Automotive Radiator Temperature Analysis Using Optical Fiber Sensor

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***Abstract*—In this work, an optical fiber-based temperature sensing system is developed for monitoring radiator coolant temperature in automotive applications. The system uses a multimode tapered optical fiber sensor operating on the principle of evanescent wave interaction and refractive index variation. As the coolant temperature changes, its refractive index decreases, which affects the evanescent field around the fiber and results in variation of transmitted light intensity. This variation is converted into an electrical signal using an optical detector and further processed by a microcontroller to display temperature on an LCD. Experimental results show that as the temperature increases from 35.5°C to 105.5°C, the output voltage increases from 2.4 V to 3.8 V, indicating a stable and nearly linear response. The refractive index measurements using a refractometer also confirm a decreasing trend with temperature. The proposed system demonstrates good sensitivity, reliability, and immunity to electromagnetic interference. Hence, it can be effectively used as an alternative to conventional electronic sensors for temperature monitoring in automotive systems.**

I. INTRODUCTION

Accurate temperature monitoring in automotive systems is essential for ensuring safe, efficient, and reliable vehicle operation [1-3]. In conventional vehicles, improper monitoring of radiator coolant temperature can lead to engine overheating, reduced efficiency, and potential mechanical failure. Similarly, in electric vehicles (EVs), inadequate thermal management of battery systems and power electronics can result in performance degradation, reduced battery lifespan, and safety risks [4] . Conventional temperature sensors, primarily based on electronic components, are widely used for such applications. However, these sensors suffer from several limitations, including susceptibility to electromagnetic interference (EMI), reduced accuracy in harsh environmental conditions, limited sensitivity, and potential degradation over time. These challenges necessitate the development of alternative sensing technologies that can provide high accuracy, reliability, and robustness under varying operating conditions. Optical fiber sensors, particularly those which based on evanescent wave principle, offer significant advantages over traditional sensors [5-6]. To overcome these limitations, optical fiber sensors have gained significant attention due to their inherent advantages such as immunity to electromagnetic interference, high sensitivity, compact size, and capability for remote sensing [7], [8]. Among various types, multimode optical fiber sensors are extensively explored because of their simple structure, ease of fabrication, low cost, and high coupling efficiency [9].

A key sensing mechanism employed in optical fiber sensors is based on the evanescent wave phenomenon. When light propagates through an optical fiber, a fraction of the optical field extends beyond the core into the cladding region in the form of an evanescent wave. This evanescent field is highly sensitive to variations in the surrounding environment, including temperature, refractive index, and pressure [10], [11]. Changes in temperature influence the refractive index of the surrounding medium, which subsequently alters the intensity of the transmitted light. This interaction forms the fundamental principle of evanescent wave-based optical fiber sensing [12].

Multimode optical fibers are particularly advantageous for such applications due to their larger core diameter, which enhances the interaction between the propagating light and the external medium, thereby improving sensor sensitivity [13]. In this context, the present work focuses on the design and implementation of an evanescent wave-based multimode optical fiber sensor for monitoring radiator coolant temperature. The variation in output voltage with respect to temperature is experimentally analyzed, demonstrating the effectiveness and reliability of the proposed sensing approach.

II. COOLANT TEMPERATURE MEASUREMENT METHODOLOGY USING OPTICAL FIBER SENSOR

Optical fiber evanescent wave-based temperature sensors are relatively new to the market when compared with the previous sensors but are gaining importance due to their natural immunity to electromagnetic radiation. Based on this demand several technologies have been appearing using optical fibers as sensing elements. The coolant temperature sensor is used to measure the temperature of engine coolant. This information is important for controlling engine performance and avoiding overheating. As temperature increases, physical properties of coolant such as refractive index change, which can be used for sensing purpose. The optical fiber sensor used in this project works on the principle of evanescent wave and refractive index variation. When light travels through an optical fiber, it undergoes total internal reflection at the interface of core and cladding. Under certain conditions, a small portion of light, called the evanescent wave, penetrates into the surrounding medium. When the surrounding medium (coolant) changes its refractive index due to temperature variation, the evanescent field interaction also changes. This results in variation of light intensity, which is converted into an electrical signal (voltage). The refractive index of coolant decreases as temperature increases. This is experimentally verified using Abbe's refractometer. The results show a decrease of approximately 0.001 in refractive index with rise in temperature. The working of optical fiber is based on Snell's law. When light travels from a medium of higher refractive index to a lower refractive index, total internal reflection occurs at certain angles. However, some portion of light penetrates into the lower refractive index medium in the form of evanescent wave. The sensor operates on intensity modulation principle, where the output voltage changes with variation in light intensity. As the coolant temperature increases, refractive index decreases, leading to increased interaction of evanescent wave and hence higher output voltage.

III. EXPERIMENTAL

3.1. Preparation of Sensing Element

The experimental setup for measuring output voltage of the etched multimode glass fiber sensor with respect to refractive index is shown in Fig. 1. In Fig. 1, a He-Ne laser (632 nm) is coupled into the etched fiber using a 20× lens and precise alignment system. The output light is detected using a silicon photo detector, and the voltage is measured with a digital multimeter

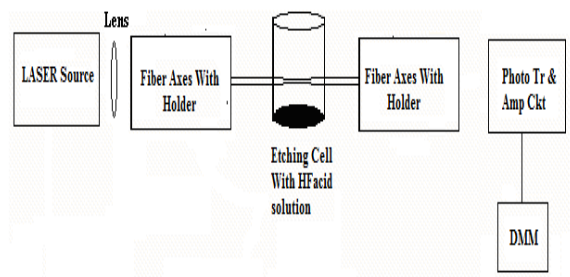

Fig1. Experimental Setup for preparation of sensing element

For fabrication, the fiber coating is first removed using ethyl acetate, then cleaned with acetone and distilled water. The bare fiber (core and cladding) is then etched using hydrofluoric (HF) acid. During etching, light transmission is continuously monitored. The etching rate is around 5.2 μm/min, and the process takes about 24 minutes. Initially, there is no major change, but as the fiber diameter reduces below a certain limit, signal loss increases rapidly, and finally the fiber gets completely etched. The etched and tapered portion about 55 μm of the fiber acts as the sensing region, where interaction with the surrounding medium takes place.

3.2. Coolant RI analysis at various temperature

The refractive index of the coolant at different temperatures is measured using an Abbe refractometer at a wavelength of 632.8 nm. The observations indicate a clear decreasing trend in refractive index with increase in temperature. At 35.5°C, the refractive index is found to be 1.33105, which gradually reduces to 1.31744 at 105.5°C. This shows that for every rise in temperature, there is a slight but consistent decrease in refractive index of the coolant. The reduction is approximately in the order of 0.001–0.002 for every 10°C increase in temperature. This behavior occurs due to decrease in density and change in optical properties of the coolant with temperature. Such variation in refractive index is very useful for optical fiber sensing applications, where temperature can be measured indirectly based on refractive index changes.

Table 1 R.I. of coolant at various temperatures

Temp in C	Refractive Index at 632.8 nm
35.5	1.33105
45.5	1.32972
55.5	1.32814
65.5	1.32636
75.5	1.32438
85.5	1.32223
95.5	1.31991
105.5	1.31744

The graph shows in fig 2 shows the variation of refractive index of the coolant with respect to temperature, measured using a refractometer at a wavelength of 632.8 nm. From the graph, it is clearly observed that as the temperature increases from around 35°C to 105°C, the refractive index of the coolant decreases steadily. The plot indicates a nearly linear downward trend, where the refractive index reduces from approximately 1.331 to 1.317. This behavior confirms that the optical property of the coolant is temperature dependent, mainly due to the reduction in density at higher temperatures. The smooth nature of the curve also indicates consistent and reliable measurements. This characteristic is useful in optical fiber sensing applications, where temperature changes can be effectively monitored through refractive index variation.

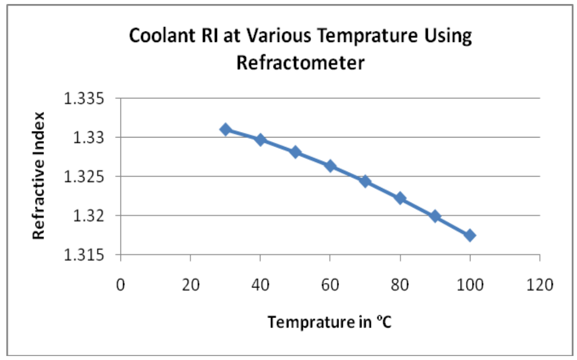

Fig. 2 Measured RI of coolant using Refractometer at various temperature.

3.3. Experimental setup

The given experimental setup in figure 3 shows an optical fiber-based temperature measurement system used for monitoring the coolant temperature in a radiator. At the input side, the laser transmitter circuit is used as a stable light source. It generates light and launches it into the optical fiber. This light travels through the fiber and reaches the tapered fiber temperature sensor, which is placed inside a coolant-filled cell. The fiber in this region is tapered or etched so that the light inside the fiber can interact with the surrounding coolant through the evanescent wave. When the temperature of the coolant changes, its refractive index also changes. This affects the evanescent field around the tapered region, causing a change in the intensity of light propagating through the fiber. Thus, the optical signal gets modulated based on temperature. The output light from the fiber is then received by the optical detector circuit, which converts the light signal into an electrical signal (voltage). This voltage varies according to the temperature of the coolant. The electrical signal is then given to the microcontroller, which processes the signal, applies calibration, and converts it into a temperature value. Finally, the measured temperature is displayed on the LCD display, giving a real-time reading of the coolant temperature. Overall, the system works on the principle of evanescent wave-based intensity modulation, providing a reliable and interference-free method for temperature measurement in automotive applications.

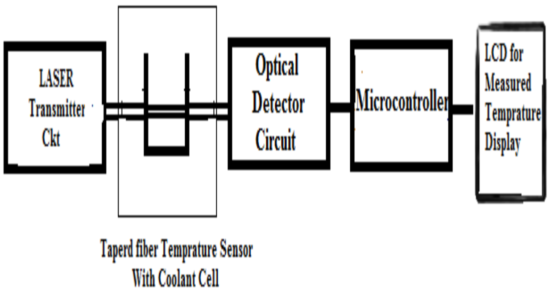

Fig.3. Experimental setup for the measurements and display of radiator temperature

IV. RESULT AND DISCUSSION FOR RADIATOR SENSOR

The coolant temperature sensor is used to measure the temperature of the engine coolant of an internal combustion engine. The reading analysis as of this sensor is input to the engine control unit (ECU), which uses this data to adjust the fuel injection and ignition timing. The temperature sensor data may also be used to switch on the electric cooling fan. The real time temperature data is display on display board using smart system.

Table 2. Output at various temperatures

Temp In ^{0}C	O/p Voltage (mv)
35.5	2.4
45.5	2.6
55.5	2.9
65.5	3.1
75.5	3.3
85.5	3.4
95.5	3.6
105.5	3.8

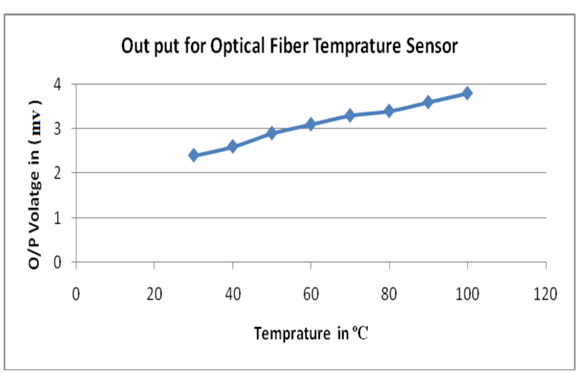

Fig. 4 Output response of temp. sensor

In our project we have used optical fiber temperature sensor. The mentioned sensor is working on evanescent wave and refractive index change. Setup used for observation is shown in figure 3. The performance of the multimode optical fiber sensor for measuring radiator coolant temperature is evaluated using the observed output voltage at different temperatures, as shown in the table 2 and in figure 4. The results clearly show that as the temperature increases from 35.5°C to 105.5°C, the output voltage increases from 2.4 V to 3.8 V, indicating a steady and near-linear response of the sensor. This behavior is explained using the evanescent wave theory. When light propagates through the multimode optical fiber, it undergoes total internal reflection at the core-cladding interface. During this process, a small portion of light, known as the evanescent wave, extends beyond the core into the surrounding medium (coolant). The penetration depth and intensity of this evanescent field depend on the refractive index of the surrounding medium. As the temperature of the coolant increases, its refractive index decreases, which enhances the interaction between the evanescent wave and the surrounding medium? This leads to a change in light intensity propagating through the fiber. In the present setup, this variation in light intensity results in an increase in the detected output voltage. Hence, the sensor works on the principle of intensity modulation due to evanescent wave interaction. The graph shows a smooth and consistent increase in output voltage with temperature, confirming stable sensor performance. The nearly linear characteristic is advantageous for practical applications, as it allows easy calibration and accurate temperature measurement. Overall, the multimode optical fiber sensor based on evanescent wave theory provides reliable and sensitive measurement of radiator coolant temperature. It also offers key advantages such as immunity to electromagnetic interference, good response, and suitability for harsh automotive conditions, making it a promising alternative to conventional sensors.

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