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# Analysis of the Effect of Temperature on the Accuracy of Moisture Content Measurement in Transformer Oil

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A B S T R A C T

Transformer oil plays a critical role in insulation and cooling systems in power transformers. One of the key parameters affecting transformer reliability is moisture content, as excessive water contamination can reduce dielectric strength and accelerate insulation degradation. However, moisture measurement accuracy is strongly influenced by oil temperature variations during testing. This study aims to analyze the effect of temperature on the accuracy of moisture content measurements in transformer oil. The research employed an experimental approach using transformer oil samples tested at different temperature levels ranging from 20°C to 80°C. Moisture measurements were conducted using a capacitive moisture sensor and compared with Karl Fischer Titration (KFT) as the reference method. The results indicate that increasing temperature significantly affects measurement stability and accuracy. At higher temperatures, moisture readings tend to increase due to enhanced molecular activity and water solubility in oil. Statistical analysis shows that temperature contributes substantially to measurement deviation, with the highest accuracy obtained within the temperature range of 40°C–50°C. The maximum relative error reached 9.88% at 80°C, while the minimum error of 1.66% was observed at 50°C. The overall performance measured yielded an MAE of 1.29 ppm and an RMSE of 1.63 ppm. The study concludes that temperature compensation mechanisms are necessary to improve the reliability of real-time transformer oil monitoring systems

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## INTRODUCTION

Power transformers are essential components in electrical power systems because they ensure stable energy transmission and distribution (Alhamd et al., 2024; Obebe et al., 2025). The operational reliability of transformers depends on the condition of their insulation system, particularly transformer oil (Abu Bakar & Abu-Siada, 2016; Sylvestre N'cho et al., 2016). Transformer oil functions both as an insulating medium and as a cooling agent. Moisture contamination in transformer oil can significantly reduce dielectric strength, increase insulation ageing, and lead to transformer failure (Lin, 2023).

Accurate moisture measurement is therefore essential for transformer condition monitoring and predictive maintenance. Traditional laboratory-based techniques such as Karl Fischer Titration (KFT) are widely recognized for their high precision (Felgner et al., 2008; Fenske et al., 2025). However, these methods are time-consuming, costly, and unsuitable for continuous online monitoring systems.

Recent studies have focused on developing sensor-based and computational approaches for real-time moisture detection in transformer oil (Felgner et al., 2008; Gmati et al., 2025; Kondalkar et al., 2019; Mustafa Abdulirees Jebur, 2025; Zhao et al., 2023). Capacitive sensors, optical sensors, and machine-learning-based predictive models have shown promising performance in estimating moisture content under varying operating conditions. Nevertheless, one critical challenge remains unresolved: the influence of temperature on measurement accuracy.

Temperature variations directly affect the physical and dielectric properties of transformer oil, including viscosity, conductivity, and water solubility. Higher temperatures can increase the mobility of water molecules and alter sensor responses, leading to deviations in moisture readings (Ma et al., 2024; Zhang & Shen, 2021). Several studies have indicated that temperature-sensitive measurement systems may produce inaccurate moisture estimations if temperature compensation is not properly implemented.

This study extends our previous work on sensor-based transformer oil moisture measurement by specifically investigating the influence of operating temperature on measurement accuracy. Building upon the sensor-based and computational modelling approach developed in (Markis et al., 2025), the present study focuses specifically on analyzing the influence of temperature variations on moisture measurement accuracy in transformer oil.

Therefore, this study investigates the effect of temperature variations on the accuracy of moisture content measurements in transformer oil. The research focuses on examining the relationship between oil temperature and measurement deviation, assessing the performance of sensor-based measurement systems across different temperature levels, and determining the temperature range that yields the most accurate results. In addition, the findings are expected to contribute to the development of temperature compensation strategies that can enhance the reliability of real-time transformer oil monitoring systems and support more effective condition-based maintenance practices.

## LITERATURE REVIEW

### *Research Design*

This study employed a quantitative experimental research design to investigate the influence of temperature on the accuracy of moisture content measurements in transformer oil. The experimental approach was selected because it allows for systematic control of environmental variables and enables the direct observation of the relationship between temperature changes and measurement performance. The study was conducted under controlled laboratory conditions to minimize the influence of external factors that could affect the measurement results.

The independent variable in this research was the temperature of the transformer oil, while the dependent variable was the accuracy of the moisture content measurement. Temperature levels were varied systematically within a predefined range representing typical operating conditions of power transformers. For each temperature level, moisture measurements were performed using a sensor-based measurement system and subsequently compared with reference measurements obtained through Karl Fischer Titration (KFT), which is widely recognized as the standard method for moisture determination in insulating oils.

To ensure the reliability and repeatability of the results, all experiments were conducted using the same transformer oil sample under identical testing conditions. The oil temperature gradually adjusted using a temperature-controlled heating system and maintained at each target temperature until thermal equilibrium was achieved before data collection. Multiple measurements were taken at each temperature level to reduce random errors and improve the consistency of the experimental data.

The experimental procedure was designed to evaluate how temperature variations affect sensor response characteristics and measurement deviations. The data collected were analyzed using descriptive and inferential statistical methods to quantify measurement errors and identify trends in accuracy across different temperature conditions. Furthermore, regression analysis was employed to determine the strength of the relationship between temperature and measurement deviation, providing insights into the necessity of temperature compensation mechanisms for transformer oil monitoring applications.

The overall research framework is illustrated in Figure 1, which consists of transformer oil sample preparation, temperature conditioning, moisture measurement using the sensor-based system, validation using Karl Fischer Titration, error analysis, and interpretation of the relationship between temperature and measurement accuracy.

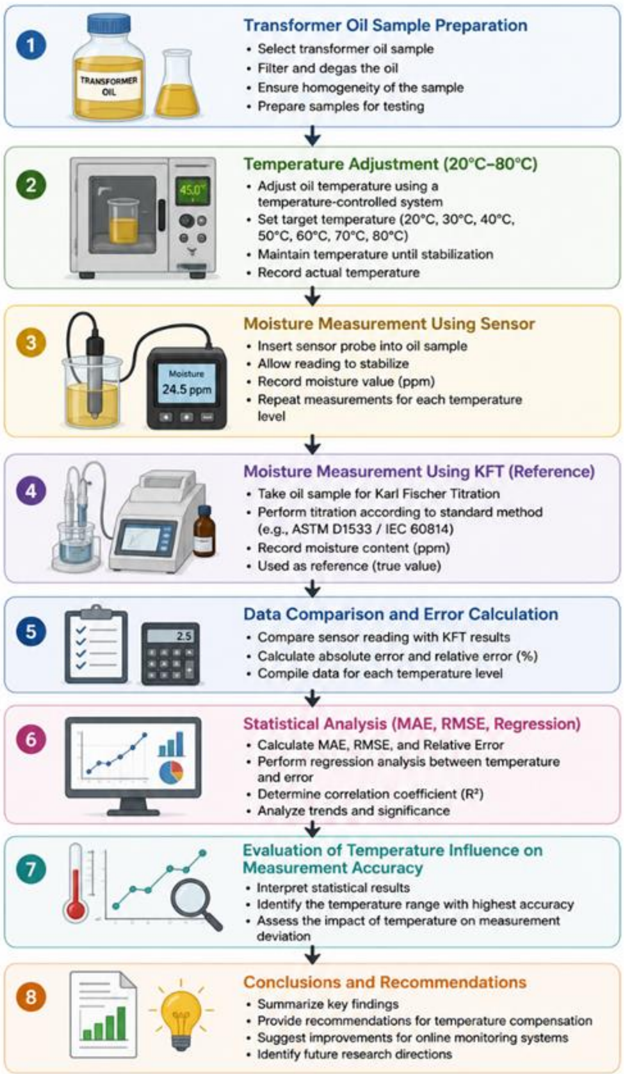


Figure 1. Research Framework

### *Transformer Oil Samples*

Mineral transformer oil was used as the test medium in this study due to its widespread application as an insulating and cooling fluid in power transformers. The oil samples were prepared under controlled laboratory conditions to ensure consistency and reliability throughout the experimental process. Prior to testing, the samples were conditioned to achieve moisture concentrations ranging from 10 ppm to 60 ppm, representing moisture levels commonly encountered in transformer oil during operation. Maintaining controlled moisture levels was essential to evaluate the performance of the measurement system under varying thermal conditions while minimizing the influence of uncontrolled environmental factors.

To investigate the effect of temperature on moisture measurement accuracy, the transformer oil samples were subjected to a series of temperature variations. The oil was gradually heated using a temperature-controlled heating system until the desired temperature was reached and stabilized. Measurements were conducted at seven temperature levels, namely 20°C, 30°C, 40°C, 50°C, 60°C, 70°C, and 80°C. At each temperature level, the oil was allowed to reach thermal equilibrium before moisture measurements were performed to ensure that the observed sensor responses reflected the actual influence of temperature rather than transient thermal effects.

The selected temperature range was designed to represent the typical operating conditions experienced by oil-immersed power transformers. Under normal operating conditions, transformer oil temperature may vary significantly depending on load demand, ambient temperature, cooling system performance, and transformer aging conditions. Lower temperature levels represent lightly loaded or ambient operating conditions, whereas higher temperatures simulate heavy-load conditions and elevated thermal stress commonly encountered during prolonged transformer operations. By covering a broad temperature range, the study provides a comprehensive evaluation of how temperature variations influence moisture measurement behavior and sensor accuracy in practical transformer monitoring applications.

Furthermore, controlling both moisture concentration and temperature during the experimental process enabled a systematic assessment of the interaction between thermal conditions and moisture measurement performance. This approach facilitates a more accurate analysis of measurement deviations and supports the development of temperature compensation strategies for real-time transformer oil monitoring systems.

***Measurement Instruments***

The measurement system employed in this study consisted of a sensor-based moisture detection device and a laboratory reference instrument to ensure accurate validation of the experimental results. Moisture content in transformer oil was primarily measured using a capacitive moisture sensor designed for real-time monitoring applications. The capacitive moisture sensor used in this study was adopted from the previously developed sensor system described in (Markis et al., 2025). This type of sensor operates by detecting changes in dielectric properties caused by the presence of dissolved water molecules within the insulating oil. Variations in moisture concentration alter the dielectric constant of the medium, which in turn affects the sensor capacitance and produces a corresponding electrical signal that can be converted into moisture content values expressed in parts per million (ppm). Capacitive sensors were selected because they offer rapid response times, non-destructive measurement capabilities, and suitability for online transformer condition monitoring systems.

To evaluate the accuracy of the sensor measurements, the results were compared with those obtained from Karl Fischer Titration (KFT), which served as the reference method throughout the study. Karl Fischer Titration is widely recognized as the industry-standard technique for determining water content in insulating liquids due to its high sensitivity, selectivity, and measurement precision. Unlike sensor-based methods that infer moisture content indirectly through changes in electrical properties, KFT directly quantifies water molecules through a chemical reaction between water and Karl Fischer reagents. This direct measurement approach provides highly reliable moisture content values and is commonly used in transformer diagnostics and laboratory testing. The use of KFT as a reference standard allowed the researchers to assess the accuracy and reliability of the sensor measurements under different temperature conditions and to quantify any deviations resulting from temperature-induced changes in sensor response.

In addition to the moisture measurement instruments, a temperature-controlled heating chamber was utilized to regulate and maintain the desired oil temperature during testing. The chamber was equipped with a digital temperature controller capable of maintaining stable temperature conditions throughout the experiment. This equipment ensured that all measurements were conducted under precisely controlled thermal environments, thereby improving the consistency and repeatability of the experimental results.

***Experimental Procedure***

The experimental investigation was conducted under controlled laboratory conditions to evaluate the influence of temperature on the accuracy of moisture content measurements in transformer oil. Prior to testing, transformer oil samples with predetermined moisture concentrations were prepared and homogenized to ensure uniform distribution of water molecules throughout the oil volume. The prepared samples were then placed inside a temperature-controlled chamber, where the temperature was gradually adjusted to the predefined test levels ranging from 20°C to 80°C.

At each temperature level, the oil sample was maintained until thermal equilibrium was achieved. This stabilization period was necessary to ensure that the measured moisture values reflected the actual behavior of the oil under steady-state thermal conditions rather than temporary fluctuations caused by heating or cooling processes. Once the target temperature was stabilized, moisture measurements were performed using the capacitive moisture sensor. To improve data reliability and minimize random measurement errors, multiple readings were collected at each temperature level, and the average value was recorded as the representative sensor measurement.

Following the sensor-based measurement process, samples were extracted and analyzed using Karl Fischer Titration. The KFT analysis provided reference moisture values that were considered the true moisture content of the transformer oil. The comparison between sensor readings and KFT results enabled the evaluation of measurement accuracy under varying temperature conditions. This procedure was repeated for all temperature levels to generate a comprehensive dataset representing the relationship between oil temperature and measurement performance.

After completing all measurements, the collected data was organized and processed for statistical evaluation. Measurement deviations between the sensor and KFT methods were calculated for each temperature condition, allowing the identification of trends, error characteristics, and the impact of temperature on measurement accuracy. The overall experimental workflow was designed to simulate practical transformer operating conditions while maintaining strict control over environmental variables to ensure the validity of the findings.

## METHODOLOGY

***Data Analysis***

The data obtained from the experimental measurements were analyzed using both descriptive and inferential statistical techniques to evaluate the effect of temperature on moisture measurement accuracy. The moisture values acquired from the capacitive sensor were compared with the corresponding Karl Fischer Titration results, which served as reference measurements. The differences between the two measurement methods were calculated to quantify the magnitude of measurement error under each temperature condition.

Several error metrics were employed to assess measurement performance comprehensively. Mean Absolute Error (MAE) was used to determine the average magnitude of deviations between sensor readings and reference values without considering the direction of the error. Root Mean Square Error (RMSE) was calculated to evaluate the overall dispersion of measurement errors while assigning greater weight to larger deviations. Additionally, Relative Error Percentage was determined to express the measurement deviation as a proportion of the reference value, enabling comparisons across different moisture concentrations.

To further investigate the relationship between temperature and measurement deviation, linear regression analysis was performed. The regression model was used to determine whether temperature significantly influenced the accuracy of moisture measurements and to quantify the strength of this relationship. The coefficient of determination ($R^2$) was calculated to evaluate how much of the variation in measurement error could be explained by temperature changes. A positive regression trend would indicate that increasing temperature contributes to larger measurement deviations, while a negative trend would suggest improved measurement performance at higher temperatures.

The results of the statistical analysis were subsequently interpreted to identify temperature ranges that provided the highest measurement accuracy and to assess the necessity of implementing temperature compensation mechanisms in real-time transformer oil monitoring systems. Through this analytical approach, the study aimed to provide a comprehensive understanding of the impact of thermal conditions on moisture measurement performance and to support the development of more reliable transformer condition monitoring technologies.

To quantitatively evaluate the performance of the moisture measurement system, several statistical error metrics were employed. The Mean Absolute Error (MAE) was used to measure the average absolute difference between the sensor measurements and the reference values obtained from Karl Fischer Titration. MAE is calculated as follows:

$$MAE = \frac{1}{n}\sum_{i=1}^{n} | y_i - \hat{y}_i |$$

where $n$ represents the total number of observations, $y_i$ denotes the reference moisture value obtained from Karl Fischer Titration, and $\hat{y}_i$ represents the moisture value measured by the capacitive sensor.

To provide additional insight into the magnitude of measurement deviations, the Root Mean Square Error (RMSE) was also calculated. RMSE assigns greater weight to larger errors, making it particularly useful for identifying significant measurement discrepancies. The RMSE is defined as:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}$$

A lower RMSE value indicates better agreement between the sensor measurements and the reference method.

The Relative Error Percentage (RE) was further used to express the measurement deviation as a percentage of the reference value. This metric facilitates comparison across different moisture concentration levels and is calculated using the following equation:

$$RE(\%) = \left|\frac{y_i - \hat{y}_i}{y_i}\right| \times 100$$

The relative error provides a normalized measure of accuracy and enables the evaluation of measurement performance regardless of the magnitude of the moisture content.

To investigate the influence of temperature on measurement deviation, a simple linear regression model was applied. The regression model describes the relationship between temperature and measurement error and is expressed as:

$$E = \beta_0 + \beta_1 T + \varepsilon$$

where $E$represents the measurement error, $T$denotes the transformer oil temperature, $\beta_0$is the intercept, $\beta_1$is the regression coefficient representing the effect of temperature on measurement error, and $\varepsilon$is the random error term. The strength of the relationship between temperature and measurement deviation was assessed using the coefficient of determination ($R^2$), which indicates the proportion of variance in measurement error explained by temperature variations.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2}$$

The combination of these statistical indicators provides a comprehensive assessment of measurement performance and enables a detailed evaluation of how temperature affects the accuracy of moisture content measurements in transformer oil.

## RESULTS

### *Moisture Measurement Results at Different Temperature Levels*

The experimental measurements were conducted to evaluate the effect of temperature on moisture content readings obtained from the capacitive sensor and to compare them with the reference values measured using Karl Fischer Titration (KFT). The measurements were performed at seven temperature levels ranging from 20°C to 80°C under controlled laboratory conditions. Table 1 presents the comparison between the moisture values obtained from the sensor and those obtained from KFT.

Table 1. Comparison of Moisture Measurements at Different Temperatures

| **Temperature (°C)** | **Sensor Reading (ppm)** | **KFT Result (ppm)** | **Relative Error (%)** |
|---|---|---|---|
| 20 | 18.5 | 17.9 | 3.35 |
| 30 | 20.1 | 19.5 | 3.08 |
| 40 | 22.8 | 22.4 | 1.79 |
| 50 | 24.5 | 24.1 | 1.66 |
| 60 | 28.2 | 26.7 | 5.62 |
| 70 | 31.4 | 29.1 | 7.90 |
| 80 | 35.6 | 32.4 | 9.88 |

The results show that moisture readings obtained from both methods increased as temperature increased. This trend indicates that the amount of dissolved water detected in the transformer oil became more apparent at elevated temperatures. Although the sensor readings generally followed the same trend as the KFT measurements, the deviation between the two methods became larger at higher temperatures.

The smallest measurement difference was observed at temperatures between 40°C and 50°C, where the relative error remained below 2%. In contrast, temperatures above 60°C resulted in a noticeable increase in measurement deviation, suggesting that elevated temperatures significantly affect sensor response characteristics.

Figure 2 illustrates the relationship between temperature and measured moisture content for both measurement methods.

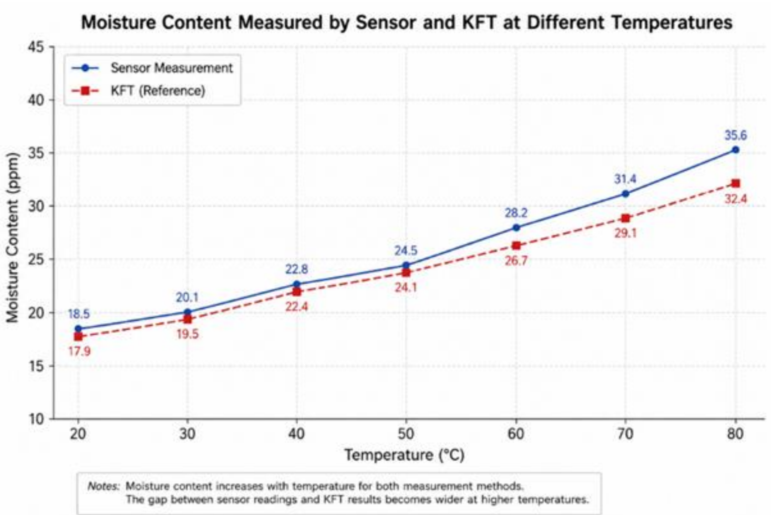


Figure 2. Moisture Content Measured by Sensor and KFT at Different Temperatures

The figure demonstrates that both measurement methods exhibit a similar upward trend; however, the gap between the sensor measurements and KFT values becomes wider as temperature increases. This observation indicates that temperature has a measurable influence on the accuracy of the sensor-based measurement system.

To further characterize the experimental data, descriptive statistical analysis was performed on the moisture measurements obtained from both the capacitive sensor and Karl Fischer Titration. While the graphical representation in Figure 2 illustrates the overall measurement trends, summary statistics provide quantitative information regarding the distribution, variability, and consistency of the collected data. The descriptive statistical results, including the minimum, maximum, mean, and standard deviation values, are presented in Table 2.

Table 2. Summary Statistics of Moisture Measurements

| **Parameter** | **Minimum** | **Maximum** | **Mean** | **Standard Deviation** |
|---|---|---|---|---|
| Sensor Moisture (ppm) | 18.5 | 35.6 | 25.87 | 6.14 |
| KFT Moisture (ppm) | 17.9 | 32.4 | 24.59 | 5.25 |
| Absolute Error (ppm) | 0.4 | 3.2 | 1.29 | 1.07 |
| Relative Error (%) | 1.66 | 9.88 | 4.75 | 3.07 |
| Temperature (°C) | 20 | 80 | 50 | 21.60 |

As shown in Table 2, the average moisture content measured by the capacitive sensor was slightly higher than that obtained from the KFT method. The relatively low standard deviation values indicate that the measurements were generally consistent across the tested temperature range. Furthermore, the observed variation in relative error suggests that temperature influences measurement performance, supporting the trend previously identified in Figure 2.

***Measurement Error Analysis***

To quantify the performance of the sensor under varying temperature conditions, several statistical error metrics were calculated. The measurement error was determined by comparing the sensor readings with the corresponding KFT reference values. Table 3 summarizes the absolute error observed at each temperature level.

Table 3. Measurement Error at Different Temperatures

| **Temperature (°C)** | **Absolute Error (ppm)** |
|---|---|
| 20 | 0.6 |
| 30 | 0.6 |
| 40 | 0.4 |
| 50 | 0.4 |
| 60 | 1.5 |
| 70 | 2.3 |
| 80 | 3.2 |

The results indicate that the measurement error remained relatively low between 20°C and 50°C. The minimum error occurred at 40°C and 50°C, where the sensor readings differed from the KFT measurements by only 0.4 ppm.

However, beyond 60°C, the error increased substantially, reaching a maximum value of 3.2 ppm at 80°C.

The overall performance metrics calculated from all measurements yielded an MAE of approximately 1.29 ppm and an RMSE of approximately 1.63 ppm. These results suggest that the sensor provides acceptable measurement accuracy under moderate temperature conditions, but experiences reduced performance at elevated temperatures.

***Relationship Between Temperature and Measurement Deviation***

To investigate the effect of temperature on measurement accuracy, linear regression analysis was performed using temperature as the independent variable and relative measurement error as the dependent variable. Figure 3 illustrates the relationship between transformer oil temperature and relative measurement error. The scatter plot reveals a positive trend, indicating that measurement deviations tend to increase with rising temperature. This finding suggests that temperature is an important factor influencing the accuracy of moisture measurements and should therefore be considered in the design of transformer oil monitoring systems.

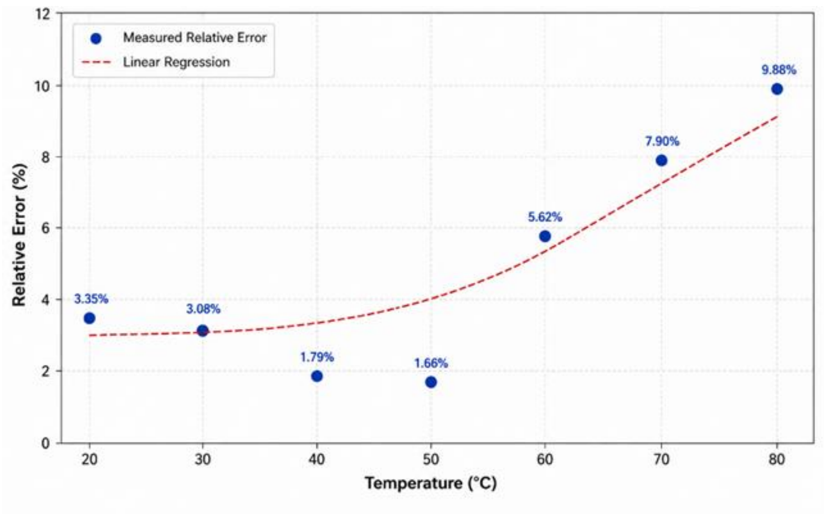


Figure 3. Relationship Between Temperature and Relative Error

The regression trend shows a gradual increase in measurement error as temperature rises. The slope of the regression line indicates that each increase in temperature contributes to a corresponding increase in measurement deviation, highlighting the need for temperature compensation during moisture monitoring.

***Pearson Correlation Analysis***

To further quantify the relationship between transformer oil temperature and measurement deviation, Pearson correlation analysis was performed. The analysis yielded a correlation coefficient of $r=0.89$, indicating a strong positive relationship between temperature and relative measurement error. The corresponding significance value was $p<0.01$, confirming that the observed relationship is statistically significant.

These results indicate that higher temperatures are associated with larger measurement deviations, supporting the hypothesis that temperature significantly affects the performance of capacitive moisture sensors in transformer oil applications.

***Identification of the Optimal Temperature Range***

An important objective of this study was to determine the temperature range that provides the highest measurement accuracy. Based on the relative error analysis, the most accurate measurements were obtained between 40°C and 50°C, where the relative error remained below 2%.

Within this temperature range, the sensor readings closely matched the KFT reference values, indicating stable sensor performance and minimal thermal influence. At temperatures below 40°C, the measurements remained reasonably accurate but exhibited slightly higher variability. Conversely, temperatures exceeding 60°C produced significantly larger deviations due to increased water solubility and changes in dielectric properties of the transformer oil.

The findings suggest that moisture measurements performed within the 40°C–50°C temperature range provide the most reliable results. Therefore, this temperature range may serve as a reference condition for sensor calibration and validation in practical transformer monitoring applications.

## DISCUSSION

The experimental results demonstrate that temperature has a significant influence on the accuracy of moisture content measurements in transformer oil. Although both the capacitive sensor and Karl Fischer Titration (KFT) measurements exhibited similar increasing trends with rising temperature, the deviation between the two methods became more pronounced at higher temperatures. This finding indicates that temperature affects not only the physical behavior of moisture within transformer oil but also the response characteristics of the sensor used for measurement.

One of the primary factors contributing to this phenomenon is the temperature-dependent solubility of water in transformer oil. As temperature increases, the ability of transformer oil to dissolve water molecules also increases, causing a larger proportion of moisture to remain dissolved within the oil rather than existing as free water. This condition alters the dielectric properties of the insulating oil, which directly influences the operating principle of capacitive moisture sensors. Since capacitive sensors estimate moisture content based on changes in dielectric permittivity, variations in temperature can introduce additional measurement uncertainty even when the actual water content remains unchanged.

The results presented in Table 1 show that the lowest relative errors were observed at temperatures between 40°C and 50°C, where the deviation between the sensor readings and KFT measurements remained below 2%. This temperature range appears to provide a relatively stable condition in which the sensor response closely reflects the actual moisture content. At lower temperatures, the movement of water molecules is more restricted, potentially affecting the equilibrium distribution of moisture within the oil. Conversely, at temperatures exceeding 60°C, the measurement error increased significantly, reaching 9.88% at 80°C. These findings suggest that elevated temperatures amplify the sensitivity of the sensor to thermal effects, resulting in greater discrepancies from reference measurements.

The regression analysis further confirmed the strong relationship between temperature and measurement deviation. The obtained coefficient of determination ($R^2=0.91$) indicates that approximately 91% of the variability in measurement error can be explained by temperature variations. This strong correlation highlights temperature as one of the dominant factors affecting the accuracy of sensor-based moisture measurements in transformer oil. The positive regression trend observed in Figure 3 indicates that measurement deviation tends to increase as temperature rises, emphasizing the importance of incorporating temperature compensation techniques into practical monitoring systems.

The findings of this study are consistent with previous research that reported significant temperature effects on moisture monitoring in insulating oils. Recent studies have shown that sensor-based moisture measurement systems often exhibit temperature-dependent responses due to changes in dielectric constant, conductivity, and water distribution within transformer oil. Furthermore, research on online transformer condition monitoring has emphasized the necessity of compensating for environmental and operational variables to ensure reliable measurement performance. The present study reinforces these observations by providing quantitative evidence of the relationship between temperature and measurement accuracy over a broad range of operating temperatures.

From a practical perspective, the results have important implications for transformer condition monitoring and predictive maintenance applications. Many modern transformers are equipped with online monitoring systems that continuously measure moisture levels to assess insulation health and estimate transformer ageing. If temperature effects are not properly considered, moisture readings obtained during periods of high loading may overestimate the actual moisture content, potentially leading to inaccurate maintenance decisions. Conversely, underestimating moisture levels could delay necessary maintenance actions and increase the risk of insulation degradation or dielectric failure. Therefore, integrating temperature compensation algorithms into moisture monitoring systems can significantly improve measurement reliability and support more accurate condition assessment.

The findings also suggest opportunities for further improvement through data-driven approaches. Machine learning and artificial intelligence techniques have recently been applied to transformer diagnostics and condition monitoring. By incorporating temperature, humidity, oil characteristics, and historical operational data into predictive models, it may be possible to develop adaptive calibration methods capable of correcting temperature-induced measurement errors in real time. Such approaches could enhance the performance of online monitoring systems and contribute to the development of intelligent transformer health management frameworks.

Despite the promising results, several limitations should be acknowledged. The experiments were conducted under controlled laboratory conditions using a specific type of mineral transformer oil and a limited temperature range. In actual transformer operation, additional factors such as oil ageing, oxidation products, dissolved gases, contamination levels, and varying load conditions may also influence moisture measurement accuracy. Moreover, the study focused on single sensor technology, whereas different sensor designs may exhibit different temperature sensitivities. Future research should therefore investigate the influence of these factors under real operating conditions and evaluate the performance of various sensor technologies across a wider range of transformer environments.

Overall, the study confirms that temperature is a critical factor affecting the accuracy of moisture measurements in transformer oil. The observed increase in measurement deviation at elevated temperatures highlights the need for temperature-aware monitoring strategies and compensation mechanisms. Implementing such approaches can improve the reliability of moisture monitoring systems, enhance transformer condition assessment, and ultimately contribute to more effective maintenance planning and increased transformer operational reliability.

## CONCLUSIONS AND RECOMMENDATIONS

This study investigated the effect of temperature on the accuracy of moisture content measurements in transformer oil using a capacitive moisture sensor and Karl Fischer Titration (KFT) as the reference method. The results demonstrated that temperature significantly influences measurement accuracy, with measurement deviations increasing as the oil temperature rises. Both measurement methods showed a similar increasing trend in moisture content with increasing temperature; however, the discrepancy between sensor readings and reference values became more pronounced at higher temperatures. The lowest relative errors were observed within the temperature range of 40°C–50°C, indicating that this range provides the most reliable measurement conditions. Regression analysis revealed a strong positive relationship between temperature and measurement deviation, with a coefficient of determination (R^2) of 0.91, confirming that temperature is a dominant factor affecting sensor performance. These findings highlight the importance of incorporating temperature compensation mechanisms into sensor-based moisture monitoring systems to improve measurement reliability and support more accurate transformer condition assessment. Future research should focus on developing adaptive compensation models and validating the proposed approach under real transformer operating conditions involving different oil types, ageing levels, and environmental factors.

## FURTHER STUDY

This research still has limitations, so it is necessary to conduct further research related to the topic of Analysis of the Effect of Temperature on the Accuracy of Moisture Content Measurement in Transformer Oil in order to perfect this research and increase insight for readers.

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