Quantification of Radiative Heat Loss for Accurate Thermoelectric Module Efficiency Measurement in RTG Applications

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1. Introduction

Accurate measurement of thermoelectric module (TEM) efficiency is required for the development of Radioisotope thermoelectric generator (RTG) systems. Any error in module efficiency directly propagates into system-level thermal and electrical design, leading to amplified prediction errors in overall system performance [1]. Therefore, improving the measurement accuracy of TEM efficiency is necessary to ensure reliable RTG system design.

In this study, we developed a TEM efficiency measurement system incorporating a radiation heat shield and accounting for parasitic heat losses during high-temperature testing. Based on this approach, accurate measurement and calibration of TEM efficiency were successfully achieved.

2. Method and Results

This section describes the methods used to quantify radiative heat loss. The analysis framework includes a radiation shield, an experimental measurement setup, and a thermal simulation model to evaluate radiative heat transfer and to calibrate efficiency.

2.1. Experimental Set up

A temperature-controlled measurement station was constructed to evaluate TEM performance. The hot-side aluminum heater module was coated with silver to reduce emissivity and then enclosed within a radiation shield to suppress radiative heat loss to ambient. To establish a defined hot-side temperature, the input power was precisely controlled, and efficiency measurements were performed under thermally steady-state conditions.

The TEM was positioned between the heater and a cooling block. The cold-side temperature was maintained using a circulating coolant system. Thermocouples were placed near the TEM interfaces on both the hot and cold sides to accurately measure the temperature difference (ΔT) across the TEM module. An external load resistance was connected to the module, and the output voltage and current were measured to determine the electrical output power.

2.2. Module characterization

A BiTe-based TEM (30 × 30 mm²) was used for the measurements. Graphite sheets were inserted between the TEM and the temperature control blocks to enhance thermal contact and reduce interfacial thermal resistance.

The hot-side and cold-side temperatures were maintained at 200 °C and 30 °C, respectively. All measurements were conducted inside a vacuum chamber at 1×10^{-5} Torr. A contact force of 80 kgf was vertically applied to the TEM to ensure stable thermal contact. The TEM efficiency was determined after thermal steady state was achieved.

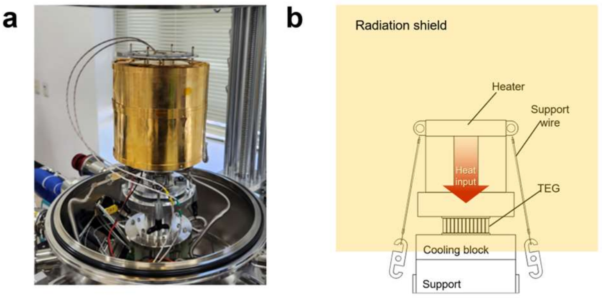

Fig. 1. (a) Photograph of the measurement station with radiation shield. (b) Cross-sectional schematic of the measurement station, including the heater, thermoelectric module, cooling block, and radiation shield.

2.3. Radiative heat loss quantification

To quantify radiative losses, the heater power was monitored under both shielded and unshielded states at a steady-state thermal gradient (T_h = 200°C, T_c = 30°C). This comparative approach allows for the precise extraction of radiative effects from the total heat balance shown in Fig. 2. Under the radiation shield condition, an input power of 14.5 W was required to maintain the hot-side temperature at 200°C. In contrast, the unshielded configuration required 15.5 W to maintain the same temperature. This 1 W radiative heat loss directly influences the evaluated efficiency of the TEM module. Neglecting this factor leads to a systemic underestimation, reducing the calculated efficiency from 4.56% to 4.21% as shown in Fig. 2a. This highlights the necessity of radiative calibration for accurate RTG system modeling. Such deviations propagate into RTG system-level thermal and electrical designs, increasing uncertainty in performance predictions. Consequently, the accurate quantification and calibration of radiative heat loss are essential for RTG system design.

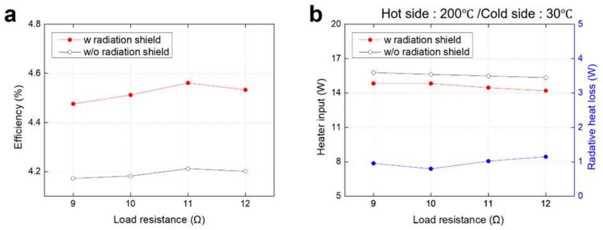

Fig. 2. (a) Measured TEM efficiency as a function of load resistance with and without radiation shield (b) Heater input power and corresponding radiative heat loss under identical boundary temperatures (hot side: 200 °C, cold side: 30 °C).

2.4. Thermal analysis

A steady-state thermal analysis was performed to support the experimental results and to evaluate radiative heat transfer within the measurement station. The simulation model replicated the heater, thermoelectric module, cooling block, and surrounding structure under identical boundary temperature conditions (200 °C / 30 °C).

Surface emissivity values were assigned based on material properties. The silver-coated heater surface was modeled with an emissivity of 0.02, while the stainless-steel support wires were assigned an emissivity of 0.2 [2,3]. Material thermal properties and boundary temperatures were incorporated into the model to calculate conductive and radiative heat flux components.

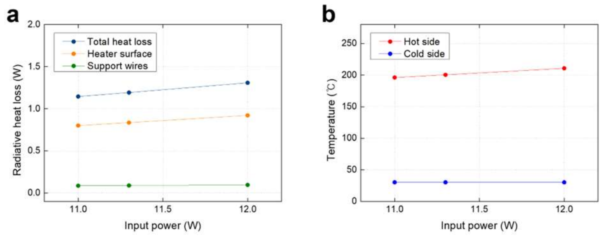

Fig. 4. (a) Simulated radiative heat loss as a function of heater input power, including contributions from the heater surface and support wires, and their total. (b) Corresponding sub-surface hot-side and cold-side temperatures under steady-state conditions.

Under the 200 °C / 30 °C condition, the simulation calculated a radiative heat loss of 0.8 W from the heater surface and 0.38 W from the four support wires, resulting in a total radiative heat loss of 1.18 W. This value was comparable to the experimentally quantified radiative heat loss, confirming the validity of the proposed efficiency calibration approach.

3. Conclusions

Radiative heat loss was quantified to improve the accuracy of thermoelectric module efficiency measurement. A radiation shield was implemented, and radiative heat transfer was experimentally evaluated and validated through steady-state thermal analysis. Neglecting radiative heat loss often results in an underestimation of Thermoelectric Module (TEM) efficiency. The calibration method proposed in this study effectively mitigates thermal uncertainties related to radiation, ensuring the high-fidelity efficiency data critical for robust RTG system design.

Acknowledgments

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