

Determination of Ethanol Concentration in Petrol Using a PMMA Optical-Fiber Evanescent-Wave Sensor

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Abstract

The quantitative determination of ethanol concentration in petrol is important for fuel-quality control and for monitoring ethanol-blended fuels. In this study, a poly (methyl methacrylate) (PMMA) optical-fiber evanescent-wave sensor is investigated as a simple method for determining ethanol concentration based on changes in refractive index. Petrol-ethanol blends of E₀, E₁₀, E₂₀, E₃₀, E₅₀, E₈₅, and E₁₀₀ were studied. The refractive index of the prepared blends was measured using an Abbe refractometer, and the corresponding output of the optical-fiber sensor was recorded at 25, 40, and 60 °C. The experimental results show that the refractive index decreases continuously with an increase in ethanol concentration, while the sensor output increases correspondingly. Linear calibration equations were obtained at the three temperatures. At 25 °C, the calibration equation was $V = 0.07392C + 0.900$ with $R^2 = 0.9799$. At 40 °C and 60 °C, the equations were $V = 0.07104C + 1.929$ with $R^2 = 0.9709$ and $V = 0.07332C + 2.692$ with $R^2 = 0.9549$, respectively. Here, V is the sensor output in mV and C is the ethanol concentration in % v/v. The corresponding sensitivities were 0.07392, 0.07104, and 0.07332 mV/% ethanol at 25, 40, and 60 °C, respectively. The similar values of the calibration slopes indicate that the sensitivity of the sensor towards ethanol concentration remains comparatively stable over the investigated temperature range. However, the change in intercept indicates that the sensor baseline is affected by

temperature. Therefore, temperature-specific calibration is required for accurate quantitative determination of ethanol concentration. The available experimental data contain calibration points and regression values, but replicate measurements, instrument-resolution information, and an independent validation dataset are not available. Hence, numerical values for measurement uncertainty, limit of detection, and recovery cannot be reliably established from the present data alone. Further experiments using replicate measurements and an independent validation set are recommended to establish the complete analytical performance of the proposed optical-fiber sensor.

Keywords: ethanol; petrol; gasoline; PMMA; plastic optical fiber; evanescent wave; refractive index; optical sensor; fuel analysis; temperature compensation

1. Introduction

The use of ethanol in petrol has increased the need for simple and fast methods to determine the ethanol concentration in fuel. The addition of ethanol changes the physical properties of petrol, including its refractive index. These changes can be measured using optical sensors. Optical-fiber sensors based on refractive-index measurement are useful because changes in the surrounding liquid can produce measurable changes in optical intensity or other optical responses. Different types of optical-fiber ethanol sensors have been reported, such as absorption-based, interferometric, grating-based and plasmonic sensors. A recent review discussed these different types of sensors and reported that the interaction of the refractive index of the surrounding liquid with the evanescent field is an important sensing principle

[1]. In a PMMA plastic optical fiber, a part of the cladding can be removed or modified so that a small portion of the guided light interacts with the surrounding liquid. This interaction produces an evanescent wave, which can be used for sensing. The sensitivity of the sensor can be increased by modifying the shape of the fiber, such as by tapering the fiber and changing the exposed length [2].

Petrol–ethanol mixtures are suitable for refractive-index-based sensing because the addition of ethanol changes the refractive index of petrol. Earlier studies have reported the determination of ethanol in gasoline using different optical-fiber techniques, including multimode interference, long-period gratings and other refractive-index-based methods [3–5]. A recent study published in 2026 also reported the measurement of ethanol concentration in petrol from 0 to 100% v/v using a weakly tilted fiber Bragg grating. This shows the continued interest in using optical-fiber sensors for measuring ethanol concentration over a wide range [6]. Temperature is an important factor in refractive-index measurement of petrol–ethanol mixtures. Previous experimental studies have shown that the refractive index of gasoline–alcohol mixtures changes with both ethanol concentration and temperature [7]. Therefore, a sensor calibrated at one temperature may not give the same quantitative result when it is used at another temperature. In the present work, this temperature effect is studied using a PMMA optical-fiber evanescent-wave sensor at 25, 40 and 60 °C.

The main objective of this study is to establish temperature-specific calibration relationships between the output of the PMMA optical-fiber sensor and the ethanol concentration in petrol. The study also aims to relate the sensor output with the refractive index, determine the linearity and sensitivity of the sensor response, and identify the main sources of uncertainty that should be controlled before using the sensor for practical fuel-quality measurement.

2. Measurement Principle

The sensing principle is based on the evanescent field produced during the propagation of light through an optical fiber. When light travels through the fiber under the condition of total internal reflection, a small part of the optical field extends outside the guiding region. This field decreases rapidly with distance from the fiber interface. The intensity of the evanescent field can be expressed as

$$I(x) = I_0 \exp(-x/d_p) \quad (1)$$

Where, I_0 is the intensity at the interface, x is the distance from the interface, and d is the evanescent-field penetration depth. For a multimode configuration, the penetration depth depends on wavelength, incidence angle, and the refractive indices of the guiding and surrounding media [1]. Removing the cladding or otherwise exposing the PMMA sensing region increases interaction between the guided field and the surrounding petrol–ethanol mixture [2].

The mixture refractive index changes with ethanol concentration. The sensor therefore follows the measurement chain

$$C_{\text{eao}} \rightarrow n_{\text{ix}} \rightarrow V \quad (2)$$

Where, C_{eao} is ethanol concentration, n_{ix} is the mixture refractive index, and V is the measured sensor output. The experimental data supplied for this work show that n_{ix} decreases as ethanol concentration increases, while V increases.

3. Materials and Methods

3.1 Sample matrix

Seven petrol–ethanol compositions were investigated. The notation E_{xx} denotes the nominal ethanol content in % v/v. The measurements were performed at 25, 40 and 60 °C.

Seven different petrol–ethanol compositions were investigated in this study, namely **E0**: E_0 , E_{10} , E_{20} , E_{30} , E_{50} , E_{85} and E_{100} . The notation **E_{xx}** represents the nominal ethanol concentration in the mixture, expressed as % v/v. Thus, **E0** represents petrol without added ethanol, while **E100** represents 100% ethanol. The intermediate compositions represent different volume percentages of ethanol mixed with petrol. The prepared samples were used to study the change in refractive index and the corresponding response of the PMMA optical-fiber evanescent-wave sensor. Measurements were carried out at three temperatures, namely **25, 40 and 60 °C**. These temperatures were selected to study the effect of temperature on the refractive index and sensor output. For each composition, the refractive index

was measured using an **Abbe refractometer**, and the sensor output was recorded under the corresponding temperature condition. The obtained results were then used to establish the relationship between ethanol concentration and sensor output. The measurements at different temperatures also helped to determine the temperature dependence of the sensor response.

Sample	Nominal ethanol (% v/v)	Measurement temperatures (°C)
E ₀	0	25, 40, 60
E ₁₀	10	25, 40, 60
E ₂₀	20	25, 40, 60
E ₃₀	30	25, 40, 60
E ₅₀	50	25, 40, 60
E ₈₅	85	25, 40, 60
E ₁₀₀	100	25, 40, 60

Table 1. Experimental sample matrix used in the dataset.

3.2 PMMA evanescent-wave sensor measurement

A PMMA optical-fiber evanescent-wave sensing arrangement was used to measure the optical response of each blend. The corresponding sensor output was recorded in millivolts. The supplied source file states that the plotted points represent the exact values used for the study.

3.3 Calibration model

For each temperature, the sensor output was fitted to a first-order linear model

$$V = mC + b \quad (3)$$

where m is the calibration sensitivity in mV/% ethanol and b is the intercept in mV. Ethanol concentration can therefore be calculated from the measured output as

$$C = (V - b)/m \quad (4)$$

4. Results and Discussion

4.1 Refractive-index response

Figure 1 shows the measured refractive index for different ethanol concentrations. The refractive index decreases continuously as the ethanol concentration increases at all three temperatures. The curves show a clear difference with temperature, indicating that both ethanol concentration and temperature affect the refractive index of the fuel mixture. This result is in agreement with earlier experimental studies on gasoline–alcohol mixtures, where the refractive index was found to depend on both composition and temperature [7].

4.2 Evanescent-wave response and linearity

Figure 2 shows the sensor output for different ethanol concentrations. At all three temperatures, the sensor output increases almost linearly with an increase in ethanol concentration. The three fitted lines are shifted vertically with temperature. This shows that, within the studied temperature range, the main effect of temperature is a change in the baseline sensor output.

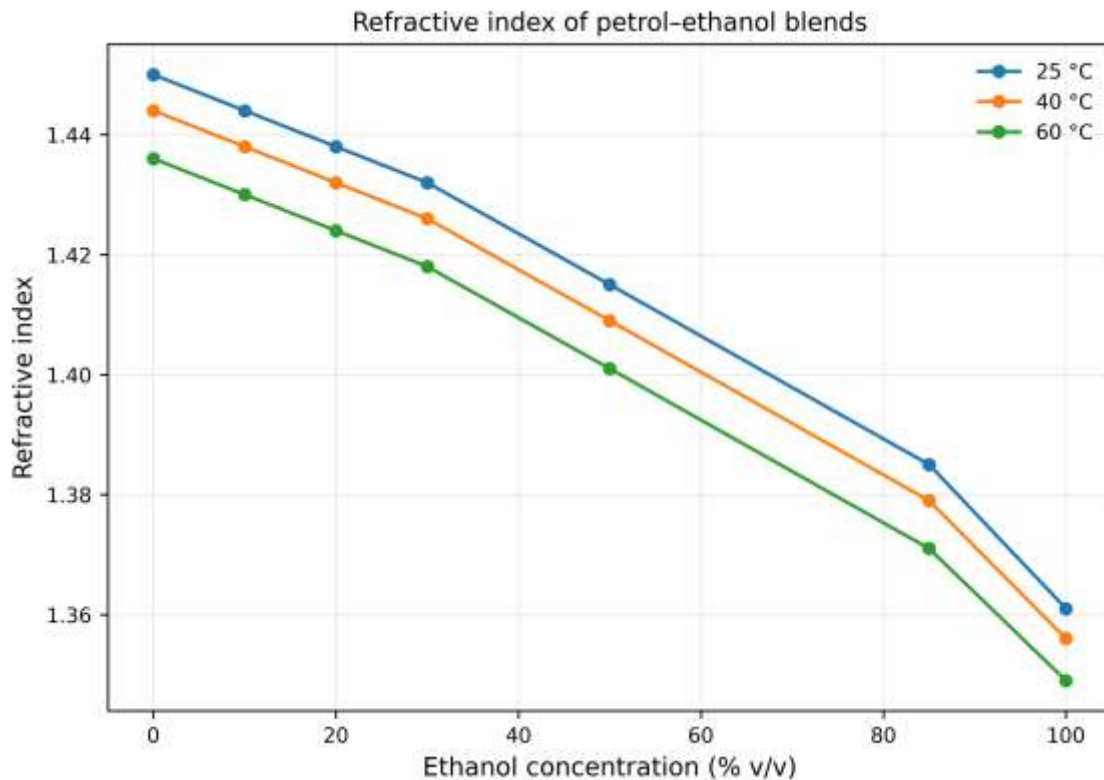


Fig. 1. Variation of refractive index of petrol-ethanol blends with ethanol concentration at 25, 40 and 60 °C.

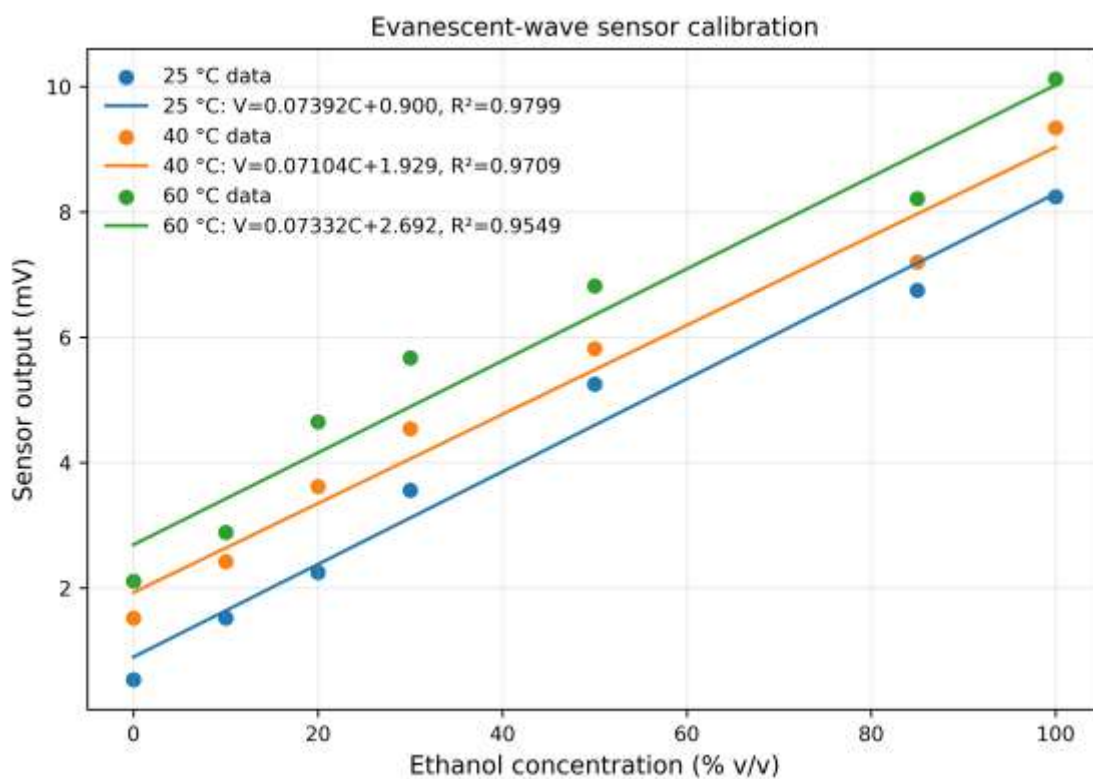


Fig. 2. Evanescent-wave sensor response as a function of ethanol concentration, with linear regression equations and R^2 values

4.3 Calibration parameters and sensitivity

Temperature	Slope m (mV/% ethanol)	Intercept b (mV)	R ²	Calibration equation
25 °C	0.07392	0.900	0.9799	$V = 0.07392C + 0.900$
40 °C	0.07104	1.929	0.9709	$V = 0.07104C + 1.929$
60 °C	0.07332	2.692	0.9549	$V = 0.07332C + 2.692$

Table 2. Temperature-specific linear calibration parameters from the experimental dataset.

The sensitivity values obtained at 25, 40 and 60 °C are 0.07392, 0.07104 and 0.07332 mV/% ethanol, respectively. The difference between the highest and lowest sensitivity is 0.00288 mV/% ethanol, which is about 4.0% of the average sensitivity. However, the intercept changes from 0.900 to 2.692 mV, giving a difference of 1.792 mV. This shows that the sensitivity of the sensor to ethanol concentration remains nearly constant, while the baseline sensor output changes significantly with temperature.

4.4 Sensor output versus refractive index

Figure 3 shows the variation of sensor output with refractive index at 25, 40 and 60 °C. The sensor output increases as the refractive index decreases, resulting in a negative slope for the calibration curves. This behavior is consistent with the results presented in Figures 1 and 2. As the ethanol concentration increases, the refractive index of the petrol–ethanol mixture decreases, while the output of the optical-fiber sensor increases. The relationship between sensor output and refractive index shows a reasonably good linear behavior at all three temperatures. The coefficient of determination (R²) values obtained from the linear fitting are 0.9480, 0.9540 and 0.9240 at 25, 40 and 60 °C, respectively. The highest R² value is obtained at 40 °C, indicating a comparatively good linear relationship between refractive index and sensor output at this temperature. The lower R² value at 60 °C indicates slightly more deviation of the experimental points from the fitted straight line. These results confirm that the sensor output is related to the refractive index of the petrol–ethanol mixture. Therefore, the change in ethanol concentration can be monitored indirectly by measuring the change in refractive index through the evanescent-wave interaction in the PMMA optical fiber. However, since the sensor response is also affected by temperature, temperature-specific calibration is required for reliable quantitative measurement of ethanol concentration.

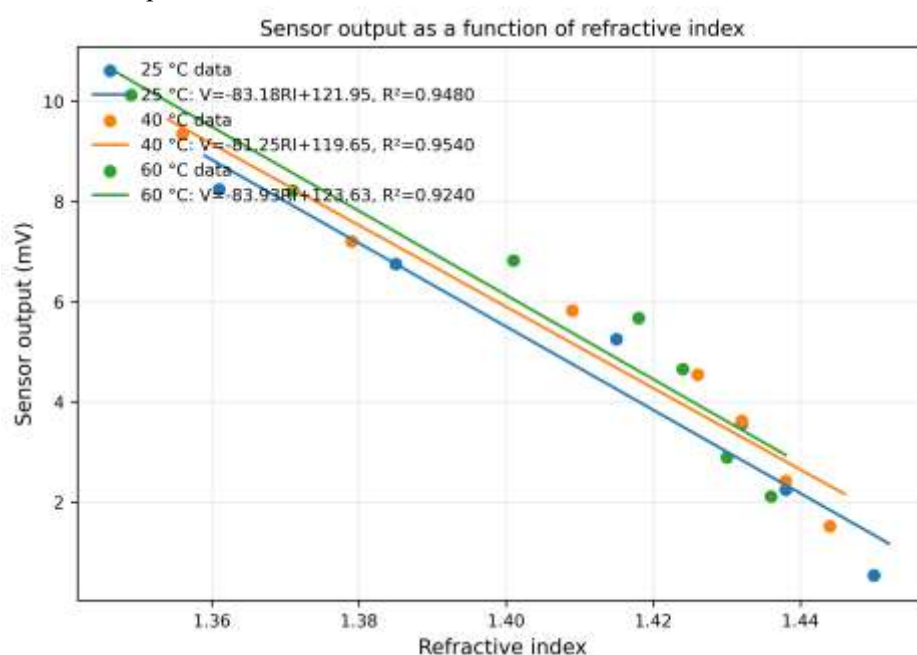


Fig. 3. Variation of evanescent-wave sensor output with refractive index of petrol–ethanol blends, including linear regression equations and R² values.

4.5 Temperature dependence and calibration strategy

Figure 4 clearly shows the effect of temperature on the sensor response. The calibration curves obtained at 25, 40 and 60 °C have nearly similar slopes, but their intercepts are different. This indicates that the sensitivity of the sensor towards ethanol concentration does not change significantly with temperature within the investigated temperature range. However, the baseline output of the sensor changes with temperature. The difference in the intercepts is important for quantitative measurement. For the same ethanol concentration, the sensor can give different output values at different temperatures. Similarly, if the sensor output is measured at an unknown temperature and a calibration equation obtained at only one temperature is used, the calculated ethanol concentration may not be correct. This difference can result in a systematic error in the measured ethanol concentration. Therefore, a single calibration equation should not be directly used for the complete temperature range of 25–60 °C. Separate calibration equations should be used for different operating temperatures, or a temperature-compensation method should be developed. In practical applications, the temperature of the petrol–ethanol sample should be measured along with the sensor output. The measured temperature can then be used to select the appropriate calibration equation or to apply a temperature correction.

Thus, Figure 4 demonstrates that temperature mainly affects the baseline response of the PMMA optical-fiber sensor, while the concentration-dependent sensitivity remains comparatively stable. Proper temperature-specific calibration is therefore necessary to improve the accuracy and reliability of ethanol concentration measurement using the proposed sensor.

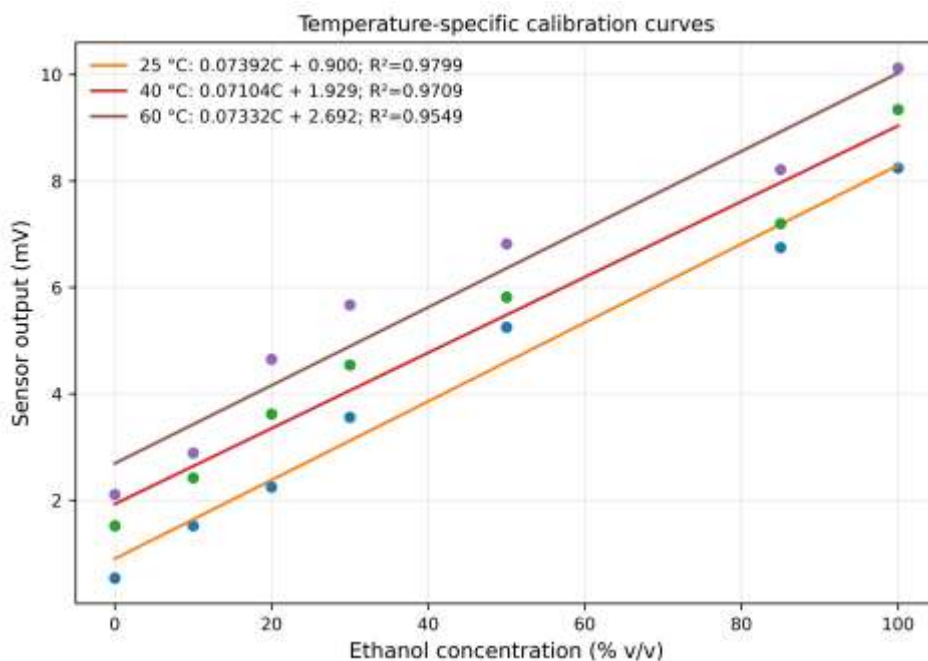


Fig. 4. Temperature-specific calibration characteristics of the PMMA evanescent-wave optical-fiber sensor for determination of ethanol concentration.

Using Eq. (4), the concentration equations for the three temperatures are

$$C_{25} = (V - 0.900)/0.07392 \quad (5)$$

$$C_{40} = (V - 1.929)/0.07104 \quad (6)$$

$$C_{60} = (V - 2.692)/0.07332 \quad (7)$$

These equations should only be used within the experimental calibration range and at the corresponding calibration temperature. For field operation, the preferred approach is a temperature-tagged calibration table or a two-variable model of the form $C = f(V, T)$, provided that additional measurements are collected at enough temperatures and concentration levels to validate such a model.

5. Uncertainty and Error Analysis

5.1 Scope of the present uncertainty analysis

Uncertainty analysis is important for evaluating the reliability and accuracy of the proposed optical-fiber sensor for ethanol concentration measurement. In the present study, the measured sensor output is affected by several factors, such as the repeatability of the sensor response, accuracy of the voltage measurement, accuracy of refractive-index measurement, temperature variation, and preparation of the petrol–ethanol samples. Therefore, a proper uncertainty analysis should consider both random and systematic sources of error. Random uncertainty is mainly related to the variation in repeated measurements under the same experimental conditions. For example, repeated measurements of the sensor output for the same ethanol concentration may show small differences due to fluctuations in the optical source, detector, electronic circuit, sample handling, or environmental conditions. These variations can be evaluated using repeated measurements and statistical parameters such as standard deviation and standard error.

Systematic effects are associated with the measuring instruments and experimental conditions. In the present experiment, important sources may include the resolution and accuracy of the digital voltage meter, uncertainty of the Abbe refractometer, accuracy and stability of the temperature measurement, and possible changes in the optical-fiber sensor response with temperature. Errors may also arise during preparation of the petrol–ethanol mixtures due to the accuracy of the volume measurement and mixing procedure. The available experimental data contain the calibration points, fitted slopes and intercepts, and coefficient of determination (R^2) values for the different temperatures. However, the supplied data do not include repeated measurements for each ethanol concentration. Standard deviations or other measures of repeatability are also not reported. In addition, the resolution and accuracy specifications of the voltage-measuring instrument, uncertainty of the Abbe refractometer, temperature measurement uncertainty, and uncertainty associated with sample preparation are not available. Because these important input quantities are not available, a complete numerical uncertainty budget cannot be reliably calculated from the present data alone. In particular, assigning a numerical expanded uncertainty would require assumptions about measurement repeatability and instrument uncertainties that are not directly supported by the experimental data. Such assumptions could give a misleading impression of the actual measurement accuracy. Therefore, the present section focuses on establishing the uncertainty model and identifying the main sources of error that should be considered in future validation of the proposed sensor. For a complete quantitative uncertainty analysis, repeated measurements should be performed for each ethanol concentration at each investigated temperature. The standard deviation of these repeated measurements can then be used to estimate the repeatability component. The specifications of the voltage meter, Abbe refractometer, and temperature sensor should also be included in the uncertainty budget. In addition, the uncertainty associated with preparation of the petrol–ethanol mixtures should be estimated from the accuracy of the measuring equipment and the sample preparation procedure.

Thus, the present analysis does not assign a numerical expanded uncertainty because the required experimental information is not available. Instead, it provides a clear basis for future uncertainty evaluation and validation of the PMMA optical-fiber evanescent-wave sensor. This approach avoids introducing unsupported assumptions and gives a more scientifically reliable assessment of the present experimental results.

Uncertainty source	Symbol	Effect on ethanol concentration	Required information
Sensor-output/readout uncertainty	u_V	u_V/m	Detector/readout resolution and repeatability
Slope uncertainty	u_m	$ C \cdot u_m/m$	Regression covariance or standard error of slope
Intercept uncertainty	u_b	u_b/m	Regression standard error/covariance
Temperature uncertainty	u_T	$(\partial C/\partial T)u_T$	Replicated calibration at multiple temperatures

Sample preparation	u _{C,prep}	Directly contributes to C	Volumetric/mass measurement uncertainty
Refractive-index reference	u _n	Indirectly affects model	Abbe refractometer specification and repeatability
Between-run repeatability	u _{rep}	Direct contribution	Independent replicate sensor runs

Table 3. Proposed uncertainty budget for quantitative deployment.

For the inverse linear calibration, $C = (V - b)/m$, first-order propagation gives

$$u^2(C) \approx (uV/m)^2 + [u_b/m]^2 + [(V-b)u_m/m^2]^2 + 2(V-b) \cdot \text{cov}(m,b)/m^3 \quad (8)$$

where $\text{cov}(m,b)$ is the slope–intercept covariance. If temperature is incorporated explicitly, an additional term $(\partial C/\partial T)^2 u^2 T$ and relevant covariance terms should be included. The regression residual standard deviation should also be evaluated from the individual calibration points and incorporated into the prediction uncertainty.

5.2 Practical error sources

The principal practical error sources are expected to be temperature variation, sample-volume error, fiber positioning and bending, contamination or incomplete cleaning of the sensing region, source/detector drift, and changes in the composition of commercial petrol. Temperature is particularly important because both the sample refractive index and the sensor baseline are temperature dependent. Published gasoline–alcohol measurements likewise identify temperature as an important variable in refractive index determination [5,7].

6. Conclusions

A PMMA optical-fiber evanescent-wave sensor was evaluated for quantitative determination of ethanol concentration in petrol using E0–E100 calibration samples and measurements at 25, 40 and 60 °C. The supplied experimental results demonstrate a consistent decrease in refractive index with increasing ethanol concentration and an approximately linear increase in sensor output. The temperature-specific calibration equations were $V = 0.07392C + 0.900$ at 25 °C, $V = 0.07104C + 1.929$ at 40 °C, and $V = 0.07332C + 2.692$ at 60 °C, with R^2 values of 0.9799, 0.9709 and 0.9549, respectively. The slopes correspond to 0.07392, 0.07104 and 0.07332 mV/% ethanol. The comparatively stable slopes indicate useful concentration sensitivity, while the large baseline shift confirms that temperature compensation is essential. The present dataset supports the feasibility of PMMA evanescent-wave sensing for ethanol determination but does not, by itself, support numerical claims for detection limit, accuracy, repeatability or expanded uncertainty. The next experimental stage should therefore focus on replicate measurements, independent validation, instrument-resolution characterization, and a validated temperature-compensated uncertainty budget.

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