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Cycle Simulation and Prototyping of Single-Effect Double-Lift Absorption Chiller

Tatsuo Fujii[a,]*, Nobuyuki Takeda[b], Minoru Miyauchi[b],
Hironobu Kawamura[a] and Mari Uchida[a]

[a]Research and Development Group, Hitachi, Ltd., 832-2, Horiguchi, Hitachinaka, Ibaraki 312-0034 Japan
[b]Hitachi-Johnson Controls Air Conditioning, Inc., 603, Kandatsu-machi, Tsuchiura, Ibaraki 300-0013 Japan

Abstract

A large amount of waste heat is exhausted in the industrial and commercial field. In particular, low temperature heat such as that below 80~90°C is not utilized enough, and the limitation of lowest release temperature also places a limit on the useful heat quantity that can be obtained from low temperature heat sources. The single-effect double-lift absorption chiller is driven by hot water around 95°C and utilizes it until under a 55°C outlet temperature. Therefore, it is expected to recover unused low temperature waste heat, and to utilize district hot water for cooling uses in the summer. In this study, a cycle simulation model of this chiller is developed and the basic characteristics are examined. This model includes a two-step evaporator and absorber construction that is used in current high efficiency absorption chillers. We estimated the performance of the two-step evaporator and absorber, the enhancement of the solution heat exchangers, and the method of circulating hot water and cooling water, using a simulation based on the model. We also manufactured a prototype machine that is driven in both single-effect double-lift operation and normal double-lift operation. As a result of a single-effect double-lift test, heat of around 90°C hot water is put in this cycle and used until below 55°C, and chilled water is cooled at 7°C. The normal double-lift operation is also conducted. In this mode, 60°C hot water is used until 56°C and 7°C chilled water is produced with cooling water of 30°C. From a comparison between simulation and experimental results, the simulation program was found to have enough function and accuracy to predict the behaviour of the SEDL absorption cooling cycle.

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Keywords: Absorption Chiller; Single-Effect Double-Lift; Cycle Simulation; Waste Heat Recovery: Energy Conservation

* Corresponding author. Tel.: +81-29-353-3372; fax: +81-29-353-3857.
E-mail address: tatsuo.fujii.tw@hitachi.com.

1. Introduction

A Large amount of waste heat is exhausted in the industrial and commercial fields. In Japan, more than 50% of energy consumption is released to the environment as unused thermal energy. In particular, low temperature heat such as that below 80~90°C is not utilized enough, and there is the limitation of lowest release temperature, which also places a limit on the useful heat quantity that can be obtained from low temperature heat sources.

An absorption heat pump is known as one type of recovering equipment for utilizing low temperature waste heat. A conventional single-effect absorption chiller uses 85~90°C hot water as its driving heat source and releases it at 75~80°C. To reduce the release temperature and increase the amount of heat recovery, Schweigler et al. studied a single-effect double-lift (SEDL) absorption cycle [1] and indicated that it uses heat down to a return temperature of about 55°C. They also designed and operated pilot plants of SEDL absorption chillers [2] and clarified their behaviours under varying practical conditions.

In this study, we developed a cycle simulation program for SEDL cycles based on a program of current absorption chillers as a cycle design tool to fit this cycle to the specific conditions of energy supply plants. Some survey design parameters were conducted for such as the performances of solution heat exchangers, evaporator and absorber pressure separation, and flow order of hot water and cooling water. On the basis of the simulation results, a test model of an SEDL absorption chiller was designed and developed. Experimental results with the model in SEDL operation and simple double-lift (DL) operation were also reported.

Nomenclature

A	Absorber	
A1	1st (upper) absorber	
A2	2nd (lower) absorber	
AA	Auxiliary absorber	
AG	Auxiliary generator	
AHX	Auxiliary solution heat exchanger	
C	Condenser	
COP	Coefficient of performance (thermal efficiency)	
DL	Double-lift	
E	Evaporator	
E1	1st (upper) evaporator	
E2	2nd (lower) evaporator	
EA	Evaporator and absorber	
Gv	Mass flow rate of vapour	kg/s
HG	High temperature generator	
HHX	High temperature solution heat exchanger	
LG	High temperature generator	
LHX	Low temperature solution heat exchanger	
p	Pressure	Pa
Q	Quantity of heat	kW
SE	Single-effect	
SEDL	Single-effect double-lift	
THW	Temperature of the heat source hot water	°C

2. Single-effect double-lift (SEDL) absorption cooling cycle

The SEDL absorption cooling cycle was proposed and studied by Schweigler et al. [1-2] for industrial use and applications in district heating networks. In this cycle, a half-effect cycle [3] and a normal single-effect cycle are merged together. Hot water with a lower return (outlet) temperature is preferred because it makes a wider temperature glide of heat source hot water and enables a higher amount of heat intake. In the SEDL cycle, this temperature glide is increased by the combining the single-effect and half-effect, i.e., the DL cycle.

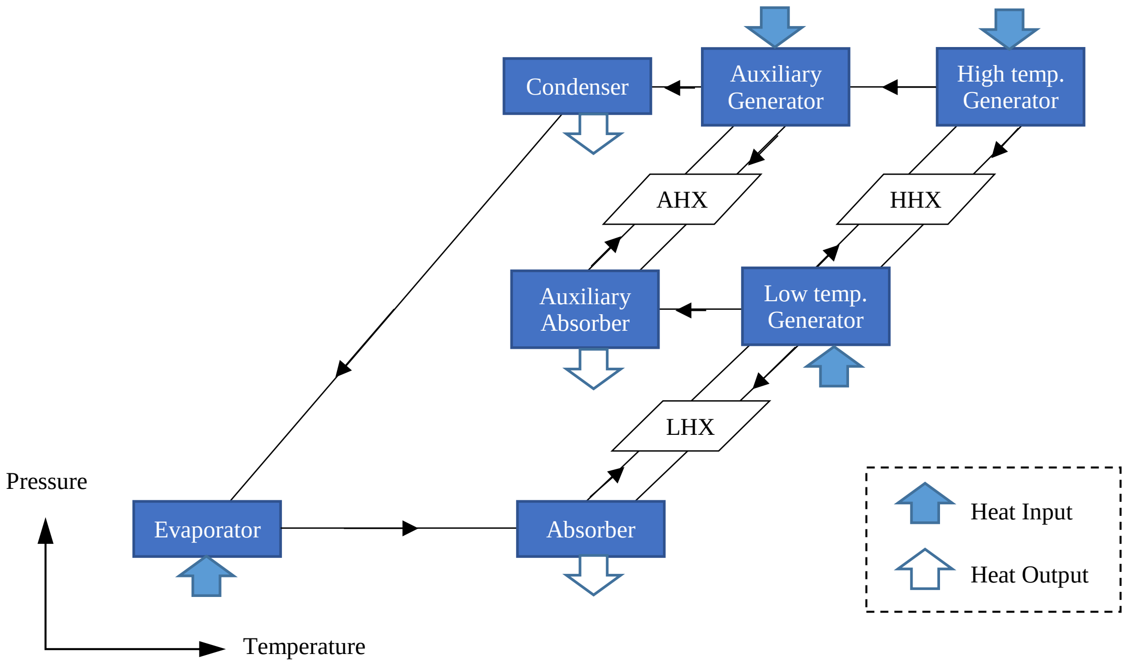


Fig. 1. Cycle configuration of SEDL cycle

A cycle schematic of SEDL is shown in figure 1. This cycle consists of seven heat exchangers with phase change and three solution heat exchangers without phase change. Two solution circuits are installed in this cycle. The first one connects an absorber (A), low temperature generator (LG), and high temperature generator (HG) and goes through a low temperature solution heat exchanger (LHX) and high temperature solution heat exchanger (HHX). The second solution circuit connects an auxiliary absorber (AA) and auxiliary generator (AG) via an auxiliary solution heat exchanger (AHX).

A heat source used as its driving energy is provided to the HG, LG, and AG. Hot water is assumed as the heat source in this report. Cooling water used as a heat sink is provided to the A, AA, and C. Thus, the cooling function is performed by the evaporator, where chilled water or non-freezing liquid flows in.

3. Cycle simulation

3.1. Simulation model and calculation method

As the simulation model of the SEDL cycle shown in figure 2, we adopted a two-step structure for the evaporator and absorber (EA) that is used in high-performance absorption chillers [4-6] and named as “two-step EA”. Thus, they are divided into E1 and E2 and A1 and A2, respectively. For this reason, there are four pressure levels in this model, i.e., p_H, p_M, p_{L1}, and p_{L2}, even though there are three pressure levels in the basic SEDL cycle shown in figure 1. Since the temperature of the chilled water in E1 is lower than that of E2, the refrigerant pressure in E1 is also lower than E2.

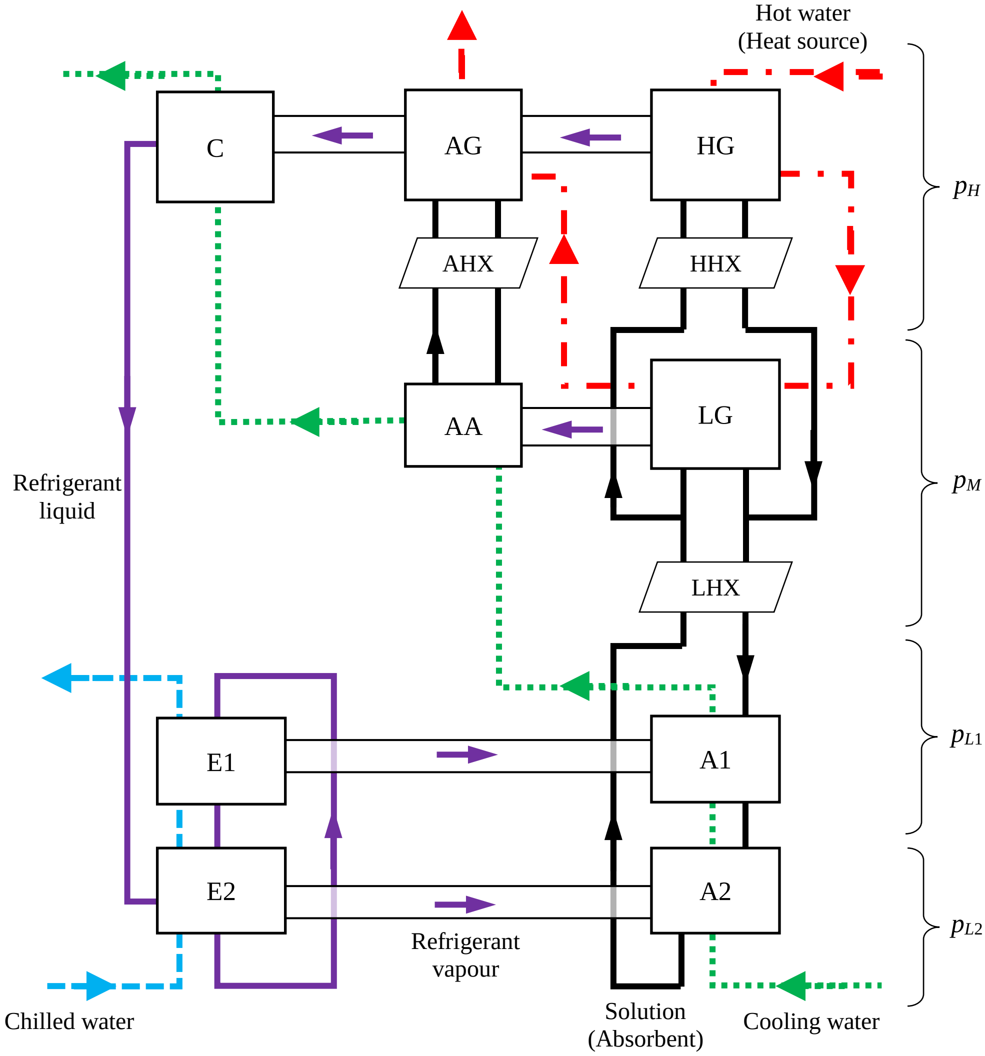


Fig. 2. Cycle simulation model of the SEDL cycle with two step evaporator and absorber

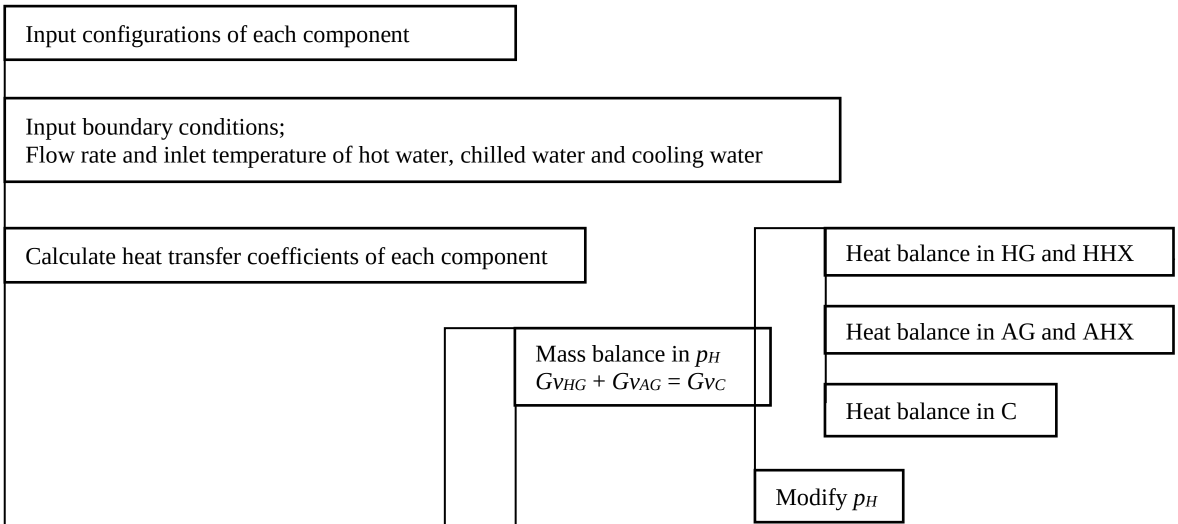


Fig. 3. Problem analysis diagram (PAD) of cycle simulation program

Figure 3 shows the calculation algorithm in a form of a problem analysis diagram (PAD). The program has a hierarchal architecture of three levels. The bottom level is where the heat balance of each heat exchange component converges. The middle level is where the mass balances of the four pressure levels shown in figure 2 converge. In the mass balance convergence, the vapour pressure is modified in each iteration step to meet the balance between vapour generation/evaporation and absorption/condensation. The top level has a convergence process to balance the energy of the whole system.

The input parameters are the configurations of each component, boundary conditions, i.e., the flow rate and inlet temperature of hot water, chilled water, and cooling water. In addition, the effects of typical construction changes such as dividing the evaporator and absorber and the method of circulating hot water and cooling water, are discussed in the next section.

3.2. Simulation results

To prepare to develop a SEDL prototype chiller, we calculated basic characteristics using the simulation program. Figure 4 shows the effect of dividing the evaporator and absorber in association with chilled water temperature drop. Two-step EA represents divided evaporator and absorber, and THW-out represents the outlet temperature of the heat source hot water, i.e., the return temperature. COP represents thermal efficiency and is defined as follows.

$$\mathrm{COP} = \frac{Q_E}{Q_{HG} + Q_{LG} + Q_{AG}} \tag{1}$$

For the two-step EA,

$$Q_E = Q_{E1} + Q_{E2} \tag{2}$$

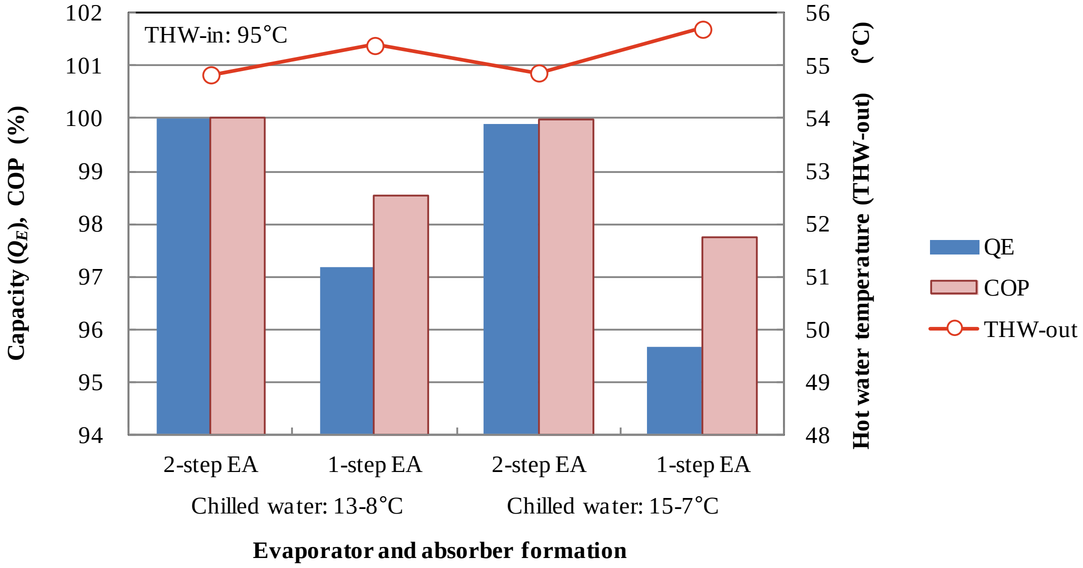


Fig. 4. Effect of two-step evaporator and absorber in association with chilled water temperature drop

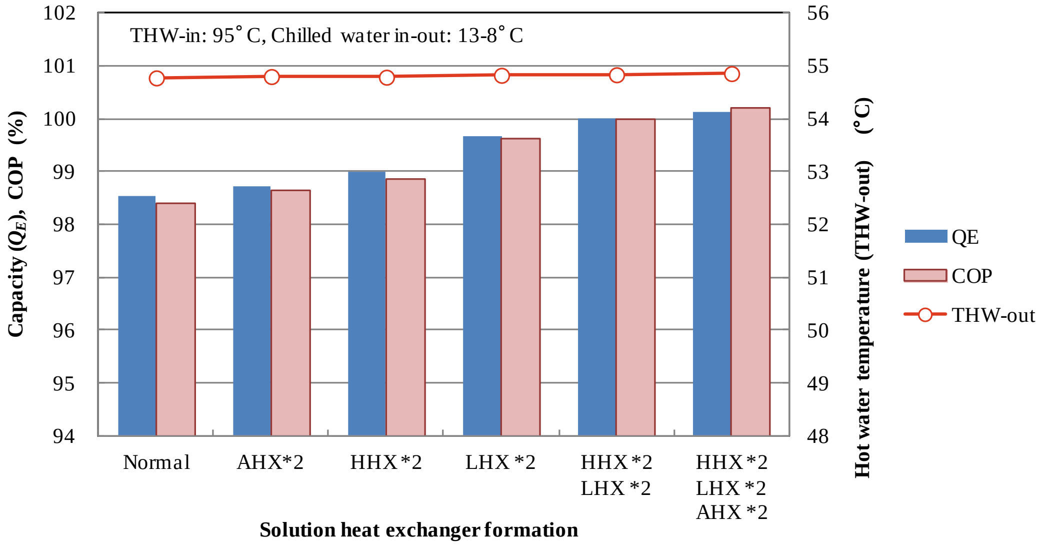


Fig. 5. Effect of enhancement of solution heat exchangers ("*2": heat exchangers with doubled heat transfer area)

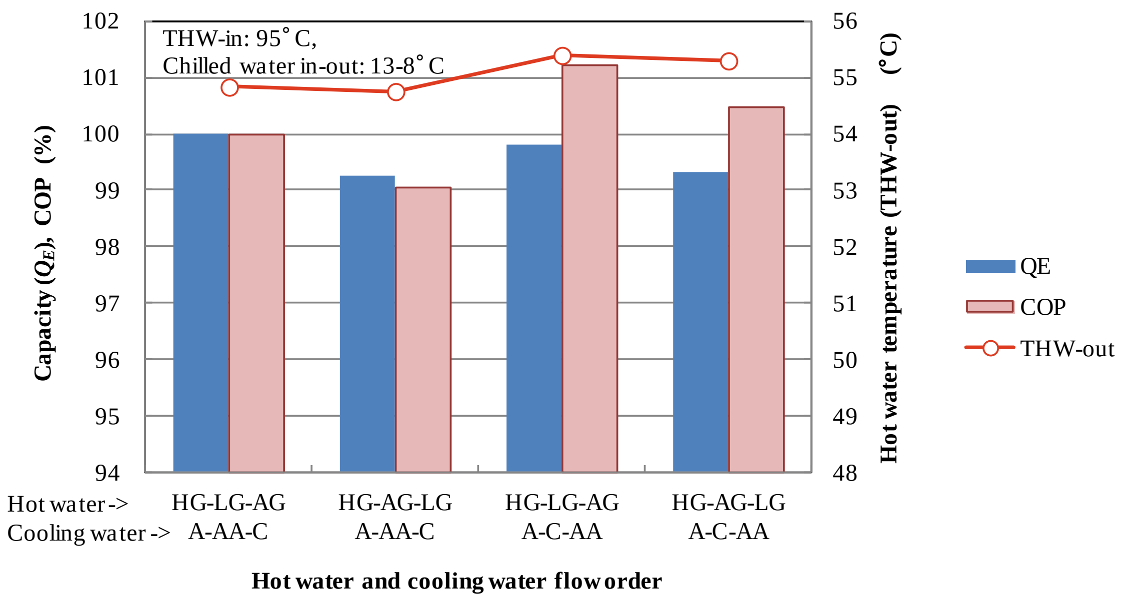


Fig. 6. Effect of hot water and cooling water circulating method

It is shown in figure 4 that the cooling capacity and the COP decrease and THW-out is higher in the case where two-step EA is not adopted. Therefore, two-step EA was applied for the SEDL prototype the same as in commercial high efficiency absorption chillers.

We also surveyed the heat exchanger area in computation. Figure 5 is the effect of the heat transfer area of the three solution heat exchangers. In this figure, "*2" means the heat exchangers with a doubled heat transfer area. The effect of enhancing heat exchangers appears as an increase in the cooling capacity (Q_E) and COP, and THW-out is almost not affected by them. Comparing the three heat exchangers, the effect of AHX is relatively small. Therefore, we selected the configuration of "HHX*2 and LHX*2" for the prototype, considering the arrangement of these solution heat exchangers under the other components.

As mentioned in section 3.1, this program can calculate the effect of the method of circulating hot water and cooling water. The calculation result is shown in figure 6. For the hot water as heat source, it is clear that the HG should be heated firstly because it works as the generator of the single effect cycle, whose efficiency is higher than the other two generators. In addition, cooling water should be provided to the absorber that is directly connected with the evaporator, which functions mainly as a chiller by cooling chilled water in its heat exchanger.

Therefore, we compared the circulating method of "HG-LG-AG" and "HG-AG-LG" for the hot water and "A-AA-C" and "A-C-AA" for the cooling water. As a result of comparison, we selected the circulating method with maximum cooling capacity, considering that the specific cooling capacity per unit hot water mass flow should be maximized for applications of this kind of heat driven chiller. Schweigler et al. [2] also pointed out this importance in application for district heating networks.

4. Prototyping and experiment

4.1. Prototyping of SEDL absorption chiller

A prototype of the SEDL absorption chiller was designed using the cycle simulation program, and the results are as follows. Figure 7 is a cycle flow diagram of the prototype. The basic configuration is the same as the simulation model shown in figure 2 and hot water and cooling water circulate as selected in section 3.2. This prototype can also be operated as a normal DL cycle by switching the solution and hot water valves indicated in figure 7.

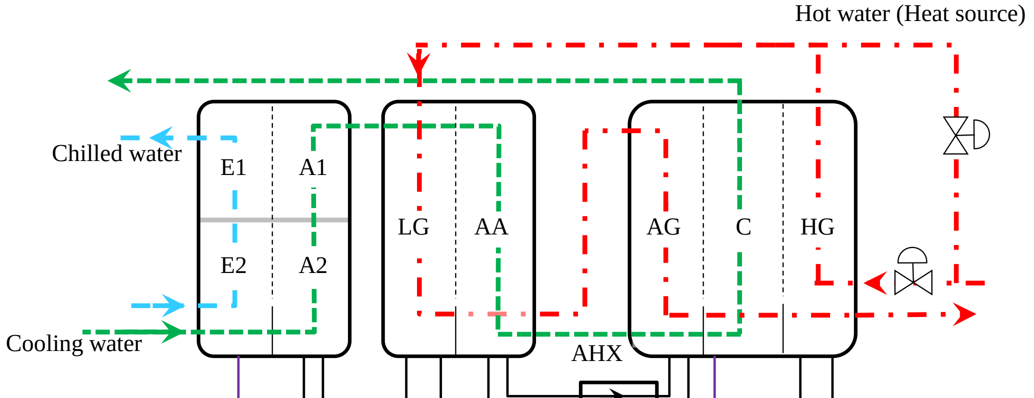
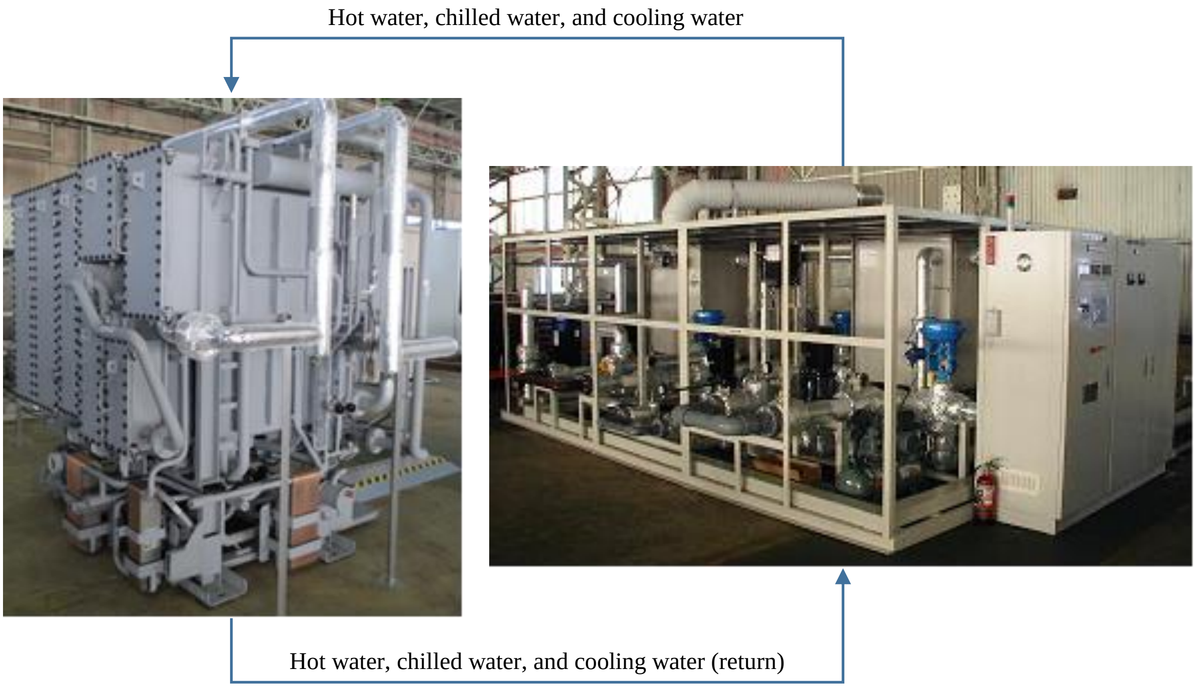


Fig. 7. Cycle flow diagram of prototype of SEDL absorption chiller

Figure 8 (a) shows the prototype of the SEDL absorption chiller. The working fluid of this chiller is the conventional LiBr/H_2O system. The experimental equipment shown in figure 8 (b) was also developed. This equipment has a combustion vacuum water heater and a cooling tower as its outdoor unit, and it provides hot water, cooling water and chilled water in controlled temperature to the prototype.



(a) Prototype of SEDL absorption chiller (b) Experimental equipment

Fig. 8. Prototype of SEDL absorption chiller and experimental equipment

Table 1. Experimental results of prototype of SEDL absorption chiller

Item		Unit	Operating mode	
			DL	SEDL
Cooling capacity		kW	42.0	106.1
Chilled water	Inlet	°C	15.0	12.0

	Outlet	°C	7.0	7.0
Cooling water	Inlet	°C	30.1	30.9
	Outlet	°C	34.5	36.6
Hot water (Heat source)	Inlet	°C	60.0	88.7
	Outlet	°C	56.3	53.0

4.2. Experimental result

The experimental results of the prototype are shown in Table 1. In DL operation, chilled water of 7°C was obtained by a 60°C heat source, 10°C lower than that of the DL absorption chillers available on the market. In SEDL operation, it performed at 106.1kW (30.2RT) in cooling capacity when 7°C chilled water was generated by using the heat provided by 88.7°C hot water, and its return temperature went down to 53.0°C. This is also lower than the current absorption chillers in the market. In both conditions, the cooling water inlet temperatures were higher than 30°C.

Figure 9 compares the response to hot water temperature change between the experiments and predicted results. In both results, the cooling capacity (Q_E) decreases linearly as the hot water inlet temperature (THW-in) goes down. The hot water outlet temperature (THW-out) also drops as well as the cooling capacity. COP also decreases with THW-in, but its decline ratio is smaller than Q_E.

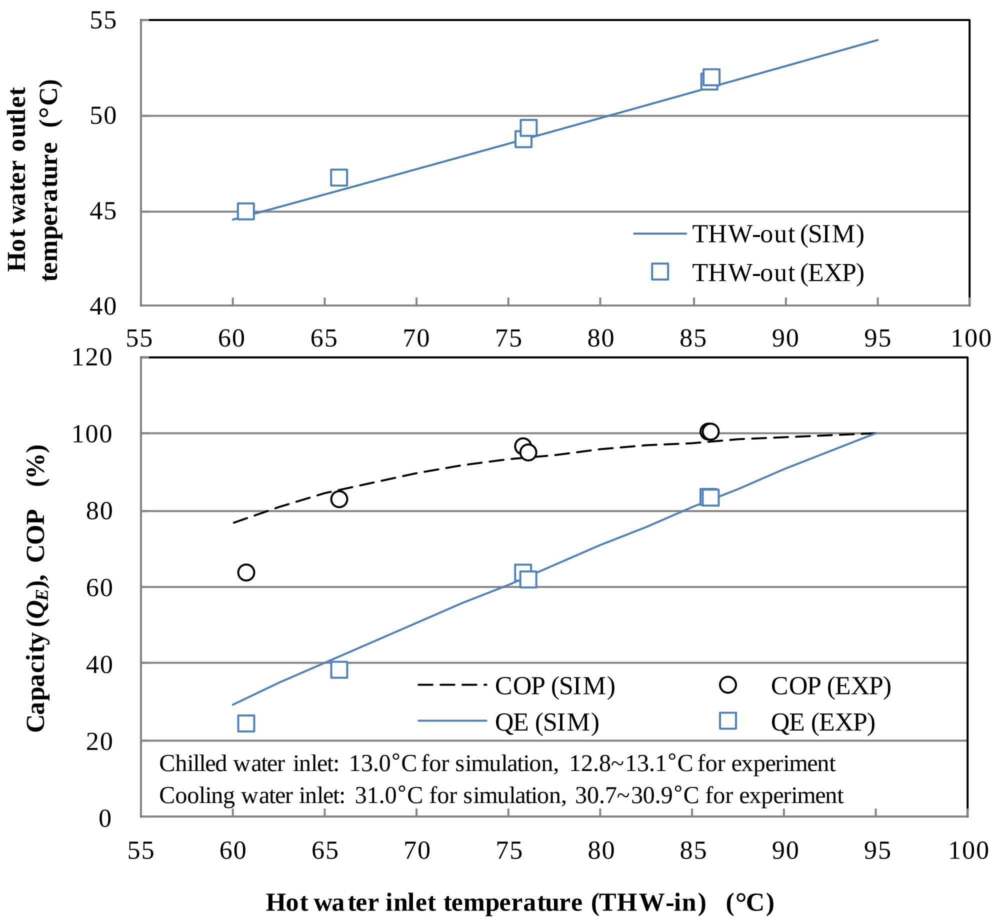


Fig. 9. Hot water inlet temperature characteristics of prototype of SEDL absorption Chiller

With respect to the comparison between the simulation and experiment, the experimental results of COP and THW-out were lower than the simulation results in the lower THW-in condition. The reason for this difference is assumed to be due to heat loss on the surface of the prototype machine. The heat loss did not decrease as much as the cooling capacity with THW-in, so the ratio of heat loss increased in the case that THW-in became lower. Comparing the cooling capacity, the simulation results are within 5% of the experimental results except the case of that THW-in was around 60°C. We validated the simulation program by using these results and assumed that this accuracy is enough to predict the behaviour of the SEDL absorption cycle. In addition, we are planning to improve the accuracy of the calculation through the feedback gained by the experimental results.

5. Conclusion

For the purpose of waste heat recovery from industrial and commercial facilities and for use in district heating networks in summer, we developed a cycle simulation and a prototype of a single-effect double-lift (SEDL) absorption chiller. As the result of this study, the following results were obtained.

(1) A simulation program to study the effect of cycle configuration was developed. The effects of dividing the evaporator and absorber, the enhancement of the solution heat exchangers, and the method of circulating hot water and cooling water were calculated.
(2) On the basis of the simulation result, we developed a prototype SEDL absorption chiller with two-step evaporator and absorber. Hot water and cooling water circulating patterns were selected to maximize its cooling capacity.
(3) This prototype performed at 106.1kW (30.2RT) in cooling capacity when 7°C chilled water was generated by using the heat provided by 88.7°C hot water, and its return temperature went down to 53.0°C, so the temperature glide exceeded 35 K. Cooling water was 30.9°C in this operation.
(4) This prototype also could be driven in normal double-lift operation, where 60°C hot water is used until 56°C and 7°C chilled water is produced, with cooling water of 30°C.
(5) From a comparison between simulation and experimental results, the simulation program appeared to have enough function and accuracy to predict the behaviour of SEDL absorption cooling cycle.

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