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# Performance Evaluation of Double-Lift Absorption Heat Transformer for Generation of Steam at 180 °C

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**Abstract**

Owing to fossil fuel depletion, global warming, and other critical environmental issues, a conscious and efficient use of energy is required. In Japan, the manufacturing industry accounts for 40% of the national energy consumption. Moreover, factories produce a large amount of hot water at a temperature of approximately 100 °C, which cannot be directly used and, hence, is rejected to the atmosphere. However, by using absorption heat transformers, this exhaust heat can be utilized effectively. Absorption heat transformers can increase temperature by using the heat released inside its absorber. A conventional single-stage absorption heat transformer can use hot water at 90 °C to generate steam at 120 °C. However, the manufacturing industry usually demands a large amount of steam at a temperature of 160–180 °C. Therefore, a multistage configuration is needed to obtain temperatures up to 180 °C. Owing to the complexity of these systems, their performance characterization is difficult and as yet incomplete.

In this research, the performance of a double-lift heat transformer is evaluated by conducting a parameter study of the volume flow rate of cooling water. The experiment was conducted using test equipment that produced a 14 kW heat output. Using cooling water at a temperature from 20–30 °C, saturated vapor at 180 °C was generated from hot water at a temperature below 100 °C. With cooling water flows from 60 to 140 L/min, the COP didn't change and steam generation rate increased as the flow rate of the cooling water increased.



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*Keywords:* absorption heat transformer, waste heat recovery, industrial application, 180°C vapor;

## 1. Introduction

The depletion of fossil fuels and the threat of global warming are major environmental issues in recent times, and consequently, there is a requirement for energy-saving technology. One way to achieve this is by using waste heat produced by factories. Saturated vapor at a temperature of over 150 °C is required in manufacturing processes. Heat pumps would become important devices if they could be used to transform waste heat into useful saturated vapor. The maximum temperature that can be generated by saturated-vapor heat pumps is 120 °C because of a decomposition of the refrigerants and a decrease in the viscosity of oil in chillers at higher temperatures. However, double-lift absorption heat transformers can meet the aforementioned requirement as they can generate saturated vapor at temperatures greater than 180 °C.

In previous studies, Xuehu Ma et al.[1] conducted an experiment and simulation of an industrial-scale single stage absorption heat transformer and heated hot water from 95 °C to 110 °C using organic vapor at 98 °C. W. Rivera et al.[2] developed a mathematical model of an absorption heat transformer coupled to a solar pond and determined the theoretical maximum temperature of the absorber to be 160 °C. However, to actually produce vapor at 180 °C is very difficult due to the complexity of the double-lift absorption cycle and air sealing at high pressure, which leads to problems with corrosion.

In this study, the double-lift absorption heat transformer test equipment was constructed and saturated vapor at 180 °C was successfully produced, a rare achievement.

The higher COP of this system is preferred for energy conservation. The theoretical COP based on a Carnot cycle is given as

$$COP = \frac{Q_{\mathrm{A}}}{Q_{\mathrm{G}} + Q_{\mathrm{E}}} = \frac{T_{\mathrm{A}}\left(T_{\mathrm{G}} - T_{\mathrm{C}}\right)}{T_{\mathrm{A}}T_{\mathrm{G}} - T_{\mathrm{E}}T_{\mathrm{C}}} \tag{1}$$

The theoretical COP of a double-lift absorption heat transformer based on Dühring's law can be calculated as follows.

$$COP = \frac{1}{1 + \frac{T_{\mathrm{C}}}{T_{\mathrm{E}}} + \left(\frac{T_{\mathrm{C}}}{T_{\mathrm{E}}}\right)^2} \tag{2}$$

In previous research [3-4], we developed a double-lift absorption heat transformer and succeeded in producing vapor at 180 °C. We also focused on evaporator temperature and conducted a parameter study for hot water and clarified the effect of the evaporator temperature on the characteristic of the system.

According to equation (1), the COP of a double-lift absorption heat transformer can be improved by increasing the temperature in the evaporator or decreasing the temperature in the condenser. However, the current trend is to decrease the flow rate of fluids in systems in order to decrease the energy used in pumps. This leads to a temperature increase in the condenser, which decreases the COP. Therefore, the characteristics of the system and the COP when decreasing the flow rate of the cooling water must be clarified. In this study, an experimental apparatus was built and experiments were conducted in order to investigate the influence of the cooling water flow rate.

## 2. System description

Figures 1 and 2 show the flow diagram and Dühring diagram of a double-lift cycle, respectively. A double-lift absorption heat transformer consists of six main components: a low-temperature generator (GL), a condenser (C), a low-temperature evaporator (EL), a low-temperature absorber (AL), a high-temperature absorber (AH), and a refrigerant separator (EH). For higher efficiency, the solution and refrigerator heat exchangers are also included.

As will become apparent below, there are several solution flow patterns. For safety, a series flow was employed in this study.

The first step of this cycle is the evaporation of refrigerants at the EL. These vapors are absorbed into the solution and exchange heat at the AL. Absorption heat makes a saturated vapor at 120 °C from the water inside the tubes and they move to the EH. In the second step, the saturated vapor at 120 °C is absorbed at the AH and heats the feed-water to a saturated-vapor at 180 °C.

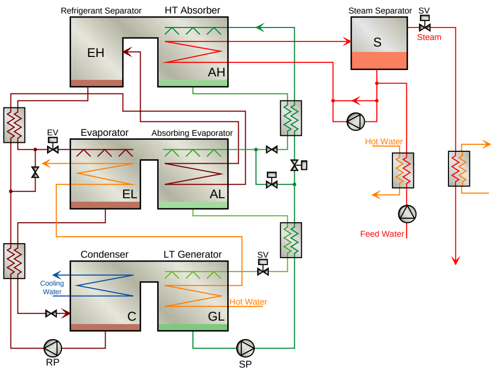


Fig. 1. Flow diagram of double-lift absorption heat transformer

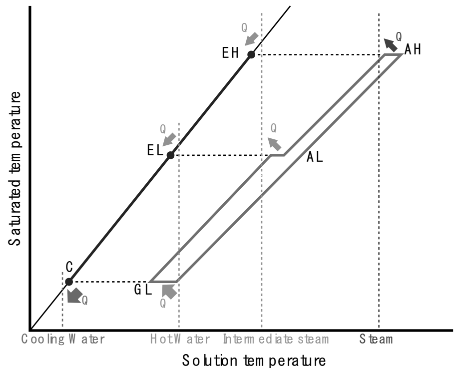


Fig. 2. Dühring diagram of double-lift absorption heat transformer

## 3. Experiment

### *3.1. Experimental apparatus*

A small prototype of the experimental apparatus was constructed in order to investigate the characteristics of a double-lift absorption heat transformer cycle. Figure 3 shows the experimental apparatus (before insulation). The system uses LiBr-aq as the absorption solution and 2-Ethylhexanol as the additive. Table 1 presents its design parameters.

Table 1. Specifications

| | | | |
|---|---|---|---|
| Steam temperature | $T_{Steam}$ | 180 | °C |
| Heat output | $Q_{AH}$ | 14 | kW |
| Hot water inlet temperature | $T_{Hot}$ | 88 | °C |
| Cooling water inlet temperature | $T_{Cool}$ | 25 | °C |
| Additive | | 2-Ethlylhexanol | |

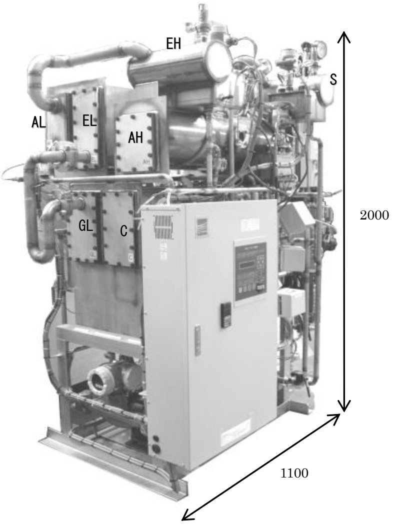


Fig. 3 Double-lift absorption heat transformer (Heat output: 14 kW, steam temperature: 180 °C)

There are several flow patterns throughout this system: series flow, parallel flow, and reverse flow. Each pattern differs in the way it routes the solution. The series flow runs the solution from the AH to the AL, the parallel flow runs it all together, and the reverse flow runs it from the AL to the AH. In a recent study, Saito et al.[2] simulated the characteristics of the flow patterns. According to this study, the concentration of the solution and AH pressure of series flow are lower than in other flow patterns. Thus, for safety, series flow was employed in this study.

The GL, EL, AL, and AH are all falling film heat exchangers with horizontal-tubes. Stainless steel tubes that are corrosion resistant are used for the AH. For the others, copper tubes are used. Table 2 shows specifications of each heat exchanger and heat-transfer tube.

Table 2. Specifications of heat transfer tubes

| Component | | C | GL | EL | AL | AH |
|---|---|---|---|---|---|---|
| Tube type | | Smooth | Enhanced | Enhanced | Smooth | Smooth |
| Material | | Cu | Cu | Cu | Cu | SUS430 |
| Outside diameter | mm | 15.90 | 15.90 | 15.90 | 15.90 | 15.90 |
| Tube length | m | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

### *3.2. Experimental method*

First, the solution between AL and G is circulated in the single-lift cycle. This is because the pressure of AH cannot be kept high during the start-up. Next, the pressure of AH was increased by controlling a valve allowing the solution to flow from G to AL and AH. Then, the cycle was shifted to a double-lift cycle.

The electrically operated valve was opened at the steam outlet to keep the steam pressure at 1000 kPa (saturation temperature: 180 °C).

After the temperature, pressure, and flow rate in the components became stable, measurements were recorded for 15 min. The average measurements were regarded as constant data.

### *3.3. Experimental condition*

Table 3 shows the experimental conditions. The hot water inlet temperature, volume flow rate, and cooling water temperature were set at fixed values. Cooling water volume flow rate was varied from 60 L/min to 140 L/min.

Table 3.Experimental condition

| | | | |
|---|---|---|---|
| Steam(saturated) | Temperature | °C | 180 |
| Hot water | Inlet temperature | °C | 88 |
| | Volume flow rate | L/min | 95 |
| Cooling water | Inlet temperature | °C | 25 |
| | Volume flow rate | L/min | 60-140 |
| Solution mass flow rate | | kg/min | 15 |
| Refrigerant volume flow rate | | L/min | 5 |

### *3.4. Data reduction*

The COP and steam generation rate were to be evaluated in this study. The steam condition was considered to be saturated.

The COP is given as follows.

$$COP = \frac{Q_{\mathrm{AH}}}{Q_{\mathrm{GL}} + Q_{\mathrm{EL}}} \tag{3}$$

The rate of heat exchange in the GL and EL were calculated using the enthalpy of the hot water.

$$Q_{\mathrm{GL}} = G_{\mathrm{GL,w}}\left(h_{\mathrm{GL,w,i}} - h_{\mathrm{GL,w,o}}\right) \tag{4}$$

$$Q_{\mathrm{EL}} = G_{\mathrm{EL,w}}\left(h_{\mathrm{EL,w,i}} - h_{\mathrm{EL,w,o}}\right) \tag{5}$$

The rate of heat exchange in the AH was calculated using the heat exchange rate of VHEX and the enthalpy of its steam condensate and feed water.

$$\begin{aligned} Q_{\mathrm{AH}} &= G_{\mathrm{AH,w}}\left(h_{\mathrm{AH,w,i}} - h_{\mathrm{AH,w,o}}\right) \\ &= G_{\mathrm{VHEX}}\left(h_{\mathrm{VHEX,o}} - h_{\mathrm{VHEX,i}}\right) + G_{\mathrm{f}} h_{\mathrm{w,VHEX,o}} - G_{\mathrm{f}} h_{\mathrm{f}} \end{aligned} \tag{6}$$

The equations of enthalpy are

$$h_{\mathrm{w}} = h_{\mathrm{w}}\left(T_{\mathrm{w}}, P_{\mathrm{w}}\right) \tag{7}$$

The solution concentration was calculated using the solution density and temperature. The strong, middle, and weak concentrations were calculated from the outlet parameters of the GL, the inlet parameters of the AL, and the outlet parameters of the AL.

$$X_{\text{strong}} = f\left(\rho_{\text{GL,s,o}}, T_{\text{GL,s,o}}\right) \tag{8}$$

$$X_{\text{middle}} = f\left(\rho_{\text{AL,s,i}}, T_{\text{AL,s,i}}\right) \tag{9}$$

$$X_{\text{weak}} = f\left(\rho_{\text{AL,s,o}}, T_{\text{AL,s,o}}\right) \tag{10}$$

## **4.** Result and discussion

Figure 4 shows the results of this experiment. Figure 5 shows the Dühring diagram when the cooling water volume flow rate is 60 L/min and 140 L/min.

Through experiment, steam at 180 °C could be generated at any cooling water volume flow rate in the range of 60–140 L/min. In addition, the COP decreased as the cooling water volume flow rate decreased. In addition, the steam generation rate, concentration, and heat exchanger rate (as shown in Figure 4) also decreased with a decrease in the cooling water flow rate.

The COP decreased owing to the increase in the C temperature. As shown in Figure 5, the temperature in the C at $V_{\text{CW}} = 60$ L/min is higher than that at $V_{\text{CW}} = 140$ L/min. From equation (1), it could be explained that the COP decreased as the flow rate of cooling water decreased because of this rise of the C temperature. However, the decrease of the COP is only a little, and therefore can be said that the decrease in cooling water flow rate does not have much effect on the COP.

Furthermore, an increase in the temperature of C also caused the pressure of the low-pressure side to increase, as shown in Figure 4. This causes the concentration of the solution to decrease, as shown in Figure 5. This will lead to the system’s safety, since one must pay attention to the crystallization of the solution when the concentration is too high. Therefore, it can be said that decreasing the flow rate of cooling water can be an efficient way to keep the system safe from crystallization, while keeping the COP high.

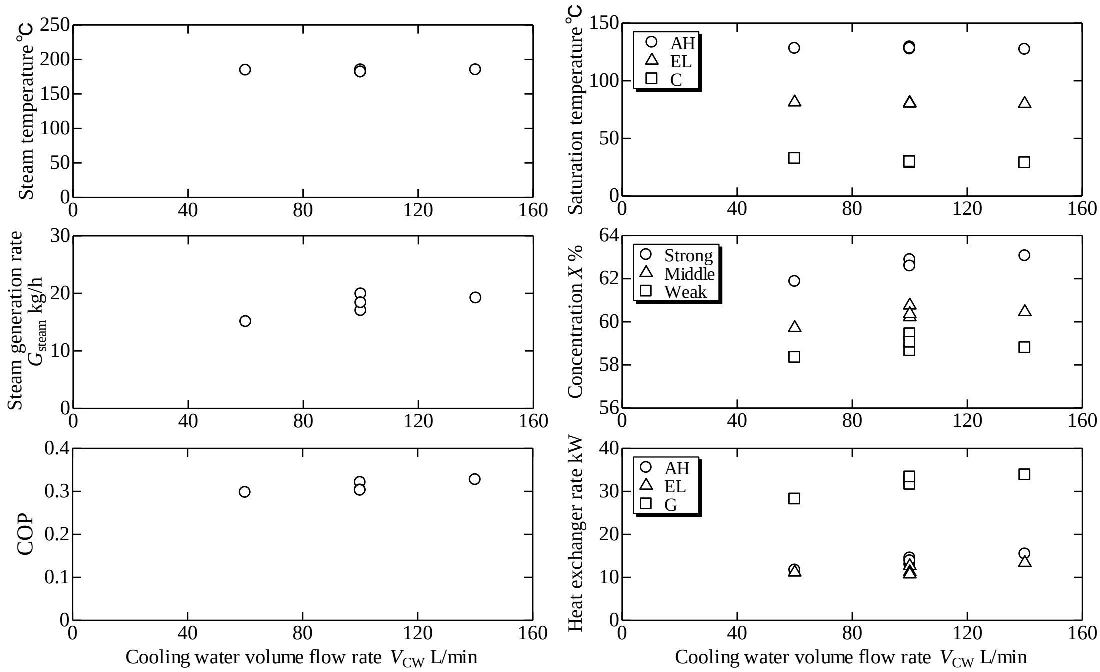


Fig. 4 Experimental result

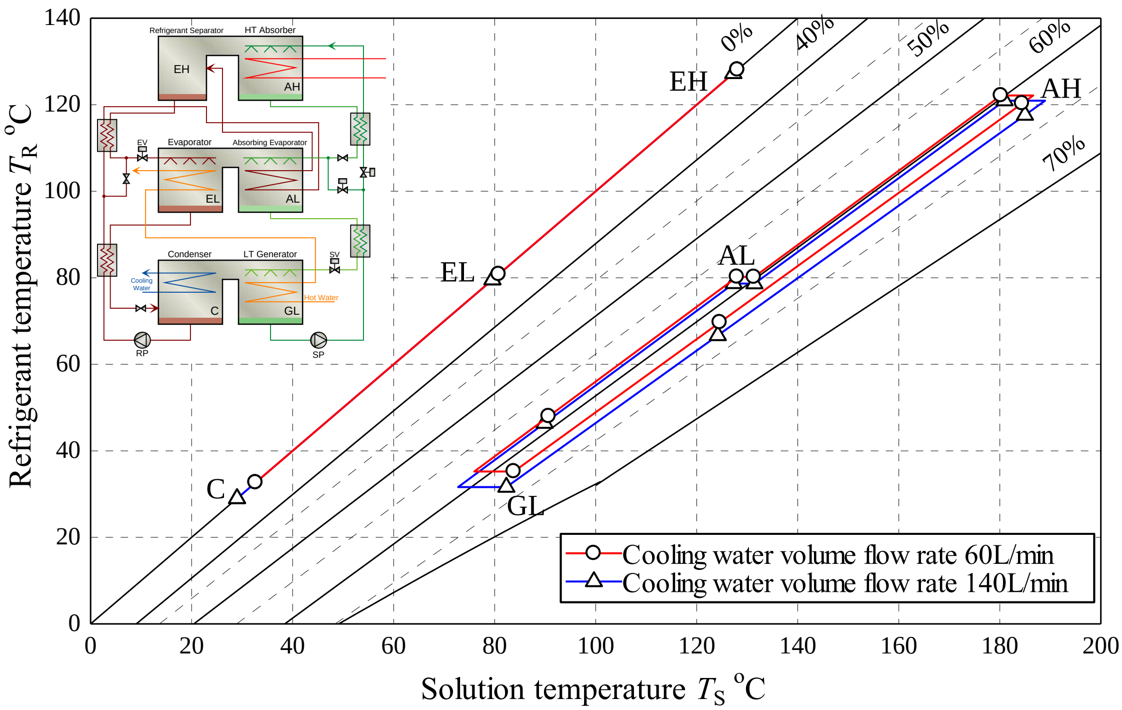


Fig. 5 Dühring diagram

## 5. Conclusion

In this study, the performance of a double-lift absorption heat transformer that can generate steam at 180 °C was evaluated while varying the cooling water flow rate from 60 L/min to 140 L/min. The following conclusions were drawn from the study.

- A practical-scale prototype can produce vapor at 180 °C from hot water at 80 °C at a cooling water flow rate of 60 L/min to 140 L/min.
- In this experimental range, the COP did not change as the flow rate of the cooling water decreased.

This study has therefore successfully clarified the influence of cooling water flow rate on the characteristics of the double-lift absorption heat transformer. Future experiments using a wider range of cooling water flow rate will be conducted.


## Acknowledgements

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## NOMENCLATURE

$COP$ : coefficient of performance, -
$G$ : mass flow rate, kg·s$^{-1}$
$h$ : specific enthalpy, J·kg$^{-1}$
$Q$ : heat exchanger rate, kW
$T$ : temperature, °C
$X$ : concentration, -
$\rho$ : density, kg·m$^{-3}$

## SUBSCRIPTS

AH : high-temperature absorber
AL : low-temperature absorber
C : condenser
EH : refrigerant separator
EL : low-temperature evaporator
f : feed water
GL : low-temperature generator
i : inlet
middle: middle solution
o : outlet
s : solution
strong : strong solution
VHEX: vapor heat exchanger
w : water
weak : weak solution

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