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Hajime Yabase
makita_k-krk@corp.khi.co.jp

Kazuyuki Makita

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Steam Driven Triple Effect Absorption Solar Cooling System

Hajime Yabase[1], Kazuyuki Makita[1]*

[1]Kawasaki Thermal Engineering, Research & Development Department,
Kusatsu, Shiga, Japan
Contact Information (Phone:+81-77-563-1111, Fax:+81-77-564-4353,
E-mail:makita_k-krk@corp.khi.co.jp)

ABSTRACT

The authors propose a solar cooling system employing a steam-driven triple effect absorption chiller as a new technique for saving CO_2 emission in the air conditioning field. The absorption chiller is a cooling machine using thermal energy as a drive source, and it is ideal for utilizing solar heat. In addition, by employing a triple effect absorption chiller of high efficiency, a high energy saving effect and a significant CO_2 saving effect can be expected. As a result of studies, it has been confirmed that the proposed system can reduce the energy consumption amount and the CO_2 emission by 86 percent as compared with the existing system.

1. INTRODUCTION

It is still fresh to our memory that Japan was devastated by a giant earthquake, a huge tsunami, and a horrible nuclear power accident at Fukushima Daiichi on March 11, 2011. On the occasion of these disasters, the energy structure is being reviewed not only in Japan but also in other parts of the world. In Japan, from the anxiety about safety of nuclear power plant, anti-nuclear activities are spreading widely. From the viewpoint of keeping of necessary energy, substitute energy is discussed, and expectations are heightening about natural energy, especially solar energy because of its abundant quantity.

On the other hand, long before the disasters, problems of global warning have been discussed as important issues, and reviewing of energy structure is being demanded in sufficient consideration of saving of energy and curtailment of CO_2 emission.

In this background, in the field of consumer products, we have been studying about a triple effect absorption cooling system by effectively utilizing the solar heat for the purpose of saving energy and cutting CO_2 emission in the air conditioner which is relatively high in the energy consumption rate.

Some solar cooling system that was used single-effect or double-effect absorption chiller was proposed conventionally. The system efficiency of our proposal is higher than these one. So CO_2 emission while the back up boiler is being operated is less, and also the aria of the solar thermal collector is smaller. The most special feature of our proposal is to use the triple effect absorption chiller which is high efficiency very much.

This paper proposes a high efficient triple effect absorption solar cooling system and reports its effects.

2. DISCRIPTION of SYSTEM

Fig. 1 shows a system diagram of the triple effect absorption solar cooling system (TEA-SCS). The proposed solar cooling system is composed of a triple effect absorption chiller, a solar thermal collector, a backup boiler, and accessory devices. The solar cooling system is operated as follows. During insolation, thermal energy radiated from the sun is collected by the thermal solar collector, and a hot steam of about 230ºC is obtained. The obtained steam is separated by a drain separator into saturated steam and drain, and the saturated steam is supplied into the absorption chiller. The heat is deprived of its heat by the absorption chiller, and becomes drain, and is supplied again into the solar thermal collector. On the other hand, the absorption chiller receives the steam supplied from the solar thermal collector, and uses it as heat source, and operates the absorption refrigeration cycle as mentioned below, and cools the water to about 7ºC. The cooled water is supplied to the user's side, and is utilized, for example,

in air conditioning, and is warmed to about 12ºC, and is returned to the absorption chiller. If the insolation is insufficient in nighttime or in cloudy weather, sufficient steam is not obtained, and the backup boiler is put in operation, and a stable steam is obtained in a total system.
Individual devices are described below.

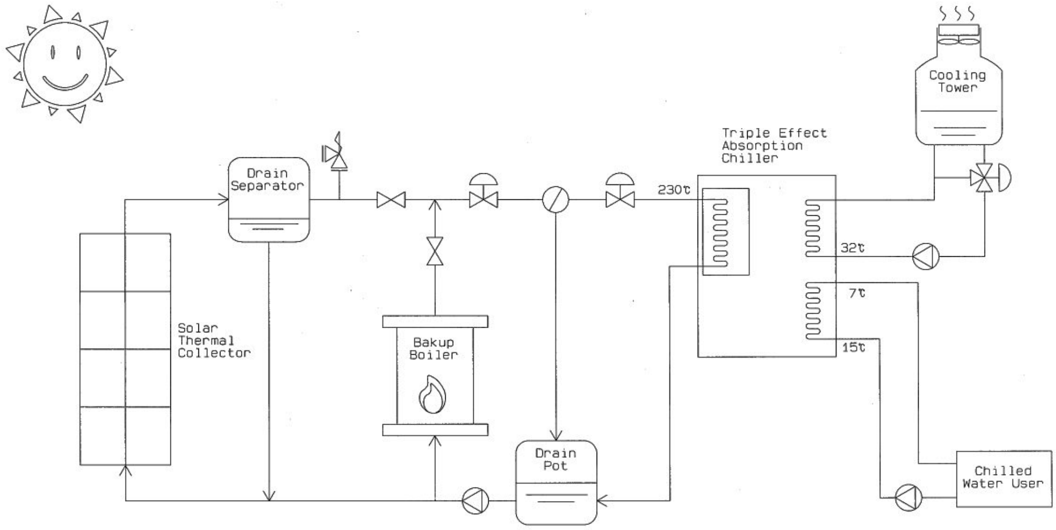


Fig. 1 System diagram of TEA-SCS.

3.TRIPLE EFFECT ABSORPTION CHILLER

3.1 Direct-fired Triple Effect Absorption Chiller

The steam-driven triple effect absorption chiller is based on the existing technology of direct-fired triple effect absorption chiller. The direct-fired triple effect absorption chiller was developed from September 2001 to March 2005, as part of operations of New Energy Development Organization.[1),2)] Four manufacturers in Japan participated in the development. After further feasibility studies, the chiller was put in practical use in 2005.
The triple effect chiller is based on the conventional double effect chiller, and is newly combined with high-temperature and high-pressure generators. As shown in the principle diagram of the triple effect chiller in Fig. 2, three generators are used in total (high-temperature, medium-temperature, and low-temperature), and the heat of high temperature generated in the high-temperature generator is sequentially used in the generators of lower temperatures.

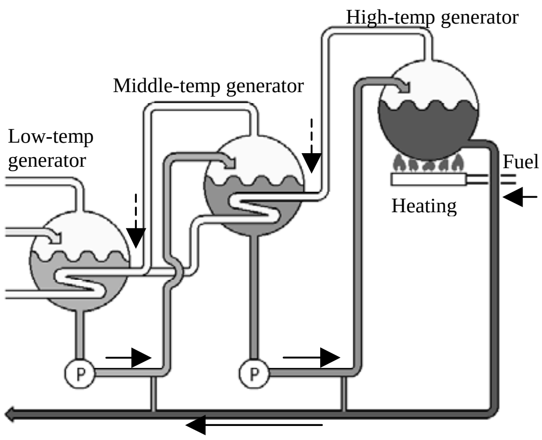


Fig. 2 Principle of triple effect chiller.

More specifically, the absorption liquid in the medium-temperature generator is heated by the refrigerant steam generated in the high-temperature generator, and further the absorption liquid in the low-temperature generator is heated by the refrigerant steam generated in the medium-temperature generator. In this manner, a high coefficient of performance is obtained by utilizing the first heat input into the high-temperature generator effectively in three steps (or two steps in the double effect type) gradually from high temperature level to low temperature level.

In the multiple-effect chiller, as mentioned above, the absorption liquid in the low-temperature generator is heated by the refrigerant steam generated in the high-temperature generator, and therefore the temperature of the refrigerant steam generated in the high-temperature generator must be higher than the saturation temperature of the absorption liquid in the low-temperature generator. The steam pressure of the high-temperature generator of the currently operating direct-fired triple effect absorption chiller is about 0.2 MPa, and the absorption liquid temperature is about 200ºC. In order to handle the absorption liquid of such high temperature and high pressure, a high-temperature generator must be manufactured as a boiler, and corrosion suppressive measures are needed.
Fig. 3 shows an outline of the direct-fired triple effect absorption chiller developed by solving the problems, designing the constituent elements efficiently and compactly, and optimizing the control. An outline specification is shown in Table 1, and in the case of direct-fired type, the COPcmb is calculated in the following formula.

COPcmb = Qout/(G•h/3600)
where Qout: refrigeration output [kW]
G: fuel gas flow rate [m^3N/h]
h: low-temperature heat generation of fuel gas [kJ/m^3N]

Table 1. Specification of direct-fired triple effect absorption chiller.

Cooling Capacity	563kW to 1,196kW
Chilled Water	Inlet 15ºC Outlet 7ºC
Cooling Water	Inlet 32ºC
Heat Source	Natural Gas
COP	1.74

A partial load characteristic of the direct-fired triple effect absorption chiller is as shown in Fig. 4, and the ratting point is 1.74, and it may reach as high as 1.85 in a load region of 50 to 70% of frequent practical use. The efficiency of the direct-fired triple effect absorption chiller is evidently highest in the world in the total load region.
In Japan, more than 20 units of direct-fired triple effect absorption chiller are installed. The oldest machine was installed in May 2006, and is operating for more than 35,000 hours so far. In this period, no fatal problem was reported, and a stable operation is continuing. Sites of installation include hospitals, office buildings, and factories, for air-conditioning applications and process applications.

Fig. 3 Outline of direct-fired triple effect absorption chiller.

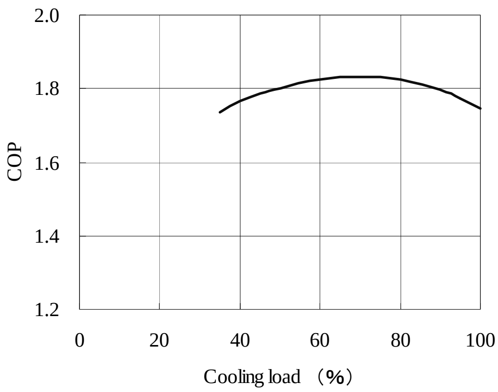


Fig. 4 Partial load characteristics of triple effect absorption solar cooling system

3.2 Steam-fired Triple Effect Absorption Chiller (our proposal)

Fig. 5 shows a cycle flow of our proposed steam-fired triple effect absorption chiller. The steam-fired triple effect absorption chiller is based on the direct-fired triple effect absorption chiller, in which only the high-temperature generator is modified from the boiler to a heat exchanger for recovery of steam heat source. The basic cycle is not changed, and elements of new development are concentrated on the steam-fired high-temperature generator, while other elements can be chosen from the existing technology of the controller, the control software, and others. As a result, in the stage of development of practical machine, a successful development is promised in a short term. In addition, the high-temperature generator of new development is similar in structure to the high-temperature generator

of the steam-fired double effect absorption chiller, and by slightly modified to be applicable to high temperature and high pressure, it may be applied as a high-temperature generator for the steam-fired triple effect absorption chiller.
Next, the efficiency of steam-fired absorption chiller is discussed. To discuss the efficiency of steam-fired absorption chiller, we often use the index called steam consumption rate. The steam consumption rate is a steam consumption amount per unit time and per unit refrigeration capacity, and it is usually expressed in the unit of kg/(h･USRT). This index is widely used because it is easy to understand for general users. The index of steam

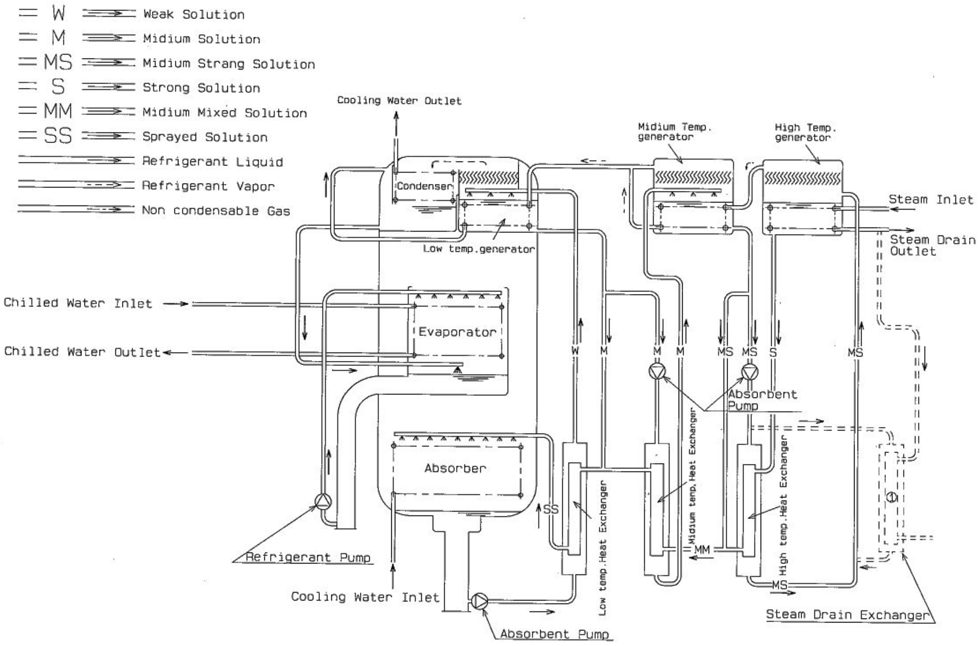


Fig. 5 Cycle flow of steam-fired triple effect absorption chiller.

consumption rate is useful for evaluation efficiency of devices in the condition of equivalent values of heat source steam, and transitional use. For example, when comparing the widely distributed double effect chillers, it is very easy to understand to determine which machine is smaller in the steam consumption rate, that is, lower in the fuel cost. However, in the steam consumption rate, nothing is evaluated about the quantity of heat possessed by the heat source steam drain discharged from the chiller. This evaluation is reasonable as far as the heat source steam drain is not recycled. However, today, saving of energy is very important, and the heat possessed by the heat source steam drain often recycled, and the machine efficiency cannot be evaluated by the steam consumption rate. It is hence regarded reasonable to evaluate by COPstm expressed in the following formula.

$$COPstm = Qout/(Gst \cdot (hst-hdr)/3600)$$

where Qout: refrigeration output [kW]
Gst: heat source steam flow rate [kg/h]
hst: heat source steam specific enthalpy [kJ/kg]
hdr: exhaust drain specific enthalpy [kJ/kg]

In the denominator of COPstm formula, the specific enthalpy difference at the inlet and outlet of the heat source steam is calculated, and it is known that the performance of evaluated by the net amount of heat supplied in the high-temperature generator of the chiller. On the other hand, in the COPcmb, the amount of heat removed by the exhaust gas is not taken into consideration. That is, the denominator of COPcmb formula is the

Table 2. Design specification of steam-fired triple effect absorption chiller

Steam Drain Exchanger		Without	With
Cooling Capacity	kW/RT	3.52	
Steam Inlet Temperature	℃	230(Saturated)	
Steam Inlet Specific Enthalpy	kJ/kg	2803	
Steam Drainage Temperature	℃	228	150
Steam Drainage Specific Enthalpy	kJ/kg	981	632
Steam Consumption (mass)	kg/(h･RT)	3.62	3.10
Steam Consumption (heat)	kW/RT	1.83	1.87
COPstm	-	over 1.9	less than 1.9

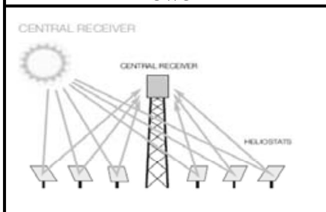
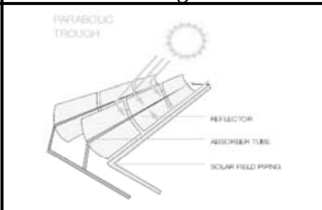
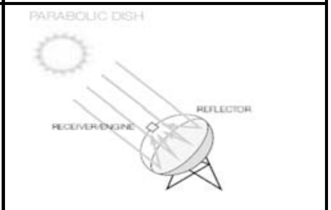
※ Chilled Water 15→7℃, Cooling Water 32℃

value obtained by dividing the net amount of heat supplied in the high-temperature generator of the chiller by the boiler efficiency. In short, COPcmb and COPstm are evidently different, and they cannot be evaluated similarly, and due attention is needed.
Herein, let us suppose the steam-fired chiller is provided with a drain heat collector in one case, and not provided in other case. Both design specifications are shown in Table 2. The two machines are identical, except for presence or absence of drain heat collector. The drain heat collector is installed at a position of ① in Fig. 5. When the drain heat collector is not provided, the estimated COPstm is over 1.9, and the steam consumption rate is 3.62 kg/ (h・USRT). When provided with the drain heat collector capable of collecting heat up to 150ºC, the estimated COPstm is less than 1.9, and the steam consumption rate is 3.10 kg/ (h・USRT). In the solar cooling system, since the heat source steam system is a closed loop, the amount of heat consumed by the chiller must be directly heated by the solar collector. That is, regardless of the magnitude of the steam consumption rate, a machine of a smaller consumption heat amount per unit cooling capacity is needed, that is, a machine of a larger COPstm is preferred. Therefore, as the steam-fired triple effect absorption chiller for use in solar heat air conditioning application, the drain heat collector is not needed. In the present proposal, therefore, without using the drain heat collector, only the latent heat of the heat source steam is collected by the high-temperature generator. However, it is required to collect drain of high temperature and high pressure, and its possibility must be also discussed. More specifically, the circulation pump, heat exchanger, controller, other auxiliary machines, ad also the solar heat panel and closed heat source steam system must be all selected from those usable at high pressure and high temperature of 3 MPa and 230ºC. Although the detail is omitted, we confirmed there are certain usable machines by checking generally and widely.

3. SOLAR THERMAL COLLECTOR

For driving a triple effect absorption cooling cycle, heat source steam of about 230ºC is necessary. At the present, a focusing type collector is proposed as a solar heat collector capable of supplying steam of about 230ºC. The focusing type collector includes various types, such as tower type, trough type, and dish type. Individual features are summarized in Table 3. Each collector has its suited steam temperature and steam supply amount, and may be used in individual suited applications. For example, the tower type is very high in construction cost, and is large in scale, and hence requires high temperature and high pressure, and it is suited to large-scale power generation plant, but is not suited to medium scale or supply of steam of medium temperature as required in the solar cooling system.

Table 3 Features of light-concentrating type collector

	Tower	Trough	Dish
			
Suitable application	・Large-scaled power generation	・Middle-scaled power generation ・Solar cooling	・Small-scaled power generation
Features	・Possible to heat up to 1000ºC ・Because of high initial cost, unsuitable for applications other than Large-scaled power generation. ・High technology is required for control of heliostat.	・Possible to heat up to 400ºC ・As to power-generation purpose, heating-up capacity is low but as cooling purpose, sufficient power can be obtained. ・Connection of modules enables application with wide capacity.	・Possible to generate power even in a small area. ・Suitable for combination with stirling engine.

The leaner fresnel type collector (Fig.6) that is similar to the trough type is suited to medium scale or supply of steam of medium temperature as required in the solar cooling system.

Features of linear Fresnel type collector are as follows.

- A sufficient long experience as collector for solar cooling system (see, for example, Fig.7).
- In particular, moving parts are light in weight, and small in driving energy.
- The entire weight is light, and the space for installation is not limited.
- Small in the area exposed to wind, and applicable in strong wind districts.
- Relatively easy to adjust the focus to the liquid phase, and a stable performance can be expected both thermally and mechanically.
- Overheating can be avoided easily by de-focusing.
- Small in dead space, and easy to dispose densely.
- Relatively easy in maintenance, especially cleaning.

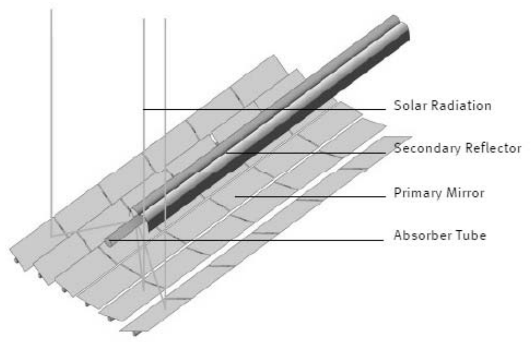


Fig. 6 Leaner Fresnel type collector

Fig. 7 Use results of Leaner Fresnel type collector (Qatar)

4. SIMULATION AND COMPARISON

The proposed steam-fired triple effect absorption cooling system was compared with the existing system. The comparative existing system examples were selected from the most popular gas-fired double effect absorption cooling system, the solar heat double effect steam absorption cooling system, double effect gas-fired and solar heat hybrid system, and triple effect gas-fired and solar heat hybrid system. In these hybrid systems, the heat source is hot water of about 90ºC collected from solar heat and the combustion heat, and the absorption chiller utilizing these heat sources is the core of the solar air-conditioning system. This system is already put in practical use in both

Fig. 8 Use example of double effect hybrid solar cooling system (Japan)

Fig. 9 Use example of triple effect hybrid solar cooling system (Japan)

double effect and triple effect absorption chillers. Example of the hybrid solar air-conditioning system are shown in Figs. 8 and 9.
The system configuration of the comparative systems and the types of heat source are summarized in Table 4.

Table 4 System configuration of the comparative systems and the types of heat source

	A Our proposal	B	C	D	E
Refrigeration machine	Steam-fired triple effect	Steam-fired double effect	Gas-fired double effect	Hybrid double effect	Hybrid triple effect
Collector	Present	Present	Absent	Present	Present
Backup method in the absence of insolation	Boiler	Boiler		Refrigerating machine combustor	Refrigerating machine combustor
In the presence of insolation	Solar heat	Solar heat	Gas combustion	Gas combustion + solar hear	Gas combustion + solar hear
In the absence of insolation	Boiler (gas combustion)	Boiler (gas combustion)	Gas combustion	Gas combustion	Gas combustion

Fig. 10 shows the heat source input heat amount per output 1RT in cooling rated operation in each system. The hatching area shows the heat input from the solar heat collector, and the blank area shows the heat input by gas combustion. Fig. 11 shows the installation area of the solar heat collector of each system in the case of designing of solar heat collector at the heat collection amount of 0.5 kW/m^2.
From these diagrams, it is known that the proposed system is capable of reducing the collector installation area by 30% as compared with the conventional steam-fired double effect system.
Fig. 12 shows the heat source input heat amount per cooling output of 1 RT in the case of use of each system by the backup by fuel in the absence of insolation in nighttime or in cloudy weather. In this case, the heat source input heat is completely supplied from the fuel. Due to difference in the boiler efficiency, it is inferior to the hybrid triple effect system, but if solar heat is not obtained, it is known that this system is excellent in energy-saving performance.
Fig. 13 shows the fuel consumption amount supposing the insolation to be present in 80% and absent in 20 percent during the entire cooling operation. In the case of this operation pattern, the proposed system is capable of saving the fuel consumption by 26% as compared with the existing steam-fired double effect system, or 86% from the direct-fired double effect system. That is, the CO_2 emission can be reduced by the same percentage.

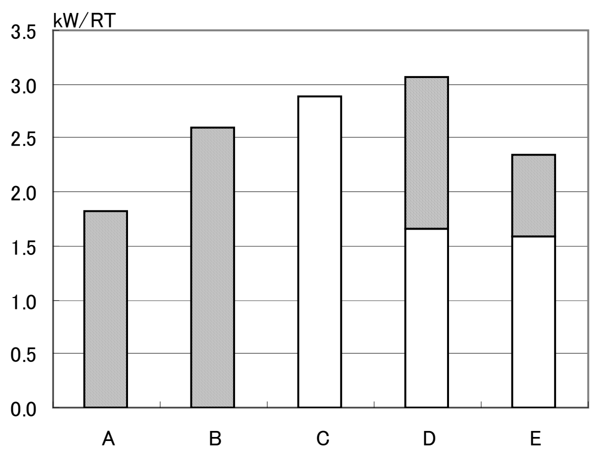


Fig. 10 Heat source heat input amount per 1RT output (during rated cooling operation)

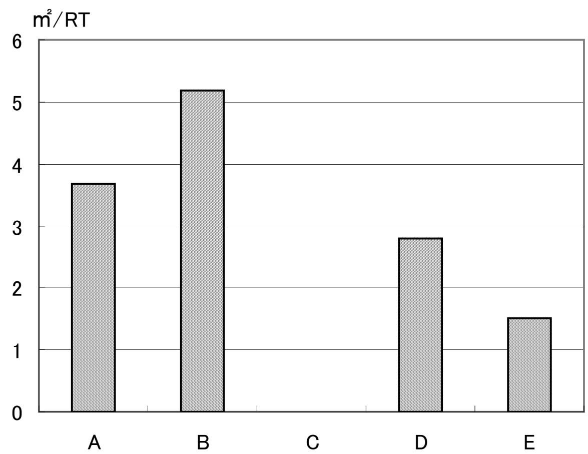


Fig. 11 Installation area of solar heat collector

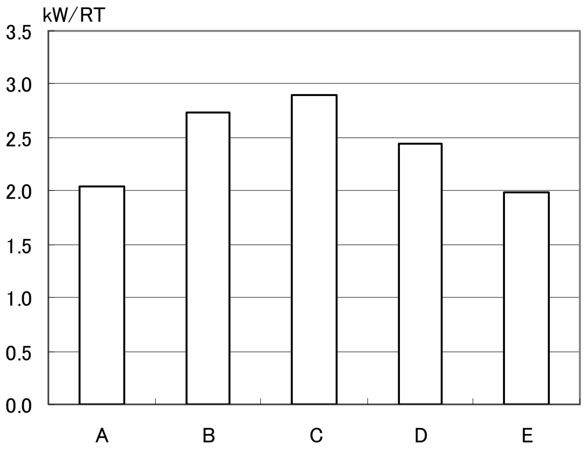


Fig. 12 Heat source heat input amount per 1RT output (during backup operation)

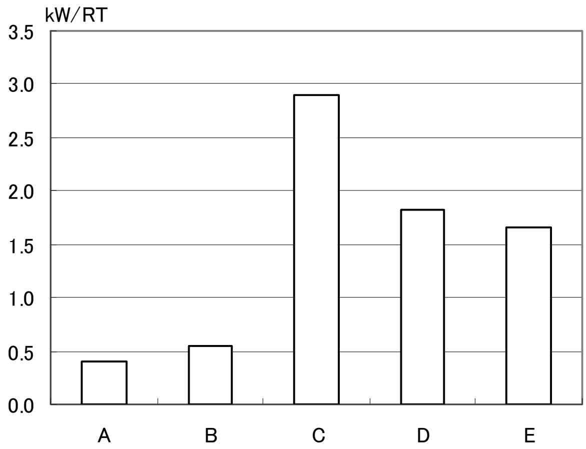


Fig. 13 Fuel consumption during cooling operation (in case of 80% solar irradiation)

5. CONCLUSIONS

The results of the present studies are summarized as follows.

- We proposed a steam-driven triple effect absorption chiller capable of realizing a rated COPstm of over 1.9, on the basis of the direct-fired triple effect absorption chiller as the key element of solar cooling system.
- The linear Fresnel type is proved to be effective as an example of solar collector for realizing this proposal.
- A new solar air-conditioning system is proposed by combining the existing technology and the newly proposed technologies.
- The proposed system is compared with the existing systems, and its superiority is presented.
  - As compared with the solar air-conditioning system based on the existing steam-fired double effect chiller, it is possible to save the fossil fuel and CO_2 emission by 26%, or 86% as compared with the direct-fired double effect chilling system.
  - As compared with the solar air-conditioning system using the existing steam-fired double effect chiller, the installation area of the solar collector can be saved by 30%.

The future problems to be solved are as follows.

- Feasibility test in actual plant.
- Execution of more realistic simulation by combining with the cooling load model, insolation model, weather model, and partial load characteristics of the refrigerating machine.

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