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DESIGN AND PERFORMANCE VALIDATION OF A DUAL-FUNCTIONAL ABSORPTION HEAT EXCHANGER

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Abstract: The large-scale utilization of low-grade waste heat is a key trend for district heating systems under the carbon neutrality strategy, necessitating large-temperature-difference technology for long-distance heat transport. This technology creates a "temperature ratio mismatch" problem due to the severe mismatch in fluid flow rates between the primary and secondary sides of the heating network. To address this, the Absorption Heat Exchanger (AHE) was developed. It has evolved into two main functional types: the first-type AHE, based on an Absorption Heat Pump (AHP) cycle for lowering the primary network's return water temperature, and the second-type AHE, based on an Absorption Heat Transformer (AHT) cycle for upgrading the temperature of low-grade heat sources. However, in applications requiring both functions, the conventional approach of deploying two separate units increases system complexity and investment. This paper reports on the design, fabrication, and experimental validation of a novel Dual-Functional Absorption Heat Exchanger (DFAHE). The device utilizes interchangeable falling-film components within a reconfigurable system architecture, allowing a single unit to switch between AHP and AHT operational modes. Experimental results demonstrate that the unit operates stably in both modes and achieves the intended thermodynamic functions. The findings indicate that a single, reconfigurable unit can perform the roles of two distinct devices, offering a compact and flexible alternative for waste heat recovery and temperature grade management in district heating systems.
Keywords: Absorption heat exchanger; Waste heat recovery; Absorption heat pump; Absorption heat transformer; District heating.

1 INTRODUCTION

Driven by the "carbon peak and carbon neutrality" strategy, China's energy structure is undergoing a profound transformation. For the district heating sector in northern cities, utilizing low-grade energy sources such as industrial waste heat to replace traditional fossil fuels is a key pathway to achieving low-carbon heating [1, 2]. As waste heat resources are often located far from urban heat load centers, a large-temperature-difference heating mode is essential to enable long-distance and low-cost heat transport. However, this mode creates a severe mismatch in fluid flow rates between the primary and secondary networks at the substation, a problem known as "temperature ratio mismatch". Using conventional plate heat exchangers under such conditions leads to significant heat grade loss and excessively high return water temperatures in the primary network, thereby limiting the grid's transport capacity and its efficiency in recovering low-temperature waste heat.

To overcome this technical bottleneck, a novel Absorption Heat Exchanger (AHE) technology based on the absorption cycle principle was proposed [3]. This technology can effectively handle conditions with extremely mismatched temperature ratios. It can significantly reduce the primary network's return water temperature from the conventional 45-50℃ down to 25-30℃ while ensuring the heating parameters of the secondary network [4]. In recent years, research on AHEs has matured, leading to engineering demonstrations. In terms of unit construction, researchers have successively proposed various designs, including vertical multi-stage [5], two-stage vertical [6], and plate-type configurations, aimed at optimizing internal heat transfer processes based on thermal performance principles [7]. Concurrently, research on the second-type AHE has been initiated to meet the demand for waste heat grade upgrading [8]. These advancements have laid a solid foundation for the application of large-temperature-difference heating technology..

In the course of technological promotion, the application scenarios for AHEs have gradually diverged into two major functional demands:

- **First-type Function (AHP mode)**: The core objective is to deeply cool the primary network's hot water to achieve an ultra-low return temperature, corresponding to the application of the first-type AHE [9, 10].
- **Second-type Function (AHT mode)**: The core objective is to upgrade the grade of medium-to-low temperature waste heat to a higher temperature to meet grid-connection or production requirements, corresponding to the application of the second-type AHE [11, 12].

In some complex application scenarios, such as industrial parks or combined heat and power plants, a demand for both functions may exist. The traditional solution requires the deployment of two separate units, which increases system complexity, footprint, and initial investment. Therefore, developing a single device that integrates both functions and can be flexibly switched on demand—a Dual-Functional Absorption Heat Exchanger (DFAHE)—holds significant engineering value. This paper presents the design, fabrication, and performance validation of such a DFAHE to demonstrate its technical feasibility [13].

2 DESIGN OF THE DUAL-FUNCTIONAL AHE

The design philosophy of the DFAHE centers on a structural innovation that allows its core components to adapt to role reversal, thereby enabling two different thermodynamic functions. The overall design is based on the falling-film heat exchange principle.

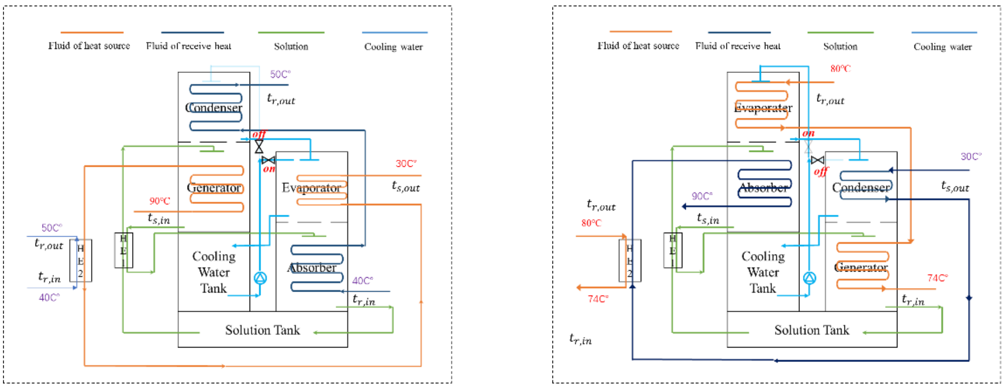
2.1 Operating Principles and Structural Innovation

The main technical challenge in designing a dual-functional unit is that the internal pressure relationships and solution flow direction are fundamentally reversed when switching modes. To solve this, the core innovation of this design is to endow the key components with a symmetrical and interchangeable structure. Specifically, the generator in the first-type AHE is designed to be identical to the absorber in the second-type AHE, both using a falling-film structure. Similarly, the condenser of the first-type AHE and the evaporator of the second-type AHE are also designed with identical falling-film structures. In this way, by means of external valve switching, the flow path of the working fluid can be altered to achieve the interchange of component functions.

Figure 1 illustrates the external water circuit flows for the two operating modes. Figure 2 depicts the reorganization of the internal working fluid (lithium bromide solution and water vapor) flow paths during mode switching, which transforms the unit's operational core from an AHP cycle to an AHT cycle.

(a) Principle of the first type AHE **(b) Principle of the second type AHE**

Figure 1 External process diagrams for (a) the first-type AHE and (b) the second-type AHE



(a) first type mode **(b) second type mode**

Figure 2. Internal process diagram of the dual-functional AHE in (a) first-type mode and (b) second-type mode

2.2 Experimental Unit

To validate the design, an experimental prototype was fabricated (see Figure 3). The unit was designed for a total heat load of 30 kW, with an evaporator capacity of 8 kW, which is approximately one-sixth the capacity of the smallest commercial units available at the time. The physical dimensions of the assembled unit are 0.7m × 0.4m × 2.5m, using lithium bromide-water (LiBr-H2O) as the working fluid pair. The overall structure is a single-stage, single-effect falling-film type, arranged in a vertical, double-cylinder configuration. This vertical layout, with the condenser placed above the generator and the evaporator above the absorber, provides a compact footprint and mitigates the risk of liquid refrigerant carryover into the solution circuit. The main vessels were constructed with an inner diameter of 215mm. To effectively isolate the high-pressure chamber (generator/condenser) from the low-pressure chamber (absorber/evaporator) and to rely on gravity for stable solution flow, U-tubes are used for pressure sealing and connection.

Figure 3 The experimental dual-functional AHE unit

The internal components of the unit, particularly the heat exchange coils and the solution distributor, are critical to its performance (see Figure 4). The heat exchange coils are made of copper tubing with a small outer diameter of 4mm and an inner diameter of 3mm, with a tube spacing of 4mm. This small-diameter design was chosen to enhance the heat transfer coefficient and reduce the overall volume of the unit. The solution is evenly distributed onto the outer surface of the coils through a precisely drilled plate, forming a stable falling film. The system is also equipped with solution and refrigerant pumps, and 5-micron filters are installed in all fluid circuits to protect the small-diameter tubes and distributor orifices from particulate fouling. It is this symmetrical internal component design that forms the technical basis for achieving dual functionality.

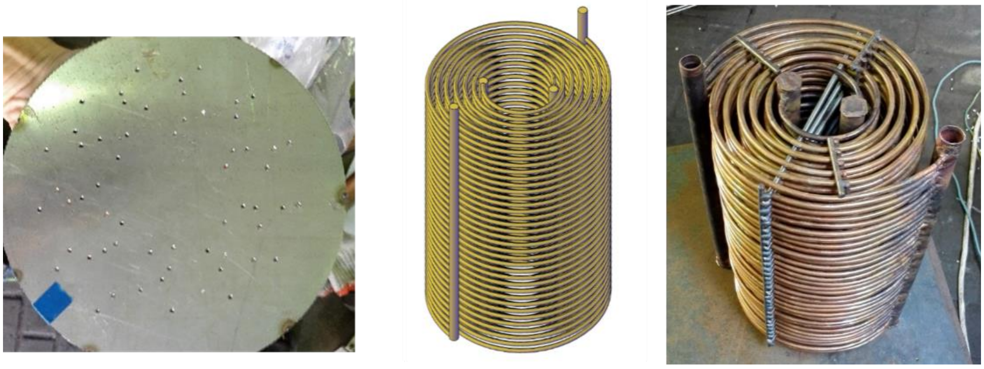


Figure 4 Internal components of the DFAHE: (a) copper coil assembly and (b) solution distribution plate

3 Results

The performance of the prototype was evaluated on a dedicated test rig. The heat source was simulated using a steam heater, while the heat sink was managed by a natural draft cooling tower, allowing for controlled and stable operating conditions. The experimental setup was instrumented with T-type thermocouples (accuracy ±0.1℃) at all fluid inlets and outlets, silicon capacitance absolute pressure sensors (accuracy ±0.5% FS) within the main vessels, and electromagnetic flowmeters (accuracy ±1.0% FS) for both water circuits. All data were collected and recorded by a data acquisition system. For each test, the unit was operated until a steady state was achieved, defined as a condition where internal pressure fluctuations remained within 5% over a 30-minute period. To ensure data reliability, a heat balance was calculated for each steady-state point by comparing the heat lost by the heat source fluid with the heat gained by the heat sink fluid. All reported data points had a heat balance discrepancy of less than 12%, which was considered acceptable for this system.

The performance of the unit was evaluated using a parameter known as temperature efficiency (ηt), as defined in previous work [12]. This index quantifies the effectiveness of the heat transformation process. In the following tables, the subscript 's' denotes the supply side (heat source fluid), and 'r' denotes the receiving side (heat sink fluid).

3.1 First-Type AHE (AHP Mode)

When configured in the first-type mode, the unit functions as an absorption heat pump. The key performance objective is to cool the source fluid (s) to a temperature below the inlet temperature of the receiving fluid (r). Table 1 presents the experimental results for three representative operating conditions. The data shows that in all tested cases, the source fluid outlet temperature $t_{s,out}$ was successfully lowered below the receiving fluid inlet temperature $t_{r,in}$ For example, in Condition 1, the source fluid was cooled from 86.7°C to 46.6°C, which is lower than the receiving fluid's inlet of 29.5°C. The calculated temperature efficiency (ηt) values, ranging from 1.14 to 1.21, quantify this performance.

Table 1 Results of the first type AHE

	$t_{s,in}$	$t_{s,out}$	$t_{r,in}$	$t_{r,out}$	$\varepsilon = \frac{t_{s,in} - t_{s,out}}{t_{s,in} - t_{r,in}}$
	°C	°C	°C	°C	
Condition 1	86.7	29.5	39.6	46.6	1.21
Condition 2	65.2	29.2	35.2	44.3	1.2
Condition 3	37.3	6.3	10.1	15.0	1.14

3.2 Second-Type AHE (AHT Mode)

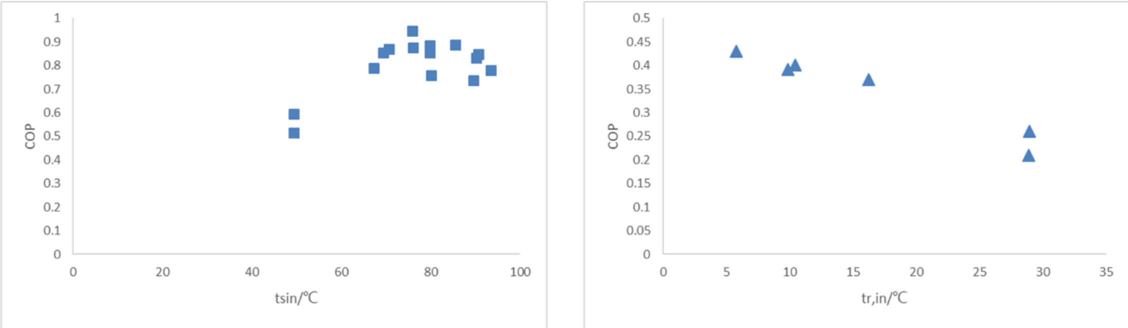
By reconfiguring the valves, the unit was switched to its second mode to operate as an absorption heat transformer. The objective in this mode is to upgrade the temperature of a process fluid to a level higher than the inlet temperature of the driving heat source. The results for this mode are presented in Table 2. The data validates the heat transformer function. For instance, in Condition 4, a driving heat source $t_{s,in}$ at 78.6°C was used to elevate a process fluid. The resulting upgraded temperature is shown in the $t_{r,out}$ column as 87.2°C, which is higher than the source inlet, demonstrating the temperature lift. The temperature efficiency (ηt) values for these conditions ranged from 1.15 to 1.18.

Table 2 Results of the second type AHE

	$t_{s,in}$	$t_{s,out}$	$t_{r,in}$	$t_{r,out}$	$\varepsilon = \frac{t_{\mathrm{r,out}} - t_{\mathrm{r,in}}}{t_{s,in} - t_{r,in}}$
	°C	°C	°C	°C	
Condition 4	78.6	70.1	29.9	87.2	1.18
Condition 5	69.2	63.3	16.1	77.5	1.16
Condition 6	21.1	18.1	4.8	23.6	1.15

3.3 Internal Cycle Performance (COP)

While the overall AHE is evaluated by its heat exchange characteristics, the performance of its internal absorption cycle can be characterized by the Coefficient of Performance (COP). For the first-type AHE, the COP is defined as the heat absorbed in the evaporator divided by the heat input to the generator. For the second-type AHE, it is defined as the heat rejected from the absorber divided by the sum of heat inputs to the generator and evaporator. Figure 5 shows the measured COP values for the internal cycles under various conditions. For the first-type (AHP) mode, the COP was generally in the range of 0.8 to 1.0 when the heat source inlet temperature $t_{s,in}$ was between 65°C and 90°C. For the second-type (AHT) mode, the COP was observed to be in the range of 0.35 to 0.45. These values are consistent with the expected performance of single-effect absorption cycles operating under similar temperature conditions and serve to validate the proper functioning of the internal components(Figure 5).



(a) first-type AHE mode **(b)) second-type AHT mode**

Figure 5 Internal cycle COP for (a) first-type AHE mode and (b) second-type AHE mode

4 CONCLUSIONS

This paper presented the design, fabrication, and experimental validation of a novel dual-functional absorption heat exchanger. The research was motivated by the need for a flexible and integrated technology to manage complex thermal demands in district heating and industrial waste heat recovery systems.

The experimental results lead to the following conclusions:

1.The proposed DFAHE structure, based on interchangeable falling-film components, is technically feasible and allows for the functional interchange between AHP and AHT cycles via valve switching.
2.A 30 kW capacity experimental prototype was constructed, and its performance was validated under various operating conditions.
3.The experimental data confirmed that the single unit can operate effectively in two modes: as a first-type AHE, it achieves deep cooling of the heat source; as a second-type AHE, it achieves grade-upgrading of heat.
4.The findings demonstrate that a single, reconfigurable AHE can perform the functions of two separate, specialized units, offering a compact and versatile solution for applications with varying thermal demands.

AVAILABILITY OF DATA AND MATERIALS

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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