

Development of a Low Cost Water Contamination Sensor using Absorption Spectroscopy

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Abstract

Water contamination in hydraulic fluid and other oils can reduce the life of machinery and equipment. Water can cause depletion of some additives; while interacting with other additives to form corrosive byproducts. These corrosive byproducts can attack metals and cause rust. In addition, water contamination can also cause a reduction in filterability, hydrogen embrittlement, and increase the chance of cavitation occurring. In order to prevent these adverse effects it is advantageous to have a mechanism for monitoring water contamination levels in a hydraulic system. While there are currently several tests for determining if water is present in a hydraulic system, all have undesirable limitations. Absorption spectroscopy using a ~1480 nm laser was investigated for use as an accurate approach to measure the concentration of water in oil. This approach will allow for real-time, inline, accurate and low cost water contamination sensors to be developed. A test cell was constructed and absorption measurements were made for two water contamination levels, 275ppm and 455ppm, at various temperatures ranging from 100-200°F. Signal varied linearly with temperature and decreased with increasing water concentrations.

Keywords: Water, Contamination, Absorption Spectroscopy

1. Introduction

Often times, machinery requires lubrication by oil in order to function properly. In other situations oil is utilized as a media for transporting power. Hydraulic fluids transmit power or pressure generated by a pump through hydraulic lines to a cylinder or actuator. Transmission fluids lubricate gearbox assemblies where power is transmitted from an engine to a driving axle. Irrespective of the application, hydraulic fluid performance will degrade if subjected to contamination. Hydraulic contaminants can be either solid particles or liquids; of the two, water is the most common¹. Solid particles can contaminate hydraulics by either chemically reacting with the fluid, or pollute the system through buildup. The action of water as a contaminant varies from system to system. Water can occasionally combine with the fluid, or it could be partly divided, floating on the surface or settle to the bottom of the fluid depending on the relative density. The presence of water eventually causes decomposition of the system components which results in contamination of the fluid by deterioration of the product¹. Water usually forms in the system as a result of condensation, coolant leakage, or free water access during equipment

cleaning or environmental exposure². Water can deplete some additives and react with other additives to create corrosive byproducts; these byproducts can destroy some metals. In addition water can also reduce filterability and cause hydrogen embrittlement³. There are established water concentration limits (SAE AIR810C 2001-03⁸) of 100 to 500 ppm for mineral oil and synthetic hydrocarbon hydraulic fluids used in test stands. The higher the water contamination is the lower the life of the machinery. The more water that gets into the oil the more it will corrode and break down additives causing failure to the machine.

Corrosion mechanisms can be very costly for consumers if oil becomes contaminated with water. When contamination occurs the hydraulic fluid in the system has to be changed, in advanced cases replacement of parts is necessary. An estimated 6% of failures in the hydraulic field can be attributed to water contamination. Application of tribological principles can lead to savings of 1.0-1.4% of an industrial country's GNP⁴, for the United States this equates to over 124 billion USD in 2005 alone⁵. Current methods for removing free and emulsified water include: polymeric filters, vacuum distillation, and headspace dehumidification⁷. Operators do these steps even when not necessary, it is a precautionary task, which costs the companies money. As hydraulic fluid accounts for ~8% of annual lube consumption⁶ or an estimated 10 billion annually, reducing the frequency with which oil changes occur can lead to significant cost savings.

Water concentration measurements in crude oils using absorption spectroscopy have been shown to work, achieving reported accuracies of 0.01% or 100 ppm⁹. These initial investigations used a broadband white light source for the irradiance and did not progress past the laboratory test stage. A new sensor has been developed utilizing a similar technique but uses a diode laser as the light source, this method reduces the cost and increases the accuracy of the system. Due to the monochromatic nature of diode lasers, no monochromator or filters are necessary to isolate the region of the spectrum of interest. Diode lasers have been used in telecommunications in recent years; which has driven major advances in availability and a reduction in cost. Diode lasers are available in wavelengths ranging from visible through the near infrared (~400 - 2000 nm).

Although there are other tests that can be used to detect water in oil, one such test being the Karl-Fischer test, each have their disadvantage which this sensor seeks to eliminate. The Karl-Fischer test is highly accurate, but an oil sample needs to be removed from the machine and titrated, making this technique useless for online real-time determination of water concentrations. The Karl-Fischer test also has several drawbacks including; incomplete solubility which limits sample size and therefore increases uncertainty, interfering side reactions caused by oil additives that can generate a false reading for water concentration. The advantages using absorption spectroscopy with a diode laser source include; in-situ, real-time, and inexpensive monitoring.

Absorption spectroscopy is the absorption of photons by one or more substances present in a sample. As electromagnetic radiation passes through a medium, photons are absorbed, which leads to an attenuation of the incident beam's intensity, I_o . This reduction in intensity is calculated by the Beer-Lambert law,

$$\frac{I}{I_o} = \exp\left(-\int_0^l \alpha \cdot C \cdot dl\right) \quad (1)$$

Where l is the path length, C is the concentration of the absorbing media, and α is the absorption coefficient of the media. The absorption coefficient for liquid water has been

thoroughly investigated^{10,11} for the lower wavelengths of the near infrared (NIR) spectrum and is shown in Figure 1 along with the absorption coefficient of crude oil.

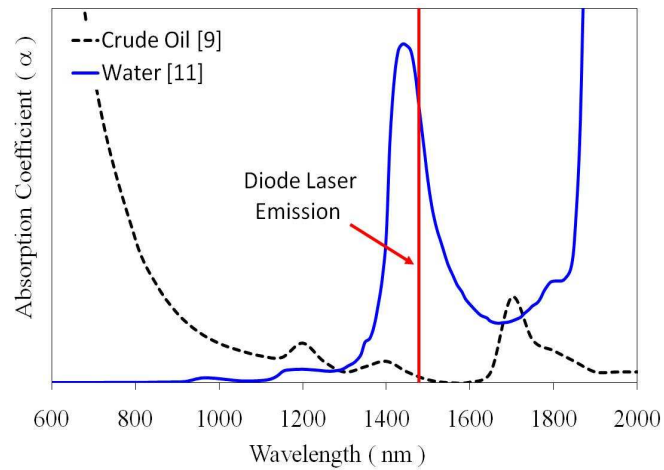


Figure 1. Absorption coefficient for pure water and crude oil in the NIR spectrum.

Figure 1 clearly shows the absorption peaks for water to be around 1470 and 1900 nm, while the crude oil does not readily absorb at these wavelengths. Although papers detailing the temperature dependence of water absorption indicate the absorption peak around 1470 nm is temperature sensitive, a linear trend is anticipated¹².

2. Technical Approach

The experimental setup used in the laboratory investigation is shown in Figure 2.

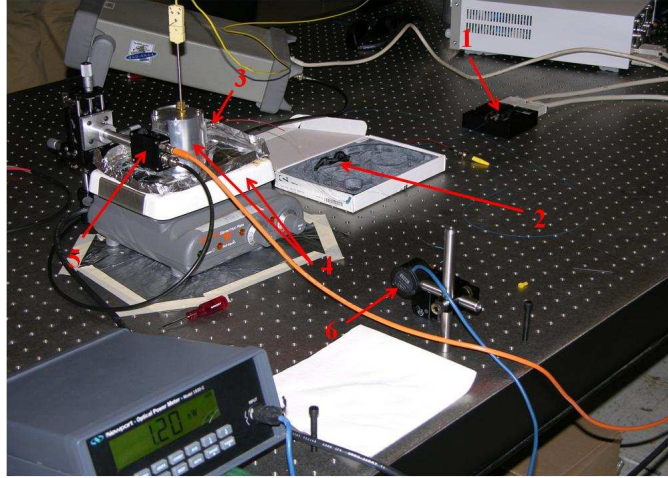


Figure 2. Experimental setup consisting of: (1) a laser light source, (2) a 50/50 splitter, (3) a collimating lens, (4) the test cell and hot plate, (5) a photo detector, and (6) a power-meter.

A FiTeL® 1480 nm pump laser module, 140 mW max output, was utilized as the light source for the absorption measurements. The laser output is controlled by a ThorLabs ITC510 bench top laser diode and temperature controller. For the purpose of the tests conducted the TEC was held at a constant temperature. Diode lasers work by giving off monochromatic light, however in the case of the laser utilized here the output spectrum and intensity will vary with LD forward current, which can be seen in Figure 3. The output of the laser is easily coupled into fiber optics for transmission and measurement of the laser's output. When the current of the laser is changed the wavelength is shifted, as such for all experiments reported a current of 600 mA was used. The ~1480 nm diode laser used in this experiment was chosen based on the spectra of crude oil and water, Figure 1. At the given wavelength oil has minimal absorption of the laser where water has a very strong peak.

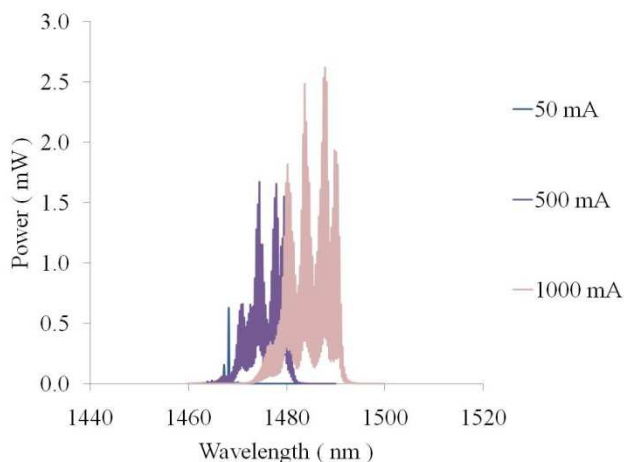


Figure 3. Laser characteristics

The output fiber from the laser is connected to a 1x2 fiber coupler (JDSU FFC-3K31AB111) allowing 50% of the lasers power to be sent to a collimating lens and 50% to a optical power-meter (Newport 818-IR). The laser beam which goes through the collimating lens (ThorLabs F260FC-1550) is passed through the test cell and collected by the photo detector (ThorLabs PDA10CS). When the laser beam passes through the test cell, it is absorbed by water in the test cell. The laser beam is then collected by the photo detector which reads out the power of the laser, referenced to as, I in the Beer-Lambert law. The power meter in turn allows for monitoring of the incident radiation, I_0 in the Beer-Lambert law. A calibration was performed in which the test cell is emptied of oil, absorption from humidity in the air is assumed to be minimal, and power meter values are correlated to voltage output from the photo detector.

The test cell used in this experiment has a path length of 1 inch with two windows on either side. The window directly in front of the laser has an anti-reflective coating on it to reduce reflection of the laser. The collimating lens is screwed directly into the test cell to reduce any influence room humidity may have. The test cell, detailed in Figure 4, also has a thermocouple offset from the laser beam, but at the same vertical position for monitoring the temperature of the oil. In addition a 1/4" hole on the top of the cell is used for removal of test oil for use in the Karl-Fischer titration tests.

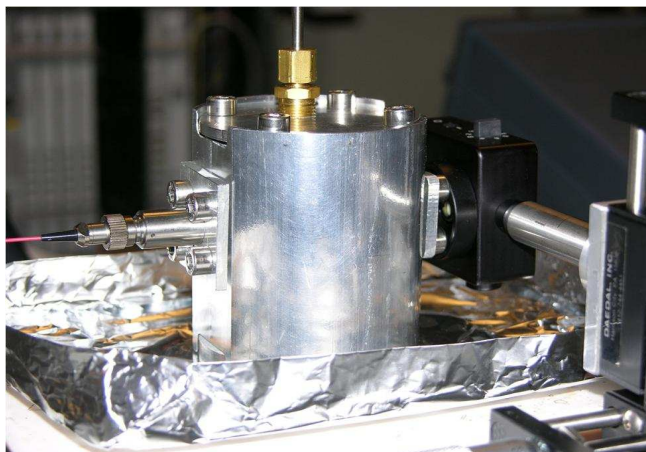


Figure 4. Test Cell

3. Experimental Procedure and Results

A large volume, ~1 L, mixture of 95% base stock (mineral oil) and 5% additive (LZ-6200 tractor fluid) was mixed for the experiment. The oil was vigorously shaken for 5 minutes so that the additive and any water was homogenous throughout the mixture. The oil was then tested by way of Karl-Fischer to see how much water contamination was already in the mixture. Five 1.6 ± 0.2 g samples were tested resulting in an average water contamination level of 275 ± 33 ppm. The test cell was filled with the oil and heated while being stirred, by way of a magnetic stirrer, until the temperature read by the thermocouple reached 200° F. The room ambient temperature and relative humidity was measured by way of sling psychrometer, with the wet bulb measurement at 62° F and the dry bulb measurement at 69° F. The oil was stirred while the temperature decreased, the stirrer was shut off, and the cell allowed to come to thermal equilibrium with the surroundings; data points were collected at approximately 5° increments, the stirrer had to be turned off due to a large vortex forming in the test cell causing interference with the laser. After the first test was complete water was inserted into the test cell. The hole in top of the test cell was used to add 20 μ L of water, from a micro-syringe, equating to approximately 200 ppm. The oil was then heated to 200° F and stirred for one hour so that the water would emulsify in the oil. The same test was then conducted on the water doped oil and plotted by way of voltage vs. temperature. The results of the two runs are shown for comparison to each other in Figure 5.

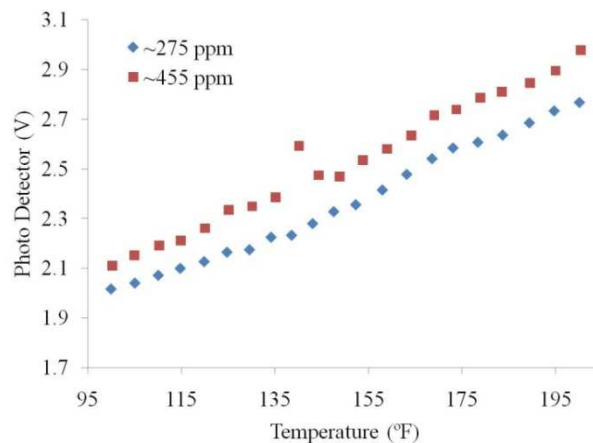


Figure 5. Photo detector voltage vs. test cell temperature with 250 ppm and 450 ppm of water.

A decrease in voltage caused by the addition of water can be seen in Figure 5, this result is as expected as the higher concentration of water should result in greater absorption of the laser's intensity. The relative humidity in the air was taken after the two experiments using a sling psychrometer. The humidity was exactly the same before and after; wet bulb: 62° F, dry bulb: 69° F. After concluding the second test, six 1.45 ± 0.13 g samples were taken to be tested in the Karl-Fischer. Three samples were taken from the middle of the cell and three samples were taken from the bottom of the cell. The sample size from the middle of the cell was 1.54 ± 0.09 g with an average water concentration of 440 ± 43 ppm, and the sample size from the bottom of the cell was

1.36±0.11g with an average water concentration of 469±24 ppm. The test confirmed that the water did emulsify in the oil and concluded an overall water concentration of water in the oil was 455±35 ppm.

4. Conclusions

It was proven that a low cost water contamination sensor using absorption spectroscopy is possible to design. The sensor would be able to detect water contamination below 500 ppm. The sensor would help reduce the cost of oil changes and part changes. There is still more testing that needs to be done, testing the oil while the oil is being stirred or moved is a must. Also thermal equilibrium is a factor; the fact that the stirrer has to be turned off during these experiments means that the temperature throughout the oil is not homogenous while the data points are being collected. Possible ways for making thermal equilibrium and movement of the oil in the test cell would be to create a hydraulic pump that pumps oil in a cycle while passing through the test cell. This would alleviate any thermal gradient by having continuous movement of the oil, as well as providing a more realistic test bed.

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