THEORETICAL STUDY AND DEVELOPMENT OF ABSORPTION CHILLERS WITH ENHANCED AUXILIARY WASTE HEAT RECOVERY

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Abstract: Absorption chillers with auxiliary waste heat recovery using absorption heat pump cycles were initially developed in 1990s and their performance has been improved in terms of their fuel or steam consumption ratio. This improvement consists of the basic performance of absorption chillers and the amount of fuel or steam reduction by means of increasing the waste heat input. We studied the principle of these machines for this report by focusing on the superposition model of a double-effect and a single-effect absorption cooling cycle. The quantity of waste heat in the recent co-generation systems is increasing due to the expanding electric-generating capacities for ensuring the energy security of buildings and energy plants. This leads the demand for putting more waste heat into practical use. Therefore, we have developed new absorption chillers with enhanced auxiliary waste heat. The fuel reduction ratio in these machines was increased from 25 to 40% for direct-fired chillers and the steam reduction ratio for steam-driven chillers was also increased from 15 to 30%. The maximum cooling capacities driven by only auxiliary waste heat also reached approximately 58% for the direct-fired machines and 50% for the steam-driven ones.

Key Words: absorption chillers, auxiliary waste heat, co-generation systems, waste heat recovery

1 INTRODUCTION

Absorption chillers with auxiliary waste heat recovery were initially developed in the 1990s in order to make use of low temperature waste heat as well as the fuel of direct-fired absorption chillers (Takeda et al. 1966). And their basic cycle analysis was conducted to optimize their configuration to use waste heat effectively (Kojima et al. 1997). Their fuel consumption ratio performance has been improved continuously (Edera and Kojima 2002).

This improvement consists of the basic performance of the absorption chillers and the reduction in necessary fuel with the increase in waste heat input. Currently, it is enhanced for steam-driven type and mainly used for the heat source equipment for air-conditioning systems installed with co-generation systems that use engines or gas turbines for electricity generation.

These engines generate electricity and also heat in the form of hot water for jacket cooling. The temperature of this hot water is generally 80-90°C at the outlet from the engine. This hot water for steam generation already lead us to putting absorption heat transformers into practical use (Fujii et al. 2008).

A single-effect absorption chiller is also available for using hot water in absorption chillers and providing chilled water. However, the cooling capacity in most cases is insufficient for the buildings compatible with the power output capacity, so additional absorption or vapor compression chillers are necessary to meet the cooling demand. Therefore, absorption chiller with auxiliary waste heat recovery are most suitable for use in co-generation systems because they can provide a sufficient level of cooling capacity, since they are driven by a high temperature heat source as well as the hot water from the engine.

An outline and the characteristic model of absorption chillers with auxiliary waste heat recovery are described in this paper. Furthermore, we report on our development of chillers with enhanced auxiliary waste heat recovery, that we put into practical use in 2013.

2 OUTLINE OF SYSTEM AND CHILLER

2.1 Typical System Flow of Co-generation Systems containing Absorption Chillers with Auxiliary Waste Heat Recovery

Figure 1 is an example of a co-generation system containing an absorption chiller with auxiliary waste heat recovery. The waste heat from a gas-engine power generator in this system is put into the chiller as 90°C hot water. This chiller is also driven by heat from the fuel gas in order to meet the cooling demand and save on footprint area by combining a hot-water driven chiller and a direct-fired chiller.

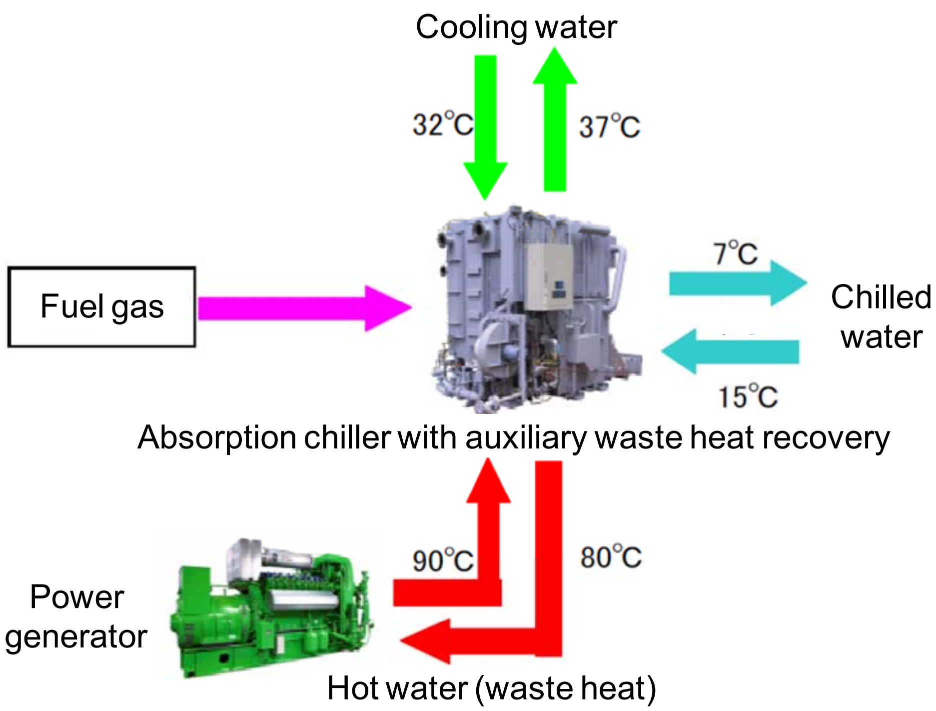


Figure 1: System flow of co-generation system with absorption chiller (For direct-fired absorption chiller)

2.2 Cycle Flow of Absorption Chillers with Auxiliary Waste Heat Recovery

Figure 2 shows the cycle flow of a direct-fired type chiller. Most of the elements are similar to those in common double-effect absorption chillers. The additional elements are a heat recovery generator and a heat recovery heat exchanger.

The heat recovery generator is located in the same shell as the low temperature generator and condenser. Part of the weak solution from the absorber is firstly heated in this generator by auxiliary waste heat provided in the form of hot water from the power generator. Then, some refrigerant vapor is generated from the weak solution, and becomes an addition to the cooling capacity of the machine. Thus, the heat from the hot water is taken into the absorption chiller in the form of the latent heat from the refrigerant.

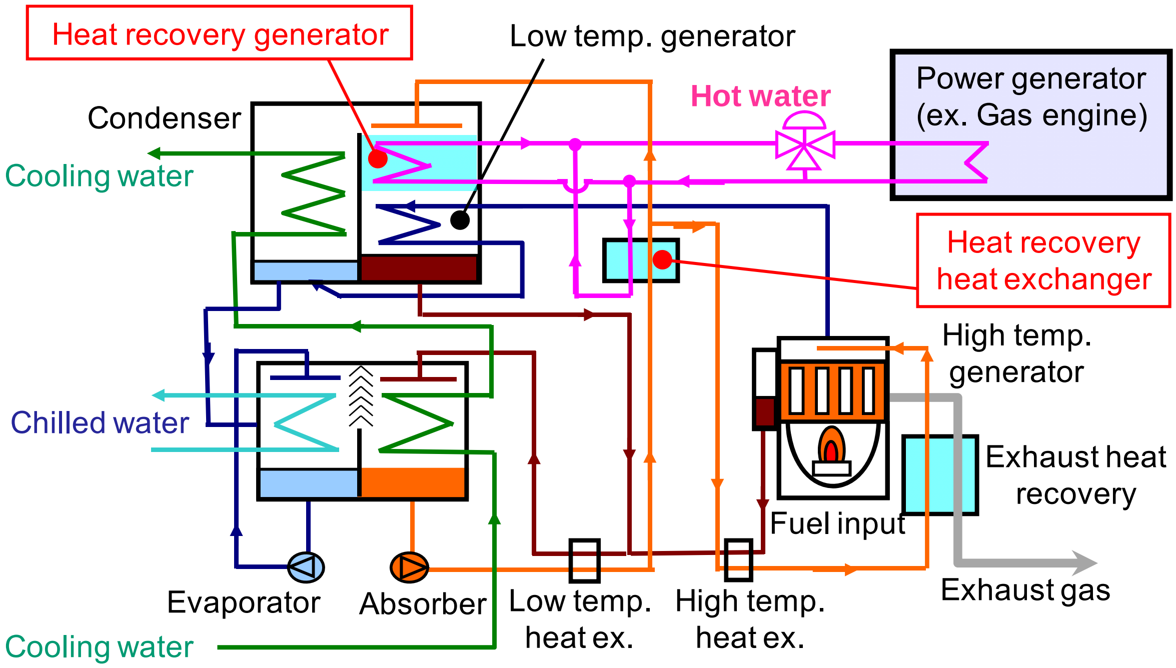


Figure 2: Cycle flow of absorption chiller with auxiliary waste heat recovery

Another element is the heat recovery heat exchanger, which is installed in the weak solution line after the low temperature heat exchanger. A weak solution from the low temperature heat exchanger is heated by the hot water in this heat exchanger, almost up to the boiling point of the heat recovery generator. This heat is also added to the low temperature generator and assists in the cooling capacity. A small plate heat exchanger can be used to accomplish this since this heat exchanger is a liquid-liquid heat exchanger.

3 THEORETICAL STUDY OF THIS CHILLER

3.1 Fundamental characteristic

A simulation tool is essential for estimating the energy consumption and cooling capacities when designing co-generation systems that include absorption chillers. The characteristics of these chillers are also generally expressed as functions of the cooling load and the temperature of the hot water as waste heat (Homma 2008). Therefore, we conducted some theoretical approaches for describing this chiller as a part of the simulation tool.

Some typical characteristics of this chiller are shown in Figures 3 and 4. Figure 3 shows the consumption ratio of the high temperature heat source (q_H, -), which is the fuel consumption in this case. The q_H reference value is the fuel consumption without waste heat recovery at a maximum cooling load ratio (q_E, -). Figure 4 shows the waste heat input ratio (q_{inW}, kW/kW-cooling) whose reference value is the maximum cooling load (Q_E, kW). These two characteristics are very important in designing and for simulating the energy consumption of co-generation systems (Fujii et al. 2011), and therefore, it would be useful if they are expressed in the form of equations.

The chiller is driven by only waste heat under smaller cooling load conditions. As shown in Figure 3, q_H is zero if the q_E is not greater than q_{E1Max}, which is the maximum cooling load capability when using only waste heat. Under this condition, q_{inW} is expressed as

$$q_{inW} = \frac{q_E}{\eta_1} \qquad (q_E \leq q_{E1Max}) \tag{1}$$

In Eq. (1), η_1 is the coefficient of performance (COP) of the condition driven by only waste heat, i.e., the single effect mode.

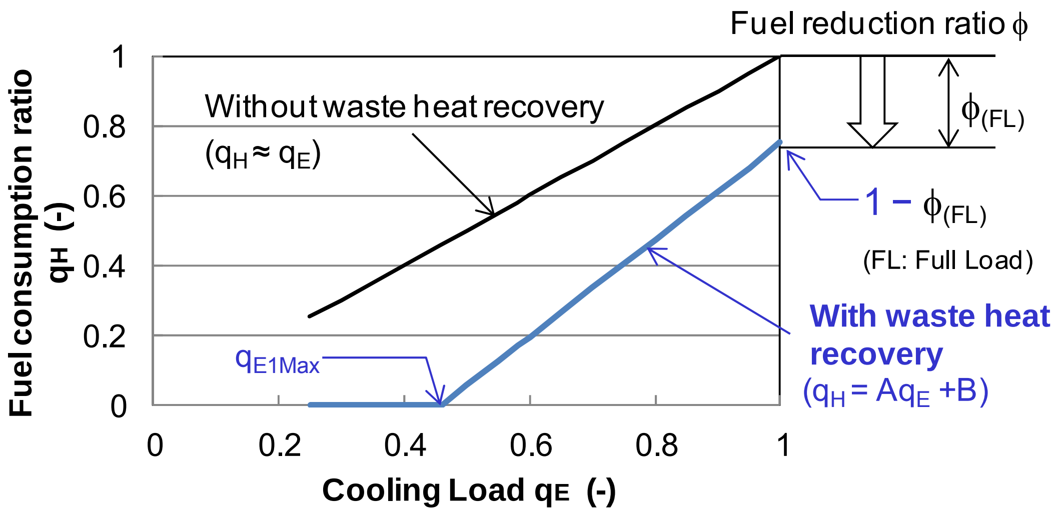


Figure 3: Typical fuel consumption ratio characteristics

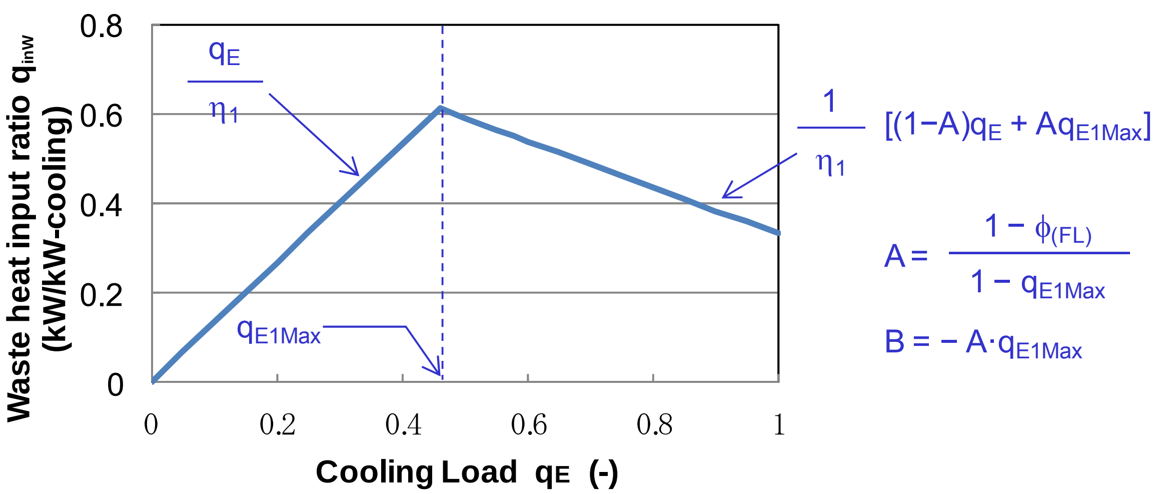


Figure 4: Typical waste heat input ratio characteristics

On the other hand, when q_E is greater than q_{E1Max}, the chiller is driven by both fuel and waste heat. This mode is defined as the "double input mode" in this paper. The fuel consumption in this mode, as seen in Figure 3, is reduced by the waste heat recovery, and as seen in Figure 4, the amount of waste heat that can be used by the chiller decreases according to the cooling load because of the temperature rise in the absorption cooling cycle.

This characteristic is approximately linier, so we assume that the fuel consumption ratio (q_H) in the double input mode (q_{Hd}) is expressed as

$$q_{Hd} = A \cdot q_E + B \tag{2}$$

As seen in Figure 3, this straight line passes through points (q_{E1Max}, 0) and (1, 1-$\phi_{(FL)}$). Here, ϕ is the fuel reduction ratio and defined as (1 - q_{Hd}). $\phi_{(FL)}$ is the value of ϕ at q_E = 1 (Full Load). Therefore, constants A and B in Eq. (2) are derived as follows.

$$A = \frac{1-\phi_{(FL)}}{1-q_{E1Max}} \tag{3-a}$$

$$B = -A \cdot q_{E1Max} = -\frac{1-\phi_{(FL)}}{1-q_{E1Max}} \cdot q_{E1Max} \tag{3-b}$$

Subsequently, since ϕ is the cooling capacity that is produced by the waste heat, it is also expressed as

$$\phi = q_{inW} \cdot \eta_1 \tag{4}$$

In addition, assuming that the q_H without waste heat recovery is equal to q_E, ϕ is

$$\phi = q_E - q_{Hd} = q_E - (A \cdot q_E + B) = q_E - (A \cdot q_E - A \cdot q_{E1Max}) = (1 - A) \cdot q_E + A \cdot q_{E1Max} \tag{5}$$

Thus, the waste heat input ratio q_{inW} for the double input mode (q_E > q_{E1Max}) is obtained as follows.

$$q_{inW} = \frac{1}{\eta_1}[(1-A) \cdot q_E + A \cdot q_{E1Max}] \qquad (q_E > q_{E1Max}) \tag{6}$$

Thus, q_H and q_{inW} are consequently described using q_{E1Max} and $\phi_{(FL)}$ by using Eqs. (2) and (6), which are easy to obtain from the characteristics chart.

3.2 Dependence of characteristics on waste heat temperature

The characteristics of the absorption chiller with auxiliary waste heat recovery also depend on the waste heat temperature or hot water temperature in Figures 1 and 2. We attempt to express this tendency by using the shift of the q_{E1Max}, to apply and extend Eqs. (2) and (6) in this paper. In addition to this, q_{E1Max} is useful because it is also the border between the single effect and double input modes.

Table 1 itemizes an example of the hot water temperature characteristics. As the temperature increases, q_{E1Max} also increases because the temperature difference widens in the heat recovery generator and heat recovery heat exchanger.

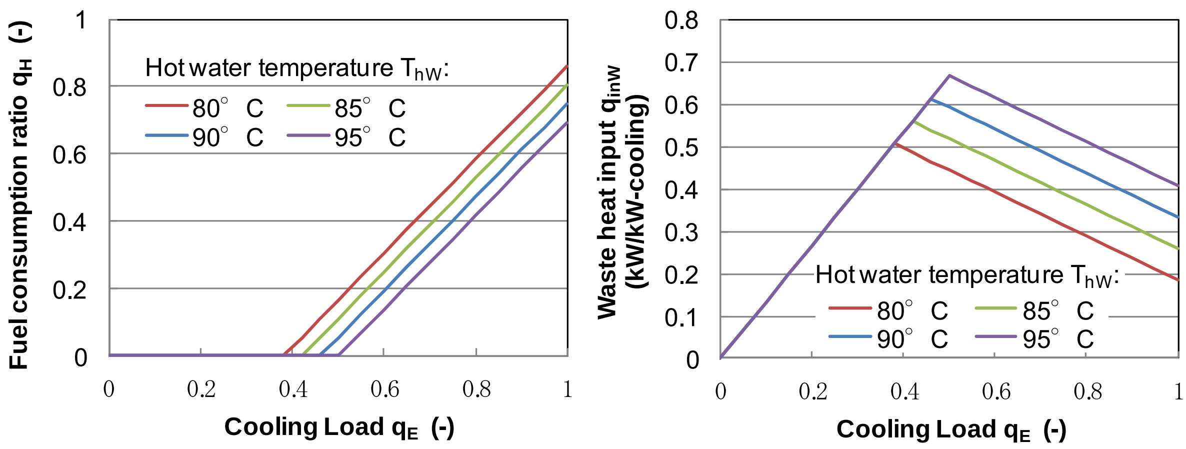
Table 1: Dependency of q_{E1Max} on hot water (waste heat) temperature

Waste heat temperature T_{hW} (°C)	80	85	90	95
q_{E1Max} (-)	0.38	0.42	0.46	0.50

From Table 1, q_{E1Max} is calculated by using Eq. (7).

$$q_{E1Max} = 0.008T_{hW} - 0.26 \qquad (7)$$

The basic characteristics shown in Figure 5 are derived by applying Eq. (7) to Eqs. (1), (2) and (6). These graphs often accompany the characteristics outline of absorption chillers with auxiliary waste heat recovery. Therefore, these behaviors include the change in cooling load, and thus, hot water temperatures become possible.



(a) Fuel consumption ratio (q_H) **(b) Waste heat input (q_{inW})**

Figure 5: Dependency of q_H and q_{inW} on hot water (waste heat) temperature

The characteristics of the absorption chiller with auxiliary waste heat recovery are studied and expressed by above equations, using only fuel reduction ratio at full load ($\phi_{(FL)}$), maximum cooling capacity of the single effect mode (q_{E1Max}) and its change according to the waste heat temperature (T_{hW}).

4 DEVELOPMENT OF ENHANCED AUXILIARY WASTE HEAT RECOVERY TYPE

4.1 Background of development

The waste heat quantity in recent co-generation systems is increasing with the expanding electricity-generating capacities for the energy security of buildings and energy plants. This leads to a bigger demand for putting more waste heat into practical use. Therefore, we developed absorption chillers with higher amounts of auxiliary waste heat that reduces more of the fuel or steam consumption than conventional chillers.

4.2 Enhancement of waste heat recovery

We mainly adopted three specialties for the purpose of enhancing the amount of waste heat recovery. The first one is to enhance the waste heat recovery section, namely the heat recovery generator and the heat recovery heat exchanger. In addition, the condenser is also enhanced because it is paired with the enhanced heat recovery generator. The second specialty is the flow rate control based on the quantity of the recovered heat. The third one is a change of the cooling water flowing order. Moreover, we adopted a two-stage evaporator-absorber shown in Figure 6 that we used for the absorption heat pump chillers (Fujii et al. 2011). This structure does not contribute to the enhancement of the waste heat recovery, but boosts the fundamental performance of the chiller.

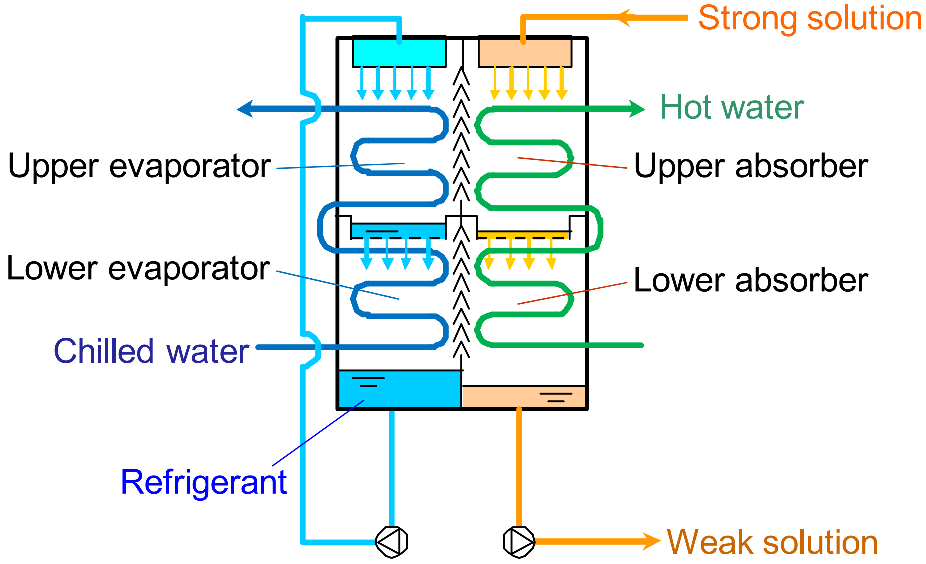


Figure 6: Configuration of two-stage evaporator and absorber (Fujii et al. 2011)

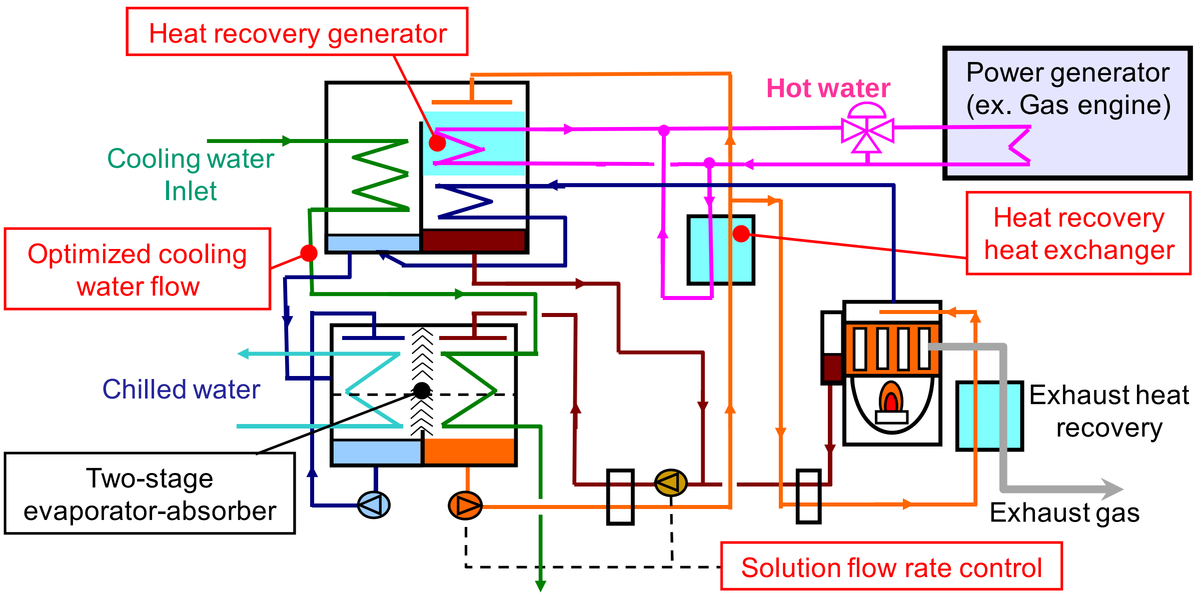


Figure 7: Main specialties for enhancement of waste heat recovery

These specialties are shown in Figure 7. The solution flow rate is controlled by the speed control of the solution pumps. The cooling water flows into the condenser at first and then flows into the absorber. This configuration is defined as “C-A flow”, whereas conventional configuration is called as “A-C flow”.

4.3 Effect of change in cooling water flow

The cooling water in conventional double-effect absorption chillers is firstly provided to the absorber, and then flows into the condenser to reduce the solution concentration at the outlet of the absorber. However, the two-stage evaporator-absorber structure that has recently been incorporated in these systems reduces the concentration, so it is now more flexible for selecting the cooling water flow. Therefore, we assumed in our current development that if the condensing temperature in the condenser decreased, then the generating temperature of the heat recovery generator also decreased. Accordingly, the temperature difference between the hot water and the solution in the heat recovery generator widened, and as a result, the amount of heat intake in the generator increased.

Eventually, we adopted “C-A flow” shown in Figure 7 instead of conventional “A-C flow” shown in Figure 2.

Table 2 lists the calculated results of the effect of the above-mentioned cooling water flow change in a conventional absorption chiller with auxiliary waste heat recovery whose $\phi_{(FL)}$ is 0.25. As a result of this change, the condensing temperature decreased by 3.2°C and the solution temperature of the heat recovery generator also decreased by 1.6°C. This boosted the waste heat intake and reduced the amount of fuel consumption. The COP in the double input mode with waste heat recovery consequently increased from 1.8 to 1.9, although the COP without waste heat recovery decreased from 1.35 to 1.34 because the concentration in the absorber increased by 1.1% due to the rise in cooling temperature in the absorber.

Table 2: Effect of change in cooling water flow during full load operations (q_E = 1)

Item	A-C flow	C-A flow
Concentration in absorber (wt% of LiBr)	ξ_{Ao0}	ξ_{Ao0} + 1.1
Condensing temperature (°C)	T_{C0}	T_{C0} − 3.2
Solution temperature in heat recovery generator (°C)	T_{SRGo0}	T_{SRGo0} − 1.6
Fuel reduction ratio at full load ($\phi_{(FL)}$)	0.25	0.29
COP without waste heat recovery	1.35	1.34
COP in double input mode with waste heat recovery	1.8	1.9

4.4 Developmental results

We have developed a new absorption chiller with enhanced auxiliary waste heat recovery. Figure 8 shows a steam-driven type of this chiller, and the specifications for the direct-fired and steam driven types of these chillers are specified in Tables 3 and 4. In these machines, the amount of waste heat recovery was set at 1.59 times in the direct-fired type and 1.80 times in the steam-driven type compare to that in the conventional chillers. In addition, the fuel reduction ratio was increased from 25 to 40% for the direct-fired chillers, and steam reduction ratio in the steam-driven chillers increased from 15 to 30%. The maximum cooling capacities driven by only using auxiliary waste heat reached approximately 58% for the direct-fired machines and 50% for the steam-driven ones. The specialties adopted for this machine are also indicated in Figure 8.

Table 3: Specifications for newly-developed direct-fired type model

Operating mode			Cooling	Heating
Capacity ratio			100	71~89
COP with no waste heat recovery (based on lower heating value)			1.47	0.97
Fuel reduction with waste heat recovery			40%	55~69%
Efficiency of waste heat transformation			0.8	1.0
Temperature condition under nominal (full load) condition	Chilled/hot water	Inlet	15°C	55°C
		Outlet	7°C	60°C
	Cooling water	Inlet	32°C	–
		Outlet	37°C	
	Waste heat hot water	Inlet	90°C	
		Outlet	80°C	

Table 4: Specifications for newly-developed steam-driven type of model

Operating mode	Cooling	Heating
COP with no waste heat recovery (based on steam input)	1.40	–
Steam reduction with waste heat recovery	30%	

- Other items are the same as for the cooling mode of direct-fired type (Table 3).

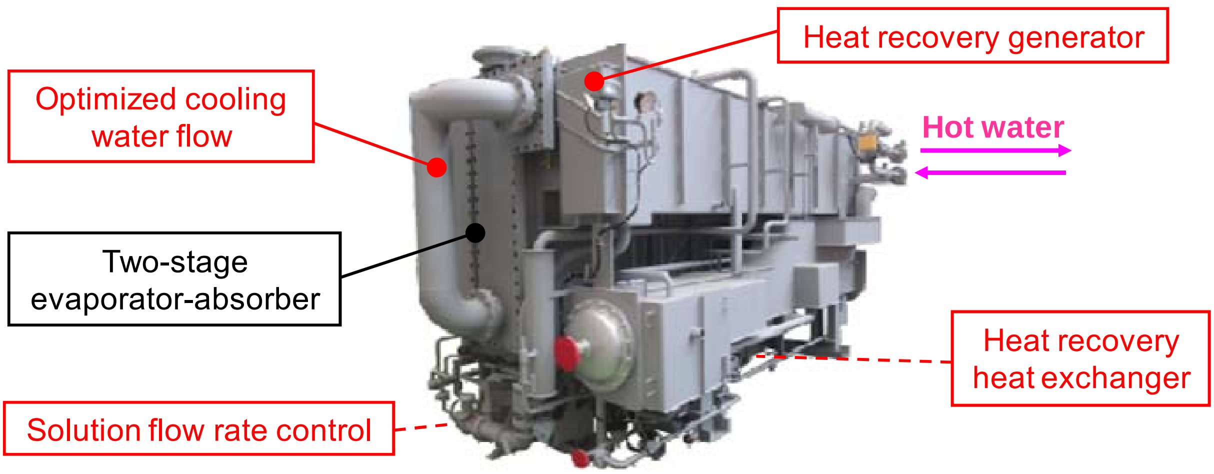


Figure 8: Photograph of absorption chiller with enhanced waste heat recovery (Cooling capacity: 949 kW (270 RT))

4.5 Comparison with conventional chillers

Finally, the cooling load characteristics of the new model are listed in Table 5 and compared with those from three conventional models. These differences in cycle configurations are also compared. When the chillers of this concept started to be studied, only the heat recovery heat exchangers were used. and then Edera and Kojima added the heat recovery generator, Homma et al. adopted the exhaust heat recovery heat exchanger, and we enhanced these heat exchangers and applied the C-A flow.

The cooling load characteristics are calculated from these two characteristics using Eqs. (1), (2), and (6), as shown in Figure 9. It can be seen in this figure that the new model has enhanced the cooling load domain of the waste heat operation without needing an additional high temperature heat source, as mentioned in Section 4.4.

Table 5: q_{E1Max} and $\phi_{(FL)}$ of conventional and newly-developed models

Item	Model A (Takeda 1996)	Model B (Edera 2002)	Model C (Homma 2008)	New model (This work)
Heat recovery HX	Used			
Heat recovery generator	Unused	Used		
Exhaust heat recovery	Unused		Used	
Cooling water	A-C flow			C-A flow
q_{E1Max}	0.2	0.34	0.46	0.58
$\phi_{(FL)}$	0.1	0.20	0.25	0.40

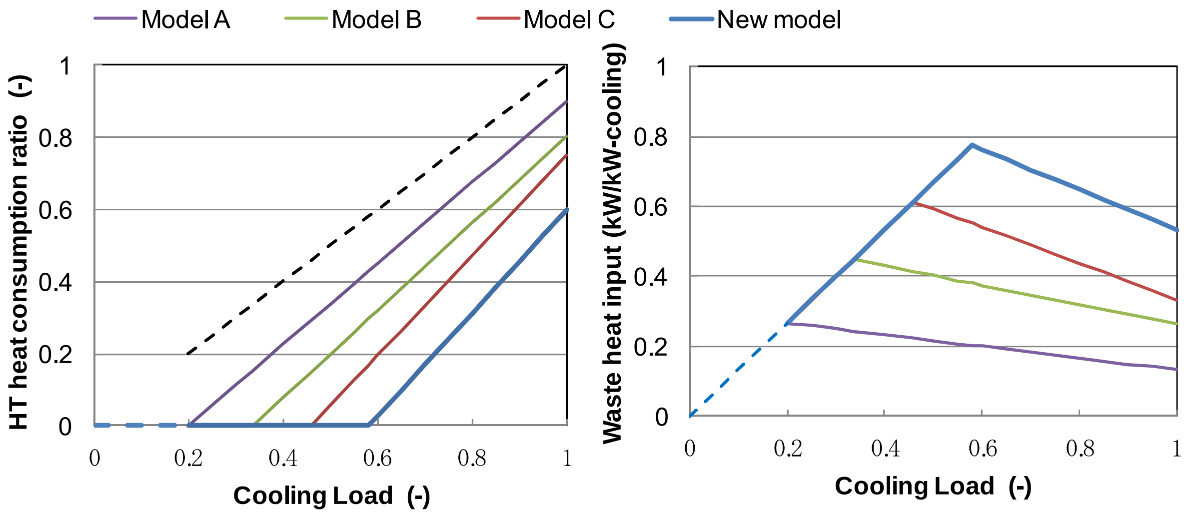


Figure 9: Comparison of cooling load characteristics of new model and conventional models, using calculated results from Eqs. (1), (2), and (6)

As Figure 9 also indicates, the high temperature heat source consumption and waste heat input are both consistently calculated using the equations mentioned in Chapter 3. Therefore, these equations are available for any new models if the q_{E1Max}, $\phi_{(FL)}$, and temperature dependency of the q_{E1Max} can be obtained from the characteristics outline.

5 EXAMPLE APPLICATION FOR SOLAR COOLING

Although conventional absorption chillers with auxiliary waste heat recovery are available for solar cooling use, the new model is more suitable for this use because of its enhanced waste heat intake capacity.

Figure 10 shows an example of a solar cooling/heating system containing an absorption chiller with auxiliary waste heat recovery. During system operation, the hot water heated by the solar panel becomes the preferred heat source. This operation reduces the fuel consumption to as small as possible and contributes to energy conservation.

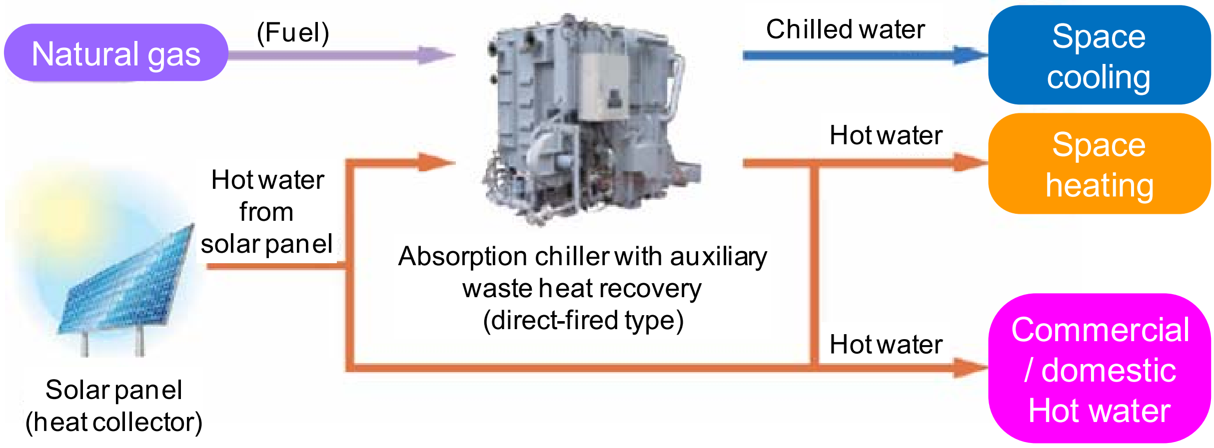


Figure 10: Example of solar system containing absorption chiller with auxiliary waste heat recovery (direct-fired type)

6 CONCLUSION

For the purpose of enhancement of the low-temperature waste heat input, we conducted a theoretical study on absorption chillers with auxiliary waste heat recovery and have developed new models with enhanced auxiliary waste heat recovery. As the result of this study, following results are obtained.

(1) In the models which we have developed, the amount of waste heat recovery was set at 1.59 times in the direct-fired type, and 1.80 times in the steam-driven type.
(2) This model was consequently driven by only waste heat up for to a 58% load for the direct-fired machines, and 50% for the steam-driven ones.
(3) The configuration of “C-A flow” which enhances the low-temperature waste heat input became available by adopting with two-stage evaporator and absorber which reduces the LiBr concentration in the absorption cooling cycle.
(4) The major characteristics were calculated from the maximum cooling load created by using only waste heat (q_{E1Max}), and the fuel reduction ratio under full load conditions ($\phi_{(FL)}$). This calculation can be applied for system simulations for buildings and district heating and cooling plants.

7 ACKNOWLEDGEMENTS

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8 REFERENCES

Edera M., H. Kojima 2002. "Development of a new gas absorption chiller heater──advanced utilization of waste heat from gas-driven co-generation systems for air-conditioning", *Energy Conversion and Management* 43, pp. 1493-1501.

Fujii T., H. Kawamura, Y. Sakano, S. Uchida, and A. Nishiguchi 2008. "A Single-effect Absorption Heat Transformer for Waste Heat Recovery in Industrial Use", *9th IEA Heat Pump Conference 2008*.

Fujii T., S. Murakami, H. Ishino and T. Yanai 2011. "Development of an Integrated Energy Simulation Tool for Buildings and MEP Systems, the BEST (Part 90) Characteristics of Newly Adopted Heat Source Equipments", *Proceedings of The Society of Heating, Air-conditioning and Sanitary engineers of Japan*, pp. 1723-1726 (in Japanese).

Fujii T., S. Uchida, and N. Nishiyama 2011. "Development of absorption heat pump chillers with improved heating efficiency by applying heat pump", *10th IEA Heat Pump Conference 2011*.

Homma R, "Absorption Chiller-Heater with Auxiliary Waste Heat Recovery", *Refrigeration*, Vol. 83, No. 967, pp. 342-346 (in Japanese).

Kojima H., A. Akisawa and T. Kashiwagi 1997. "Advancement of Double Effect Absorption Cycle by Input of Low Temperature Waste Heat (1st Report : Basic Cycle Analysis)", *Trans. Of the JSRAE*, Vol. 14, No. 2, pp. 201-212 (in Japanese).

Takeda N., S. Miyake, and Y. Takeuchi 1996. "Development of Absorption Chiller Heater with an Auxiliary Waste Heat Recovery", *Proceedings of the Ibaraki Conference*, pp. 107-108 (in Japanese).