

A SINGLE-EFFECT ABSORPTION HEAT TRANSFORMER FOR WASTE HEAT RECOVERY IN INDUSTRIAL USE

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Abstract: A single-effect absorption heat transformer has been developed. It is driven by waste heat, as 90°C water, from a gas engine, and the outlet temperature from its generator and evaporator is 85°C. The output temperature from its absorber is 137°C, so the temperature boost is 52°C. We proposed a new performance evaluation method, based on thermodynamics and Duhring's law, for comparing machines, which are designed for different operating temperatures. By this method, the coefficient of performance (COP) and temperature boost are estimated from the ratio to their theoretical values. According to this method, the temperature boost of the heat transformer is 84% of the theoretical value and exceeds previously developed single-effect absorption heat transformers. The COP of the heat transformer is 0.484. Additionally, two solution pumps, adopted for the solution circuit, shorten the start-up time to less than one hour. This absorption heat transformer was installed with a co-generation system in a hydraulic machinery factory. Regular operation began in April 2007. This system has been operating as originally designed and without any problems.

Key Words: *absorption heat transformer, waste heat, co-generation, energy service*

1 INTRODUCTION

Now is the beginning of the Kyoto protocol's first commitment period, and the demand for reducing greenhouse gases is growing steadily. The most prominent green house gas is carbon dioxide (CO₂). In Japan, approximately 40% of CO₂ emissions originate from the industrial sector. Therefore, the reduction of CO₂ emissions from industrial plants is an important issue. Additionally in Japan, revision of the Rationalization in Energy Use Law asks the manufacturers to conserve energy further, and the ISO 14001 certification also requests them to decrease their energy consumption from the viewpoint of environmental protection.

Many kinds of industrial plants produce large amount of waste heat, which is discharged without reclamation. Therefore, reduction of CO₂ emissions can be accomplished by effectively using this waste heat, which mainly consists of hot water below 100°C and hot air below 150°C.

As introduced by Herold and Radermacher, an absorption heat transformer is a machine for reclaiming waste heat. It is actually driven by waste heat and produces useful heat, with higher temperatures compared to the original heat source, without any additional fuel input.

In the 1980's, the development of absorption heat transformers was actively carried out. Sano, Kusakabe and Ikumi developed a heat transformer with a capacity of 2,350 kW and a coefficient of performance (COP) of 0.47, which was installed in 1983. Mashimo reported 11 absorption heat transformers, which began operation between 1981~85, including Sano's machine. The capacities and COPs of these machines ranged from 270~6,420kW and 0.47~0.49. Susai et al. also developed an absorption heat transformer for use at an alcohol distillation plant. The capacity of their machine is 2,670 kW and its COP is 0.48. After this period, the development of absorption heat transformers slowed, because energy supplies stabilized and economic circumstances improved.

We report a single-effect absorption heat transformer installed into a co-generation system. The performance of this machine is compared with those previous machines by calculating the ratios of their COPs and temperature boost (TBs) to their theoretical values.

2 ABSORPTION HEAT TRANSFORMER CYCLE

2.1 Configuration of the cycle

A single-effect absorption heat transformer cycle is shown in Figure 1. It consists of mainly four heat exchangers, an absorber, generator, condenser and evaporator. Additionally, a solution heat exchanger is added between the absorber and generator. Alefeld and Radermacher indicated the importance of this heat exchanger. This cycle operates with two pressure levels. The absorber and the evaporator work at high pressure, and the generator and condenser work at low pressure.

Waste heat is supplied to the evaporator and generator, and cooling water is supplied to the condenser, and useful heat is obtained from the absorber. As shown in Figure 1, the temperature of useful heat (T_2) is higher than supplied heat (T_1), so we sometimes call this cycle "temperature booster". In this example, 135°C water is obtained by supplying 90°C waste heat and from the temperature difference between the waste heat and surrounding temperature (T_0).

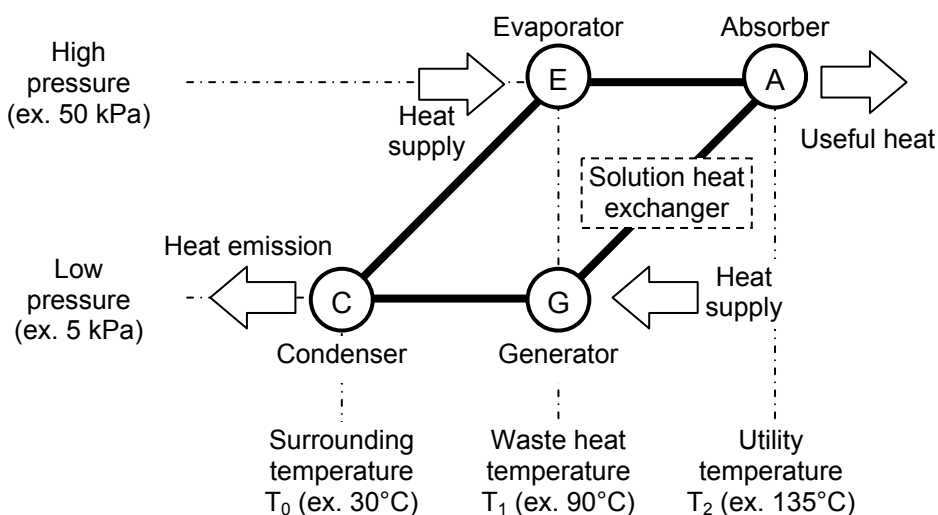


Figure 1: Absorption heat transformer cycle

2.2 Utilization of waste heat

Since most of the unused energy from industrial plants is low-temperature waste heat below 100°C, it would be more effective to utilize this unused waste heat. As its temperature drops, it becomes economically more difficult to recover.

We propose our absorption heat transformer as an effective means for the utilization of low temperature waste heat. Since this machine is driven by waste heat and does not need any additional high temperature heat, the whole industrial energy plant becomes more efficient.

An energy conservation concept with an absorption heat transformer by Uchida, Nishiguchi, Toyo and Sakano is shown in Figure 2. In many industrial plants, waste heat is obtained from co-generation, chemical process, and other systems. The output heat with boosted temperature can be used for heating, washing, drying, and other processes.

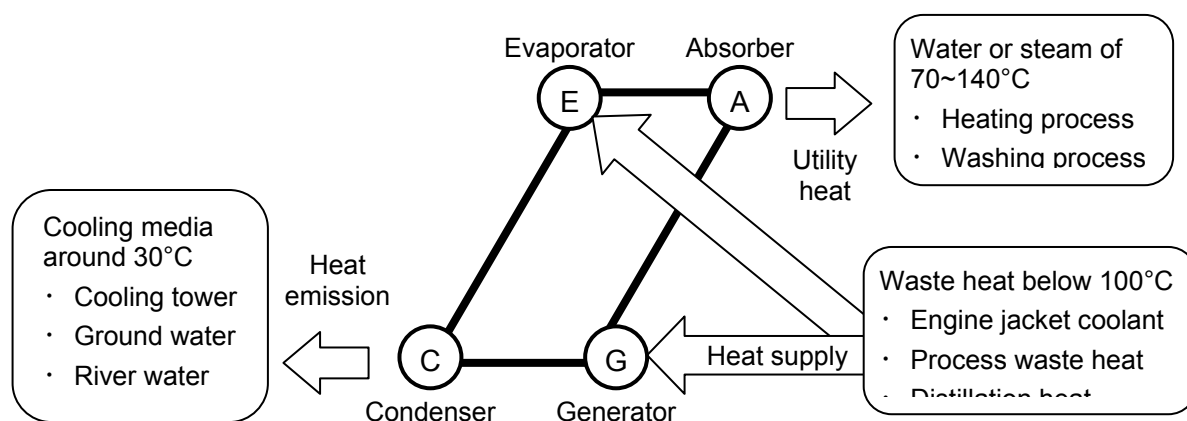


Figure 2: Concept of energy conservation with an absorption heat transformer

3 THEORETICAL COP AND TB

3.1 Objective of theoretical investigation

Absorption heat transformers, which are already installed and in operation, are designed for various output, heat source, and cooling water temperatures. For the heat transformers introduced by Mashimo, their output temperature ranges from 111 to 150°C, and their heat source temperature ranges from 78 to 100°C. Cooling tower or ground/sea water cool the condensers of all 11 heat transformers. These cooling water temperatures range from 15 to 32°C.

We compared the performance of the newly developed absorption heat transformer with the previously developed machines. The COP and TB were selected as the performance index. For the purpose of comparison under equal conditions, we compared them by the ratios of their COPs and TBs to their theoretical values. We determined these values with T_0 , T_1 , and T_2 From Figure 1. Consequently, we calculated the theoretical performance from T_0 , T_1 , and T_2 .

3.2 Performance characteristics based on the First and Second Law of Thermodynamics

Several studies have been made on the theoretical characteristics of the absorption heat transformer cycle. The COP of an absorption heat transformer (COP_{HT}) is the amount of useful high temperature heat (Q_2) divided by the total amount of waste heat required (Q_1). Herold, Rademacher, and Klein derived Eq. 1 from the first and second laws.

$$COP_{HT} = \frac{Q_2}{Q_1} = \frac{T_1 - T_0}{T_1} \frac{T_2}{T_2 - T_0} \quad (1)$$

Sawanobori applied an assumption on Eq.1 and calculated the theoretical COP_{HT} and TB (COP_{HTt} and TB_t) for several types of heat transformer cycles, including single-effect. This assumption states that all iso-concentration lines on a Duhring chart reach the origin of absolute temperature, as shown in Figure 3. From this assumption, Eq. 2 is derived.

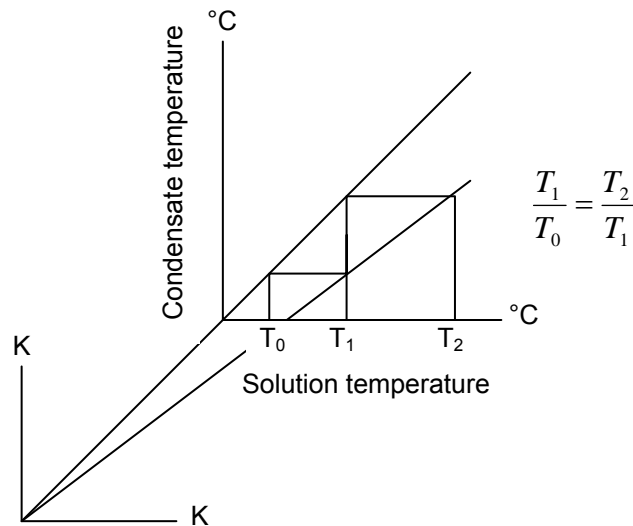


Figure 3: Duhring chart on assumption of working temperature (T_0, T_1, T_2) relationship

$$T_2 = T_1 \frac{T_1}{T_0} \quad (2)$$

By applying Eq.2 to Eq.1, COP_{HTt} is described as Eq.3.

$$COP_{HTt} = \left\{ 1 + \frac{T_1}{T_2} \right\}^{-1} = \left\{ 1 + \left(\frac{T_0}{T_2} \right)^{1/2} \right\}^{-1} = \left\{ 1 + \frac{T_0}{T_1} \right\}^{-1} \quad (3)$$

Note that T_0, T_1 and T_2 are absolute temperatures, and TB_t is calculated using Eq.4.

$$TB_t = T_2 - T_1 = T_1 \left(\frac{T_1}{T_0} - 1 \right) \quad (4)$$

Equations 3 and 4 shows that COP_{HTt} and TB_t are both described using only T_0 and T_1 . These characteristics for a single-effect cycle appear in Figure 4. The TB_t varies widely, according to T_0 and T_1 compared to COP_{HTt} .

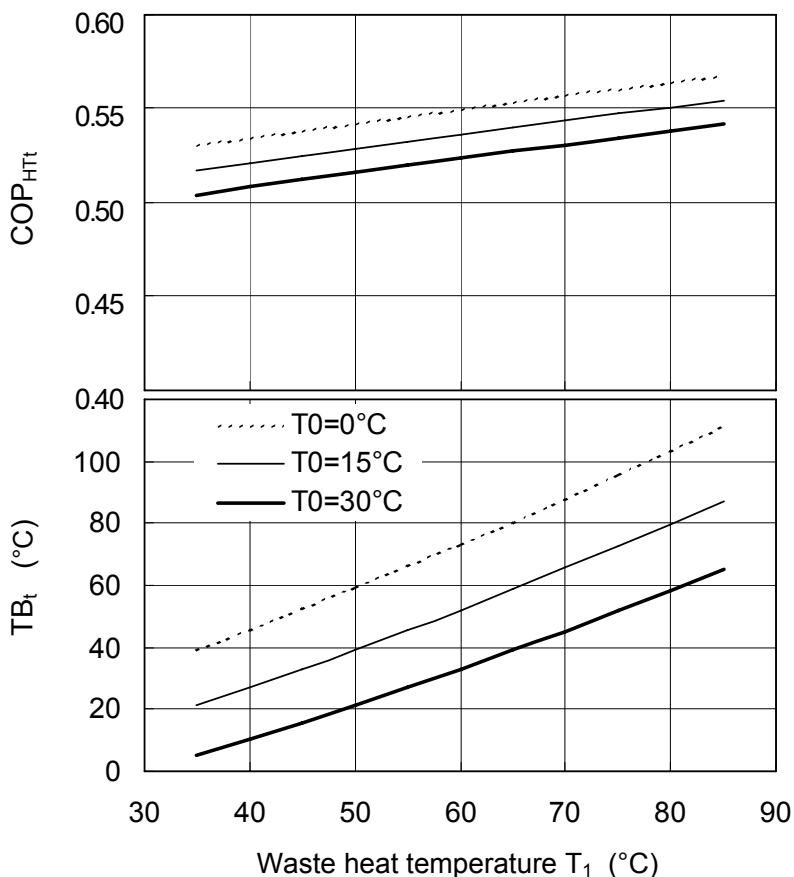


Figure 4: COP_{HTt} and TB_t of a single-effect absorption heat transformer

4 DEVELOPMENT OF NEW ABSORPTION HEAT TRANSFORMER

4.1 Target performance and cycle flow

Our new absorption heat transformer has the target performance of generating over 130°C output for heating or washing from approximately 90°C waste heat, obtained from the cooling water of a gas engine, as the heat source. If the temperature difference of the heat source is assumed to be 5°C, the outlet temperature is 85°C. Thus the TB must be over 45°C. According to Figure 4, this specification can be obtained from an 85°C heat source and 30°C cooling water. Therefore, we adopted a single-effect cycle for this machine with a heating capacity of 150 kW. This capacity is smaller than all the heat transformers introduced by Mashimo. Therefore, it is possible that this development can extend application of absorption heat transformers to smaller facilities and contributes to energy conservation.

Figure 5 shows the cycle flow of our developed absorption heat transformer. The main body of the absorber is cylindrical, and separated into three parts. The condenser, the generator, and the evaporator are the shell-and-tube type, similar to the absorption chillers. For the generator, a low temperature generator of an absorption chiller is applied. Its falling film heat transfer makes has the advantage of waste heat recovery by a smaller temperature difference. The other three components are also falling film heat exchangers similar to the absorption chillers.

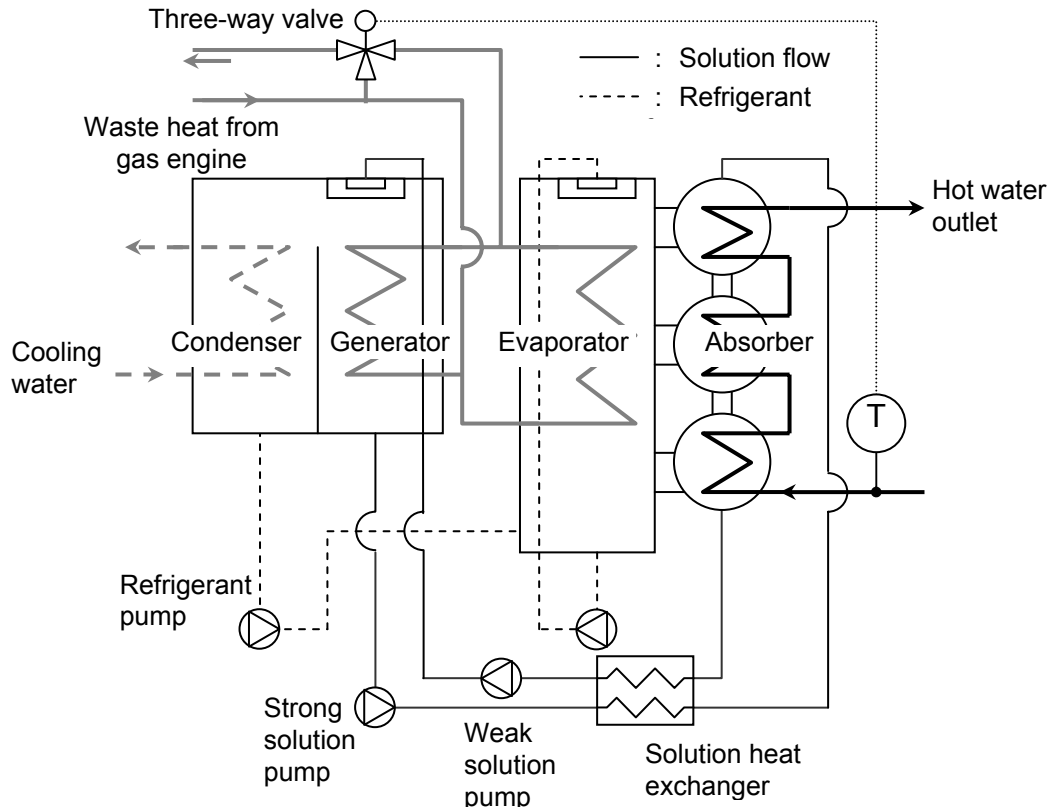


Figure 5: Cycle flow of developed absorption heat transformer

Two solution pumps were adopted for both strong and weak solutions for the following two purposes. The first is to shorten the start-up time of the heat transformer, and the second purpose is to flexibly arrange the components. In the conventional machines developed by Sano et al. and Susai et al., the generator and absorber must be arranged vertically or at different height. We arranged the tops of the generator and the absorber at similar levels and reduced the height of the whole machine by circulating the solution using two solution pumps. Two inverters were set for these solution pumps to prevent an increase in electricity consumption.

As shown in Figure 4, TB varies in accordance with the waste heat temperature (T_1) and the cooling water temperature (T_0). In our proposed machine, T_1 does not vary because the heat source is provided as hot water from a gas engine, but T_0 varies with the season and climate. Therefore, we put a three-way valve on the waste heat circuit to stabilize the TB and the output temperature.

4.2 Newly developed absorption heat transformer and its performance

A picture of the newly developed absorption heat transformer is shown in Figure 6. Since the pressure of the hot water output exceeds the atmospheric pressure, the headers of hot water are spherical to maintain strength. The condenser, generator, evaporator, and absorber have the same top level; similar to the absorption chiller we developed.

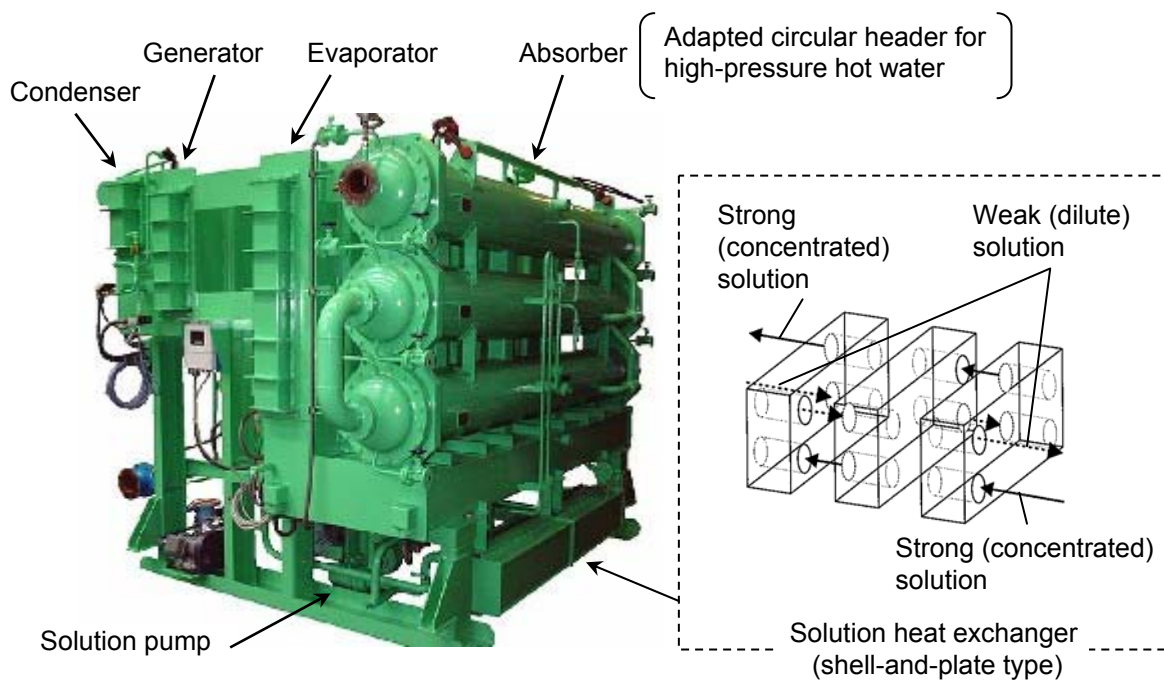


Figure 6: Picture of developed absorption heat transformer and diagram of solution heat exchanger

The solution heat exchanger is a shell-and-plate type and located under the absorber. This heat exchanger has a multi-pass structure shown in Figure 6, which improves heat recovery and COP. We previously developed this structure to improve the efficiency of absorption chillers.

5 PERFORMANCE OF THE NEW MACHINE

5.1 Performance test results

Table 1 shows the results from the performance test of our newly developed machine shown in Figure 6. The target values are results from a cycle simulation based on the performance of each component. The cycle simulation program was developed by referring to the simulation model of Grossman and Childs.

Table 1: Test result of the new absorption heat transformer

Item	Target value	Test result
Available heat output	150 kW	153.8 kW
Hot water temperature	Inlet	133.0°C
	Outlet	137.0°C
Heat source water temperature	Inlet	90.0°C
	Outlet	85.0°C
Cooling water temperature	Inlet	27.0°C
	Outlet	32.0°C
COP	0.47 or more	0.484
TB	52.0°C	52.1°C
Start-up time	Within 1 hour	Approx. 50 minutes

We see from table 1 that heat output and COP both satisfy the target values. The TB is defined as the difference between outlets of the hot water and the heat source water. Thus, the value of TB is as follows.

$$TB = 137.1 - 85.0 = 52.1 \text{ (}^\circ\text{C)} \quad (5)$$

This value exceeds all those of the heat transformers reported by Mashimo and Susai.

5.2 Reduction of start-up time

Start-up time is important for the energy conservation of an absorption heat transformer as well as its usability. Therefore, we assigned the target value of the start-up time as within one hour. To soothe the start-up process, circulation of the solution for the intake of waste heat into the generator is important. In our developed machine, two solution pumps were adopted to force the circulation of the solution, as described in section 4.1. Thus, the circulation is kept stable, in spite of the fact that the pressure difference between the absorber and generator is relatively small in the start-up period.

To validate this effect, start-up characteristics without a weak solution pump was compared with two solution pumps. The results are shown in Figure 7. As the trend chart indicates, the start-up time was shortened from 90 to 50 minutes by using two solution pumps. This is a result of the forced solution circulation that smoothes the intake of waste heat. This heat concentrates the solution and finally heats the water rapidly. This characteristic is also an advantage over the previously developed machines, which have only one solution pump.

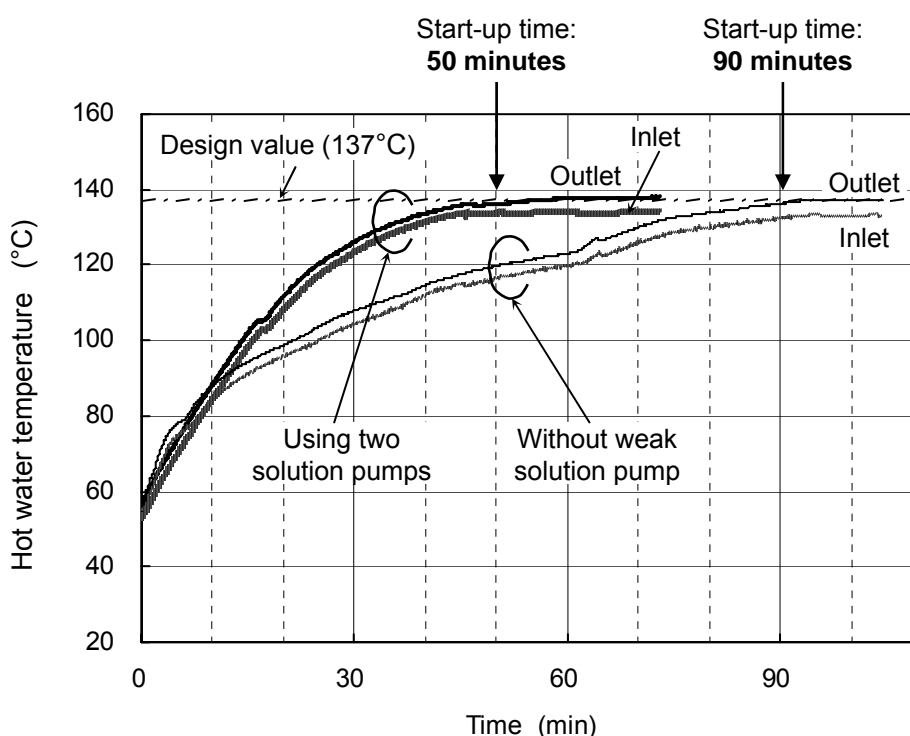


Figure 7: Effect of start-up time reduction by installing two solution pumps

5.3 Comparison with the previously reported absorption heat transformers

As described in section 3.1, the performance of our new absorption heat transformer was compared with that of the previously reported heat transformers by estimating the ratios of their COPs and TBs to their theoretical values. These values are defined in Eq. 6. (COP_{HTt} and TB_t are calculated by Eq. 3 and Eq. 4, respectively).

$$\eta_{COP} = \frac{COP}{COP_{HTt}}, \quad \eta_{TB} = \frac{TB}{TB_t} \quad (6)$$

Figure 8 summarizes this work, Susai’s machine, and Mashimo’s 11 heat transformers, which includes Sano’s machine. For the previous heat transformers, η_{COP} was almost the same value of around 88 to 90%. In contrast, η_{TB} ranged from 45 to 75%. Turning now to the absorption heat transformer developed in this work, η_{COP} and η_{TB} was 90% and 84%, respectively. The η_{COP} was almost the same value as the others, and η_{TB} clearly exceeded those of the previous heat transformers. This is the result of adopting a high performance heat exchanger to each component, e.g. the multi-pass plate heat exchanger shown in Figure 6.

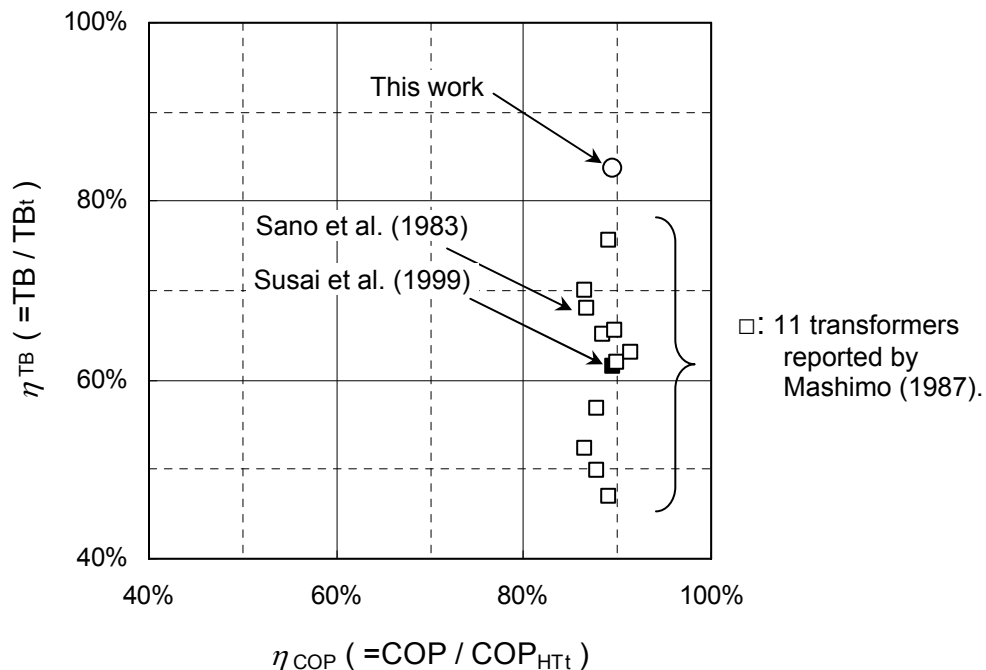


Figure 8: Comparison of this work to the former examples by η_{COP} and η_{TB}

5.4 Practical chart for further production

Figure 9 is based on the above-mentioned development and the cycle simulation, which is mentioned in section 5.1. As seen in Figure 9, the hot water heat source was available from about 70 to 95-°C. An availability condition is limited by the concentration in which crystallization of the solution is prevented, and there is a margin between the limit line in Figure 9 and the crystallization limit. We hope that the use of absorption heat transformers will spread and contribute to energy conservation and reduction of CO₂ emission in the industrial field.

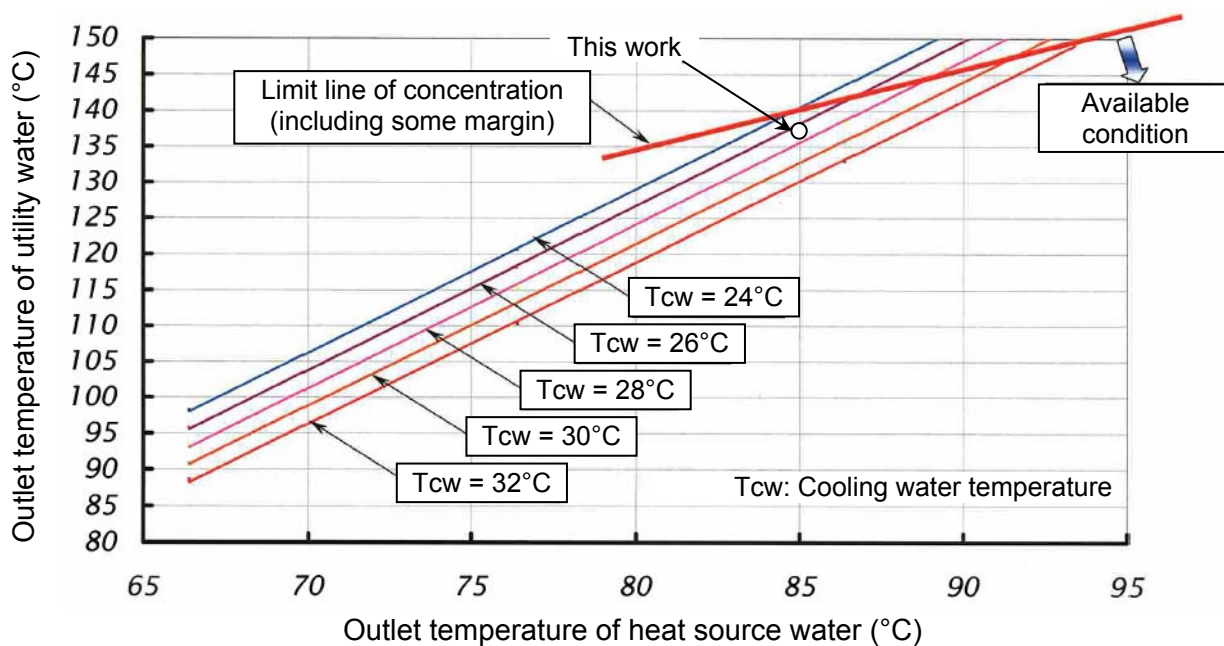


Figure 9: Practical characteristics chart

6 INSTALLATION WITH A CO-GENERATION SYSTEM

We installed our developed absorption heat transformer with a co-generation system in an industrial plant in Japan. The entire system diagram is shown in Figure 10. This plant is a factory, which produces hydraulic machinery and parts for motorbikes. In this plant, direct-fired boilers were providing the vapor for the heat demand. We introduced a co-generation system with gas engines and replaced some of these boilers with exhaust gas boilers.

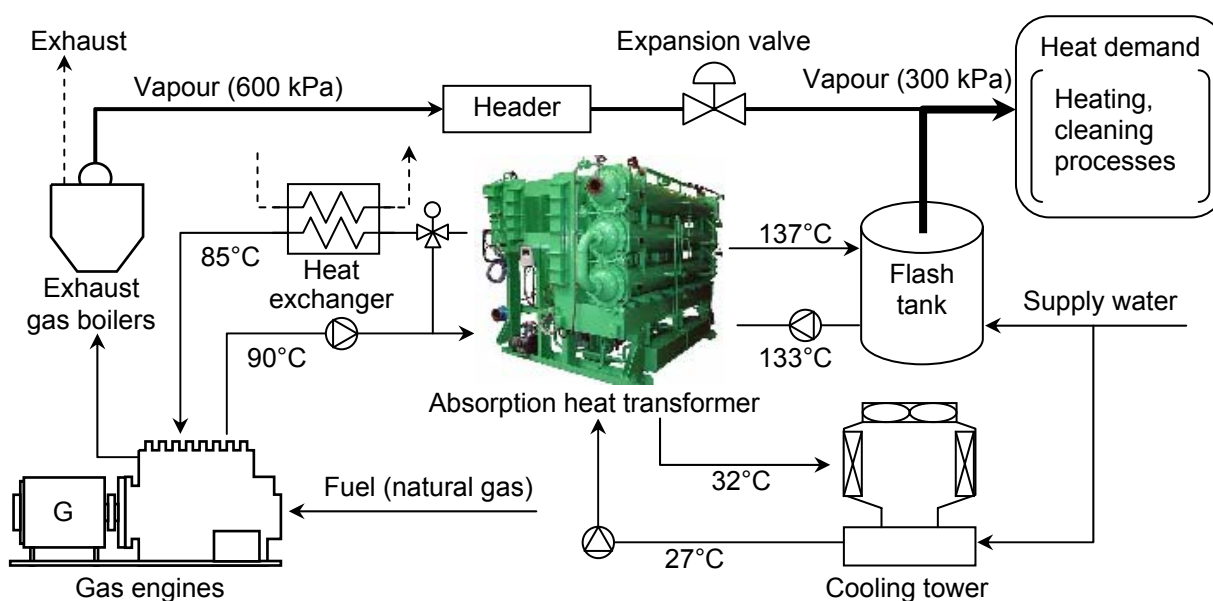


Figure 10: Installation example in an industrial plant

In this system, 90-°C water from the gas engines is applied as the heat source for the absorption heat transformer. The absorption heat transformer produced 137-°C hot water in its absorber. This water became 300-kPa vapor in the flash tank and then used for heating, cleaning, drying after painting, and so on. The maximum production of 300-kPa vapor is 250 kg/h.

This system began operation in April 2007. The total efficiency of the system is estimated to be 74.3% and 60.6% for a co-generation system without an absorption heat transformer. Thus, the efficiency is estimated to improve by 13.7% with the installation of the absorption heat transformer. Additionally, the pay back period is estimated to be less than four years assuming there are 8,000 operation hours annually. This system is presently operating as originally designed.

7 CONCLUSION

For the purpose of energy conservation in the industrial field, we have developed an absorption heat transformer driven by 90-°C waste heat with a heating capacity of 150 kW, and the following results were obtained.

- (1) The TB of the developed absorption heat transformer was 52°C, which exceeds all the previously developed heat transformers, as a single-effect cycle.
- (2) A new performance evaluation method is proposed. This method compares the absorption heat transformers designed for different output, heat source, and cooling water temperatures by estimating the ratios of their COPs and TBs to their theoretical values.
- (3) According to this method, our new machine performed better in terms of temperature boost ratio (η_{TB}) compared with other previous machines.
- (4) The COP of the developed absorption heat transformer was 0.484.
- (5) The start-up time was 50 minutes, accomplished by circulating the solution in two solution pumps.
- (6) Our developed machine was installed in an industrial plant and has been operating since April 2007 as originally designed and without any problems. In this plant, 250 kg/h of 300-kPa vapor is produced from the output of the new absorption heat transformer.

8 ACKNOWLEDGEMENTS

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