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Thermodynamic and economic analysis of new multiple generation system with steam turbine combined with ejector cooling based on sulfur dioxide

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Extended Abstract

Introduction

Energy is the fundamental driving force of modern societies, and the evolution of human civilization has been closely linked to the discovery and utilization of various energy resources. Rising fossil fuel prices, increasing environmental concerns, and limitations in large-scale electricity storage have shifted global attention toward energy efficiency and demand-side management as strategic energy resources. In this context, combined cooling, heating, and power (CCHP) systems—also known as trigeneration systems—have gained significant attention due to their high overall efficiency and reduced greenhouse gas emissions.
Conventional power plants typically convert only about 30% of the fuel input into electricity, while the remaining energy is dissipated as waste heat. In contrast, CCHP systems recover this waste heat for heating and cooling applications, enabling overall efficiencies of up to 90%. However, the performance and economic feasibility of CCHP systems strongly depend on equipment selection, configuration, and capacity matching. Moreover, traditional CCHP systems primarily rely on natural gas, which contributes to environmental pollution and operational costs.
To address these challenges, this study proposes a novel multigeneration system based on a steam turbine-driven Rankine cycle integrated with an ejector-based cooling system using sulfur dioxide (SO_2) as the working fluid. Replacing gas turbines with a steam cycle reduces fossil fuel dependency and emissions while enhancing thermodynamic performance. The proposed configuration introduces a new approach to utilizing waste heat from the Rankine cycle for both heating and cooling purposes, which has not been previously investigated in the literature.

Methodology

A novel CCHP configuration was developed by integrating a steam turbine-based Rankine cycle with an innovative SO_2 ejector refrigeration system. In the proposed system, saturated liquid water is pressurized by a pump, heated in a boiler, and expanded in a steam turbine to generate power. The exhaust steam is subsequently directed to a heat exchanger to meet heating demands and then to a vapor generator heat exchanger, where recovered waste heat drives the ejector refrigeration cycle.
Sulfur dioxide is selected as the working fluid in the ejector cooling subsystem due to its favorable thermophysical properties. The ejector system consists of a motive nozzle, suction nozzle, mixing chamber, diffuser, separator, evaporator, compressor, and multiple heat exchangers. A portion of the SO_2 stream acts as the motive flow, while the remaining flow undergoes expansion, compression, condensation, and evaporation to produce cooling capacity.
A comprehensive thermodynamic analysis was conducted using mass, energy, and exergy balance equations. Energy and exergy efficiencies were calculated to evaluate system performance. Additionally, a detailed thermoeconomic analysis was performed by integrating exergy-based cost accounting with updated component cost correlations. Capital investment, maintenance costs, fuel costs, and exergy destruction rates were incorporated to determine the total system cost.
Parametric analyses were carried out to investigate the effects of key operational parameters, including the inlet temperature of the SO_2 turbine and the isentropic efficiency of the compressor, on system performance, exergy destruction, and total cost.

Results and Discussion

The proposed multigeneration system demonstrated satisfactory thermodynamic and economic performance. Model validation was conducted by comparing the results with a reference study, showing negligible deviations

and confirming the accuracy of the developed model. The overall energy efficiency and exergy efficiency of the system were found to be 20% and 26%, respectively. The steam turbine produced 1094 kW of power, while the SO_2 turbine generated 47,150 kW. Exergy analysis revealed that the total exergy destruction of the system was 49,189 kW. Among all components, the SO_2 turbine exhibited the highest exergy destruction, whereas the steam turbine showed the lowest, indicating effective utilization of the Rankine cycle.
Economic analysis showed that the total system cost was approximately 233 USD/GJ. The ejector accounted for the highest cost rate among system components, while the steam pump had the lowest cost contribution. These results highlight the economic feasibility of the proposed configuration, despite the relatively high cost of specific advanced components.
Parametric analysis indicated that increasing the SO_2 turbine inlet temperature from 430°C to 470°C improved both energy and exergy efficiencies but also increased total system cost and exergy losses. Conversely, improving the compressor isentropic efficiency reduced total system cost and exergy destruction while enhancing energy efficiency, although a slight reduction in exergy efficiency was observed.

Conclusion

This study introduces a novel steam turbine-based CCHP system integrated with an innovative SO_2 ejector cooling cycle, offering a promising solution for high-efficiency and low-emission energy generation. The use of a Rankine cycle as the primary energy source, combined with effective waste heat recovery for heating and cooling, significantly improves system sustainability compared to conventional gas-based systems.
Future research may focus on multi-objective optimization of system parameters, integration of renewable heat sources, and environmental impact assessments such as life-cycle analysis. Experimental validation and scalability studies are also recommended to facilitate real-world implementation. Overall, the proposed configuration demonstrates strong potential as an efficient and economically viable multigeneration system for advanced energy applications.

key words: Steam turbine, ejector cooling, exergy, economic analysis, thermal recovery

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