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Next-Generation Geothermal Power: Conceptual Design and Prospects of a Maglev Compound Cascade Power Generation System (MCCPGS)

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Medium-to-low temperature geothermal energy is expected to play a crucial role in future low-carbon energy systems by providing a reliable, sustainable, and abundant energy supply. Organic Rankine Cycle (ORC) is widely regarded as the most promising technology for its power generation. However, its large-scale deployment remains constrained by poor temperature matching during the heat absorption process and relatively low turbine efficiency. To overcome these limitations, this paper proposes an innovative approach with multi-technology integration that integrates the dual-pressure evaporation ORC with maglev turbine–generator integrated units, and a Maglev Compound Cascade Power Generation System (MCCPGS) is established, which is expected to remarkably improve the geothermal power generation efficiency. Future research should focus on key aspects including multi-level and multi-criteria coupled optimization techniques for the system, coordinated design of two-stage turbines, and maglev shafting design with dynamic–static clearance control for coordinated operation of two-stage turbines. These efforts aim to further improve geothermal power generation and contribute to the global transition toward low-carbon energy systems.

INTRODUCTION

As an important renewable resource, geothermal energy has abundant reserves. According to the International Energy Agency (IEA), the technically recoverable potential of global geothermal energy at depths of up to 8 km with existing technologies is approximately 3.0×10^5 EJ, equivalent to around 1.0×10^{13} tons of coal equivalent.[1] Global geothermal resources exhibit advantages including environmental sustainability, operational stability, and relatively low operating costs.[2] Compared with intermittent renewable energy sources like solar and wind energy, geothermal energy is less affected by weather conditions and can provide continuous and stable energy output.

Notably, medium-to-low temperature geothermal energy below 150°C accounts for more than 70% of the global geothermal energy.[3] Among the utilization pathways of medium-to-low temperature geothermal energy, direct applications such as heating, cooling, and drying are often constrained by limited long-distance transmission capability as well as mismatches between energy supply and demand in both temporal and spatial dimensions, which significantly restrict their large-scale deployment. In contrast, power generation not only enables the conversion of medium-to-low temperature geothermal energy into higher-grade electricity, but also offers broader application scenarios, larger market demand, and convenient long-distance transmission, thereby exhibiting greater development potential. As of 2023, the global installed capacity of geothermal power generation in 32 countries reached 16.3 GW, representing an increase of approximately 7.7 times compared with that in 2010. However, geothermal electricity still accounts for only about 0.34% of global power generation.[4] This disparity underscores the challenges in efficiently exploiting medium-to-low temperature geothermal energy, whose relatively low temperatures limit the applicability of conventional power generation technologies.

Organic Rankine Cycle (ORC) is a power technology with low-boiling organic fluid as working fluid, achieving a power generation efficiency for medium-to-low temperature geothermal energy.[5] ORC technology offers advantages, including simple system structure, stable operation, easy maintenance, and strong adaptability to various heat sources.[6] Consequently, ORC has become one of the most extensively studied technologies for medium-to-low temperature geothermal power generation. For example, more than 100 peer-reviewed papers on advanced ORC configurations have been published over the past decade, with over 70% appearing in the most recent five years,[3] indicating rapidly growing research interest. Current research on ORC systems primarily seeks to enhance power generation efficiency through working fluid selection and system parameter optimization, with increasing attention devoted to low global warming potential (GWP) working fluids such as hydrofluoroolefins and parameter optimization strategies considering heat source/sink conditions and cycle configuration.[7]

To further improve the power generation efficiency of medium-to-low temperature geothermal ORC systems, exergy analyses reported in the literature have been widely employed, indicating that total exergy loss is mainly concentrated in the heat absorption process and the expansion process.[3] Among these, the exergy loss during the heat absorption process accounts for a significant portion of the total exergy loss. This is primarily attributed to the poor temperature matching between the geothermal water and the working fluid. The exergy loss during the expansion process also remains high, mainly due to insufficient aerodynamic performance of existing turbine units and significant friction losses from bearings, seals, and gearbox transmission. Therefore, improving temperature-profile matching during the heat absorption process and enhancing turbine unit performance are two critical directions for power generation efficiency improvement in medium-to-low temperature geothermal ORC systems.

EFFICIENCY ENHANCEMENT THROUGH DUAL-PRESSURE EVAPORATION ORC AND MAGLEV TURBINE–GENERATOR INTEGRATION

To address the poor temperature matching effect, the introduction of the dual-pressure evaporation ORC has been proposed as an effective solution, as illustrated in Figure 1A. As an advanced type of ORC, the dual-pressure evaporation ORC features two evaporation stages operating at different pressure levels and a common condensation process.[3] By distributing the working fluid to high- and low-pressure evaporators, the heat absorption can be carried out in a staged manner across multiple temperature levels. The vapor streams generated from the two evaporators subsequently expand to produce power and are then condensed and pumped back to complete the cycle. Compared with conventional single-pressure evaporation ORC, the

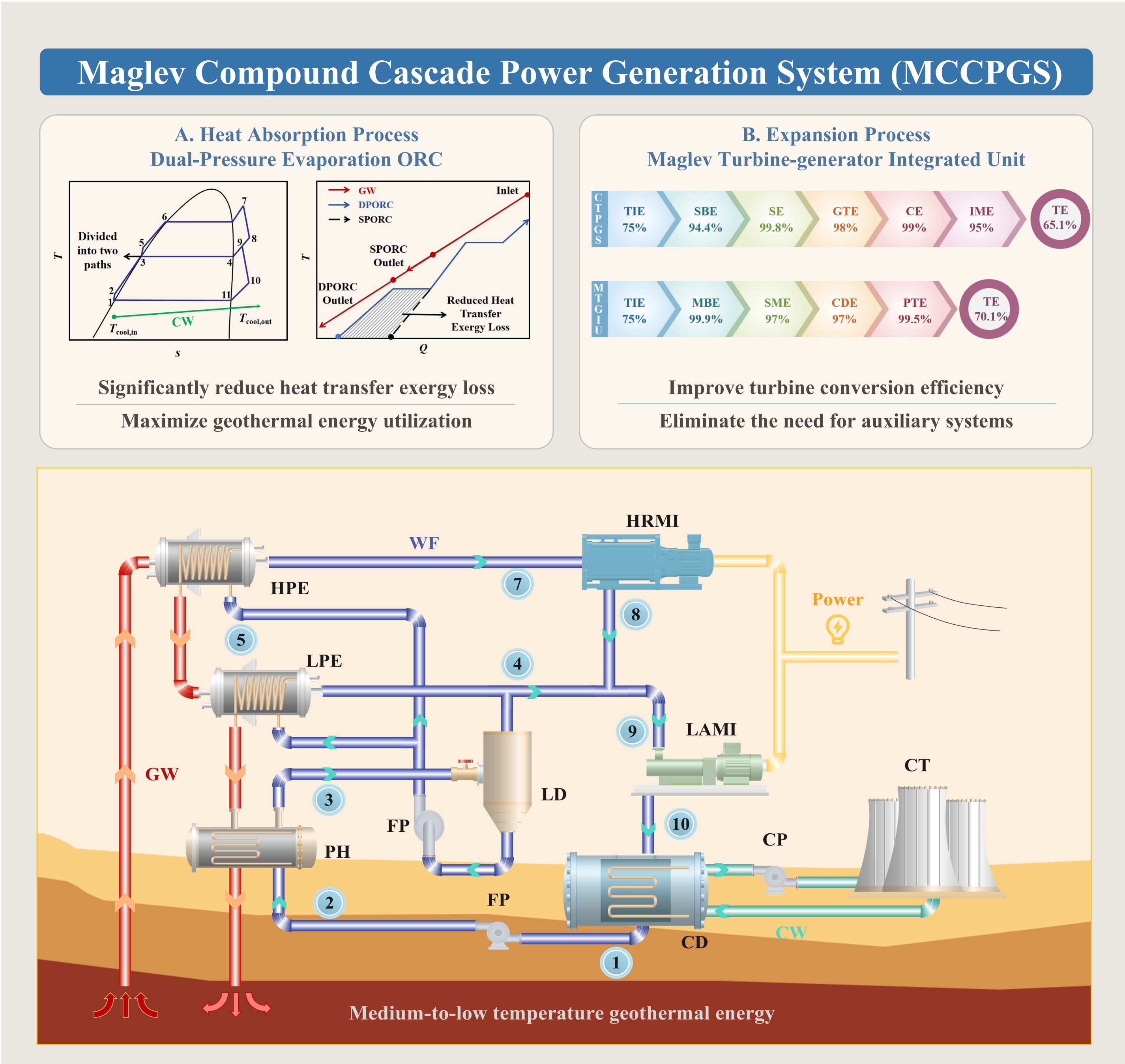

Figure 1. Maglev Compound Cascade Power Generation System (MCCPGS) (Abbreviations: GW, geothermal water; CW, cooling water; WF, working fluid; PH, preheater; HPE, high-pressure evaporator; LPE, low-pressure evaporator; LD, liquid distributor; HRMI, high-pressure radial maglev turbine–generator integrated unit; LAMI, low-pressure axial maglev turbine–generator integrated unit; CD, condenser; CP, circulation pump; FP, feed pump; CT, cooling tower; DPORC, dual-pressure evaporation organic Rankine cycle; SPORC, single-pressure evaporation organic Rankine cycle; CTPGS, conventional turbine power generation system; TIE, turbine isentropic efficiency; SBE, sliding bearing efficiency; MBE, magnetic bearing efficiency; SE, sealing efficiency; GTE, gearbox transmission efficiency; CE, coupling efficiency; IME, induction motor efficiency; SME, synchronous motor efficiency; CDE, converter device efficiency; PTE, power transformer efficiency; TE, total efficiency.)

dual-pressure evaporation ORC enables a more flexible adaptation to the heat release characteristics of geothermal resources by independently optimizing the evaporation pressures and working fluid flow distribution in each stage. This staged heat absorption process not only reduces heat transfer exergy losses and improves temperature-profile matching between the working fluid and geothermal water, but also allows a lower geothermal outlet temperature to be achieved, thereby enhancing the overall utilization efficiency of geothermal energy. For example, at a geothermal source temperature of 95°C, the DPORC exhibits a 21.1% increase in exergy efficiency compared with the SPORC.[3] Furthermore, at geothermal source temperatures ranging from 100 to 200°C, the maximum net power output of the DPORC is 21.4%–26.7% higher than that of the SPORC.[5]

To address the low efficiency of conventional turbine units, innovative maglev turbine–generator integrated units have been introduced. The core components of the maglev turbine–generator integrated unit are mounted on a single main shaft and housed within a hermetically sealed enclosure, eliminating the gearbox, coupling, and lubrication system required in conventional turbine units. The shaft supports a turbine impeller at its front end, a generator rotor–stator assembly in the midsection, and radial magnetic bearings at both ends. Combined with an axial thrust magnetic bearing, these elements enable fully contact-free rotor operation, thereby eliminating the friction losses associated with conventional sliding bearings.[8] As illustrated in Figure 1B, although the turbine isentropic efficiency in conventional systems can reach approximately 75%, losses arising from downstream components such as bearings, mechanical transmission, and auxiliary systems reduce the turbine efficiency to about 65.1%. By contrast, the maglev turbine–generator integrated configuration removes gearboxes and couplings, replaces sliding bearings with magnetic bearings, and employs a high-efficiency synchronous generator, thereby reducing mechanical, transmission, and auxiliary losses. Consequently, the turbine efficiency can be increased to around 70.1%, reflecting the efficiency gains achieved through system integration and magnetic levitation technology.

An innovative method integrating the dual-pressure evaporation ORC with the maglev turbine–generator integrated units is proposed, leading to the development of a Maglev Compound Cascade Power Generation System (MCCPGS) for medium-to-low temperature geothermal utilization. The overall configuration and operating principle of the proposed system are illustrated in Figure 1. By adopting the dual-pressure evaporation ORC, the system enables cascaded utilization of medium-to-low temperature geothermal energy, thereby improving temperature-profile matching during the heat absorption process. Meanwhile, maglev turbine–generator integrated units effectively reduce losses associated with bearing friction, sealing, and gearbox transmission, while eliminating the need for auxiliary systems such as external cooling, lubrication, and sealing. Through the synergistic integration of these advantages, the overall power generation efficiency of geothermal ORC technology is significantly enhanced.

FUTURE RESEARCH DIRECTIONS OF THE PROPOSED MCCPGS

As an emerging research direction in contemporary energy science, high-efficiency power generation utilizing medium-to-low temperature geothermal energy offers significant academic value and practical engineering relevance, while also contributing to the development of reliable and low-carbon energy systems toward carbon neutrality.[9] Within this context, to further enhance the power generation performance of the proposed MCCPGS and facilitate its large-scale deployment, three recommendations are put forward for future development.

(1) Develop multi-level and multi-criteria coupled optimization techniques for the MCCPGS. Cycle parameters, working fluid properties, and component configurations are the key factors governing power generation efficiency. Meanwhile, the system optimization typically involves multi-objective (thermodynamic–economic–environmental) trade-offs, in which different optimization objectives often constrain or even conflict with each other, while the above design variables are strongly coupled. As a result, single-objective or single-factor optimization is generally insufficient to achieve optimal overall system performance. Improper matching among these elements not only diminishes local performance advantages but may also lead to significant degradation in system performance. Therefore, it is necessary to develop multi-level and multi-criteria coupled optimization techniques for the MCCPGS that enable coordinated optimization of cycle parameters, working fluid properties, and component configurations under multi-objective constraints, thereby providing a solid theoretical foundation for maximizing overall system performance.

(2) Develop coordinated high-efficiency optimization techniques for two-stage turbines. Energy matching among two-stage turbines directly affects stage inlet–outlet conditions, achievable isentropic efficiency, and temperature matching with geothermal heat sources.[10] Strong energy-flow and pressure coupling between high-pressure and low-pressure turbines makes single-stage aerodynamic optimization inadequate and may degrade overall system performance. In addition, emerging low-GWP working fluids exhibit turbine loss characteristics that differ significantly from those of conventional fluids, primarily due to their lower vapor-phase speed of sound. This characteristic increases the likelihood of supersonic flow at turbine exits, resulting in shock-wave formation and associated aerodynamic losses. Therefore, system-level investigation of energy-flow coordination mechanisms and the development of coordinated high-efficiency optimization strategies for two-stage turbines are essential to achieve synergistic performance enhancement.

(3) Develop maglev shafting design with dynamic–static clearance control for coordinated operation of two-stage turbines. Maglev turbine–generator integrated units operate at high speeds, making stable and reliable dynamic–static clearance control a foundation for maglev shafting design, turbine aerodynamic optimization, and stable system operation.[8] However, in practical medium-to-low temperature geothermal ORC applications, turbine output torque, dynamic loads, and power fluctuate significantly with varying heat-source and heat-sink conditions. Moreover, pronounced differences in dynamic characteristics between high-pressure and low-pressure turbines further complicate shaft system behavior. Ensuring rotor dynamic stability under such multi-condition operating environments therefore becomes a critical challenge for maglev shafting systems. Therefore, it is essential to develop maglev shafting design with dynamic–static clearance control adaptable to multi-condition operation and coordinated operation of two-stage turbines, providing critical technical support for prototype development and engineering deployment of geothermal maglev cascade power generation systems.

CONCLUSION

This paper proposes an innovative approach that integrates a dual-pressure evaporation ORC with maglev turbine–generator integrated units, leading to the development of MCCPGS. By adopting the dual-pressure evaporation ORC, the MCCPGS improves temperature-profile matching between the working fluid and geothermal water and reduces the geothermal outlet temperature, thereby effectively decreasing exergy losses in the heat absorption process and enhancing geothermal energy utilization efficiency. Meanwhile, the use of maglev turbine–generator integrated units significantly reduces energy losses associated with bearing friction, sealing leakage, and gearbox transmission. The synergistic integration of these two technical measures results in a substantial improvement in overall power generation efficiency.

The development of MCCPGS involves interdisciplinary fields such as thermodynamics and electromagnetism, which not only promotes the integration of cross-disciplinary theories and technologies but also provides new perspectives for the advancement of medium-to-low temperature geothermal power generation. Future research should focus on key aspects including multi-level and multi-criteria coupled optimization techniques for the MCCPGS, coordinated design of two-stage turbines, and maglev shafting design with dynamic–static clearance control for coordinated operation of two-stage turbines. Overall, with continued technological advancements, MCCPGS is expected to become an important pathway for promoting geothermal power generation, providing strong support for ensuring energy security and advancing the development of low-carbon energy systems.

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DECLARATION OF INTERESTS

The authors declare no competing interests.