Side-polished fiber sensor for measurement of the color concentration in lubricant products

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Abstract. Color concentration is a key parameter to mark lubricant product specifications. Lubricant color does not necessarily indicate product quality, but the grade’s color range can indicate possible contamination by another product. This study aims to design a side-polished fiber to measure color concentration in lubricants. The sensor is obtained by stripping the cladding of 1 mm polymer optical fiber. The side-polished fiber weaken light intensity due to the absorptive properties of color concentrate for visible light. The light source in this study is tri-color LED and the OPT101 as a light detector. Light passing through the fiber is converted by the detector into a voltage output. The results showed that the sensor is capable of detecting the concentration of color with measurement ranging from 10 mg/L to 200 mg/L. The output voltage of sensor’s sensitivity is up to 0.039 (mg/L)/mV, 0.042 (mg/L)/mV and 0.047 (mg/L)/mV for the red, green and blue light sources respectively. The average linear correlation is 97.3 % in liquid lubricants. The designed sensor could be applied in ASTM D-1500 for color scale measurement of lubricant oil products.

1. Introduction
Performance efficiency and effectiveness of motor vehicle engines is strongly influenced by lubricant quality. Lubricant oil is used to avoid direct friction between metals in engine, so that the degree of worn metals that may cause engine damage can be reduced [1]. The optimum lubrication state can be achieved if the choice of oil is suitable with the needs and the conditions of the engine. Keys physical characteristics of lubricant includes viscosity, viscosity index, flash point, pour point, total base number (TBN), carbon residue, density, specific gravity, and color [2]. Color is usually added by manufacturers using color concentrates (dyes) to identify the type of lubricant, as shown in figure1. Vibrant colors are usually more appealing than regular lubricants. Lubricating colors does not necessarily indicates product quality, but the color range may indicate possible contamination with another materials. Changes in lubricant color indicates a chemical reaction, hence the presence of contaminants. Examples include oxidation, different types of lubricant being mixed, thermal failure produced in the combustion process, and friction in the engine. The color scale for grading lubricant products is specified in ASTM D1500 [3].
Figure 1. The color of lubricant based on the types of color concentrates (dyes).

Measuring lubricant color concentration is done through visual response by detecting light intensity transmitted through to the lubricant. Changes of light intensity responses depend on absorptivity index that results from the color concentration grade. Obtaining information about lubricant’s absorptivity index can be done using optical fiber sensors with reference to the color concentration measurement. Optical fiber applications as sensors has been developing very rapidly in the industry. Measurements with high accuracy and resolution with low procurement cost are continuously sought. Optical fiber has been utilized as a sensor in various fields including to measure oil viscosity [4]. This sensor is made of optical fiber with and without cladding. It works by being dipped into lubricant samples with different concentration of viscosity percentage. Zhao et al. [5] used fiber optic using with surface plasmon resonance (SPR) sensor method to the detect temperature. A thermosensitive liquid was combined with SPR fiber structure to measure changes in temperature by using the refractive index. Fiber optic is also used to identify change or differences in concentration is by using a fiber coupler method. Yasin et al. [6], detected magnesium ion concentration by sensing probe displacement from a concave mirror. In sum, fiber optic is proven to be versatile in the studies above, but none of them examines color concentration in lubricants with high sensitivity and accuracy, which is why the current study focuses on the area.

Sheeba et al. [7] has developed a sensor to detect the concentrations of paraffin in coconut oil based on a side-polished plastic optical fiber. The polished fiber is made by removing a cladding section of the fiber to create the penetration of the evanescent field on the optical fiber. The evanescent field can attenuate light radiation that spreads in the optical fiber as the refractive index changes. This sensor uses a polymer (plastic) fiber optic of 1 mm, whose core is exposed directly to the liquid. The device is designed to be washable and reusable.

The focus of this study is to the design a side-polished fiber to measure lubricant’s color concentration by stripping the 1 mm polymer optical fiber’s cladding. The principle of this sensor is to examine transmitted light intensity from tri-color LED by looking at the refractive index changes received by the light detector OPT101. The light intensity captured by the detector is converted into a voltage output. Changes of response based on color concentration lubricant products are then recorded.

2. Methods

2.1. Side-Polished Fiber Sensor

Figure 2 shown measurement of color concentration using an optical fiber sensor. As shown in the picture, tri-color LED is light source, polymer cladded fiber FD-620-10 is the light transmission media and OPT101 is the light detector. Fiber FD-620-10 type is made of polymer with a core and 1 mm cladding. It is classified as step-index multimode fiber. To create an evanescent field for different refractive indexes, side-polished fiber is used. The polished fiber is made by removing one side of the cladding and polished 1 cm sensing area by using alcohol. Light output is affected by refractive index of the surrounding medium on the polished surface. After it is dipped into the lubricant samples, it detects color concentration with the parameter of light intensity response.
2.2. Development of Color Concentration Measurement

As mentioned previously, the measurement system consists of a FD-620-10 fiber optic, tri-color LED, OPT101 photodiode sensor, voltage amplifier circuit, power supply circuit, ATmega8535 microcontroller minimum system board, 2×16-character liquid crystal display and serial port monitor software. The device image is presented in figure 3. The light source is a three-color 5 mm LED with separate red (λ=630 nm), green (λ=525 nm) and blue (λ=470 nm) chips inside [8]. Visible light is captured by placing a light detector at the end of the optic fiber for 400 to 700 nm wavelength. OPT101 is a monolithic photodiode used to measure light intensity with a 5-volt power supply [9]. Output voltage is released by the photodiode, which is then amplified by the voltage amplifier circuit. Output voltage is connected to the analog port via microcontroller. The voltage is then converted into a digital signal by the ADC. The results that have been processed by the microcontroller form the values for each different sample viewed on the 2x16-character LCD. To store the data, serial port monitor is connected to the computer unit using serial communication.

Lubrication sample testing is done by using transparent 250 ml plastic cuvette with two parallel holes on both sides. The hole is above the surface of the bottom. The first hole is used as a line of the light source and the second hole as a line of the detector. Fiber that has been polished on its side with the length of 1mm is passed through the hole. In this way, the sensing area is located in the center of the cuvette. Each hole is glued with adhesive so that it can clog and the sample does not leak while in the cuvette. Then, the lubricant is poured into the cuvette, with the sensing probe set. Data retrieval is done by recording the value of the output voltage in each sample.
Figure 3. Color concentration measurement system.

Table 1. Components of color concentration measurement system

| No. | Component                                      |
|-----|-----------------------------------------------|
| 1   | Tri-color LED                                 |
| 2   | FD-620-10 fiber optic                         |
| 3   | OPT101 photodiode sensor                      |
| 4   | Voltage amplifier circuit                     |
| 5   | Power supply circuit                          |
| 6   | ATMega8535 microcontroller board              |
| 7   | 2×16 character LCD                            |
| 8   | Cuvette                                       |

2.3. Lubricant Samples with Different Color Grades
The lubricant sample is prepared by dissolving dyes into transparent oil-based lubricant. The color changing from transparent to opaque is used as reference samples. The color concentration of the sample is obtained from 1 liter oil-based lubricant added with 10-250 mg color concentrate powder. The mixture of 1 liter oil-based lubricant with 10 mg color concentrate powder, can identify 10 mg/L or 10 ppm. Lubricant samples with different concentrations are shown in figure 4. They are prepared with concentration of 10, 50, 100, 150, 200 and 250 mg/L. They are placed into each transparent plastic cuvette in the sample with the volume of 2 mL.
3. Results and Discussion

By using photodiode sensor, RGB lights from the LED are emitted on the samples within different colors. Output is displayed on the monitor in the form of analog voltage converted to 10-bit ADC. The LCD is used as a monitor and the computer unit is used to store data by serial communication. The installation of the lights is parallel to the optic fiber device. The voltage is displayed on the monitor to show intensity of light captured by the photodiode.

The peak voltage characteristic is tested to determine the output voltage of the detector based on a different color wavelength. The detector is designed to receive LED light in different colors (red ($\lambda=630$ nm), green ($\lambda=525$ nm) and blue ($\lambda=470$ nm)), with input voltage supply ranging between 4.8 and 5.1 volt. The voltage value is to obtain output signal from the detector. The first test is done by forcing the light source directly to the detector without passing through the optical fiber, with a distance of 5 mm. The second test is done by placing the light source through the fiber in an empty cuvette and clear water filled in the cuvette to determine the voltage response of the detector. Figure 5 shows the comparative characteristics of the detector.
Figure 5. Comparative characteristics of the detector.

Table 2 shows the peak voltage characteristic of the detector using OPT101. The testing is to determine the voltage response of the detector without the optical fiber, using optical fiber with air and water inside the cuvette. For each test, responses are taken from the three different colors from the light source. The difference is the maximum voltage values that is produced by the detector before it is amplified. The peak voltage of the detector is in the range of 0.1-0.8 volt. Based on the range of values in voltage, it can be seen that responses without the optical fiber are higher than others. The detector shows voltage responses for the red, green and blue color. Blue has the highest value and red has the most sensitive value. With air inside the cuvette, red is in the range of 0.13 volt. With water inside the cuvette, the peak voltage of red is within the range of 0.27 volt.

| Condition                        | Output Voltage (V) |
|----------------------------------|--------------------|
|                                  | Red    | Green  | Blue   |
| Without optical fiber            | 0.41   | 0.56   | 0.75   |
| Using optical fiber in air       | 0.13   | 0.16   | 0.34   |
| Using optical fiber in water     | 0.27   | 0.33   | 0.45   |

The analysis is then carried out to examine the color concentration measurements of the lubricant with the principle of side-polished optical fiber, with variation of the light source. The color of the oil being tested has a concentration of 10mg/L, 50mg/L, 100mg/L, 150mg/L, 200mg/L and 250 mg/L. The light source is the tri-color LED through the fiber FD-620-10, with wavelength of 630 nm, 525 nm and 470 nm. PWM is used to generate different voltages for the LED to get the desired color. The detector is placed on the tip of the fiber by using the monolithic photodiode.
Figure 6. Relationship concentration and output voltage using red light source.

Figure 7. Relationship concentration and output voltage using green light source.

Figure 8. Relationship concentration and output voltage using blue light source.
Table 3. Characteristic of the color concentration sensor.

| Light Source Color | Sensor Sensitivity (mg/L)/V | Sensor Linearity % |
|--------------------|-----------------------------|-------------------|
| Red                | 0.39                        | 91.75             |
| Green              | 0.42                        | 94.17             |
| Blue               | 0.47                        | 96.98             |
| Average linear correlation |                     | 94.27             |

Figure 6 to figure 8 show the relationship between the concentration and the output voltage for each light source color from LED and the test samples from the colored lubricants with concentration ranging from 10mg/L to 250 mg/L. The data trend line increases as the color concentration increases, which results in the increase of output voltage. The output voltage is obtained by a linear regression function of the concentration to find the characteristic of the sensor. The highest sensitivity and linearity obtained by the sensor as shown in Figure 7 is 0.47 (mg/L)/V and the light source is 96.98% the blue color.

4. Conclusion

It can be concluded that there is inversely proportional relation between the color source wavelength and the voltage output in the detector the greater the wavelength, the smaller the output voltage. There is directly proportional relation between the level of dye concentration and the voltage output the greater the level of concentration, the greater the output voltage there is increasing sensitivity along with increasing light source wavelength the value of sensitivity up to 0.39 (mg/L)/V, 0.42 (mg/L)/V and 0.47 (mg/L)/V for red, green and blue respectively, and the measurement range of 10 mg/L to 200 mg/L with a linear correlation is 94.27% on average.

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