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### RESEARCH ARTICLE

## DEVELOPMENT AND CHARACTERIZATION OF A SURFACE PROBE CALIBRATION SYSTEM AT NIS

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#### Abstract

This paper presents the development and characterization of a dedicated calibration system for surface temperature probes over the temperature range from 50 °C to 300 °C. The system was developed at the National Institute for Standards (NIS) to improve the traceability and reliability of surface temperature measurements. The calibration setup is based on a precision-machined aluminum plate combined with a flat spiral heater to ensure uniform heat distribution. The system performance was evaluated in terms of temperature stability, temperature inhomogeneity, and agreement with a calibrated reference thermocouple. The results demonstrate that the system achieves high stability, ranging between  $\pm 0.1$  °C and  $\pm 0.2$  °C, while temperature inhomogeneity is limited to values between 0.2 °C and 0.5 °C across the investigated range. A comprehensive uncertainty analysis was carried out considering all significant sources of uncertainty. The expanded uncertainty ( $k = 2$ ) was found to range from  $\pm 0.3$  °C to  $\pm 0.6$  °C over the operating temperature range. The developed system provides a reliable, traceable, and practical solution for surface temperature probe calibration, representing an improvement over conventional calibration method.

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#### Introduction:-

Surface temperature sensors are widely used in industrial, medical, and environmental applications, where accurate and traceable temperature measurements are essential. However, conventional calibration methods for surface temperature probes often face limitations related to temperature stability, repeatability, and restricted temperature ranges [1,2].

Several studies have addressed the calibration of surface temperature sensors using different techniques and reference systems. Contact calibration methods based on flat plates and embedded sensors have been widely used in dimensional metrology and industrial applications [1,2]. Other approaches have focused on improving thermal contact and minimizing heat losses to enhance measurement accuracy. Despite these efforts, conventional calibration systems still suffer from several limitations, including non-uniform temperature distribution, instability over time,

and limited traceability. In addition, many systems operate over a restricted temperature range and do not provide a comprehensive uncertainty evaluation in accordance with international standards.

Conventional calibration systems for surface temperature probes often suffer from several limitations, including poor thermal contact, non-uniform temperature distribution, limited stability over time, and restricted operating temperature ranges. In many cases, these systems also lack a comprehensive uncertainty evaluation in accordance with international standards, which reduces the reliability and traceability of measurements.

In this work, a dedicated calibration system has been developed at the National Institute for Standards (NIS) to overcome these limitations. The proposed system provides improved temperature stability, reduced temperature inhomogeneity, and a well-defined uncertainty budget in accordance with international standards. Furthermore, the system covers a wide temperature range from 50 °C to 300 °C, making it suitable for various industrial and metrological applications. Compared to conventional calibration systems, the developed system demonstrates improved temperature stability, reduced in-homogeneity, and enhanced measurement reliability. This work therefore presents a practical and traceable calibration methodology with improved performance.

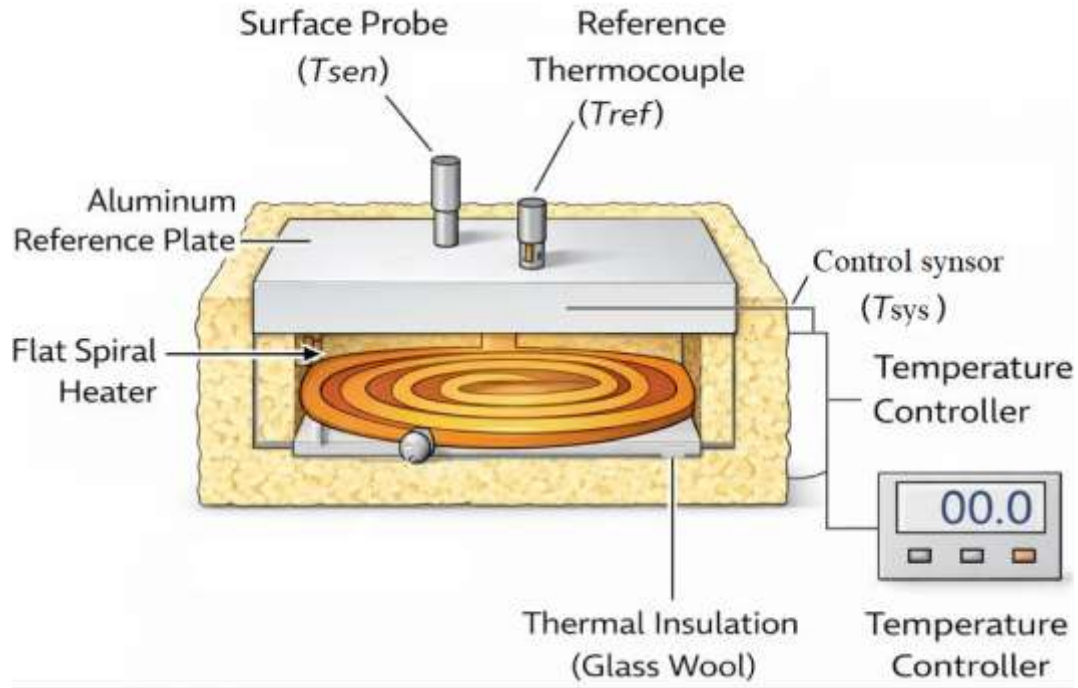
Compared to previously reported calibration systems, which often suffer from limited temperature stability (typically  $\pm 0.5$  °C or higher) and non-uniform temperature distribution, the developed system demonstrates improved performance. The proposed system achieves enhanced temperature stability ( $\pm 0.1$ – $0.2$  °C), reduced inhomogeneity ( $0.2$ – $0.5$  °C), and a wider operating range ( $50$ – $300$  °C). These improvements provide a more reliable and traceable solution for surface temperature probe calibration.

#### **Experimental Setup:-**

A schematic diagram of the NIS surface probe calibration system is shown in Fig. 1. The system is specifically designed for the calibration of surface-mounted temperature probes. The aluminum reference plate used in the system has approximate dimensions of 50 mm  $\times$  50 mm  $\times$  10 mm, providing a sufficiently large and uniform surface for probe placement. The heating element consists of a flat spiral heater with a power rating of approximately 200 W, mounted beneath the plate to ensure uniform heat distribution. The internal control sensor is positioned directly below the center of the plate to regulate the system temperature accurately. The reference thermocouple used in this study is a Type K thermocouple with an accuracy of  $\pm 0.1$  °C, calibrated and traceable to national standards at NIS. It is mounted in direct contact with the surface, with a flattened junction positioned flush with the plate surface to ensure accurate measurement of the true surface temperature.

To minimize heat conduction errors, the thermocouple wires are arranged horizontally along the surface for a minimum distance of 10 mm before being routed away. A thin layer of thermal paste is applied to improve thermal contact. The measurement region is thermally insulated using glass wool to reduce heat losses due to convection and radiation. The reference thermocouple and the surface probe under calibration are positioned in close proximity and at the same radial distance from the center to minimize the effect of surface temperature inhomogeneity.

Uniform heat distribution across the surface is achieved using the flat spiral heater clamped to an integrating block beneath the surface plate. The internal control sensor ensures accurate temperature regulation. The calibration system operates over a temperature range from 50 °C to 300 °C.



**Fig. 1. Schematic diagram of the developed surface probe calibration system showing the aluminum reference plate with embedded reference thermocouple ( $T_{ref}$ ) and horizontally embedded control sensor ( $T_{sys}$ ), surface probe ( $T_{sen}$ ), flat spiral heater, and surrounding thermal insulation (Glass wool)**

### Results and Discussion:-

To investigate the efficiency of the system, a series of tests were performed throughout the operating temperature range. The system performance was evaluated through the following parameters [3]:

- The temperature difference between the system temperature ( $T_{sys}$ ) and the temperature measured by the reference thermocouple on the surface ( $T_{ref}$ ).
- Comparison between the reference thermocouple and the calibrated surface probe.
- Temperature stability over time.
- Monitoring temperature variations across different positions on the reference surface using a calibrated reference thermocouple.

#### Temperature Difference between System and Surface:-

The temperature difference between the system temperature ( $T_{sys}$ ) and the temperature measured by the reference thermocouple on the surface ( $T_{ref}$ ) is shown in Fig. 2. These measurements were obtained using two sensors: the internal control sensor located beneath the reference surface ( $T_{sys}$ ) and a reference thermocouple placed directly on the surface ( $T_{ref}$ ). The results show that the temperature difference remains small across the investigated range, indicating good agreement between the system control and the actual surface temperature.

This small temperature difference indicates good agreement between the system control temperature and the actual surface temperature, confirming effective heat transfer and accurate system regulation.

This behavior indicates efficient heat transfer between the heating system and the surface plate, as well as accurate temperature control by the internal sensor.

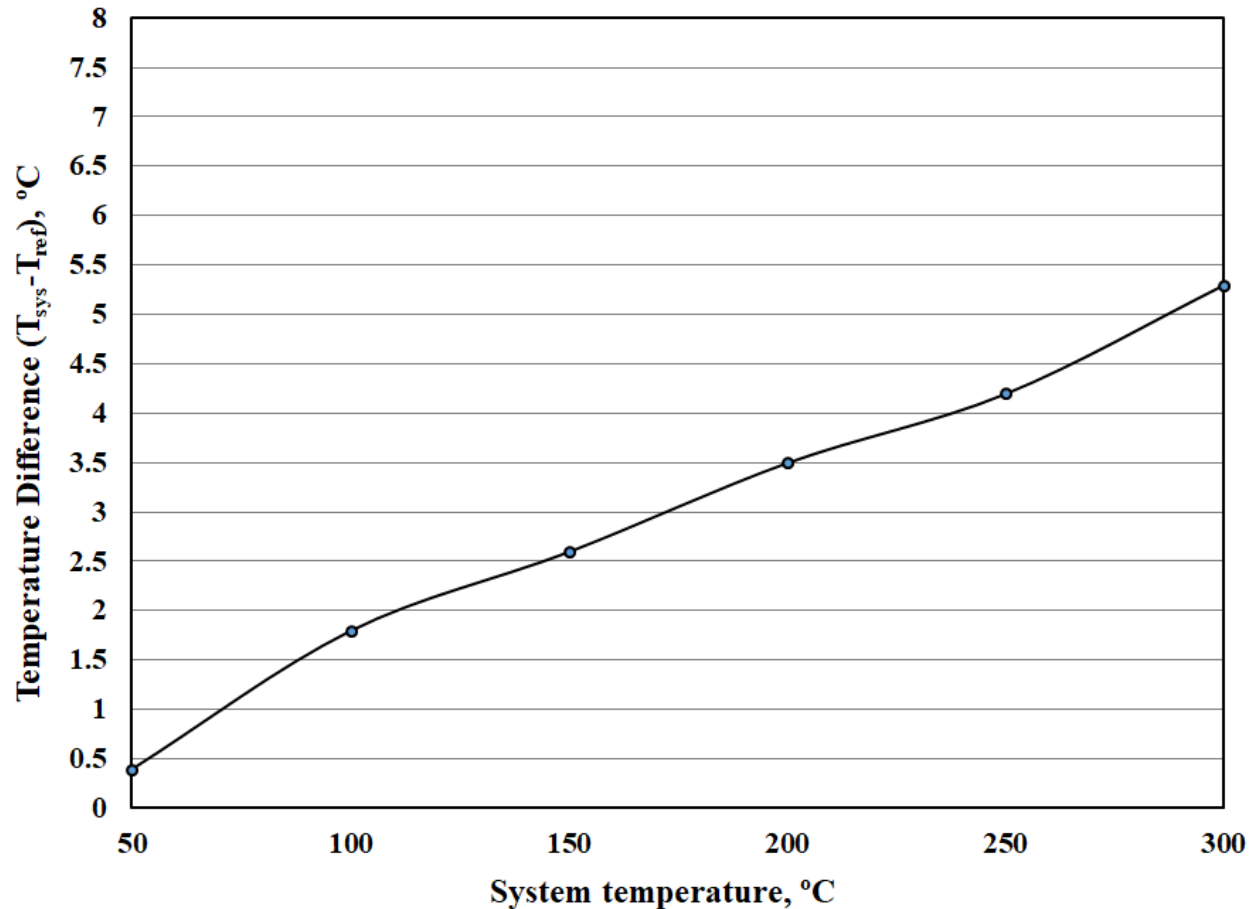


Fig. 2. Temperature difference (°C) between system temperature ( $T_{\text{sys}}$ ) and surface temperature ( $T_{\text{ref}}$ ) as a function of system temperature (°C), demonstrating system accuracy.

#### Temperature Stability:-

Temperature stability was evaluated by recording temperature variations over a period of at least one hour after steady-state conditions were achieved. For each temperature point, at least 30 measurements were recorded at constant time intervals. Stability measurements were conducted at the center of the surface for each temperature set point [4].

An example of temperature stability measurements at 100 °C is shown in Fig. 3. The temperature stability of the system, measured using the reference thermocouple, was found to be  $\pm 0.2$  °C. Over the full temperature range from 50 °C to 300 °C, the stability was found to lie between  $\pm 0.1$  °C and  $\pm 0.2$  °C.

The system demonstrates high stability, with temperature fluctuations limited to approximately  $\pm 0.2$  °C at 100 °C. Similar behavior was observed across the full temperature range, confirming the reliability of the system.

This high level of stability can be attributed to the uniform heat distribution provided by the flat spiral heater and the effective thermal insulation, which minimize heat losses and external disturbances.

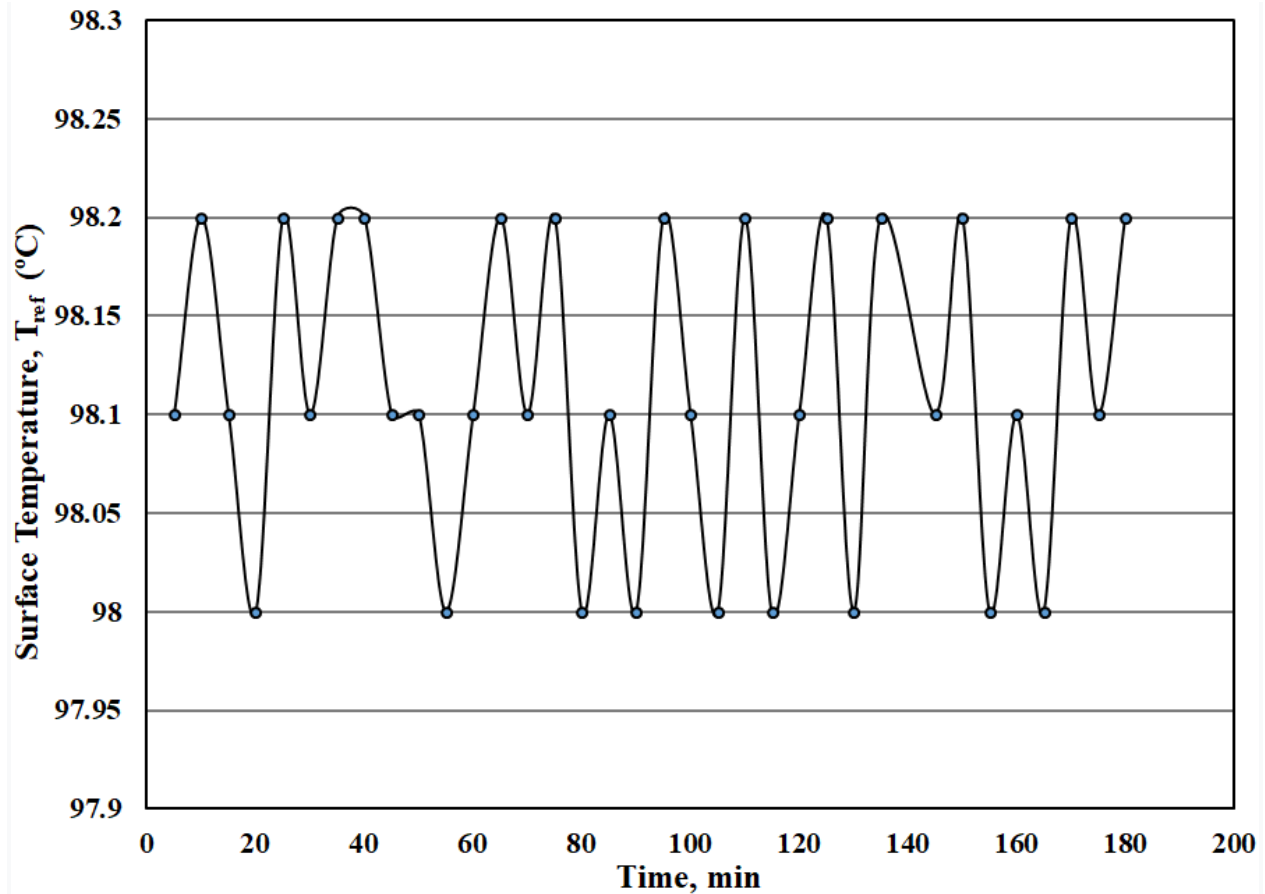


Fig. 3. Temperature stability at 100 °C showing temperature variation (°C) as a function of time (minutes), demonstrating system stability under steady-state conditions.

#### Comparison between Reference Thermometer and Surface Probe:-

Measurements obtained from the reference thermometer ( $T_{ref}$ ) were recorded simultaneously with those of the calibrated surface probe ( $T_{sen}$ ). The comparison results are presented in Fig. 4, where the observed temperature difference, ranging from 0.2 °C to 0.4 °C, indicates reasonable agreement between the reference thermocouple and the calibrated surface probe. This level of agreement confirms the reliability of the developed calibration system. The difference remains relatively consistent over the investigated temperature range, indicating stable system performance.

The small deviations can be attributed to differences in thermal contact between the probe and the surface, as well as the response characteristics of the sensors. In addition, slight positioning differences and local temperature gradients may also contribute to the observed variations.

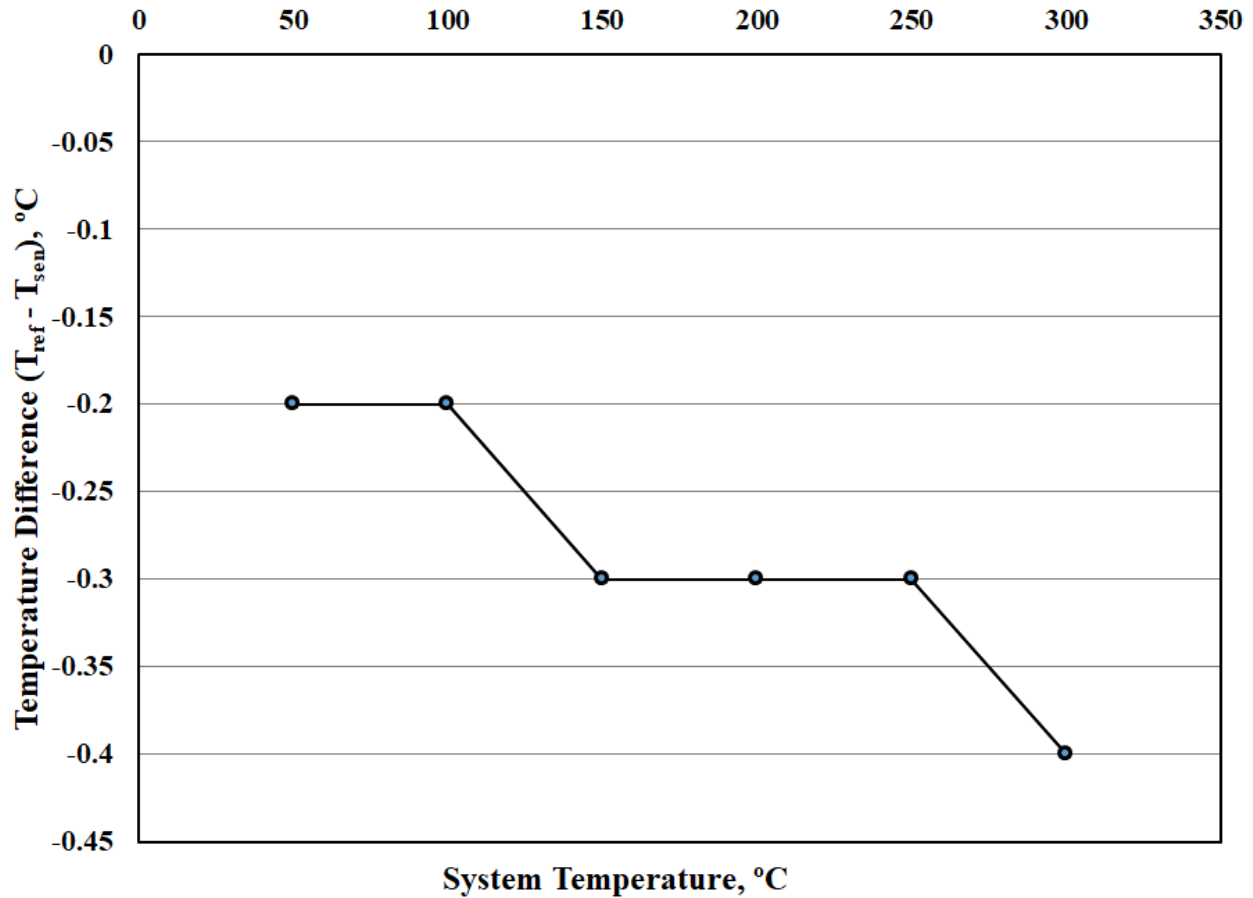


Fig. 4. Temperature difference (°C) between the reference thermocouple ( $T_{ref}$ ) and the calibrated surface probe ( $T_{sen}$ ) as a function of system temperature (°C), showing good agreement and small deviations between both sensors.

#### Temperature In-homogeneity:-

Temperature in-homogeneity was evaluated by measuring the reference thermometer output at different positions on the surface plate. The measurement points on the flat surface of the calibration system are shown in Fig. 5. The distances from the center were varied from 1 cm to 2 cm in both horizontal and vertical directions.

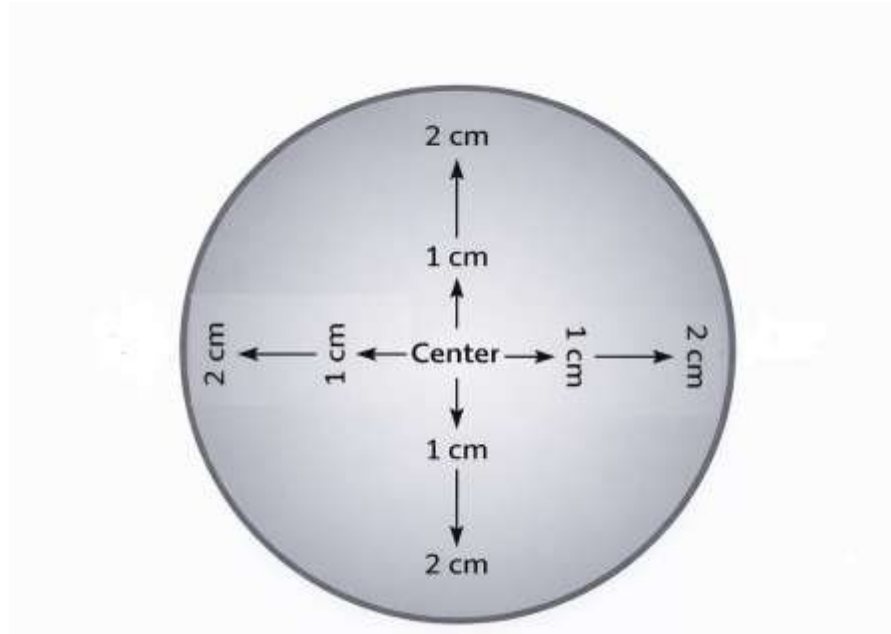
The temperature in-homogeneity was determined as the maximum deviation between the temperature measured at the center ( $T_{center}$ ) and that measured at other positions ( $T_{corner}$ ), according to:

$$\text{In-homogeneity} = 0.5 \times (\max(T_{center} - T_{corner}) - \min(T_{center} - T_{corner})) \quad (1)$$

This approach is commonly used in surface temperature measurements to evaluate spatial temperature variation and provides a practical representation of temperature uniformity across the surface.

The measured temperature in-homogeneity values were found to range from 0.2 °C to 0.5 °C.

The results of these tests indicate that the system efficiency is adequate for operation within the temperature range from 50 °C to 300 °C [5]. The observed in-homogeneity is mainly influenced by edge heat losses and radial temperature gradients across the plate surface.



**Fig. 5. Measurement positions on the aluminum reference plate for evaluating temperature in-homogeneity at radial distances of 1 cm and 2 cm from the center.**

Additional measurements were performed at representative temperature points, including 50 °C, 150 °C, 200 °C, and 300 °C. The results showed consistent performance across the full temperature range. Overall, the system maintains temperature stability within ±0.1 °C to ±0.2 °C, while temperature in-homogeneity is limited to values between 0.2 °C and 0.5 °C, demonstrating high performance and reliability.

**Uncertainty of measurement:-**

The uncertainty budget of the developed calibration system was evaluated in accordance with the ISO/IEC Guide 98-3 (GUM). All significant sources of uncertainty were identified and quantified. The uncertainty of the reference thermocouple ( $U_{st}$ ) was obtained from its calibration certificate. The resolution uncertainty ( $U_{res}$ ) is associated with the measurement system. The stability component ( $U_{stab}$ ) was determined from repeated measurements under steady-state conditions. The temperature inhomogeneity ( $U_{hom}$ ) was evaluated based on spatial variations across the surface, while hysteresis ( $U_{hys}$ ) was determined from heating and cooling cycles. The repeatability component ( $U_{rep}$ ) was evaluated statistically and considered as Type A uncertainty.

Each component was divided according to its probability distribution, and the combined uncertainty was calculated using the root-sum-square method. The expanded uncertainty was obtained using a coverage factor of  $k = 2$ , corresponding to a confidence level of approximately 95%. The results indicate that the dominant contributions arise from temperature inhomogeneity and system stability. The expanded uncertainties were found to range from ±0.3 °C to ±0.6 °C over the temperature interval from 50 °C to 300 °C [6]. Table 1 presents an example of the uncertainty budget calculated at 100 °C, where the expanded uncertainty was ±0.3 °C using a coverage factor of  $k = 2$ .

**Table 1. Uncertainty budget at 100 °C for the surface probe calibration system**

Symbol	Source uncertainty	Value	Divisor	Sensitivity coefficient	Uncertainty contribution
$U_{st}$	Uncertainty of reference	0.1	2	1	0.015
$U_{res}$	Resolution	0.1	3.46	1	0.003
$U_{stab}$	Stability of the system	0.2	3.46	1	0.057713

Symbol	Source uncertainty	Value	Divisor	Sensitivity coefficient	Uncertainty contribution
$U_{\text{hom}}$	In-homogeneity of the system	0.2	1.73	1	0.1155
$U_{\text{hys}}$	Hysteresis	0.1	1.73	1	0.0577
$U_{\text{rep}}$	Repeatability (Type A)	0.05	1	1	0.05
Combined Un.			0.149		
Expanded Un.			$\pm 0.3 \text{ }^{\circ}\text{C}$		

### Conclusion:-

A dedicated calibration system for surface temperature probes has been successfully developed and characterized at the National Institute for Standards (NIS). The system demonstrated reliable performance over the temperature range from 50 °C to 300 °C. The results confirm high temperature stability ( $\pm 0.1 \text{ }^{\circ}\text{C}$  to  $\pm 0.2 \text{ }^{\circ}\text{C}$ ) and low temperature inhomogeneity (0.2 °C to 0.5 °C). The uncertainty analysis shows expanded uncertainties ranging from  $\pm 0.3 \text{ }^{\circ}\text{C}$  to  $\pm 0.6 \text{ }^{\circ}\text{C}$  ( $k = 2$ ).

The developed system provides a practical, reliable, and traceable solution for calibration laboratories and industrial applications, with potential for further improvement and extension to higher temperature ranges. Overall, this work demonstrates the capability of the proposed system as an effective calibration tool for surface temperature measurements in both industrial and metrological fields.

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