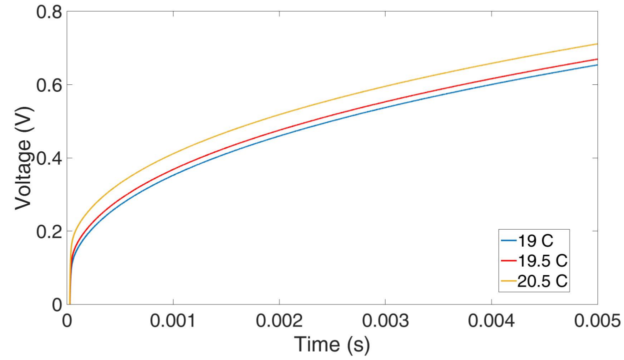


(a) Repeatability of readings at fixed temperature without changing the sample

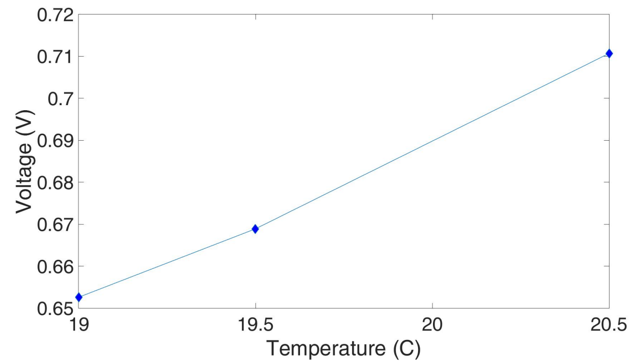


(b) Repeatability of readings at fixed temperature by changing the sample

Figure 2: Repeatability tests at fixed temperature



(a) Varying temperature



(b) Linearity with temperature

Figure 3: Effect of temperature on the sensor

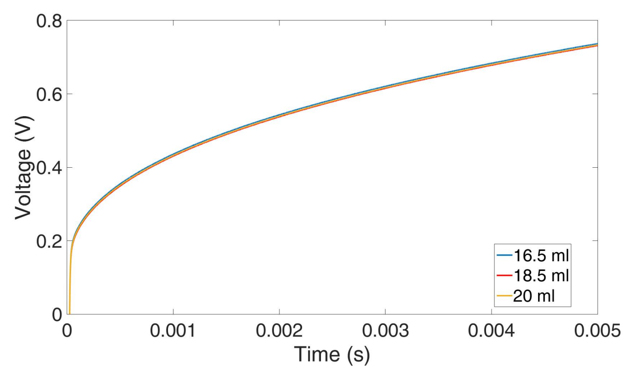


Figure 4: Effect of quantity of liquid on the sensor

We also find that the shift is linear with temperature as shown in figure 3b.

EFFECT OF QUANTITY

Another parameter that needs to be considered is the amount of quantity of liquid in the container. In actual operation this may vary significantly and is difficult to keep constant. Tests were conducted with three different quantities of acetone. The results as shown in figure 4 clearly show that increasing the volume had no effect on the sensor's readings. The volume has no effect on the sensor's readings although care has to be taken that there is enough liquid present to cover the sensor.

EFFECT OF MAGNET

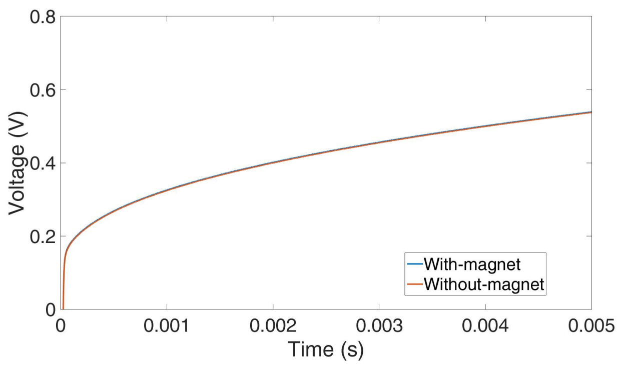
A magnet was placed in the container above the sensor as shown in figure 5a. This test was done as the final version of the sensor will have powerful magnets beneath the Macor®to attract ferromagnetic particles. From figure 5b we can see that the magnet has no effect on the sensor's readings.

From the above tests, the sensor satisfies most of the general sensor requirement and is being used for further tests on oil and fuel samples.

In the case of oil tests, both metallic and non metallic contaminants. Metallic particles of of size 50 μm and 200 μm from M50, S82D and S135D steel and non metallic particles of 10 μm size from silicon nitride (Si_3N_4) powder were used. These materials were chosen as they are used in bearings, gearbox etc. in engines.

In the case of fuel samples, only two samples were tested. The first sample was non-clay treated and the second sample was clay treated which removes all the water and other surfactants.

(a) Setup with magnet



(b) Thermal product of distilled water with and without magnet

Figure 5: Effect of magnet on the sensor

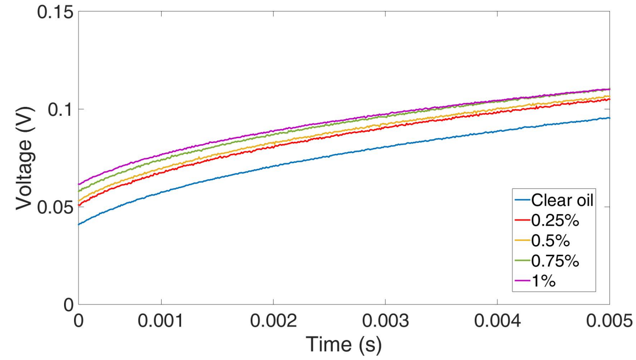
OIL TESTS

As discussed in the introduction, contamination in oil is a major issue and can lead to excessive wear and failure of machinery. Experiments were conducted with SAE 5/30 oil with metallic and non-metallic contaminants.

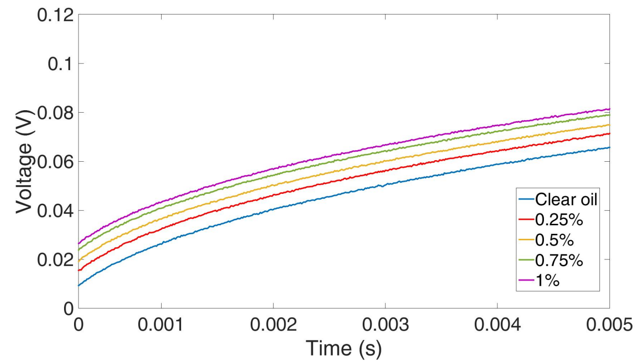
METALLIC PARTICLES 50 μm and 200 μm

Figures 6 and 7 shows the thermal product curves for a standard SAE 5/30 oil with various metallic contaminants of 50 μm particles generated from three different steels generally found in aerospace applications: M50, S82 and S135. In the experiments, the contamination (metallic powder) is increased in steps of 0.25%. Future experiments will be focussed on getting the exact sensitivity of the sensor. From figure 6, we see that the thermal product curve shifts higher as the concentration of the contaminants is increased. This is due to the fact that the thermal product of steel particles ($\sqrt{\rho ck}_{M50} = 9501$) is much greater than oil ($\sqrt{\rho ck} = 446$).

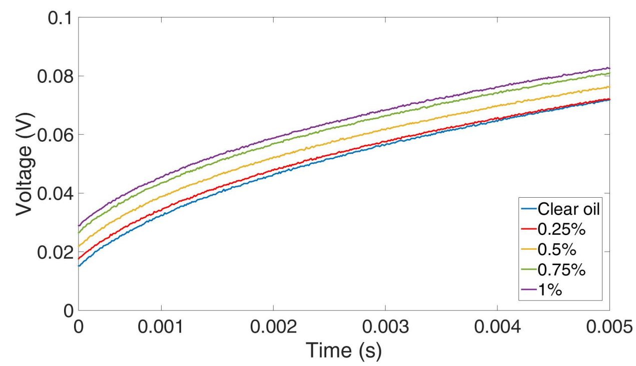
The next step was to increase the size of the particles from 50 μm to 200 μm. Again, we increase the concentration in steps of 0.25 %. Figure 7 shows the thermal procut for all three metallic contaminants and we find that as the concentration increases, the thermal product curve increases. The effect of particle size at present seems to have no effect on the sensor.



(a) M50 50 μm particles in oil



(b) S82 50 μm particles in oil



(c) S135 50 μm particles in oil

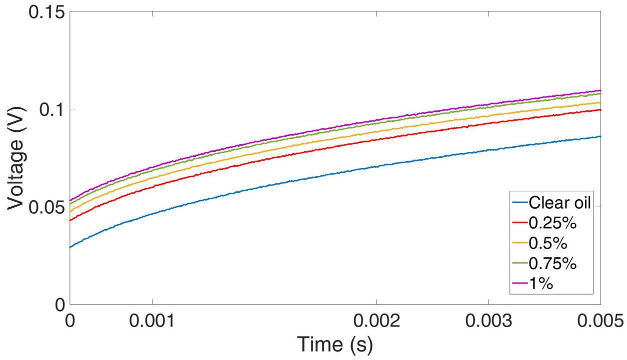
Figure 6: 50 μm metallic contaminants in oil

NON-METALLIC PARTICLES 10 μm

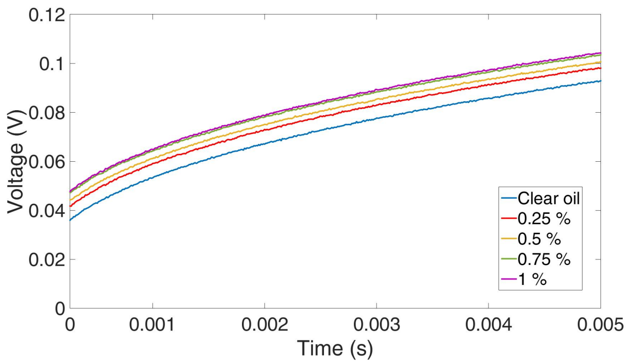
Tests were also conducted with silicon nitride powder of 10 μm and as shown in figure 8, the thermal product increases as the concentration increased.

LINEARITY

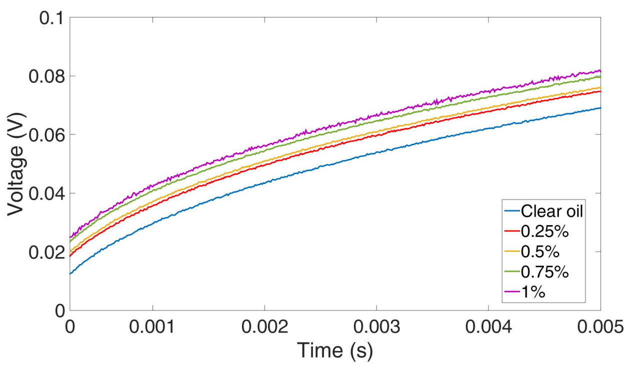
Using all the previous data, from figure 9, the sensor's response to contamination is linear. At present, the sensor is found to be sensitive as it is able to detect 0.25 percent of the contamination. Based on the results, the size of the particles does matter as the particles in contact with the sensor changes based on the



(a) M50 200 μm particles in oil



(b) S82 200 μm particles in oil



(c) S135 200 μm particles in oil

Figure 7: 200 μm metallic contaminants in oil

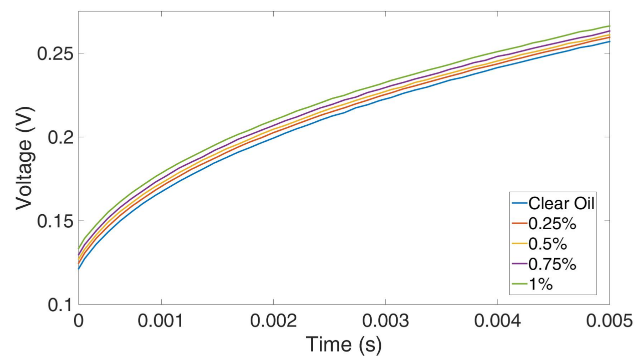


Figure 8: 10 μm Si3N4 particles in oil

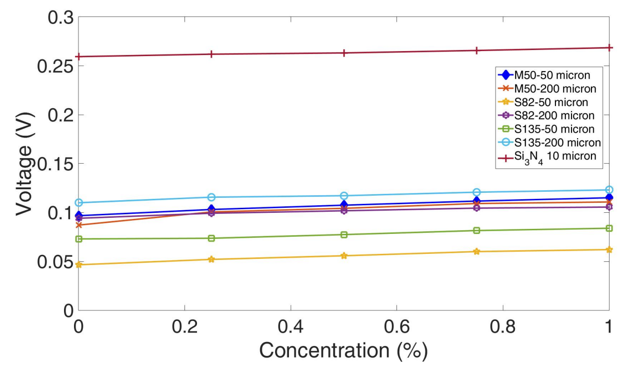


Figure 9: Linearity of the sensor

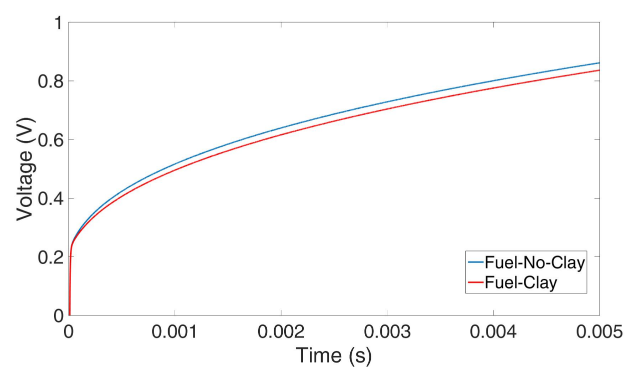


Figure 10: Clay treatment of fuel samples

size.

FUEL TESTS

Clean and dry fuel are generally obtained by using filter/separators containing coalescer cartridges. These filters remove water by coalescing the small water droplets, generated by pumps, into large drops which can settle in filter/separator housings. However, the fuel contains surfactants which are carried over from refinery or cross-contamination of pipelines. These are chemical compounds attracted to surfaces and interfaces and move to the interface of fuel and water, and disrupt the coalescing process. Clay treaters is know to remove these surfactants and allow coalescers to perform their function [6]. However, in order to know whether the fuel sample is clay treated or not will require spectroscopy which is a time consuming process and currently cannot be carried out on-line.

The sensor was used in the present case to check if it can distinguish between the two fuel samples which can be very useful for checking the quality of fuel. Figure 10 shows the thermal product curves for the two fuel samples with and without clay treatment and notably the sensor is able to show changes in the thermal product.

CONCLUSION

A novel sensor based on measurement of thermal product is developed and is found to work well in detecting contamination. The sensor is found to be immune to electric and magnetic interferences and is independent of the quantity of fuel used. In the present scenario, the sensor was able to detect 0.25 percent of contamination and was found to have linear variation with contamination.

ACKNOWLEDGMENT

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