Emissivity Measurement Using Heat Flux Method at Cryogenic Temperatures

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Abstract. This article presents a method for assessing surface emissivity at cryogenic temperatures using heat flow analysis. This approach calculates emissivity by directly evaluating heat transfer across the surface, providing a more efficient alternative to conventional calorimetric techniques. Unlike conventional approaches, which rely on applying precise amounts of heat or monitoring temperature variations to infer emissivity, this technique minimizes complexity by removing the need for exact thermal insulation or controlled heat inputs. By employing heat flux sensors, it achieves highly accurate, real-time heat flow measurements, enabling dependable emissivity assessments. This approach is particularly advantageous for evaluating advanced materials designed for extended space missions. The research employed a commercially accessible heat flux sensor to assess the emissivity of various materials such as black paint, stainless steel, aluminium foil, and aluminized mylar over a temperature range of 90K to 180K. The paper discusses the underlying theory, experimental design, and results of the investigation.

Key Words: Emissivity, Heat flux method, Heat flux sensor.

1. Introduction

At low temperatures, the emitted thermal radiation is significantly weaker, making the measurement process highly sensitive to environmental factors and the precision of instrumentation. These measurements are particularly critical in areas such as cryogenics, space exploration, and low-temperature material science, where understanding thermal behavior is key to system performance and material design.

Determining emissivity at low temperatures is essential for understanding the thermal radiative behavior of materials in conditions where radiation plays a minimal role. These measurements can be classified by the techniques used and the testing environment. Broadly, the methods are divided into direct and indirect approaches. Direct techniques involve measuring the radiation emitted directly from the sample

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surface, while indirect techniques, such as reflectometry, deduce surface emissivity by analyzing optical properties [9].

Typical direct approaches for measuring emissivity at cryogenic temperatures include calorimetric [3], [4], [10],and radiometric methods [2], [5], [6], [12], [14], [15]. Calorimetric techniques measure total hemispherical emissivity, while radiometric methods target spectral and directional emissivity [14] .Additionally, heat flux-based methods, which assess net heat transfer between a sample and a reference surface, are widely used. These techniques are further divided based on the testing environment, such as vacuum chambers to minimize convection and conduction or atmospheric conditions where these effects are incorporated into the analysis. Instruments like heat flux sensors or radiometers are employed to detect subtle differences in radiative heat exchange between the sample and a reference blackbody.

Calorimetric emissivity measurements demand precise temperature control but are inherently time-consuming, as each test provides data for only one temperature. They also require a detailed understanding of the surface's thermal history, significant data handling, and complex setups , making them challenging for space applications. Moghaddam et al. [7], [8], addressed these challenges by implementing the heat flux approach. This method employs a heat flux sensor placed between the test specimen and a conductive base. These sensors, known for their high sensitivity to small heat flow variations, are particularly effective for measuring low-emissivity materials. By directly measuring heat transfer, the heat flux approach streamlines the procedure, removing the requirement for complex measuring equipment. Additionally, this method is ideal for ongoing emissivity tracking in dynamic systems where material properties or temperatures vary.

The heat flux-based method for measurement described in this paper provides a simple solution by directly measuring heat transfer across the emitting surface. This method eliminates the need for tracking the temperature history or thermally insulating structures with varying emissivity surfaces, significantly simplifying the process. It reduces data complexity and avoids the need for external heating, making it highly advantageous for space missions where energy availability is constrained.

The compact design provides the spatial resolution needed to analyze surfaces with non-uniform emissivities. Additionally, this method supports simultaneous testing of multiple surfaces with differing emissivities. The main objective of this study is to evaluate the effectiveness of the technique in measuring emissivity across the 90K to 180K temperature range.

2. Materials and Methods

A heat flux sensor (Figure 1) is an instrument that generates an electrical signal proportional to the heat transfer passing through its surface. By knowing the heat flux and the steady-state temperatures of both the emitting and receiving surfaces, emissivity can be determined. The small size of the heat flux sensor allows it to be easily integrated with small heaters. Additionally, it holds potential for applications where monitoring spatial variations in emissivity across a surface is required.

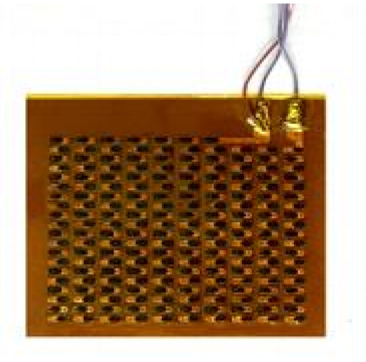

Fig. 1. Heat flux sensor

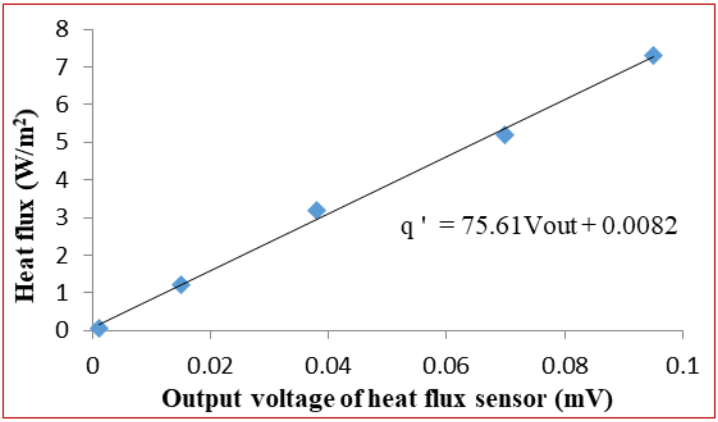

Fig. 2. Calibration Graph of the Heat Flux Sensor.

The heat flux sensor is composed of multiple thermocouples positioned on both sides of a thin polyimide film, forming a thermopile. As heat flows through the sensor, it induces a temperature gradient across the film, producing an electromotive force at the output terminals. The heat flux value can be calculated by using a calibration curve (heat flux vs. output voltage of the sensor). During calibration, the sensor's output voltage and corresponding heat flux values were recorded for various power inputs. The collected data was used to plot a curve (Figure 2), which revealed a best-fit line aligning closely with the manufacturer's provided data, confirming its stability and accuracy. The connection between the heat flux and the sensor's output voltage is mathematically expressed by Eq. (1).

$$q' = 75.61V_{out} + 0.0082 \qquad (1)$$

2.1. Experimental Setup

Figure 3 illustrates the experimental configuration for the heat flux-based emissivity measurement method. The recorded output voltage represents the applied heat load. By determining the steady-state temperatures of both the heater and the surface receiving the radiation, along with the measured heat flux, the sample's emissivity is calculated. The small size of the sensor allows easy integration with smaller heaters, increasing its flexibility. Using the calculated heat flux, the emissivity of the material is determined through the application of Eq. (2).

$$\varepsilon = \frac{q'}{\sigma(T_1^4 - T_3^4)} \qquad (2)$$

In this context, q′ denotes the heat flux calculated using Eq. (1), σ represents the Stefan-Boltzmann constant, and T_1 and T_3 are the temperatures of the emitting and receiving surfaces, respectively. These parameters are integral to determining the emissivity of the surface under investigation.

2.2 Experimental Procedure

The heater and the sensor are supported by FRP strips attached to a thermal baffle and is housed within an inner vacuum chamber. This chamber is cooled to 80 K by being surrounded with liquid nitrogen. To ensure a high vacuum environment, the vessel is evacuated to a pressure of 1×10^{-6} mbar using a turbo molecular pump. Temperature and heat flux voltage data are collected at regular intervals until thermal equilibrium is achieved. Once equilibrium is reached, the heater is powered by a constant power source at varying current levels (0.05, 0.07, 0.09, and 0.11 A). Measurements are taken again until a new state of thermal equilibrium is attained, which typically requires 4 to 5 hours. At equilibrium, the emissivity of the sample is calculated using the recorded temperatures of the emitting and receiving surfaces along with the heat flux sensor’s voltage output.

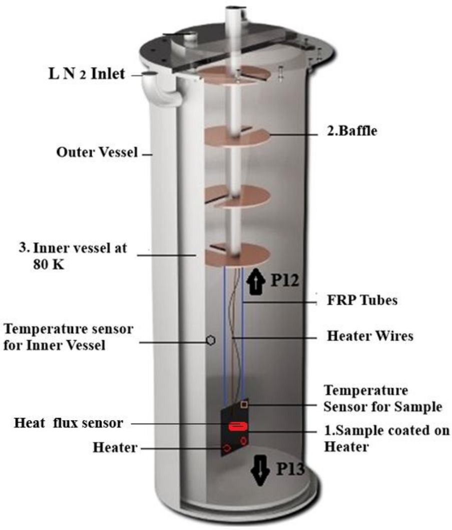

Fig. 3. Configuration for heat flux method.

2.3. Error Analysis

Several factors contribute to inaccuracies in emissivity measurements: (1) Radiation loss from the sample to the lowest thermal baffle, (2) inaccuracies in the measurement device, and (3) conductive and convective heat dissipation. It was found that the error associated with the view factor was 0.92%, with errors in calculating the areas of the emitter and receiver at 1.6%. Conductive and convective heat losses resulted in errors of under 0.11%.and variations in heater power had minimal effects on temperature and heat flow measurements. With the view factor close to 1, and the emissivity factor $F12$ in the heat transfer equations was small enough (0.0003) to be neglected.

Instrumental inaccuracies stem from the measurement tools used. The thermistor and the data logger had accuracy tolerances of ±1.24 K and ±0.04 K, respectively, resulting in an overall temperature measurement error of approximately ±1.2 K (±1.543%). Heater power measurement precision depends on current and voltage readings, with a multimeter error of 0.004 V over a 100 mV range. When all error sources—instrumental inaccuracies, view factor, and emitter/receiver area were combined, the total measurement error was estimated to be 7.89 %.

3. Results

3.1. Emissivity of different materials tested

The next section presents the results of experimental investigations conducted on various samples using the heat flux method. To ensure the consistency of the measured values, the experiments were repeated multiple times. Each experiment was performed approximately five times to confirm repeatability. The results are shown graphically, with the graphs displaying both the measured temperatures and corresponding emissivity values. Figure 4 illustrates the emissivity values obtained for black paint using the heat flux method, while Figure 5 presents the emissivity values for stainless steel, aluminum foil, and aluminized mylar.

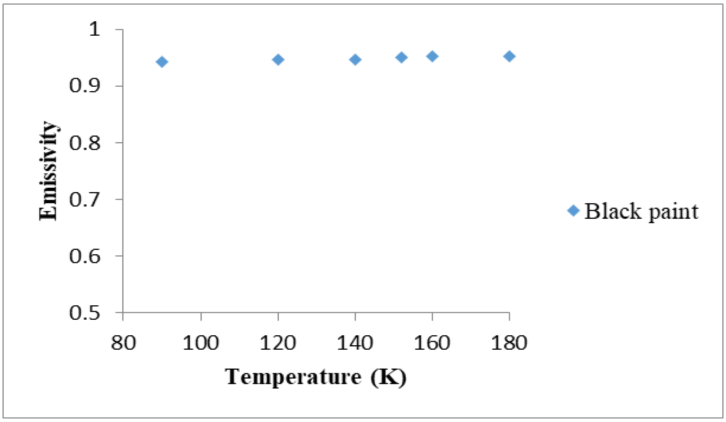

Fig. 4. Emissivity Vs temperature of Black paint

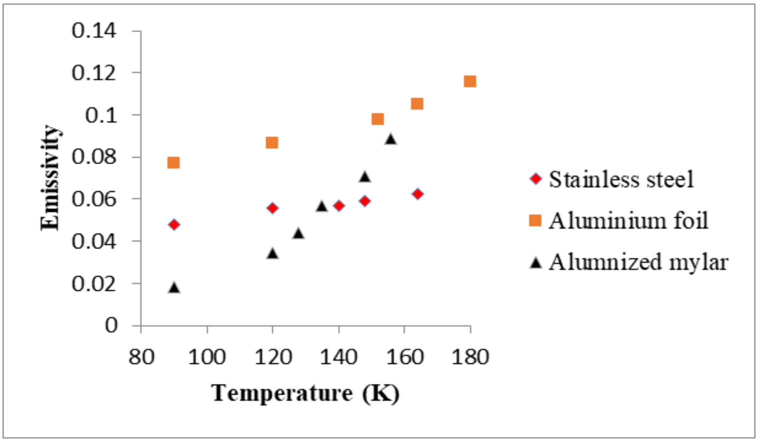

Fig. 5. Emissivity Vs temperature of Stainless steel, Aluminium foil, Alumnized Mylar

3.2. Comparison of Experimental and Published Data

To assess accuracy of measurements the results were compared against published literature values for black paint [11], stainless steel [1],[12], and aluminum foil [1],[13]. This comparison is illustrated in Figures 6 to 8. For black paint, Aeroglaze Z307, which has the same composition as the material used in the study by [11], was applied to the sample surface and its emissivity was measured. The results were then compared directly with those reported in their study.

The reliability and precision of the comparison, careful attention was given to ensuring that the sample properties aligned with those in the literature. Specifically, the same manufacturer, identical thickness, and comparable polishing techniques were used for the samples to minimize any discrepancies that could arise from material or surface treatment differences. This rigorous approach allowed for a more reliable validation of the heat flux method's performance and its ability to produce consistent emissivity measurements.

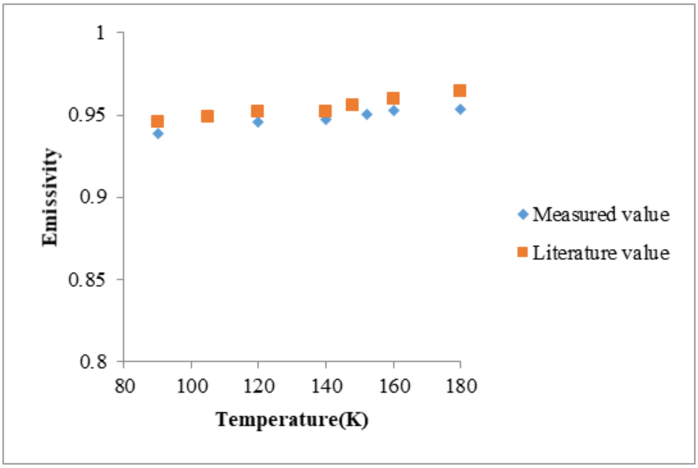

Fig. 6. Comparison of Measured and Literature Data for Black Paint

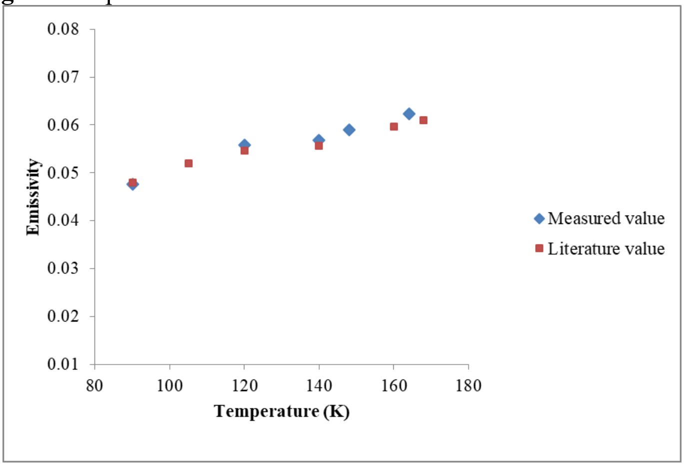

Fig. 7. Comparison of Measured and Literature Data for Stainless Steel

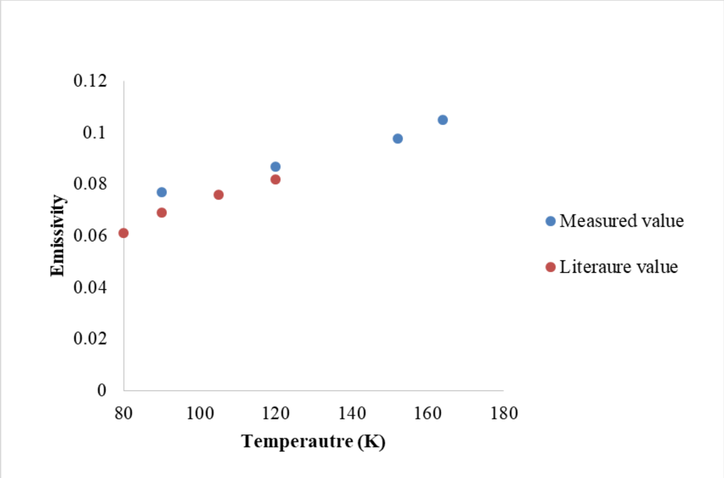

Fig. 8. Comparison of Measured and Literature Data for Aluminum Foil

4. Discussion and Conclusion

Measurements were conducted over a temperature range from 90K to 180K. For all samples, the emissivity values obtained were in close agreement with those found in the literature, with discrepancies within ±1.4%, confirming the reliability of the experimental setup. The emissivity of black paint differed by only 0.4% from the reported values. Likewise, the emissivity values for stainless steel were consistent with existing data, showing a maximum variation of 1.5%. For aluminum foil, the discrepancies compared to the literature ranged between 4% and 7%. In summary, the application of the heat flux method has significantly enhanced the accuracy and reliability of the emissivity measurements.

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