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Energy and Exergy Performance Analysis of a Counter-Flow Secondary System in an Economical Mini Water Chiller

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ABSTRACT*:* Mini water chillers are small-capacity cooling systems widely used in laboratory applications and light industries due to their ability to maintain stable temperatures with relatively low power consumption. Nevertheless, the thermal efficiency of these systems can be further improved through optimization of fluid flow configurations in the secondary loop. This study investigates the effect of a counter-flow heat exchanger configuration on the energy and exergy performance of an economical mini water chiller secondary system. The research employs both theoretical and experimental approaches by measuring inlet and outlet fluid temperatures, mass flow rates, and electrical power consumption. Energy analysis is applied to determine the coefficient of performance (COP), while exergy analysis is used to evaluate exergy efficiency (η_{ex}) and the rate of exergy destruction ($\dot{E}d$). The results indicate that the counter-flow configuration enhances the system COP by approximately 8–12% compared to a parallel-flow model. In addition, overall exergy efficiency increases by up to 9%, with the most significant reduction in exergy destruction occurring in the secondary heat exchanger. These findings demonstrate that the implementation of a counter-flow model is effective in improving both energy performance and exergy quality in energy-efficient mini cooling systems.

KEYWORDS: counter-flow configuration; water chiller; energy efficiency; exergy efficiency; secondary system

INTRODUCTION

The demand for energy-efficient cooling systems has continued to rise in line with the expansion of industrial and commercial sectors, as well as increasing pressure to reduce electricity consumption and carbon emissions. Water chiller systems are among the most widely applied technologies for cooling in buildings, industrial processes, and small-scale applications such as mini water chillers (Hassan et al., 2022). However, the thermal performance and energy efficiency of these systems are strongly influenced by the fluid flow configuration within heat exchanger components, which play a critical role in heat transfer processes in secondary systems (Khalid et al., 2023).

One of the most extensively studied flow configurations in heat exchangers is the counter-flow arrangement. From a theoretical perspective, counter-flow heat exchangers are able to maintain a more effective temperature gradient along the flow direction of hot and cold fluids compared to parallel-flow configurations, thereby enhancing heat transfer rates and overall thermal efficiency (Khalid et al., 2023). Comparative energy and exergy studies of heat exchangers have demonstrated that counter-flow configurations exhibit distinct and often lower energy losses in terms of exergy destruction, indicating superior energy quality in real thermodynamic systems.

The performance of cooling systems can be evaluated using two principal approaches: energy analysis and exergy analysis. Energy analysis focuses on the quantity of energy transferred, whereas exergy analysis assesses energy quality and the degree of irreversibility occurring within individual system components (Bejan, 2020). Through exergy analysis, components with the highest exergy destruction—such as compressors, condensers, or secondary heat exchangers—can be identified, enabling optimization efforts to be concentrated on the most critical elements (Rahman et al., 2021).

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Yoon et al. (2023) emphasized the importance of combined energy and exergy analysis in cascade mixed-refrigerant Joule–Thomson cooling systems, reporting an improvement in exergy efficiency of up to 47% through operational optimization. Their findings confirm that exergy analysis provides deeper insights into energy losses at the component level, particularly in heat exchangers and compressors, which are also key elements in secondary mini water chiller systems.

Similarly, Yıldız (2024), through a 4E (Energy, Exergy, Economic, and Environmental) analysis of a photovoltaic–thermal (PV/T)-based cooling system, demonstrated that integrating renewable energy sources not only enhances energy efficiency but also reduces environmental impacts by up to 18%. The 4E approach has emerged as a contemporary trend in cooling system research, as it enables a holistic evaluation encompassing thermodynamic performance, cost considerations, and sustainability. This framework offers a potential direction for the future development of economical mini chillers with improved overall efficiency and environmental performance.

Miri (2024) also contributed to this field by analyzing a wind-powered, water-cooled vapor compression system equipped with thermal storage. The study revealed that proper cooling capacity control and energy management in small-scale systems could increase the coefficient of performance (COP) by up to 12%, while achieving an exergy efficiency of approximately 65%. These results support the notion that counter-flow-based mini cooling systems have strong potential to deliver high efficiency at relatively low operating costs, particularly when coupled with alternative energy sources.

In the context of heat exchanger design, Al-Qazzaz (2024) compared the performance of underground heat exchangers and wet cooling towers using energy, exergy, and environmental analyses. The study found that appropriate flow configurations, including counter-flow arrangements, could reduce exergy destruction by up to 22% compared to conventional systems. This finding aligns with design principles applied in secondary mini water chiller systems, where counter-flow patterns generate larger temperature gradients and improve heat transfer quality.

Furthermore, Naderi Pak et al. (2023), through an exergy and economic analysis of a Combined Cooling and Power (CCP) system, demonstrated that integrating waste heat recovery could enhance system exergy efficiency by 15–20%. Although conducted on a larger-scale system, the exergy optimization principles presented are applicable to the development of smaller cooling systems such as mini chillers. This approach reflects a broader global research trend toward integrating thermodynamic, economic, and energy-efficiency analyses simultaneously.

Recent research trends also indicate growing interest in innovative heat exchanger designs, both in terms of materials and flow patterns. Experimental studies on triply periodic minimal surface (TPMS) heat exchangers (Letlhare-Wastikc & Yang, 2025) reported heat transfer effectiveness improvements of up to 5.8% compared with conventional tubular heat exchangers. These findings highlight that flow configuration optimization—including counter-flow arrangements as investigated in this study—remains a central topic in enhancing the thermodynamic performance of cooling systems.

Overall, previous studies confirm that energy and exergy analyses represent the most comprehensive approaches for evaluating modern cooling system performance. These findings reinforce the relevance of the present study, which investigates the influence of counter-flow configurations on the energy and exergy performance of a secondary mini water chiller system. Counter-flow design not only improves heat transfer rates and COP but also reduces irreversibility, bringing the system closer to ideal thermodynamic behavior and offering long-term economic benefits. Accordingly, this study aims to evaluate the effect of counter-flow configuration on the energy and exergy performance of the secondary system in an economical mini water chiller. The results are expected to provide a basis for designing energy-efficient cooling systems with high performance and low operational costs.

METHODOLOGY

System Design

The experimental study was conducted on an economical mini water chiller prototype with a cooling capacity of 0.75 kW. The system consists of a hermetic compressor, a finned-tube condenser, a thermostatic expansion valve, and an evaporator connected to a secondary system incorporating a counter-flow heat exchanger. R134a was used as the primary refrigerant, while the secondary fluid consisted of a water–glycol mixture (10%) to prevent freezing.

Testing Procedure

a. Inlet and outlet temperatures of both the refrigerant and secondary loop were measured using K-type thermocouples with an accuracy of ±0.1 °C.
b. Mass flow rates were measured using a digital flowmeter.
c. Electrical power consumption of the compressor and pump was recorded using a precision wattmeter.
d. Experiments were conducted under steady-state conditions with variations in secondary flow rates ranging from 2 to 6 L/min.

Energy Analysis

a. Heat exchanger effectiveness

$$\varepsilon = \frac{1 - \exp[-NTU(1-C)]}{1 - C\exp[-NTU(1-C)]}$$

b. Heat transfer rate

$$\dot{Q} = \varepsilon\, C_{min}\,(T_{h,in} - T_{c,in})$$

c. System coefficient of performance

$$COP = \frac{\dot{Q}_{evap}}{W_{comp} + W_{pump}}$$

Exergy Analysis

a. Physical exergy of the working fluid

$$e = (h - h_0) - T_0(s - s_0)$$

b. Rate of exergy destruction

$$\dot{E}_d = T_0 \dot{S}_{gen}$$

c. Overall system exergy efficiency

$$\eta_{ex} = \frac{\dot{E}_{useful}}{\dot{E}_{input}}$$

RESULT

Energy Performance Analysis

The results indicate that the counter-flow configuration yields higher heat exchanger effectiveness values, ranging from 0.85 to 0.92, compared to parallel-flow configurations (0.70–0.78). This improvement directly influences system COP, which increased from an average of 3.45 to 3.83, representing an enhancement of approximately 11%. The COP improvement is attributed to the higher logarithmic mean temperature difference (LMTD) achieved under counter-flow conditions, resulting in more efficient heat transfer between the refrigerant and secondary fluid.

Exergy Performance Analysis

Exergy analysis reveals that the highest exergy destruction occurs in the compressor (40–45%), followed by the secondary heat exchanger (25–30%). After implementing the counter-flow configuration, the overall system exergy efficiency increased from 58% to 63%, accompanied by a significant reduction in exergy destruction within the secondary heat exchanger. These results indicate that counter-flow arrangements effectively reduce irreversibility caused by extreme temperature differences along the heat exchanger.

DISCUSSION

Overall, the counter-flow configuration enhances heat transfer quality and reduces exergy losses in the secondary system. Although pump power consumption increased slightly (approximately 3%) due to higher pressure drops, the gains in COP and exergy efficiency were more significant, rendering the system more economical overall. These findings are consistent with previous studies by Zhang et al. (2022) and Khalid et al. (2023), which reported thermodynamic efficiency improvements of 10–15% through optimized fluid flow arrangements.

SUMMARY

1. The counter-flow configuration in the secondary system of a mini water chiller increases system COP by approximately 8–12% compared to parallel-flow arrangements.
2. System exergy efficiency improves from 58% to 63%, with the most substantial reduction in exergy destruction occurring in the secondary heat exchanger.
3. The counter-flow model is proven effective in enhancing overall thermodynamic efficiency and is suitable for the development of energy-efficient and economical mini water chiller systems.
4. Future studies are recommended to focus on heat exchanger geometry optimization and comprehensive economic analysis to identify the most efficient operating conditions.

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