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Performance Enhancement Strategies for Compact Thermoelectric Generation Systems in Hydrothermal Geothermal Applications

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INTRODUCTION

Global geothermal resources are widespread and immense，offering substantial potential for power generation[1]. Thermoelectric generators (TEGs), converting heat directly into electricity via the Seebeck effect, offer a mechanically simple pathway for harnessing low-grade geothermal resources[2,3]. TEG efficiency depends primarily on maintaining effective temperature gradients (ΔT) across modules rather than solely on the material figure of merit (ZT). Plate-type heat sinks, favored in geothermal applications for their modular scalability and superior thermal contact, provide an advantageous hardware platform[4,5]. However, two thermal resistances—convective losses at fluid-solid boundaries and contact resistance at sink-module interfaces—systematically collapse effective ΔT. Existing research has pursued flow channel geometries (twisted fins, wavy configurations) and advanced thermal interface materials independently, yet lacks a systematic investigation of multi-parameter synergistic mechanisms. The proposed multidimensional collaborative optimization framework for flat-plate TEG systems provides significant technical guidance and practical insights for the design of low-grade geothermal power generation systems.

METHODS

This study employs a two-tier experimental strategy to quantify how channel geometry, thermal interface materials (TIMs), and assembly pressure affect TEG performance. Tier 1: Controlled Single-Factor. Testing operates with cold-side temperature fixed at 20°C and hot-side regulated from 50–170°C via electric heating. Three parameters are systematically investigated: channel configurations, TIMs and assembly pressures. Tier 2: Integrated System Validation. Optimization strategies were further validated experimentally in a scaled-up TEG system (consist of 24TIMs) under simulated hydrothermal conditions with hot-side water circulation(50–90°C, 1.5 t/h) and cold-side water (20°C, 1 t/h). Electrical characterization across variable loads (0–200 Ω) validates whether single-factor optima translate to system-level gains under realistic convective dynamics, flow maldistribution, and module interactions.

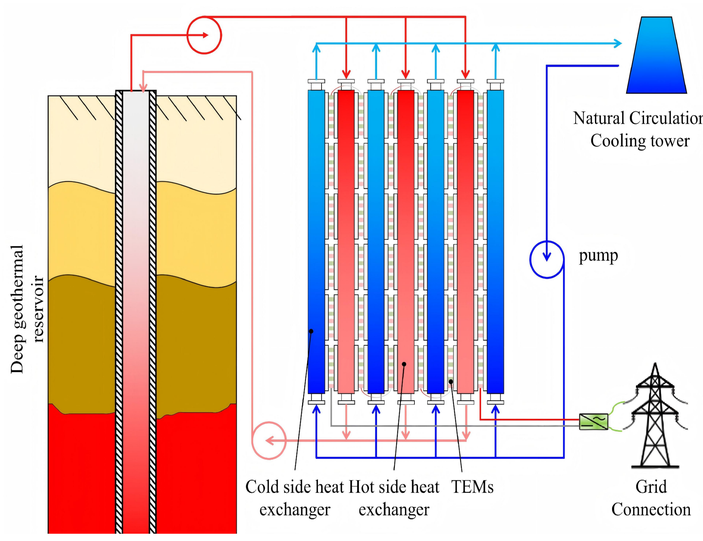


Fig. 1. TEG system applied in hydrothermal geothermal.

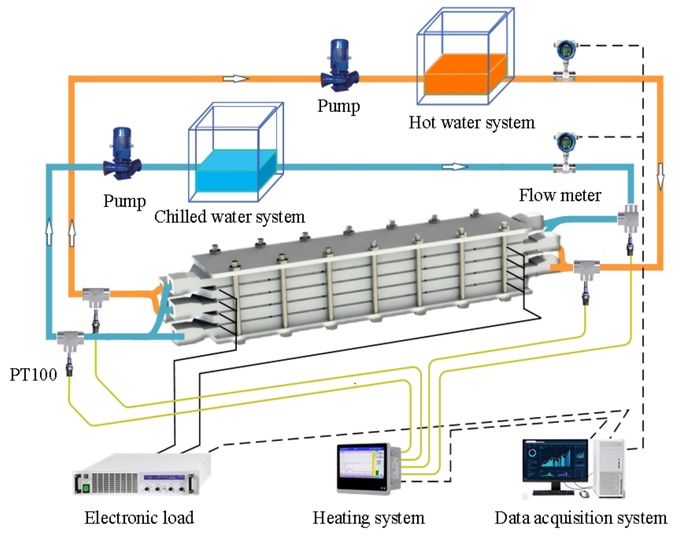


Fig. 2. Validation of Optimization Strategies in a Scaled-Up TEG System.

RESULTS

This study is based on a self-built experimental platform. In order to systematically evaluate the influence of key design parameters on the output performance of TEMs, it focuses on the optimization effects of single factors such as heat sink configuration, TIM type and assembly pressure. On this basis, integrated optimization experiments based on the above-mentioned optimal parameters are further carried out to reveal their synergistic mechanism. The experimental results are as follows:

(1)Impact of different heat sink configurations: Under identical temperature conditions, the straight-channel configuration exhibited approximately 37–45% higher maximum output power than those with other channel geometries (Fig. 4a).

(2)Impact of different TIMs: For the TEM module using the Thermal Conductive Silicone sheet (TCS) TP1000, its efficiency was higher than that of TP1200 (which has a higher thermal conductivity) due to better gap-filling performance (Fig. 4b).

(3)Impact of different clamping pressures : With increasing assembly pressure, the maximum output power increased from 0.19 to 0.25 W (Fig. 4c).

(4)Experiments on TEG unit tests based on TEM optimization results: Replacing only the interface material increased average power by about 6.3%, while optimizing the heat sink structure yielded an improvement of around 10.4%. Compared with the unoptimized configuration, combined optimization of the heat sink and TIM further enhanced power output by 10–30% (Fig. 5).

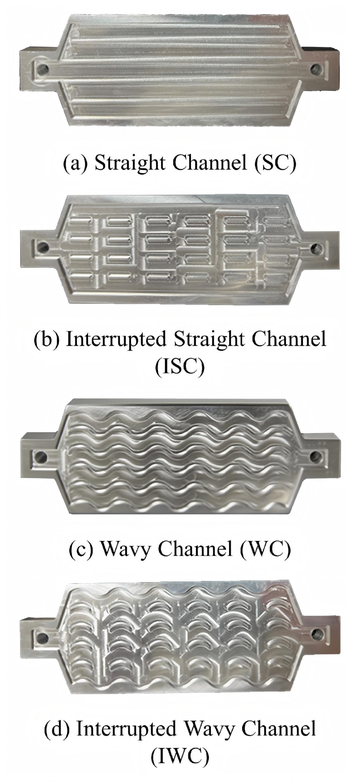


Fig. 3. Different Heat Sink Channel Configurations.

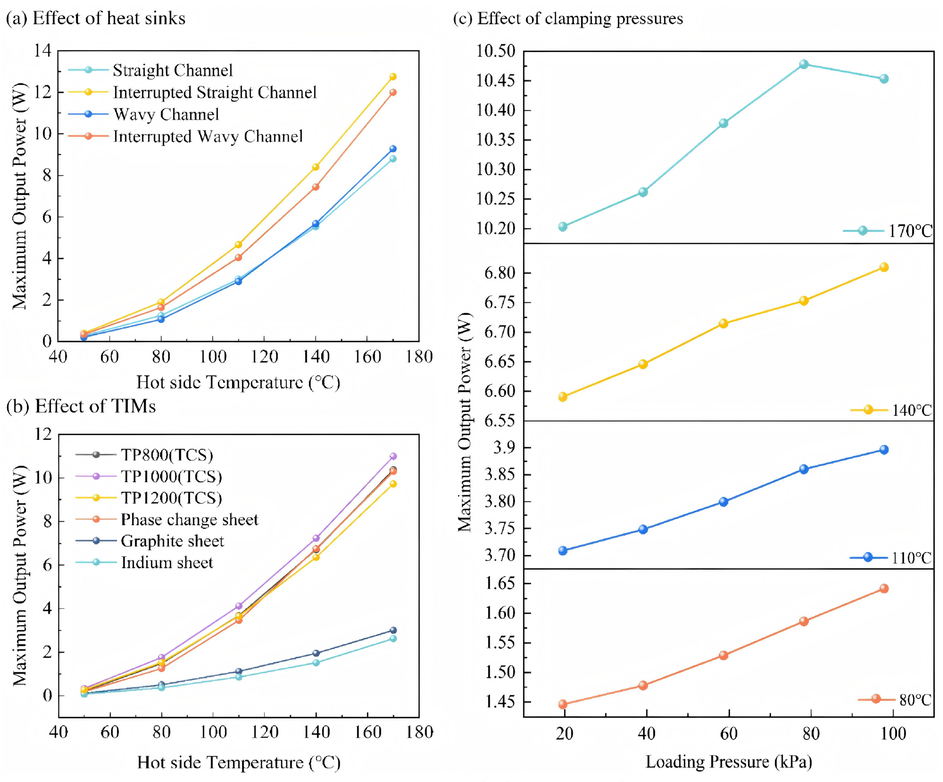


Fig. 4. Key Impact of the TEM Performance.

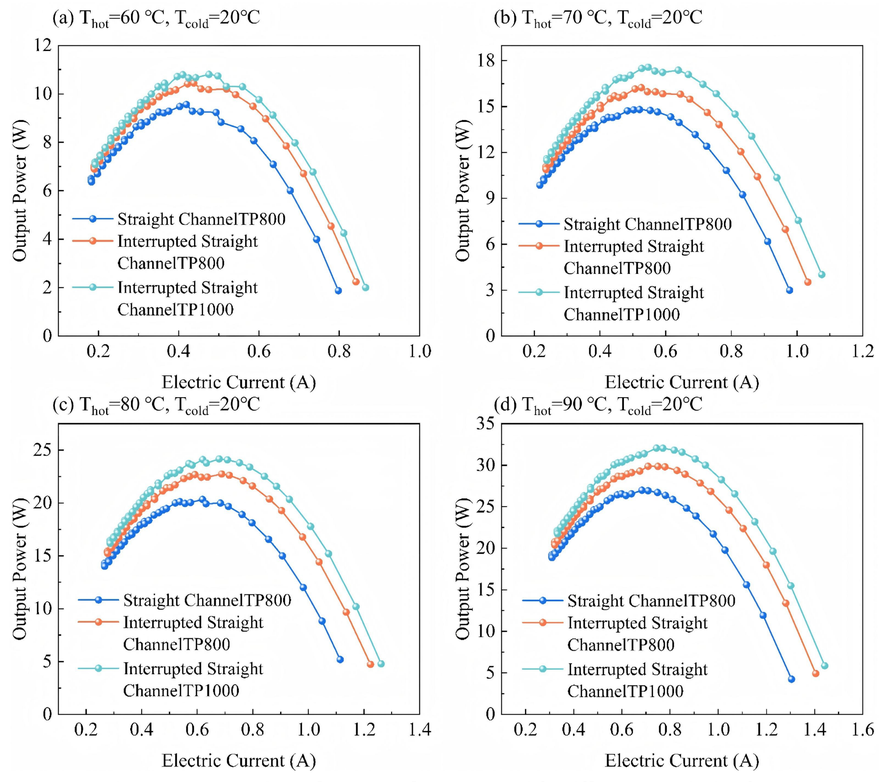


Fig. 5. Comparation of TEG Performance with Different Optimized Designs.

CONCLUSION

The TEG unit employing the interrupted straight-channel configuration achieves a power enhancement of approximately 40% compared with the conventional straight-channel design.

On the one hand, thermal conductivity is a core consideration when selecting TIMs; on the other hand, its capacity to fill interfacial gaps is another key factor in determining TIM performance.

Increasing clamping pressure boosts the TP800's maximum output power from 0.19 W to 0.25 W. Notably, adjusting clamping pressure is less costly than replacing TIMs or heat sinks; thus, selecting an appropriate clamping pressure is crucial for TEG systems.

Integrated optimization of channel configuration, TIM, and clamping pressure yields lower power gain than single-dimensional optimization. This indicates TEM optimization results from laboratory scenarios need verification in complete TEG units for actual efficiency, to guarantee engineering applicability.

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