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A Study on Effect of Temperature on Lubricating Oil Using Bare and Bent Optical Fibre Sensor: A Theoretical and Experimental Approach

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***Abstract*— This paper describes a bare and bent multimode optical fibre sensor to study the effect of temperature on a pure lubricating oil sample. It describes both mathematical and experimental analysis of the oil sample when subjected to high temperature. The sensor system consists of (i) a bare and bent multimode optical fibre (BBMOF) sensor (ii) LM35 temperature sensor (iii) microcontroller system for sampling of data. The BBMOF is immersed in a lubricating oil sample and subjected to varying temperature. The BBMOF is used to measure the refractive index (RI) of the oil sample and the LM35 is used to provide the measure of temperature of the lubricating oil sample. The measure of the refractive index (RI) and temperature are sampled by an ATmega 32 microcontroller based system for processing and further analysis of measured data.**

***Keywords*— Lubricating oil, optical fibre, refractive index, microcontroller**

I. INTRODUCTION

Lubricating oils are employed in internal combustion engines and are required to perform a variety of task. Foremost is the minimization of wear. Due to its viscosity and non-compressible nature, lubricating oil keeps the moving components from contacting with each other.

Lubricating oil is also used for resisting shear forces, minimize gear wear, maintain engine cleanliness and control acid corrosion, resist foaming and control rust corrosion. However, if the oil is highly viscous and has greater internal resistance then the oil tends to increase the temperature of the engine. Decrease in the viscosity of the oil also degrades the lubricating oil [1].

Viscosity plays an important role as it brings out the oil capacity to lubricate [2]. For this reason lubricant standard were developed. Nowadays oil viscosity is identified by its SAE (Society for Automotive Engineers) number.

The thinner the oil, lower is its number, e.g. SAE 10 W. The numerical relates to viscosity at particular temperature and the letter 'W' indicates the oil suitability for colder temperatures. However, there is another service classification of oil apart from its viscosity, developed by API (American Petroleum Institute), which indicates service characteristics. It is graded on a scale from SA (the lowest) to SJ (the highest), for gasoline engines it is graded on a scale from CA to CG [3].

The viscosity of lubricating oil is affected by the temperature of the engine, the ambient temperature, its use in the engine, additives, shear forces etc. The temperature changes during use affects the viscosity. As the temperature increases, the viscosity decreases. Shear forces within the engine, especially during transmission, can also reduce the viscosity. Ambient temperature also reduces the oil viscosity. Oil thickens as the outside temperature decreases, leading to pumpability and circulation problems. Oil viscosity is also reduced due to normal use [1].

Fluid temperature grossly affects chemical stability and particularly the oxidation rate of the basic elements of oil [3]. The primary accelerator of all oxidation reactions is temperature. Like any other reaction, the oxidation rate of hydrocarbons will approximately double for every 15 degree Celsius increase in temperature. Below 60 degree Celsius, the reaction is comparatively slow, but the life of oil is reduced by 50 per cent for every 15 degree Celsius temperature rise above 60 degree Celsius, according to the Arrhenius equation for chemical reaction rates. Hence, for high–temperature applications, the oxidation stability of oil can have great significance [4].

The viscosity of oil (kinematic viscosity) is related to the density which is again related to the dielectric constant by the Debye equation [5]. The effect of temperature on viscosity of lubricating oil has been studied by observing the change in electrical conductivity of oil with change in temperature [6].

Since $\varepsilon_r = n_l^2$, (as shown by the Clausius–Mossotti equation) [5], where ε_r is the dielectric constant and n_l is the refractive index, the relation of RI with temperature, polarizability, dipole moment, density, molecular mass and kinematic viscosity (as given in the Debye equation and Clausius–Mossotti relation), can be used for finding the degradation of lubricating oil.

One of the common methods of measuring the RI of a material is the use of a Refractometer [7, 8]. Optical fiber refractometer has been used in the simultaneous analysis of RI and temperature in transformer oil [9].

This paper describes a microcontroller based instrumentation system to study the effect of temperature on a pure lubricating oil sample using a BBMOF based optical sensor and LM35 IC temperature sensor. To prepare the BBMOF, a length measuring 40 mm around the center of a multi-mode optical fiber (whose length is 60 cm) is made open by removing the plastic jacket and then removing the cladding of the BBMOF portion of the optical fibre by mechanical stripping. The bare portion of the optical sensor is given a shape of a semicircular arc of fixed radius of curvature to add macro bending effect. The BBMOF is used to fabricate an optical sensor, using a Diode laser source and a LDR as a detector. Laser beam from the Diode laser Source is launched at one end of the optical fibre. The power transmitted through the bare and bent portion of the multi-mode optical fiber depends on the RI of the liquid applied around it. The laser beam propagates through the BBMOF is incident on the surface of the LDR. The resistance value of the LDR changes according to the change in RI value of the liquid surrounding the BBMOF. The LDR is connected across a 5 volts supply with a series resistance to form a potential divider circuit. The output of the potential divider circuit changes according to the change in resistance of the LDR which is again a function of RI. The output voltage of the LDR based potential divider circuit and output voltage of the LM35 IC is stored in the microcontroller flash memory sampling the input voltages from the potential divider and temperature sensor IC.

II. RELATION BETWEEN REFRACTIVE INDEX, VISCOSITY AND TEMPERATURE

The relation between the dielectric constant ε_r and the microscopic polarizability α, of the molecules constituting the lubricating oil is given by the Clausius–Mossotti [5] relation as-

$$\alpha = \frac{3}{N}\left(\frac{\varepsilon_r - 1}{\varepsilon_r + 2}\right) \qquad (1)$$

Where, ε_r is the permittivity (dielectric constant) of the oil, α is the polarizability and N is the number of molecules per unit volume.

Again we have

$$\frac{n^2-1}{n^2+2} = \frac{1}{3}\sum_i n_i\alpha_i \qquad (2)$$

Where n is the refractive index of the oil and $n^2 = \varepsilon_r$.

$N\alpha = \sum_i n_i\alpha_i$ represent the individual polarizabilities as additive.

Equation (2) is further modified as-

$$\frac{M}{\rho}\frac{n^2-1}{n^2+2} = \frac{1}{3}A\alpha$$

Therefore,

$$\frac{n^2-1}{n^2+2} = \frac{A\rho\alpha}{3M} \qquad (3)$$

Where A is the Avogadro's number (6.02×10^{23} molecules of oil/mole), ρ is the density of the oil (gram/cm^3) and M is the molar mass of the oil (gram/mole).

According to Stokes-Einstein relation,

$$\mu_0 \propto \rho$$

$$= \vartheta_0\rho$$

Therefore

$$\rho = \frac{\mu_0}{\vartheta_0} \qquad (4)$$

Where μ_0 is the dynamic viscosity and ϑ_0 is the Kinematic viscosity

Effects of temperature on solvent viscosity can be correlated by the following well-accepted empirical relation [6]

$$\mu_0 = A' exp\frac{B}{T-T_0} \qquad (5)$$

Where A' and B are constants, T_0 is reference temperature and T is the absolute temperature in degree Kelvin.

Substituting equation (4) and (5) in (3), we have

$$\frac{n^2-1}{n^2+2} = \frac{AA'\alpha}{3M\vartheta_0} exp\frac{B}{T-T_0} \qquad (6)$$

Taking $\frac{AA'\alpha}{3M\vartheta_0} exp\frac{B}{T-T_0} = K_8$, equation (6) becomes-

$$n^2 - 1 = K_8 \times (n^2+2)$$

Or $$n^2 = (2K_8+1)(1-K_8)^{-1}$$

Or $$n^2 = 1 + 3K_8 + 3K_8{}^2 + 3K_8{}^3 + \cdots + 3K_8{}^{n+1} \qquad (7)$$

The higher order term can be neglected if $K_8 \ll 1$. To determine a possible value of K_8, the following values are taken for Solvent dewaxed high parafanic oil (64742-56-9) (which is a lubricating oil) [10].

i. Viscosity $\vartheta_0 = \frac{8.4mm^2}{sec} = 8.4 \times 10^{-3} pa - sec$
ii. Average molecular mass M=280gm
iii. Polarizability value is taken only for carbon molecules
 $\alpha = 11 \times 1.64878773 \times 10^{-41}$ Coulomb.metre^2/Volt
iv. Avogadro's number A
 (6.02×10^{23} molecules of oil/mole)
v. $A' = 0.000575 Pa - S$ and $B = 980K$ [10]
vi. $T_0 = 150.13K$ [10] and $T = 313K$(for 40°C)

From these values K_8 has been calculated as 3.65126×10^{-18}.

Since $K_8 \ll 1$, the higher terms can be neglected. Thus equation (7) can be expressed as-

$$n^2 = 1 + 3K_8$$

Or $$n^2 = 1 + \frac{AA'\alpha}{M\vartheta_0} exp\frac{B}{T-T_0} \qquad (8)$$

Expressing n as n_l,

$$n_l^2 = 1 + \frac{AA'\alpha}{M\vartheta_0} exp\frac{B}{T-T_0} \qquad (9)$$

Or $$n_l = \sqrt{1 + \frac{AA'\alpha}{M\vartheta_0} exp\frac{B}{T-T_0}} \qquad (10)$$

Equation (10) describes a relation among RI (n_l), Kinematic viscosity (ϑ_0), Molar mass (M) and Temperature (T).

III. RELATION BETWEEN OPTICAL POWER AND REFRACTIVE INDEX FOR A BARE AND BENT MULTIMODE OPTICAL FIBRE

When a multimode fiber is put at a sharp bend (Macrobend) with a fixed radius of curvature, light rays are lost into cladding, which results in power loss and thus attenuation. Since higher modes are bound less tightly to the fiber core than the lower order modes, the higher order modes radiate out of the fiber first [9] resulting in loss or attenuation as shown in figure 1.

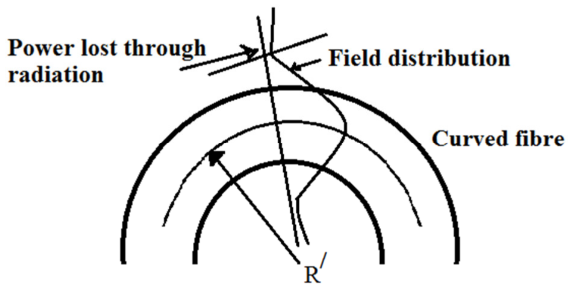

Fig.1. Schematic representation of the radiation loss of a mode at a fiber bent [9]

For a Macro-bend multimode optical fiber, the output optical power $P(L)$ is related to the input optical power and the refractive index as shown in equation- 11 [9]

$$P(L) = P(0)\left[1-\frac{0.4608bk_0(n_1^2-n_{cl}^2)L}{n_1}\,exp\left\{-\frac{2}{3}n_1k_0R'\left(\frac{b(n_1^2-n_{cl}^2)}{n_1^2}-\frac{2a_0}{R'}\right)^{3/2}\right\}\right] \quad (11)$$

Where, $P(L)$ and $P(0)$ denotes the output and input power and L denotes the length of the fiber, Here R' represents the radius of curvature, a is the core radius, n_1 and n_{cl} represents the core and cladding RI of the fiber, β is the propagation constant, b is also called the propagation constant ($0 \leq b \leq 1$, for guided mode) and $k_0(=\omega/c)$ is the wave number.
The bare and bent portion of the optical sensor is placed a liquid whose refractive is given by n_l then n_{cl} for the bare portion will be replaced by n_l as shown in figure 2

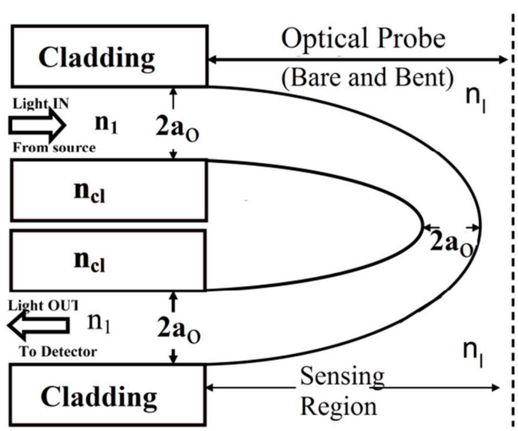

Fig.2. Geometry of the bare and bent portion of the optical sensor [9]

The term n_{cl} of Equation (1) can is replaced by refractive index of the medium (n_l) in the bare and bent portion of the optical sensor is immersed. The new equation is given by equation -12

$$P(L) = P(0)\left[1-\frac{0.4608bk_0(n_1^2-n_l^2)L}{n_1}\,exp\left\{-\frac{2}{3}n_1k_0R'\left(\frac{b(n_1^2-n_l^2)}{n_1^2}-\frac{2a_0}{R'}\right)^{3/2}\right\}\right] \quad (12)$$

If $P(0), n_1, n_{cl}, R', K, k_0, b$ and L are kept fixed, then the output power $P(L)$ will be a function of $n_1^2-n_l^2$. Thus output optical power $P(L)$ can be expressed as-

$$P(L) = f(n_1^2-n_l^2) \quad (13)$$

Substituting the expression of n_l^2 of equation (12) in equation (13), $P(L)$ is a function of temperature, kinematic viscosity, molar mass and polarizability (equation-14).

$$P(L) = f\left[n_1^2-\left(1+\frac{AA'\alpha}{M\vartheta_0}exp\frac{B}{T-T_0}\right)\right] \quad (14)$$

IV. DESCRIPTION OF THE OPTICAL SENSOR

The sensor used for the measurement of unknown refractive index of liquid is a plastic clad silica core multimode fiber. The fiber has a dimension of 200/230 with diameter 500µm. the RI of the core of the fiber (n_1) is 1.48 and cladding (n_{cl}) is1.46. The length of the fiber is 60cm from which a length of 4 cm has been unclad by mechanical stripping around the centre. The bare portion of the fiber is then made into a bend of fixed radius of curvature which constitutes the "Sensor probe (SP)". The optical fiber with cladded and jacket portions are cemented together using m-seal and keeping the bare and bent portion exposed outside them as shown in figure-2. The plastic jacket (black color thick line in figure-) around the unexposed fiber is cemented with m-seal to make the sensor configuration mechanically stable, so that the shape of the bare portion of the optical probe always remains the same.

The multimode optical fibre with the sensor probe is fixed to a support for the following purposes-

i. To maintain a fixed radius of curvature R' thereby eliminating the need for determining the value of R' for every measurement.

ii. To nullify mechanical vibration as it would be an interfering input to the measurement system.

Figure 3 shows the configuration of the experimental setup. A Diode Laser source (Make: Optochem international, 5mW power) is used for launching the input power through one end of the fiber. The laser source is fitted with a high performance voltage stabilizer circuit to ensure constant voltage across the electronic components of the laser source to maintain the intensity of the laser beam unchanged in the event of fluctuation of the power supply. The Laser source is mounted on an optical breadboard with the help of post and held in position using screws. A LDR is used as the detector to detect the outgoing light coming from the other end of the fiber. The LDR is also mounted with the help of post and held in position using screws.

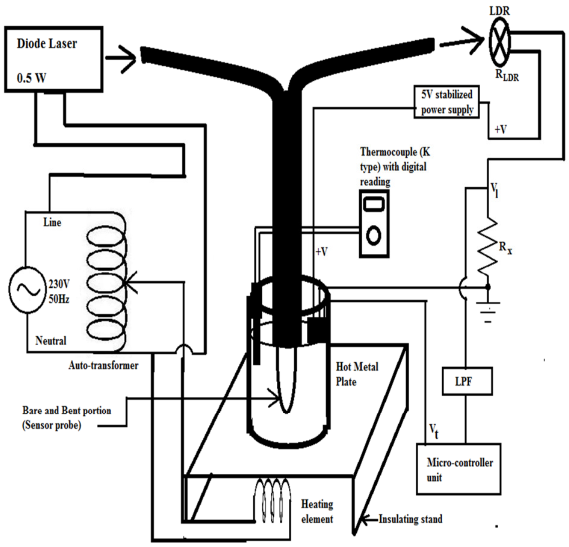

Fig.3. Sensor probe consisting of a BBMOF sensor and a LM 35 IC temperature sensor

The LDR is connected across a 5 Volts DC supply with a series resistance with a fixed resistance R to form a potential divider circuit, as shown in figure 4. The LDR is connected across a 5 Volts DC supply with a series resistance with a fixed resistance R_x to form a potential divider circuit.

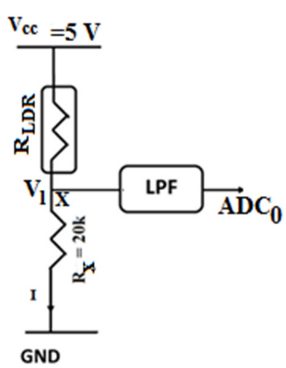

Fig. 4. LDR based potential divider circuit

Where, R_{LDR} represents the resistance of the LDR, R_X= 20 KΩ and V_l is the voltage across the potential divider circuit. I represent the current passing through the circuit. I decreases with increase in the value of R_L. Therefore, V_l $(= IR_x)$ also decreases with increase in R_{LDR}. The value of R_L increases with increase in RI of the liquid in which is applied around the sensing region of the BBMOF. The output optical power is proportional to the electrical power at the measurement point *x*. The variation of power at the measurement point *x* can be expressed as [9]

$$P(L) \propto \frac{(V_{cc}-V_l)^2}{R_{LDR}} \quad (15)$$

Since, $P(L)$ is dependent on refractive index, which is a function of molar mass, temperature and viscosity of a lubricating oil sample, the square of output analog voltage (V_l^2) of the LDR based potential divider circuit would provide the measure RI of the lubricating oil sample at a given temperature. The output analog voltage of the LDR based potential divider circuit is interfaced to the ADC_0 (ADC pin 1) of the ATmega 32 microcontroller based instrumentation system via a LPF which has a cut off frequency of 8 Hz.

The power supply point of the Diode Laser Source is connected to 230V main and the LM35 IC temperature sensor is connected to a stabilized 5 Volts supply as shown in figure-3. The LM35 is a three terminal precision centigrade temperature sensor which is used to measure the temperature of the heated lubricant oil samples. It rated for full -55°C to +150°C temperature range and has a scale factor of 10mV/°C [11]. The output of the LM35 IC, V_t is fed to the ADC_1 (ADC pin 2) of the microcontroller.

V. ATMEGA 32 BASED INSTRUMENTATION SYSTEM

Figure 5 shows the configuration of the ATmega 32 based instrumentation system for the sampling the measure of RI and temperature of the lubricating oil samples.

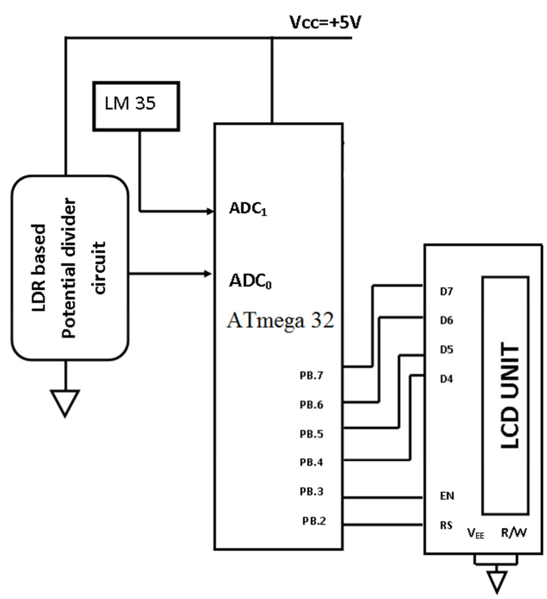

Fig.5. ATmega 32 based instrumentation system for the sampling the voltage V_l and V_t

It has a microcontroller ATmega 32 which reads the analog voltage from the LDR based potential divider sensor circuit (V_l) and voltage from LM35 temperature sensor (V_t) through its ADC_0 channel (pin number 1, analog channel-0) via a LPF and ADC_1 channel (pin number 2, analog channel-1). The display unit of the microcontroller system consist of 16×2 (i.e. two rows having 16 character LCD display) LCD display units. The LCD has been configured as a 5×7 dot matrix 4 bit mode character display [12].

VI. EXPERIMENTAL PROCEDURE AND RESULTS

During experimentation process, fresh lubricating oil sample of grade 20W-40 synthetic engine oil (MAK Gold plus) was taken in a 100 mL glass beaker.

At first, the BBMOF portion of the optical sensor fiber is cleaned by immersing it in methanol(CH_3OH). The BBMOF of the Sensor Probe is immersed in the oil sample which is heated from 30° to 120°C and the microcontroller is used to sample the analog signal of the potential divider circuit (which represents the value of V_l) and the temperature (which represents the value of (V_t) of the sample. The lubricant oil samples are heated by using an electric heater. To control the temperature of the heater, an auto-transformer is used at its input.

The experimental graph shows the variation of the output voltage of LM35 V_t in the lubricating oil sample temperature from 30° to 120°C with $(V_{cc} - V_l)^2$, which provides the measure of optical power of the lubricating oil sample at a given temperature. The plot $(V_{cc} - V_l)^2$ vs. V_t is presented in figure 6.

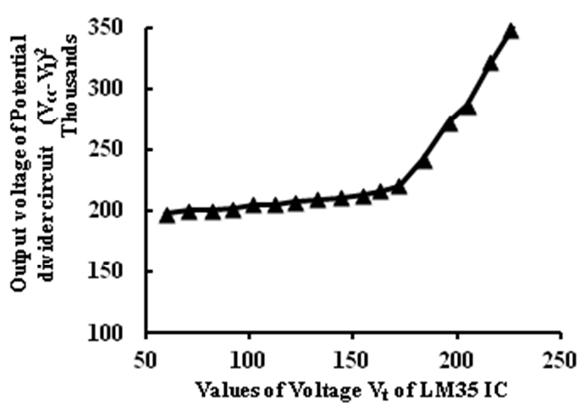

Fig. 6. Plot of $(V_{cc} - V_l)^2$ vs V_t for temperature 30° to 120°C

It has been observed from the graph that

i. The curves showed an upward slope of $(V_{cc} - V_l)^2$ with increase in V_t. With the increase in temperature the term $\frac{AA'\alpha}{M\vartheta_0} exp \frac{B}{T-T_0}$ decreases due to increase in $T - T_0$. The decrease in $\frac{AA'\alpha}{M\vartheta_0} exp \frac{B}{T-T_0}$ increases the difference between n_1^2 and $\frac{AA'\alpha}{M\vartheta_0} exp \frac{B}{T-T_0}$ and so there is a relative increase in $P(L)$

ii. The rate of rise of the curve become more significant after 60°C, which corresponds to Arrhenius equation for chemical reaction rates which states that below 60°C, the reaction is comparatively slow, but the life of oil is reduced by 50 per cent for every 15 degree Celsius temperature rise above 60 °C.

VII. CONCLUSION

The paper describes a system to study the effect of temperature on a sample of pure and unused lubricating oil using a bare and bent optical fibre sensor. A mathematical analysis has been carried out relating the optical power $P(L)$ to the viscosity, molar mass, polarizability and temperature. Since refractive index of the oil sample is dependent on the temperature, the sample is heated up and the change in optical power is measured. It has been experimentally found that with the increase in temperature of the liquid there has been a relative increase in $P(L)$ which corresponds to the theoretical analysis. Thus the measure of $P(L)$ will give a measure of some parameters of the oil sample which are dependent on temperature.

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