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Cryogenic emissivity testing apparatus for insulating materials cooled by a cryocooler

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Abstract. The emissivity of low-temperature materials can exhibit variations with changes in temperature. Currently, measuring low-temperature emissivity often includes the use of cryogenic liquids like liquid nitrogen and liquid helium, which presents challenges such as handling inconvenience and limited adaptability to a broad temperature range. Furthermore, materials like aluminium-coated polyester films exhibit surface emissivity levels lower by several orders of magnitude compared to materials like copper and stainless steel, presenting significant challenges in achieving high-precision measurements. In this research, a low-temperature emissivity testing apparatus based on a pulse tube cryocooler has been developed. The measurement temperature range extends from 50 K to room temperature, and with the option to change the cryocooler, measurements at even lower temperatures, such as 4 K, can be achieved. The measurement principles and essential structural elements of the newly developed testing apparatus, designed specifically for low emissivity samples, are outlined. Additionally, preliminary experimental results from measurements on a double aluminium-coated polyester film sample at different temperatures are presented.

1. Introduction

The surface emissivity of materials is a crucial parameter in calculating radiative heat transfer, which typically varies with decreasing temperature. Thus, obtaining accurate material emissivity is essential during the design of low-temperature systems. Currently, measuring the emissivity of low-temperature materials commonly involves the calorimetric method and the radiometric method [1]. In these measurement techniques, cryogenic liquids such as liquid nitrogen and liquid helium are often used as the refrigeration source [2], posing challenges such as handling inconvenience and limited adaptability across a broad temperature range. Moreover, materials such as aluminium-coated polyester films exhibit surface emissivity levels lower by several orders of magnitude compared to materials like copper and stainless steel, thereby posing significant challenges in achieving high-precision measurements.

In this study, a low-temperature emissivity measurement device suitable for insulating materials (especially films) has been developed, utilizing a high-frequency pulse tube cryocooler known for its compact structure and operational convenience [3]. The cryocooler can provide a broad measurement temperature range compared to cryogenic liquids, although it may require a long time for thermal equilibrium due to the limited cooling capacities.

2. Description of the developed device

2.1 The measurement device structure

The two-dimensional and three-dimensional schematic diagrams of the designed device for measuring low-temperature emissivity of insulating materials are shown in Figures 1 and 2, respectively. The device primarily includes a high-frequency pulse tube cryocooler, vacuum chamber, low-temperature sample chamber, emission plate, absorber plate, calorimetric rod, multi-layer insulation unit, and heating control unit.

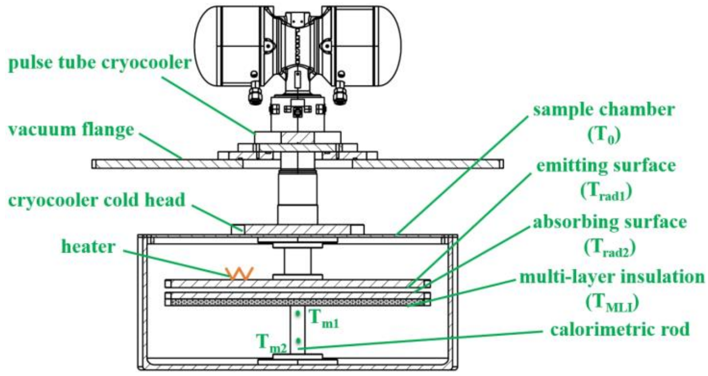

Figure 1. Schematic diagram of the developed low-temperature emissivity measurement device for insulating materials based on a high-frequency pulse tube cryocooler.

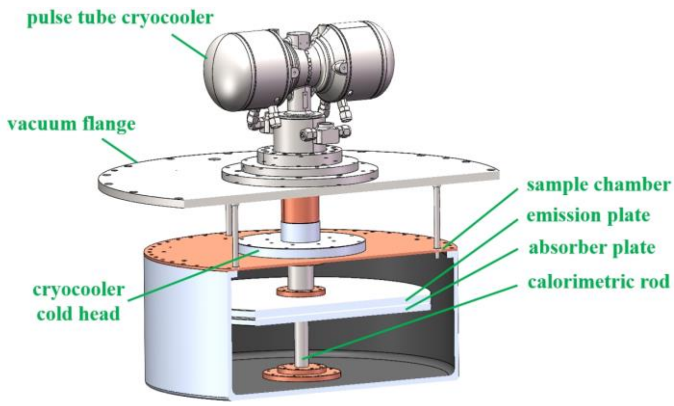

Figure 2. Three-dimensional schematic diagram of the low-temperature emissivity measurement device for insulating materials developed based on a high-frequency pulse tube cryocooler.

During sample installation, two identical samples are mounted on the underside of the emission plate and the upper side of the absorber plate. Given that insulating materials such as aluminum foil and copper foil have inherently low emissivity, which decreases further as temperatures drop, the diameters of both the emitter plate and absorber plate have been intentionally increased to enhance radiative heat transfer between samples. This feature distinguishes the device from conventional emissivity measurement devices used for standard materials [4]. At this point, due to the larger surface areas of the emitter and absorber plates, both are housed within a sample chamber. The external surface of the sample chamber is wrapped with 50 layers of multi-layer insulation, and the internal surfaces are treated with a black coating. The temperature uniformity within the entire chamber is maintained to within ±1K.

The cryocooler depicted in the figure is a high-frequency pulse tube cryocooler with a cooling capacity of 60 W at 77 K, which features a cold head without moving parts, low vibration, and a long operational lifespan. The sample chamber can achieve a lowest temperature of around 45 K. The setpoint temperature is adjusted via PID control of the electrical power (voltage) supplied to the cryocooler, ensuring a temperature control precision of ±0.01 K. By replacing the pulse tube cryocooler with a G-M cryocooler with a cooling capacity of 1.5 W at 4 K, the sample chamber can reach temperatures as low as 4 K. At this point, it is necessary to install a heater on the cryocooler cold head to control the sample chamber's temperature, as the input power of the GM cryocooler is not as easily adjustable. Once the sample chamber and its internal components reach the set temperature, the temperature of the emission plate is regulated by adjusting the heating power applied to the heater mounted on its surface.

2.2 The measurement device principle

After heat is applied to the emitter plate, the total heat Q_{total} transferred to the absorber plate by radiation is further conveyed to the sample chamber through two mechanisms, as shown in Equation 2-1: firstly, by solid conduction via the calorimetric rod, labelled as Q_m; and secondly, by radiation, labelled as Q_{rad}.

$$Q_{total} = \frac{A \cdot 5.67 * 10^{-8} * (T_{rad1}^4 - T_{rad2}^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} = Q_m + Q_{rad} \tag{2-1}$$

T_{rad1} and T_{rad2} represent the temperatures of the emitter plate and absorber plate, respectively. ε_1 and ε_2 denote the emissivities of the insulation materials attached to the emitter plate and absorber plate. Because the insulation samples on both plates are identical and the temperatures of the two plates are close, ε_1 and ε_2 are assumed to be equal, representing the emissivity to be measured.

Q_m is determined by reading the values from two temperature sensors placed on the calorimetric rod and applying Fourier's law of heat conduction, as shown in Equation 2-2. PT100 temperature sensors are used for measurements at liquid nitrogen temperatures and above, while rhodium-iron temperature sensors are used for lower temperatures. The accuracy of the apparatuses used in the measurement is shown in Table 1.

$$Q_m = k * A * \frac{T_{m1} - T_{m2}}{L} \tag{2-2}$$

k represents the thermal conductivity of the calorimetric rod, which varies with temperature according to a known relationship. A denotes the cross-sectional area of the calorimetric rod, while T_{m1} and T_{m2} represent the temperatures at its hot and cold ends, respectively. L is the distance between the two temperature sensors on the calorimetric rod.

Table 1. Accuracy of the apparatuses.

Apparatus	Accuracy
Temperature sensor	0.1 K
Power supply	0.1mV/0.01mA

Radiative heat transfer between the absorber plate and the sample chamber is challenging to accurately measure. To address this, the value of Q_{rad} needs to be minimized until its impact on emissivity measurement is negligible. To achieve this goal, 30 layers of multi-layer insulation material have been installed on the lower surface of the absorber plate to reduce radiative heat transfer between the absorber plate and the sample chamber. Moreover, the small temperature difference between the emitter plate and the sample chamber significantly reduces radiative heat transfer. During the measurement and calibration process, thermometers are also placed on the surface of the multi-layer insulation material of the absorber plate for quantitative calculation, as shown in Equation 2-3.

$$Q_{rad} = K * A * \frac{T_{rad2} - T_{MLI}}{L_{MLI}} = \frac{A \cdot 5.67 * 10^{-8} * (T_{MLI}^4 - T_0^4)}{\frac{1}{\varepsilon_3} + \frac{1}{\varepsilon_4} - 1} \tag{2-3}$$

K represents the apparent thermal conductivity of the multi-layer insulation material, *A* denotes the measurement area of the multi-layer insulation, T_{MLI} is the temperature on the outer surface of the multi-layer insulation material, L_{MLI} is the thickness of the multi-layer insulation material, T_0 is the temperature of the sample chamber, and ε_3 and ε_4 are the emissivities of the outer surface of the multi-layer insulation material and the surface of the sample chamber, respectively. During equipment calibration, aluminum foil identical to the multi-layer insulation material is applied to the sample chamber. Due to the close proximity of temperatures between the multi-layer insulation material and the sample chamber, ε_3 and ε_4 are considered to be equal.

3. Experimental results and discussion

The apparatus designed for measuring the emissivity of insulation materials at low temperatures is shown in Figure 3. Currently, we are using aluminium-coated polyester film as the sample to conduct emissivity measurements ranging from 50 K to room temperature.

Figure 3. Photograph of the low-temperature emissivity measurement device for insulating materials developed based on a high-frequency pulse tube cryocooler.

Figure 4 depicts a typical temperature variation curve observed during the measurement process. Due to the low emissivity of materials such as aluminum foil, particularly at lower temperatures, the emissivity values decrease further. Consequently, the heat transfer between the emitter plate and the absorber plate is minimal, requiring an extended period to achieve thermal equilibrium. It typically takes nearly one week to measure a single temperature point. Figure 5 presents the measurement results of the aluminum-coated polyester film, demonstrating close alignment with known emissivity values measured at room temperature. The next step involves comparing these results with standard samples to determine the measurement accuracy of the equipment.

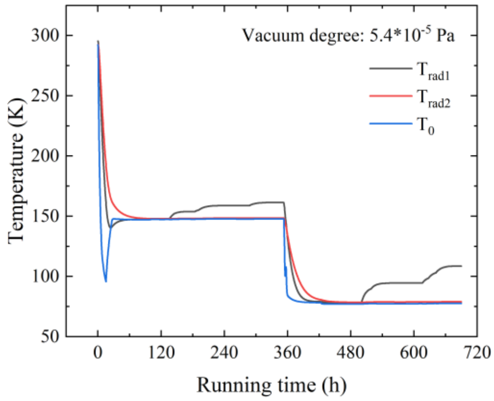

Figure 4. Typical cooling curve for low-temperature emissivity measurement of insulation materials.

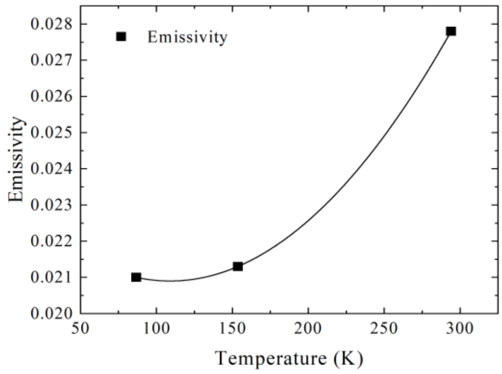

Figure 5. Measurement results of emissivity at different temperatures for aluminium-coated polyester film.

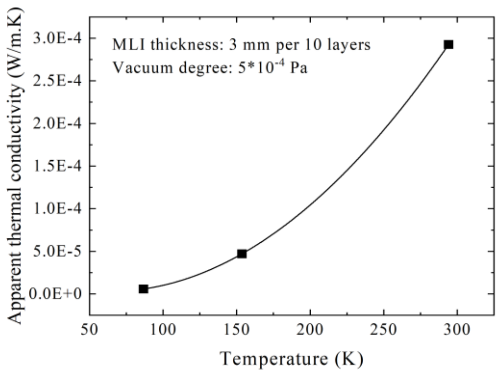

Figure 6. Measured apparent thermal conductivity of multi-layer insulation materials at different temperatures.

Figure 6 displays the apparent thermal conductivity of the multi-layer insulation material at different temperatures based on measurements taken at various temperature points. During the experimental process, the multi-layer insulation comprised 30 layers. At this stage, radiative heat transfer between the absorber plate and the sample chamber accounts for 3.5% of the total heat transfer between the emitter plate and the absorber plate. Based on the apparent thermal conductivity results shown in Figure 6, the impact of multi-layer insulation thickness on radiative heat transfer between the absorber plate and the sample chamber was also assessed, as illustrated in Figure 7. It is observed that with 10 layers of multi-layer insulation, radiative heat transfer constitutes up to 10% of the total heat transfer. However, increasing the layer count from 30 to 40 and 50 reduces this percentage from 3.5% to 2.7% and 2.2%, respectively. The diminishing reduction beyond 30 layers indicates that 30 layers are comparatively suitable.

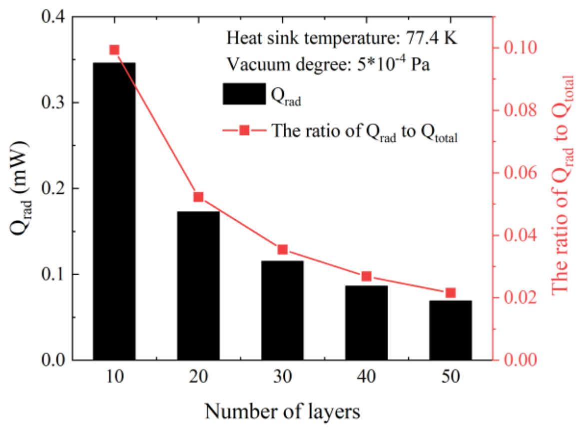

Figure 7. The effect of multi-layer insulation thickness on radiative heat leakage.

4. Conclusions

A low-temperature emissivity testing apparatus based on a pulse tube cryocooler has been developed. The measurement temperature range extends from 50 K to room temperature, and with the option to change the cryocooler, measurements at even lower temperatures, such as 4 K, can be achieved. The measurement principles and essential structural elements of the developed apparatus are outlined. Additionally, preliminary experimental results from measurements on a double aluminium-coated polyester film sample at different temperatures are presented.

Acknowledgments

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References

[1] Zhao Y, Li X, Zhang H, et al: Preliminary development of emissivity measurement system at low temperature based on radiometric method. Cryogenics 132, 1–6 (2023).
[2] Musilova V, Hanzelka P, Kralik T, et al: Low temperature radiative properties of materials used in cryogenics. Cryogenics 45, 529–536 (2005).
[3] Yang B, Gao Z Z, Chen L B, et al: First high-frequency pulse tube cryocooler down to 2.5 K and its promising application in China's deep space exploration. Science China Technological Sciences 66, 2454-2456 (2023).
[4] Shen F Z, Xu D, Li X, et al: Cryogen-free apparatus for rapid thermal emissivity measurements at low temperature. IOP Conference Series: Materials Science and Engineering 502, 012190 (2019).