

Energy, exergy, and thermal performance analysis of a geothermal-based tri-generation system for power, cooling, and fresh water using aluminum oxide (Al_2O_3) and titanium dioxide (TiO_2) nanoparticles

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Abstract

This paper presents a thermodynamic investigation into an innovative geothermal-based tri-generation system, designed for simultaneous production of power, cooling, and fresh water, using Al_2O_3 and TiO_2 nanoparticles. The primary objective is to integrate three sub-systems to improve thermal performance by utilizing nanofluids within the intermediate fluid stream. Parametric analysis results indicate that increasing the nanoparticle volume fraction and geothermal source temperature enhances heat transfer rates in heat exchangers, increases the convective heat transfer coefficient, and raises net power output, with Al_2O_3 nanoparticles demonstrating superior performance. Furthermore, the use of nanofluids enhances the energy extractable from the geothermal source, leading to an increase in cooling capacity. Finally, at a volume fraction of 0.05 for Al_2O_3 nanoparticles, the system demonstrates high energy extractable from the geothermal source and enhanced cooling capacity. This study confirms the substantial potential of combining renewable geothermal energy sources with nanotechnology for industrial applications.

Keywords: Intermediate Fluid Stream, Nanoparticles, Thermodynamic Analysis, Thermal Performance, Gain Output Energy, Tri-generation system, Geothermal, Cascade Refrigeration Cycle

1. Introduction

From a research perspective, the integration and combination of different energy systems provide an effective approach for enhancing system efficiency and reliability. In this regard, geothermal energy is regarded as an ideal option for integration with other technologies due to its cost-effectiveness, long-term sustainability, and environmental compatibility [1]. Such combinations lay the foundation for the development of cogeneration and tri-generation systems capable of simultaneously producing power, cooling, and freshwater. These approaches improve the energy and exergy efficiencies of the system and consequently contribute to loss reduction and enhanced sustainability [2]. On the other hand, the use of nanofluids in thermal systems can play a significant role in improving heat transfer performance. The addition of nanoparticles to working fluids increases thermal conductivity and enhances the heat transfer rate in heat exchangers. This capability is of particular importance in cooling and heating processes [3].

In this paper, the design, analysis, and thermodynamic and thermal performance evaluation of a geothermal-based tri-generation system producing power, cooling, and freshwater, using aluminum oxide and titanium dioxide nanoparticles within an intermediate fluid stream, are investigated. The main novelty of this study lies in the integration of power generation, cooling, and freshwater production subsystems while introducing an intermediate fluid stream at the inlet of the cascade refrigeration system in order to enhance heat transfer through the use of nanoparticles. Furthermore, although comprehensive thermodynamic and thermal performance analyses have previously been conducted for various thermodynamic systems, such as combined power and freshwater production systems or stand-alone refrigeration systems, no such investigation has been carried out for geothermal-based tri-generation systems, particularly in the presence of nanoparticles within the intermediate fluid stream.

2. Methodology

Initially, based on the assumptions derived from the reference literature, mass and energy balance equations are formulated for each component to determine the thermodynamic state properties, including temperature, pressure, enthalpy, entropy, and mass flow rate, for all state points of the proposed system. Furthermore, the output parameters, such as power generation, heat transfer rates, and gain output energy, are calculated. Subsequently, an exergy analysis is conducted to determine key indicators, including exergy efficiency, exergy destruction of individual components, and exergy flow throughout the system pathways. Finally, the impact of incorporating nanoparticles within the intermediate fluid stream on the system output parameters is evaluated, and the percentage of improvement in the overall system performance is quantified.

2.1. Energy and Exergy Analysis

The general governing equations for energy, mass, and concentration in the steady state, based on the laws of thermodynamics, are expressed as follows [4, 5]:

$$\sum (\dot{m}h)_{in} - \sum (\dot{m}h)_{out} + \dot{Q} - \dot{W} = 0 \quad (1)$$

$$\sum (\dot{m}X)_{in} - \sum (\dot{m}X)_{out} = 0 \quad (2)$$

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \quad (3)$$

In the above equations, $\dot{m}$ denotes the mass flow rate of the fluid, X represents the lithium bromide concentration, $\dot{Q}$ is the heat input, and $\dot{W}$ is the work output of the control volume. Furthermore, h represents the enthalpy, while the subscripts in and out signify the inlet and outlet, respectively.

The total exergy rate is calculated as the sum of physical and chemical exergy according to the following relation [5]:

$$\dot{E}x = \dot{E}x_{ph} + \dot{E}x_{ch} \quad (4)$$

2.2. Nanoparticle-related Correlations

The heat transfer rate in the presence of nanoparticles within the intermediate fluid stream is calculated using the following relation [6]:

$$\dot{Q} = \dot{m} \cdot C_p (T_{out} - T_{in}) \quad (5)$$

In Equation (5), C_p denotes the specific heat capacity, T_{out} and T_{in} represent the outlet and inlet temperatures of the intermediate fluid stream, respectively, and $\dot{m}$ is the mass flow rate.

The Nusselt number for the nanofluid (Nu_{nf}), which is employed to determine the convective heat transfer coefficient, is obtained from the following correlation [7]:

$$Nu_{nf} = 0.023 \times Re^{0.8} \times Pr^{0.3} \quad (6)$$

where Re and Pr denote the Reynolds and Prandtl numbers, respectively. The convective heat transfer coefficient of the nanofluid (h_{nf}) is then calculated as [6]:

$$h_{nf} = \frac{Nu_{nf} \cdot k_{nf}}{D_i} \quad (7)$$

The thermophysical properties of the nanofluid, including density, specific heat capacity, thermal conductivity, and dynamic viscosity, are determined using the following correlations [6]:

$$\rho_{nf} = \rho_{bf} \cdot (1 - \phi) + \rho_{np} \cdot \phi \quad (8)$$

$$Cp_{nf} = \frac{\rho_{bf} \cdot (1 - \phi) \cdot Cp_{bf} + \rho_{np} \cdot \phi \cdot Cp_{np}}{\rho_{nf}} \quad (9)$$

$$k_{nf} = k_{bf} \cdot \frac{k_{np} + 2 \cdot k_{bf} - 2 \cdot \phi \cdot (k_{bf} - k_{np})}{k_{np} + 2 \cdot k_{bf} + \phi \cdot (k_{bf} - k_{np})} \quad (10)$$

$$\mu_{nf} = \mu_{bf} \cdot (1 + 2.5\phi + 6.5\phi^2) \quad (11)$$

In the above relations, ϕ represents the volume fraction, and the subscripts nf, bf, and np denote the nanofluid, base fluid, and nanoparticles, respectively.

2.3. Output Variables

The net power output ($\dot{W}_{net}$), gain output energy (GOE), exergy efficiency (η_{exergy}), gained output ratio (GOR), and coefficient of performance (COP) for the proposed system are defined as follows:

$$\dot{W}_{net} = \dot{W}_{ST1} + \dot{W}_{ST2} - \dot{W}_{pump} - \dot{W}_{comp} \quad (12)$$

$$GOE = \frac{\dot{W}_{net} + \dot{Q}_{Eva} + (\dot{m}_{freshwater} h_{fg})}{\dot{m}_1 (h_1 - h_{50})} \quad (13)$$

$$\eta_{exergy} = \frac{\dot{W}_{net} + (\dot{E}x_{37} - \dot{E}x_{36}) + (\dot{m}_{43} (h_{fg} - T_0 s_{fg}))}{\dot{E}x_1 - \dot{E}x_{50}} * 100 \quad (14)$$

$$GOR = \frac{\dot{m}_{freshwater} h_{fg}}{\dot{Q}_{HX1}} \quad (15)$$

$$COP = \frac{\dot{Q}_{Eva}}{(\dot{Q}_{HPG} + \dot{W}_{comp} + \dot{W}_{pump})} \quad (16)$$

3. Results and Discussion

3.1. Model Validation

The model's validity is substantiated by the excellent agreement between the simulation results and existing studies [8–10]. Specifically, Figure 1 validates the double-flash geothermal cycle against [8], Figure 2 compares the desalination subsystem with [9], and Table 1 evaluates the absorption refrigeration system against [10]. Any minor discrepancies are negligible and attributable to differences in boundary conditions or modeling parameters. Nevertheless, the consistent trends across all subsystems confirm the model's high predictive accuracy.

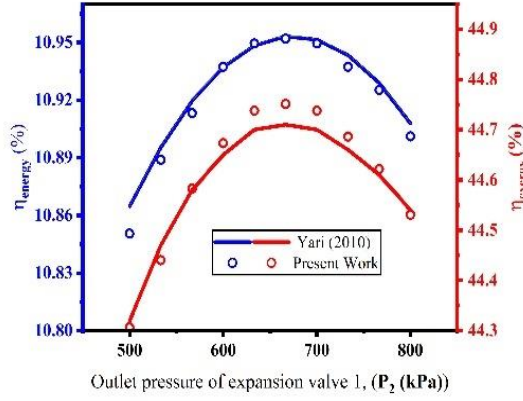


Figure 1. Validation of the double-flash geothermal cycle

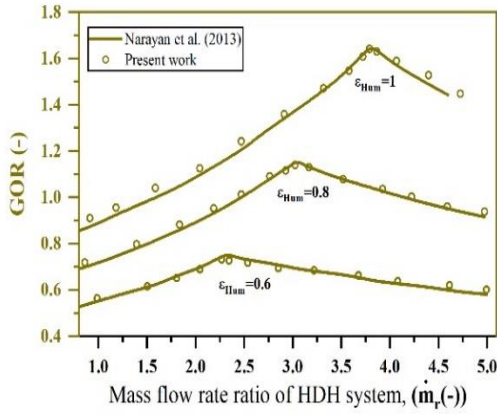


Figure 2. Validation of the desalination system

Table 1. Validation of the double-effect absorption refrigeration system performance

Parameter	Present work	Reference	Error (%)
$\dot{Q}_{HPG}$ (kW)	250.703	252.407	0.68
$\dot{Q}_{Con}$ (kW)	165.92	167.205	0.77
$\dot{Q}_{Eva}$ (kW)	298.943	300	0.35
$\dot{Q}_{Abs}$ (kW)	385.805	385.236	0.15
COP (-)	1.186	1.189	0.25

3.2. Parametric Analysis

To evaluate the impact of nanoparticles on heat exchanger thermal performance and system outputs, the thermal conductivity of the nanofluid was investigated for volume fractions (ϕ) from 0 to 0.05. As shown in Figures 3 and 4, increasing the Al_2O_3 and TiO_2 volume fractions leads to a nearly linear increase in heat transfer rates across the high- and low-pressure generators, absorber, and evaporator. This enhancement is driven by the increased effective thermal conductivity of the base fluid due to the high intrinsic conductivity of the nanoparticles. Notably, Al_2O_3 outperforms TiO_2 in terms of thermal conductivity, heat transfer, and overall thermal performance, attributed to its superior intrinsic

properties, stability, and uniform distribution. Ultimately, increasing the nanoparticle volume fraction up to 0.05 enhances heat exchanger performance, thereby increasing the system's cooling capacity.

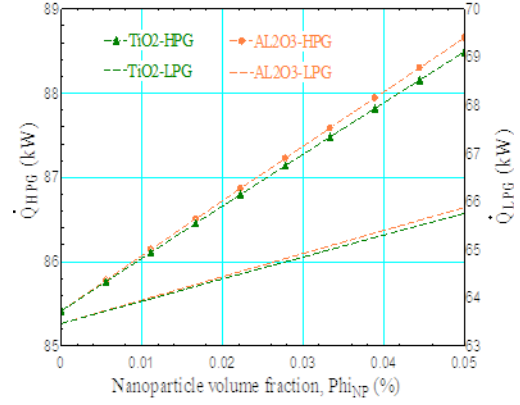


Figure 3. Effect of nanoparticle volume fraction on the heat transfer rate in high- and low-pressure generators

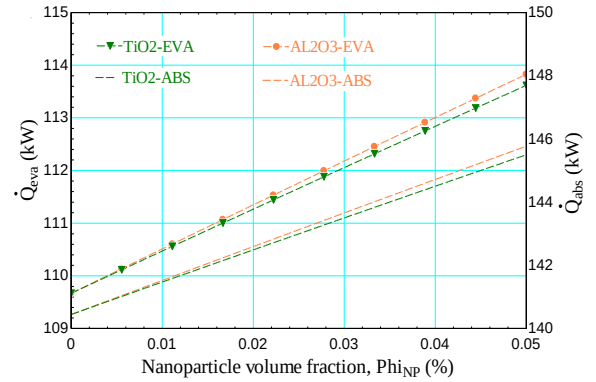


Figure 4. Effect of nanoparticle volume fraction on the heat transfer rate in the evaporator and absorber

In addition to enhanced thermal conductivity, the convective heat transfer coefficient (h_{nf}) of the nanofluid was investigated. Figure 5 demonstrates that h_{nf} depends directly on the operating temperature; as temperature rises, decreased viscosity and improved thermophysical properties enhance convective heat transfer. This indicates that the system is more sensitive to nanoparticle addition at higher geothermal source temperatures, significantly improving thermal performance. This finding is critical for hybrid geothermal system design, as it allows for a reduction in the required heat transfer surface area. This trend holds for both nanoparticle types, with Al_2O_3 demonstrating superior performance compared to TiO_2 .

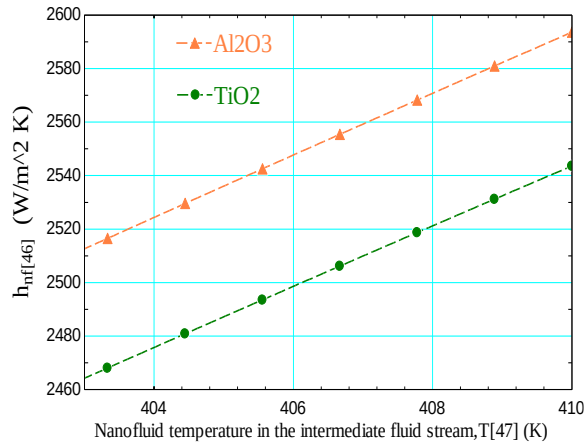


Figure 5. Effect of operating temperature on the convective heat transfer coefficient of the nanofluid

4. Conclusions

In this study, the thermal and thermodynamic performance of an innovative geothermal-based tri-generation system—providing simultaneous power, cooling, and water desalination—was investigated using Al₂O₃ and TiO₂ nanoparticles. The proposed configuration integrates a double-flash geothermal cycle, a cascade double-effect compression-absorption refrigeration system, and a humidification-dehumidification (HDH) desalination unit. The results show that nanoparticle integration enhances heat absorption and improves the utilization of available thermal energy. In addition, increasing the nanoparticle volume fraction raises the heat load of the heat exchangers, with the Al₂O₃ nanofluid at a volume fraction of 0.05 yielding the greatest performance improvement. Exergy analysis also identified the heat exchangers and dehumidifier as the main sources of exergy destruction. Overall, by exploiting the thermal advantages of the selected nanofluids, the proposed system demonstrates strong potential for efficient simultaneous tri-generation.

5. References

- [1] F. Musharavati, S. Khanmohammadi, and A. Pakseresht. A Novel Multi-Generation Energy System Based on Geothermal Energy Source: Thermo-Economic Evaluation and Optimization, *Energy Conversion and Management*, 230, pp. 113829, 2021.
- [2] M. Ebadollahi, B. Shahbazi, and H. Ghaebi. Efficiency and Flexibility Enhancement of Nanofluid-Based Hybrid Solar Desalination System Equipped with Thermoelectric Generator for Eco-Friendly Freshwater and Power Cogeneration, *Process Safety and Environmental Protection*, 190, pp. 108–122, 2024.
- [3] A. H. Pordanjani, S. Aghakhani, M. Afrand, B. Mahmoudi, O. Mahian, and S. Wongwises. An Updated Review on Application of Nanofluids in Heat Exchangers for Saving Energy, *Energy Conversion and Management*, 198, pp. 111886, 2019.
- [4] J. Xu, Z. Su, J. Meng, Y. Yao, M. S. Vafadaran, and A. K. Salavat. A Thermodynamic, Exergoeconomic, and Exergoenvironmental Investigation and Optimization on a Novel Geothermal Trigenation System to Sustain a Sport Arena, *Process Safety and Environmental Protection*, 177, pp. 278–298, 2023.
- [5] H. Ghaebi, A. S. Namin, and H. Rostamzadeh. Performance Assessment and Optimization of a Novel Multi-Generation System from Thermodynamic and Thermoeconomic Viewpoints, *Energy Conversion and Management*, vol. 165, pp. 419–439, 2018.
- [6] N. Modi, B. Pandya, and J. Patel. Comparative Analysis of a Solar-Driven Novel Salt-Based Absorption Chiller with the Implementation of Nanoparticles, *International Journal of Energy Research*, 43, pp. 1563–1577, 2019.
- [7] M. Mehrpooya, M. Dehqani, S. A. Mousavi, and S. A. Moosavian. Heat Transfer and Economic Analyses of Using Various Nanofluids in Shell and Tube Heat Exchangers for the Cogeneration and Solar-Driven Organic Rankine Cycle Systems, *International Journal of Low-Carbon Technologies*, vol. 17, pp. 11–22, 2022.
- [8] M. Yari. Exergetic Analysis of Various Types of Geothermal Power Plants, *Renewable Energy*, vol. 35, pp. 112–121, 2010.
- [9] G. P. Narayan, M. G. John, and S. M. Zubair. Thermal Design of the Humidification Dehumidification Desalination System: An Experimental Investigation, *International Journal of Heat and Mass Transfer*, vol. 58, pp. 740–748, 2013.
- [10] R. Gomri and R. Hakimi. Second Law Analysis of Double Effect Vapour Absorption Cooler System, *Energy Conversion and Management*, vol. 49, pp. 3343–3348, 2008.