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Research Article

Enhancing Split-Type Air Conditioning System Efficiency through CLOHP Integration

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Abstract:
This study investigates the impact of integrating looped oscillating thermosyphon heat pipes (CLOHPs) in a 3.52 kW (12,000 BTU/hr) split-type air conditioning system. The CLOHP uses water as the working fluid and R-134a for sensible heat exchange, with the goal of reducing refrigerant temperature before reaching the capillary tube, improving system efficiency. Performance tests were conducted at ambient temperatures of 294.2K, 296.2K, 298.2K and 300.2K. Results showed up to a 15.84% improvement in evaporation rate (Qevap), 16.37% in coefficient of performance (COP), and 16.13% in energy recovery rate (ERR), with higher effectiveness at higher temperatures. These findings demonstrate the potential of CLOHPs in enhancing energy efficiency and thermal performance in air conditioning systems, offering a promising solution for energy savings in residential and commercial applications.

Keywords: *Looped oscillating thermosyphon heat pipe (CLOHP), split-type air conditioning, energy efficiency, coefficient of performance (COP), energy efficiency ratio (EER).*

1. Introduction

Energy efficiency and thermal performance optimization in air conditioning systems have become important due to rising global energy demand and the urgent need for sustainable solutions in residential and commercial buildings [1]. Innovative technologies, such as closed-loop oscillating heat pipes (CLOHPs) and closed-loop thermosyphon, have emerged as promising solutions for enhancing heat transfer and reducing the energy consumption of air conditioning systems [2-4]. CLOHPs are remarkably advanced thermal management devices capable of transferring large amounts of heat through phase change mechanisms with minimal temperature differences, making them ideal for cooling applications. CLOHPs operate on the principle of phase change heat transfer, where the working fluid undergoes continuous evaporation and condensation within a closed loop. This mechanism allows for the transfer of large amounts of heat with minimal temperature differences, making them highly efficient for cooling applications. Unlike conventional heat exchangers, CLOHPs efficiently rely on an oscillating flow of liquid and vapor within a closed loop, facilitating efficient heat transfer with no moving parts. This design improves reliability and reduces maintenance costs [5].

To clarify the novelty and effectiveness of the proposed technique, it is important to highlight how CLOHPs enhance refrigeration and air conditioning performance. CLOHPs improve system efficiency by pre-cooling the refrigerant before it enters the capillary tube, thereby reducing the refrigerant temperature and increasing the cooling capacity of the system. This process reduces the compressor load, leading to higher energy efficiency and a better coefficient of performance (COP) [6, 7].

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Additionally, the phase change mechanism of CLOHPs allows for efficient heat transfer with minimal temperature differences, making them particularly effective in high ambient temperature environments.

The working fluid in CLOHPs plays a critical role in their performance. Water is commonly used due to its high latent heat and thermal conductivity, which enable efficient heat absorption and transfer within the system. However, the interaction between CLOHPs and the refrigerant cycle in air conditioners remains an area of intensive ongoing research. Factors such as ambient temperature, refrigerant properties, and the behavior of the working fluid under different operating conditions can significantly influence the overall system performance. Using CLOHPs to pre-cool the refrigerant before it enters the capillary tube has shown potential for reducing the refrigerant's temperature and increasing the cooling capacity of split-type air conditioning units [8].

Recent advancements in CLOHP technology have demonstrated their potential to improve the energy efficiency of air conditioning systems. By integrating CLOHPs, the compressor load can be reduced, leading to a higher coefficient of performance (COP) and improved energy efficiency, particularly in high ambient temperature environments [6, 9]. This is especially relevant for split-type air conditioning systems, which are widely used in residential and commercial settings and often operate under high loads for extended periods. Conventional air conditioning systems face efficiency limitations due to thermal losses in the refrigerant cycle, particularly in the capillary tube and evaporator sections. To address these challenges, integrating advanced heat transfer technologies, such as CLOHPs, has emerged as a highly promising solution for enhancing system performance [10].

This study investigates the thermal performance improvements in a 3.52 kW (12,000 BTU/hr) split-type air conditioning system by integrating CLOHPs with water as the working fluid and R-407C as the primary refrigerant. The objective is to evaluate the impact of CLOHP integration on the system's evaporation rate (Q_{evap}), coefficient of performance (COP), and energy recovery rate (ERR) at various ambient temperatures. The system will be tested at four different temperatures (294.2K, 296.2K, 298.2K, and 300.2K). The findings are expected to provide valuable insights into the feasibility of using CLOHPs to enhance the energy efficiency and sustainability of air conditioning systems, particularly in warmer climates. By demonstrating the practical benefits of CLOHP integration, this study aims to establish the novelty and effectiveness of the proposed technique in addressing the limitations of conventional air conditioning systems.

The integration of CLOHPs into air conditioning systems represents a significant step forward in the development of energy-efficient cooling technologies. As global energy demand continues to rise, innovations like CLOHPs are essential for reducing energy consumption and minimizing the environmental impact of HVAC systems. This research contributes to the growing body of knowledge on advanced heat transfer technologies and offers a promising solution for improving the performance and sustainability of air conditioning systems in both residential and commercial applications. [9].

Table 1: Ranges of parameters in the investigation.

Air Conditioning Capacity (kW)	3.52
Working fluid in CLOHP	Water
Refrigerant	R-407C
Sensible Heat Exchange Medium in CLOHP	R-134a
T (K)	294.2, 296.2, 298.2, 300.2
A (m^2)	12.09
D (m)	0.00149
L (m)	5.97
Density of the working fluid R-134a (kg/m^3)	1146.5

2. Methodology

This study aimed to evaluate the impact of integrating closed-loop oscillating heat pipes (CLOHPs) on the thermal performance of a split-type air conditioning system. A schematic diagram of the experimental apparatus is presented in Fig. 1. The experimental setup involved a 3.52 kW (12,000 BTU/hr) split-type air conditioner, charged with R-407C refrigerant, as the base system (see Fig. 2). The CLOHP, designed as a closed-loop heat pipe with water as the working fluid, incorporated R-134a to enhance sensible heat exchange. This system was connected to the refrigerant circuit of the air conditioner to pre-cool the refrigerant before it entered the capillary tube. The performance was tested under varying ambient temperatures to assess the effects of temperature changes on system performance. Detailed parameters in the investigation are given in Table 1. The CLOHP was fabricated using copper tubes with a diameter of 0.00149 m and a length of 5.97 m, ensuring effective thermal performance.

2.1 Experimental procedure

The experimental procedure involved modifying the air conditioning unit to integrate the closed-loop oscillating heat pipe (CLOHP), ensuring secure connections and minimizing thermal losses between components. All parts of the system were insulated to maintain accurate thermal measurements. The performance testing was conducted at four target ambient temperatures (294.2K, 296.2K, 298.2K and 300.2K). For each temperature, the system was operated until it reached a steady state to ensure consistent performance data. Key parameters, such as evaporation rate (Q_{evap}), coefficient of performance (COP), and energy recovery rate (ERR), were measured at each temperature. The power input to the compressor was recorded, and the heat absorbed in the evaporator was used to calculate the COP. The ERR was calculated by comparing the energy recovered by the CLOHP to the total input energy. The system setup includes coiled tubes that facilitate efficient heat exchange with the surrounding environment, valves with red handles for fluid control, and a metal support frame to ensure stability. Insulated pipes on either side help reduce heat loss, preserving the system's efficiency. This configuration is part of a larger experimental setup used for studying heat transfer processes and optimizing air conditioning performance through CLOHP integration.

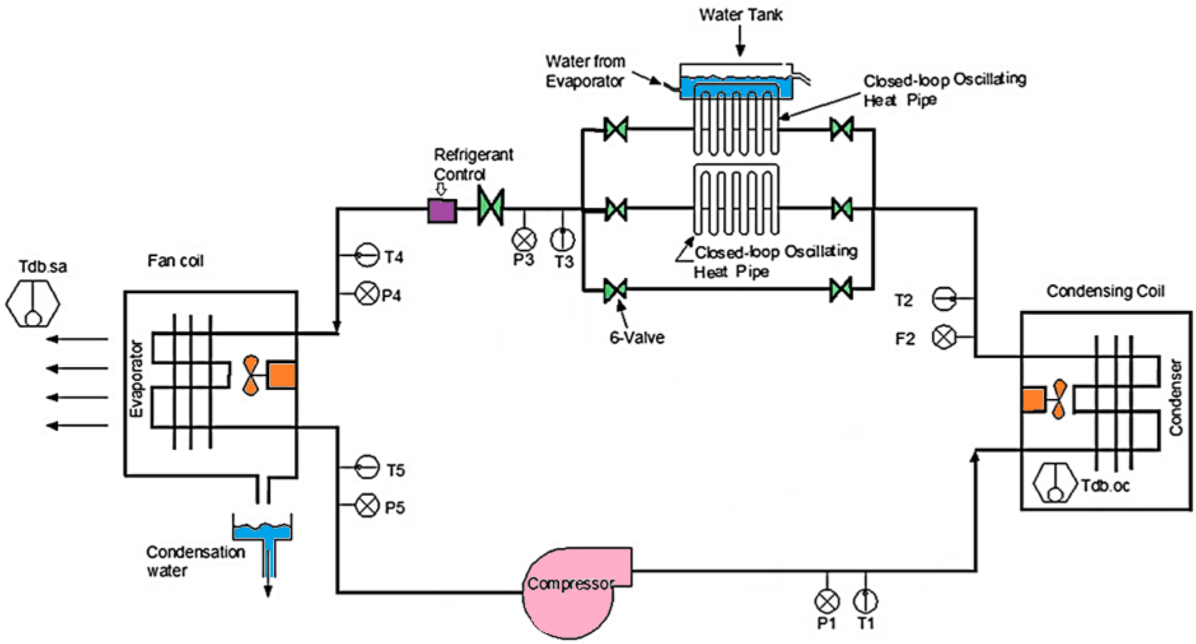
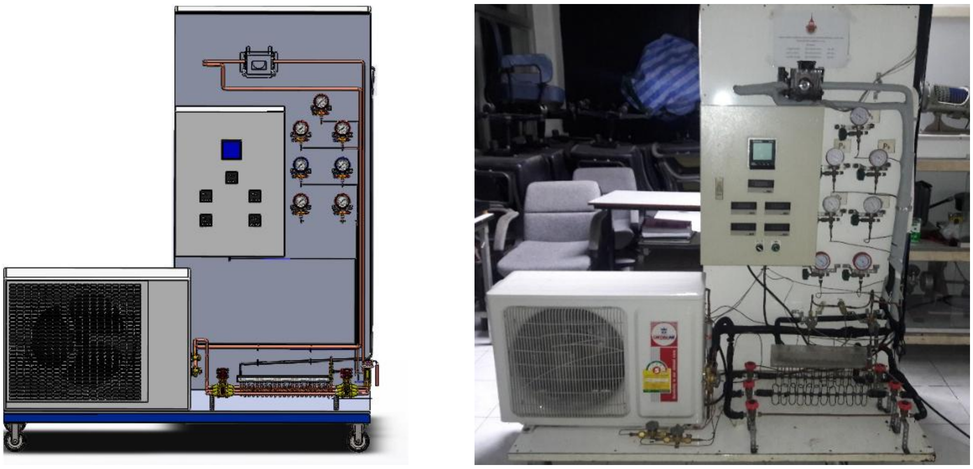


Fig. 1. Schematic diagram of the experimental setup.

This study employed a split-type air conditioning unit with a cooling capacity of 3.52 kW (12,000 BTU/hr). The system used R-407C as the primary refrigerant, while the CLOHP was strategically charged with R-134a. The CLOHP design incorporated water as the secondary working fluid, which oscillates within a closed-loop heat pipe structure.

The CLOHP was integrated into the system to extract sensible heat from the refrigerant cycle before it entered the capillary tube, thereby reducing the refrigerant temperature and enhancing the overall cooling process. Figure 2 shows the components and layout of the air conditioning systems. The main parts include the air conditioning unit, control panel, and various sensors or gauges accurately attached to the thermosyphon loop. The cooling temperature during the test was controlled by regulating the refrigerant flow rate and adjusting the environmental conditions in the test chamber. A thermostatic control system maintained a stable ambient temperature, while the compressor and expansion valve settings ensured consistent cooling performance. Additionally, temperature sensors were strategically placed at key points in the system to monitor and maintain the desired cooling temperature.



(a) CAD drawing (b) Physical setup

Fig. 2. Air conditioner equipped with a cooling device for an oscillating thermosyphon loop

Figure 3 shows a close-up view of a heat exchange section within a thermosyphon loop system. It consists of a series of interconnected copper pipes and coils, through which a working fluid flows.

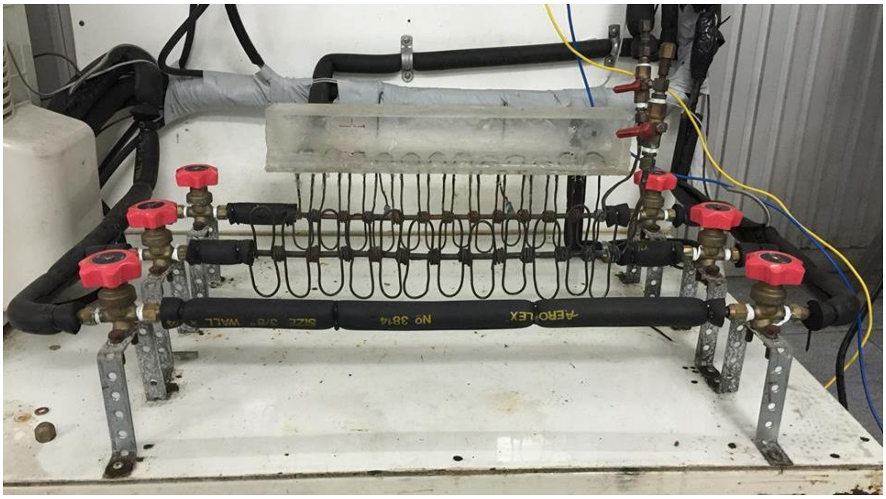


Fig. 3. Close-up view of a heat exchange section

2.2 Performance measurement and calculations

The performance measurement and calculations are described in this section. Figure 4 shows the P-h diagram of the refrigeration cycle. The cycles consist of the basic four processes for the standard cycle and plus one process of superheat for actual cycle. The coefficient of performance can be calculated as the ratio of the cooling capacity to the power input [10]:

$$\mathrm{COP} = \mathrm{Q}_{\mathrm{evap}} / \mathrm{W}_{\mathrm{comp}} \tag{1}$$

where the cooling capacity from the evaporator (kW) is:

$$\dot{\mathrm{Q}}_{\mathrm{evap}} = \dot{\mathrm{m}}\left(h_1 - h_4\right) \tag{2}$$

where the work input to the compressor (kW) is:

$$\dot{W}_{comp} = \dot{m}\left(h_2 - h_1\right) \tag{3}$$

and where $\dot{m}$ and h are mass flow rate if the refrigerant (kg/s) and enthalpy (kJ/kg). The energy efficiency ratio can be calculated as the ratio of cooling capacity to electrical energy consumption:

$$ERR = Q_{all}/P_{input} \tag{4}$$

where Q_{all} and P_{input} are the total cooling capacity received from the evaporator (kW) and the total electrical power input to the air conditioner (kW). The percentage improvements for each performance metric (Q_{evap}, COP, and ERR) were calculated by.

$$\% \text{ Improvement} = \left(\text{CLOHP value} - \text{Normal value}\right) / \text{ Normal value} \times 100\% \tag{5}$$

which we will use below.

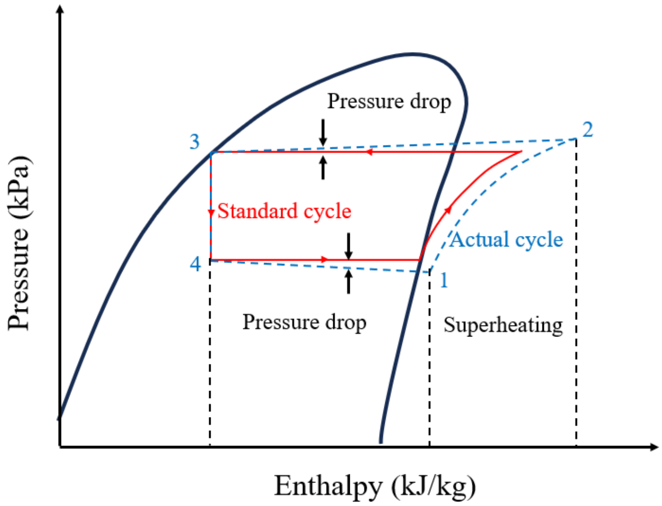


Fig. 4. P-h diagram of the refrigeration cycles

3. Results and Discussion

In this work, we examine the impact of integrating closed-loop oscillating heat pipes (CLOHPs) with water as the working fluid on the performance of a 3.52 kW (12,000 BTU/hr) split-type air conditioning system. We analyze the key performance metrics across varying ambient temperatures (294.2K, 296.2K, 298.2K and 300.2K). Table 2 provides the experimental results when using the CLOHP over the normal configurations.

3.1 Q_{evap} (Evaporation Rate) improvement

The Q_{evap} values for the CLOHP setup are consistently higher than those for the normal setup across all tested temperatures, showing an improvement range of approximately 14.94% at 294.2K to 15.84% at 300.2K. This improvement is attributed to the reduction in refrigerant temperature before the capillary tube, which enhances the refrigerant's capacity to absorb heat in the evaporator. This indicates that the CLOHP configuration significantly enhances the evaporation process, which is essential for applications requiring efficient heat transfer. Additionally, the slight increase in percentage improvement as temperature rises suggests that the CLOHP setup may perform more effectively in warmer conditions, possibly due to improved fluid dynamics or heat transfer characteristics at higher environmental temperatures.

Table 2: Experimental results.

Parameters	Configuration	Temperature (K)			
		294.2	**296.2**	**298.2**	**300.2**
Average Q_{evap}	Normal	3.28	3.26	3.24	3.22
	CLOHP	3.77	3.75	3.74	3.73
	% Improvement	14.94	15.03	15.43	15.84
Average COP	Normal	2.88	2.86	2.84	2.81
	CLOHP	3.31	3.29	3.28	3.27
	% Improvement	14.93	15.03	15.49	16.37
Average ERR	Normal	11.50	11.43	11.32	11.28
	CLOHP	13.24	13.18	13.12	13.10
	% Improvement	15.13	15.31	15.90	16.13

3.2 COP (Coefficient of Performance) Improvement

The COP improvement in the CLOHP setup follows a similar trend, beginning at 14.93% at 294.2K and reaching 16.37% at 300.2K. This improvement is attributed to the reduction in refrigerant temperature before the capillary tube, which enhances the refrigerant's capacity to absorb heat in the evaporator. A higher COP indicates greater energy efficiency, meaning the CLOHP configuration requires less input energy to maintain the same performance level. The gradual increase in COP improvement at higher temperatures suggests that the CLOHP system may be more effective in warmer conditions, boosting energy efficiency in hotter environments. This makes it particularly beneficial for applications in climates or seasons with higher ambient temperatures.

3.3 ERR (Energy Recovery Rate) Improvement

The ERR values exhibit the highest improvement among the parameters, starting at 15.13% at 294.2K and increasing to 16.13% at 300.2K. This improvement results from the CLOHP's two-phase heat transfer mechanism, which efficiently recovers waste heat and transfers it to the refrigerant, reducing overall energy consumption. A higher ERR means the system can recover more energy, making it especially valuable for sustainable energy applications. The gradual rise in ERR improvement with temperature suggests that the CLOHP configuration may optimize energy recovery more effectively under warmer conditions, possibly by improving the thermal conductance or flow efficiency of the heat transfer fluid.

3.4 Overall Trends and Implications

For all three parameters, the CLOHP configuration consistently outperforms the normal setup, with effectiveness increasing as temperatures rise. This trend highlights the CLOHP's ability to leverage higher ambient temperature gradients for improved heat exchange efficiency, along with its combination of sensible and latent heat exchange mechanisms to maximize thermal performance. This trend suggests that the CLOHP system may be particularly advantageous for high-temperature applications, where its efficiency and energy-saving benefits are maximized. In practical applications such as solar thermal systems or other heat-intensive technologies, implementing CLOHP could yield substantial operational cost savings, enhanced sustainability, and optimized performance.

The observed improvements underscore the potential of CLOHP as a viable enhancement for heat transfer systems and mechanisms. Its ability to lower refrigerant temperature, enhance heat exchange, and reduce compressor workload makes it a promising solution for energy-efficient air conditioning. Its consistent and increasing efficiency gains with temperature make it a promising solution for applications requiring high thermal performance, particularly in warmer settings. This could lead to more energy-efficient designs and pave the way for further research into temperature-dependent optimizations of heat transfer fluids in polymer processing applications [11-16].

4. Conclusion

From Table 2, The results clearly show that the CLOHP configuration significantly enhanced system performance, with improvements of up to 15.84% in Q_{evap}, 16.37% in COP, and 16.13% in ERR. These improvements indicate that CLOHP integration optimizes sensible heat transfer and energy efficiency, particularly in warmer environments, where higher ambient temperatures further amplify the thermal performance. The increased COP implies that the

CLOHP system effectively reduces the compressor load, thereby lowering energy consumption, while the enhanced ERR reflects more effective energy recovery, contributing to sustainable and environmentally friendly cooling operations. Moreover, the performance gains become more pronounced at higher ambient temperatures, suggesting that the CLOHP benefits from increased temperature gradients, which further amplify heat transfer and phase change efficiency.

Overall, the CLOHP system presents a promising approach to significantly improving the efficiency and energy savings of air conditioning units, especially in residential and commercial applications in warmer climates. Its superior thermodynamic performance is attributed to the combined effects of refrigerant pre-cooling, enhanced heat absorption, and efficient thermal energy recovery. The adaptability of the CLOHP system to temperature variations highlights its potential for use in diverse environments, where it can deliver substantial cost and energy savings. Based on the findings, it is recommended that CLOHP technology be considered for wider adoption in energy-efficient air conditioning systems, particularly in settings with exceptionally high cooling demands [17].

Manufacturers and engineers should actively explore integrating CLOHP designs into split-type systems to help meet energy-saving and sustainability goals. A thorough evaluation of the design parameters, such as filling ratio, tube diameter, and loop configuration, is crucial for maximizing performance in practical applications. Regulators might also consider offering incentives for using advanced heat pipe technology like CLOHP to encourage energy savings in the HVAC industry. Working with HVAC manufacturers could speed up the adoption of this technology, resulting in major energy savings and supporting global efforts for more sustainable climate control solutions. By promoting these partnerships and incentives, everyone involved can collectively help drive innovation and create more energy-efficient, environmentally friendly and thermodynamically optimized HVAC systems that benefit both the environment and the economy [18].

Nomenclature

A	Area, m^2
COP	convective heat transfer coefficient
D	Copper CLOHP diameter, m
ERR	Energy efficiency ratio
h	Enthalpy, kJ/kg
L	Copper CLOHP length, m
$\dot{m}$	mass flow rate, kg/s
P_{input}	Total electrical power input to the air conditioner, kW
Q_{all}	Total cooling capacity received from the evaporator, kW
Q_{evap}	Evaporation Rate, kW
T	Ambient Temperature, K
W_{comp}	Work input to the compressor, kW
Subscripts	
1	the refrigerant exiting the compressor
2	the refrigerant exiting the condenser
3	the refrigerant exiting the thermosyphon unit
4	the refrigerant exiting the capillary tube
5	the refrigerant exiting the evaporator

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