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Design of Combined Heat and Power (CHP) Cycles Compatible with Waste Heat Sources for Decarbonization

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ABSTRACT

Decarbonization efforts are crucial for mitigating climate change, with direct air capture (DAC) technologies playing a key role by removing carbon dioxide (CO_2) directly from the atmosphere. However, the substantial energy requirements of DAC processes pose significant challenges to their scalability and sustainability. To address this, leveraging waste heat recovery methods offers a promising strategy to reduce the overall energy footprint of DAC systems, thereby enhancing their economic and environmental viability. Waste heat represents a considerable portion of industrial energy losses and presents immense potential for integration with DAC processes. By utilizing existing waste heat streams, it is possible to partially offset the high energy demands of DAC, leading to improved energy efficiency and decreased reliance on primary energy sources. Among various waste heat recovery techniques, combined heat and power (CHP) cycles are particularly advantageous due to their ability to concurrently generate electricity and useful thermal energy. This dual-generation capability not only maximizes energy utilization but also aligns with sustainability objectives by minimizing waste and optimizing resource use. In this study, our primary objective is to design and evaluate a CHP cycle integrated with DAC processes that harnesses high-temperature waste heat to drive the system. The proposed cogeneration system comprises of a recompression supercritical CO_2 (SCO_2) cycle featuring a precompression compressor along with a compression and main compressor as the topping cycle, paired with a simple transcritical CO_2 (TCO_2) bottoming cycle. Waste heat is recovered through a heat exchanger from a high-temperature source operating between 450–550 °C, which acts as the driving force for the CHP cycle. Energy analysis indicates that the system achieves a thermal efficiency of 41% with approximately 128 kW of electricity generation, while exergy analysis—a critical design criterion—reveals an exergy efficiency of around 67%. Additionally, the bottoming cycle produces roughly 90 kW of heat that can be utilized for hydrogen production as a valuable byproduct. These results confirm that the integration of waste heat recovery through CHP cycles not only meets but exceeds the primary objectives of reducing energy consumption and enhancing efficiency, thereby providing a viable pathway for sustainable DAC operation and broader decarbonization goals. Moreover, additional hydrogen production enhances the overall energy portfolio of the system.

Keywords: Direct Air Capture, Waste Heat Recovery, Combined Heat and Power, Decarbonization, Energy Efficiency, Exergy Analysis, Exergoeconomics