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Solar Rankine Cycle System Using Scroll Expander*

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Abstract
A unique solar thermal electric system is proposed and tested in the present study. In this system, an organic working fluid, which is suitable for a temperature range appropriate for solar energy, is adopted. We call this system as “solar organic Rankine cycle system” (SORCS). In order to improve the thermal efficiency by using solar energy, a displacement-type scroll expander and compound parabolic concentrator (CPC) solar collector are used. This system consists of very simple components that are similar to the ones used in an air conditioner and is very cost effective. The present paper reports on the experimental results of the scroll expander unit and the practical operation of the proposed SORCS under actual solar radiation input. The total thermal efficiency of the present SORCS attains 7% (42% when cooling water is used for the cogeneration system).

Key words: Organic Rankine Cycle, Solar Thermal Electric, Solar Energy, Low-Temperature Difference, Scroll Expander, Organic Working Fluid, Cogeneration System

1. Introduction

In recent years, environmental problems such as the heat island phenomenon and global warming caused due to carbon dioxide (CO_2) emissions have surfaced. In addition, due to the expected increase in the world population at the end of the 21st century, it is feared that fossil fuels will be exhausted. For these reasons, there is an increased demand for new energy systems that actively use renewable energy and emit a smaller amount of CO_2, such as the hydrogen fuel system, solar power generation system and waste heat recovery system.

On the other hand, the existing energy systems, particularly power plants, have increased in size and have become more centralized. This forces such power plants to be built in areas far from the locations where the electricity is actually required, that is, urban areas. As a result, power loss occurs during distribution and waste heat from the power plants is not effectively used. Moreover, there are possibilities of an electricity breakdown, due to the shutdown of nuclear power plants, as was recently witnessed in the Kanto region. This shows the fragility of modern society if it depends on large-scale power plants.

Thus, distributed power generation systems that are located at specific locations such as

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residential homes, supermarkets, hotels, hospitals and public buildings are of considerable importance. Heat sources such as hydrogen and biogases are desirable for power generation. In addition, combustion heat, solar energy and other forms of waste heat are also preferable as low-temperature heat sources. Nevertheless, the thermal efficiency of energy recovery from low-temperature heat sources by using the existing systems is considerably low. Hence, their practical applications and implementations are being avoided even today.

In this paper, we propose and develop a new and unique Rankine cycle system that includes a scroll expander; we aim to provide high efficiency particularly for a small-sized distributed power generation system. This system operates as a heat source in the temperature range of 200°C and below, and it also uses solar energy, which is clean and inexhaustible. In order to obtain high efficiency, an organic working fluid was selected. Hence, this system is known as the solar organic Rankine cycle system (SORCS). In this paper, the thermal and total efficiencies based on the solar radiation are examined, and the possibility of implementing system and its feasibility are studied.

Nomenclature

G	: Flow rate of working fluid, kg/s
h	: Enthalpy, kJ/kg
H	: Wrap height, mm
I	: Average solar radiation at CPC collector surface, W/m^2
n	: Rotational speed, rpm
p	: Pressure, MPa
Δp	: Pressure difference at expander, MPa
Q_s	: Total solar radiation at solar collector aperture, W
t	: Wrap thickness, mm
T	: Temperature, °C or K
T_{rq}	: Torque, N·m
V	: Suction volume, cm^3/rev
W	: Scroll expander power output, W
η_c	: Solar collector efficiency
η_e	: Expander efficiency
η_{net}	: Rankine cycle net efficiency
η_o	: System efficiency
η_{th}	: Theoretical Rankine cycle efficiency
η_{total}	: Total efficiency based on solar radiation

Subscripts

a	: Ambient
in	: Collector inlet
out	: Collector outlet
t,in	: Expander inlet
t,out	: Expander outlet
$tank$	: Accumulator
w	: Cooling water
1,2,3,4	: p-h diagram position

2. Solar Organic Rankine Cycle System; SORCS

2.1 System Outline

By using of low-temperature heat sources, the Rankine cycle has a relatively higher thermal efficiency as compared to other heat cycles [(4)]. The conventional Rankine cycle comprises five components, namely, the working fluid, heater, expander, condenser and compressor (or pump). In the present SORCS, solar collectors are added and they function as heaters. In addition, the accumulator and evaporator are also added to the system; thus, the SORCS has seven components. A schematic diagram of the SORCS is shown in Fig.1. By using the accumulator, instabilities in the power supply are avoided; instability is a feature specific to the use of renewable energy since it depends significantly on the daily and seasonal weather conditions. Electric load leveling is also accomplished.

In the SORCS, water is used as the primary working fluid and it is heated in the solar collector. The generated steam is transferred to a heat exchanger where heat is transferred to the organic working fluid in the secondary loop at the evaporator. Subsequently, the heated organic working fluid becomes a high-pressure vapor in the evaporator; it is then introduced into the expander, thereby rotating the generator. The vapor exhausts from the expander is cooled and condensed at the condenser; it then flows downward into the surge tank before being refed to the evaporator by using the pump.

In general, expanders can be classified into two types; one is the velocity type and includes expanders such as axial turbines, and the other is the volume type, for example, scroll expanders and reciprocal expanders.

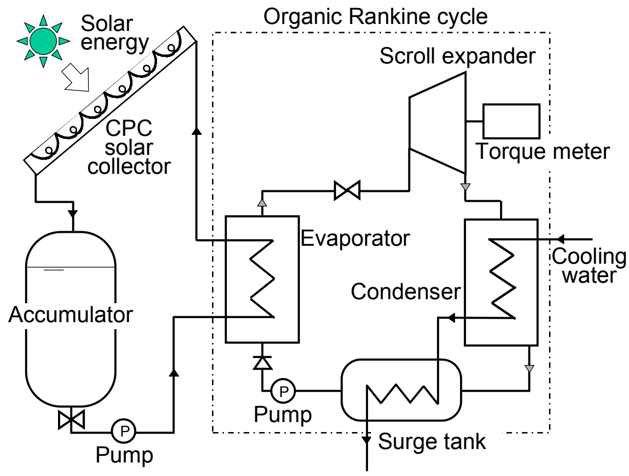

Fig. 1 Schematic diagram of solar organic Rankine cycle system

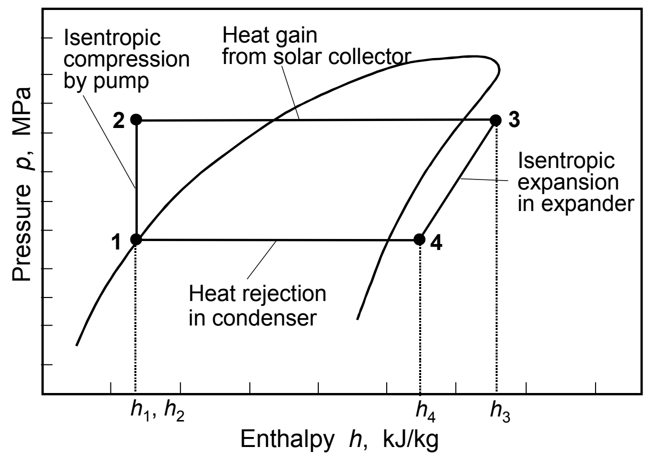

Fig. 2 *p-h* diagram of Rankine cycle

Figure 2 shows the *p-h* diagram of a Rankine cycle using the organic working fluid. Process 1→2 implies an increase in the pressure resulting from using the pump. Due to the high density of the working fluid, the work done by the pump during compression is small as compared to the work done by the expander. Process 2→3 is the heating process in the solar collector. Process 3→4 is the isothermal expansion in the expander, and process 4→1 indicated the cooling and condensation in the condenser.

2.2 Scroll Expander

In this study, we assume that the SORCS will be applied as a small and distributed power generation system; hence, the temperature difference at the expander is in the range of 100~200°C, and the output power of the SORCS is expected to be of the order of several hundred watts to several kilowatts. Generally, the theoretical Rankine cycle efficiency is low for such small temperature differences. Thus, it is important to achieve high efficiency for the expander process. However, there are only a few researches that have developed expanders with high efficiency at such small temperature differences.

In order to meet the abovementioned demands, we apply the scroll expander, which is expected to have high efficiency even for low-power specifications. The scroll-type fluid machinery is conventionally applied as a scroll compressor in air conditioners with small capacity; however recently, it has been developed for use as a scroll expander. Yanagisawa et al. [(7)] have modified the scroll compressor that is employed in automobiles for air conditioning systems and have measured its operating performance. Nagatomo et al. [(8)-(10)] have constructed an air conditioning system based on the Rankine cycle by using a scroll expander and have reported its performance. Saitoh et al. [(11)] have developed a new Rankine cycle system by using a scroll expander in which water vapor is used as the working fluid and solar energy is used as the heat source. They showed that the total efficiency of 5% based on solar radiation.

In Fig.3, the conventional operational cycle of the scroll expander is shown. In the scroll expander, two wraps having a swirl shape are combined; one wrap is fixed and the other rotates. In the cycle, when the rotational direction of the moving wrap coincides with the swirl, the space between the two wraps will decrease and they work as a compressor. When the wraps rotate in opposite directions, the space will increase and they work as an expander. In this research, the scroll compressor employed in an automobile air conditioner is modified and used as a scroll expander. The principal specifications of the scroll expander are listed in Table 1.

Table 1 Specifications of scroll expander

Suction volume	*V*	60	cm^3/rev
Scroll wrap curve		Involute	
Wrap height	*H*	50	mm
Wrap thickness	*t*	3.5	mm

2.3 Organic Working Fluid

In this research, solar energy is assumed to be the heat source; the heat source has a temperature range of 100°C to 200°C (in the summer, the range may become 220°C to 230°C). We tested and adopted the organic working fluid R113 ($C_2Cl_3F_3$), which is expected to yield high efficiency for low temperature ranges. Hung et al. [(12)] and Hung [(13)] have proved that R123 and R113 are effective organic working fluids when used in the organic Rankine cycle for energy recovery systems extracting energy from low-temperature waste heat. Yamamoto et al. [(14)] adopted R123 in their organic Rankine cycle system that used a radial-type microturbine as the expander, and clarified its performance both theoretically and experimentally.

However, R113 is one of the standard chlorofluorocarbons that has high ozone-depleting potential (ODP), and its production has already been prohibited. Furthermore, the regulations concerning the recovery and destruction of fluorocarbons have been enforced, and releasing R113 into the atmosphere is strictly prohibited since April 1, 2002.

From the viewpoint of engineering and environmental ethics, the use of such chlorofluorocarbons should be avoided in new developments. Therefore, in the future, the SORCS will require an alternative working fluid that has a similar thermal efficiency as that of R113. Two candidates have already been examined: HFC and R-600a. In this study, for the purpose of comparison and verification of previous researches (12) ~ (14) R113 was used with great care and strict safeguards to prevent its leakage into the atmosphere.

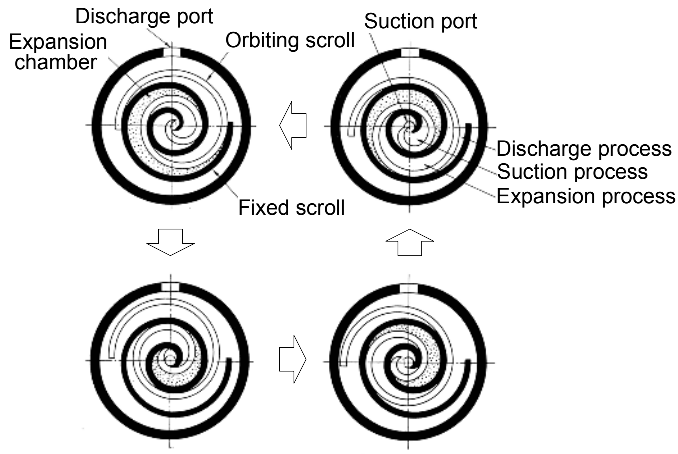

Fig. 3 Operational cycle of scroll expander

Table 2 Comparison of thermal properties between water and R113

Substance	Units	Water	R113
Boiling point*1	°C	100	47
Freezing point*1	°C	0	–35
Saturated vapor pressure*2	MPa	1.6	2.8
Latent heat*2	kJ/kg	1939	54
Specific volume*2	m^3/kg	0.127	0.00379
Specific heat at constant pressure*3	kJ/(kg·K)	4.179	0.96
Kinematic viscosity*2	10^{-6} m^2/s	2.01	0.0738

*1: Values at 0.1 MPa, *2: Values at 200°C, *3: Values at 20°C

The thermal properties of water and R113 are listed in Table 2. In comparison to the Rankine cycle using water, the organic Rankine cycle has a smaller latent heat and lower boiling temperature, as shown in Table 2. These properties will cause the organic Rankine cycle to have higher thermal efficiency for the operating condition involving small temperature difference, which is an important advantage. In addition, the organic Rankine cycle can be used as a bottoming cycle for energy recovery systems extracting energy from various low-temperature heat sources.

2.4 Solar Collector

In the proposed SORCS, solar collectors work as heaters and their performance is directly linked to the total efficiency of the SORCS, i.e., higher thermal efficiency of the solar collectors will lead to higher total efficiency of the SORCS. Hoshi and Saitoh (16) have developed a compound parabolic concentrator (CPC) solar collector. A nontracking CPC solar collector has higher efficiency as compared to that of conventional flat-plate type and evacuated-tube type collectors in the heat source temperature range of 100~200°C. In this study, we used a trough-type (i.e., two dimensional) CPC solar collector (2D-CPC).

2.5 Theoretical Efficiency of the SORCS

The system's total efficiency on the basis of the solar radiation can be obtained by using the following equation:

$$\eta_{total} = \eta_c \times \eta_{net} = \eta_c \times \eta_{th} \times \eta_e \times \eta_0 \tag{1}$$

where η_c is the solar collector efficiency of the CPC solar collector; η_{net}, the Rankine cycle net efficiency of the organic Rankine cycle system, which indicates the area sectioned by the dotted line in Fig. 1; η_{th}, the organic Rankine cycle theoretical efficiency calculated according to the *p-h* diagram of the Rankine cycle and eqn. (2); η_e, the expander efficiency calculated by dividing the actual output W by the flow rate of the working fluid G and the enthalpy difference $(h_3 - h_4)$ obtained from the accumulator and cooling water temperatures, as shown in eqn. (3); and η_0, the system efficiency that is mainly described by the total heat loss of the system.

$$\eta_{th} = \frac{h_3 - h_4}{h_3 - h_1} \tag{2}$$

$$\eta_e = \frac{W}{G(h_3 - h_4)} \tag{3}$$

For example, if the accumulator temperature T_{tank} is 200°C and the cooling water temperature is 20°C, η_{th} will become approximately 28%. Assuming that the expander efficiency η_e and η_c are less than or equal to 80%, η_0 is ideally 100%; subsequently, theoretical η_{net} will become 22.4% and η_{total} will attain 17.9%.

3. Experimental Result

3.1 Experimental Apparatus

After assembling the SORCS using the abovementioned components, experiments for the output characteristics of the scroll expander and autonomous operation tests using solar radiation were conducted. Figure 4 shows the prototype of the SORCS. The principal specifications of the system are also mentioned in Table 3. The system comprises the CPC solar collector (with an effective area of 5.75 m^2), accumulator, evaporator, condenser, scroll expander, surge tank and pump, as shown in Fig. 1. The measurement system for the data acquisition consists of torque and rotational speed meters, a data logger and a PC. The temperature at each point, pressure and solar radiation are stored in the PC through the data logger.

3.2 Output Characteristic Test the Scroll Expander

At first, in order to clarify the scroll expander's performance, the accumulator will be filled with hot water having a temperature of 140°C and the water is circulated through the evaporator. Thus, the evaporator is constantly at a high temperature. Subsequently, the R113 vapor will flow into the scroll expander and the output characteristics of the expander will be determined. Table 4 lists the experimental conditions of the output performance test. The temperature of the accumulator tank, T_{tank} is held constant at 140°C during the system operations by using the installed electrical heater.

Figure 5 shows the relation between the rotational speed, torque and output power of the scroll expander. The maximum output power is approximately 450 W at 1800 rpm under the condition that the pressure difference at the expander is 0.9 MPa, the accumulator temperature T_{tank} is approximately 140°C, and the condenser temperature T_w is 20°C.

The efficiencies are calculated from the results obtained at the maximum output power are summarized in Table 4, where the expander efficiency is 63%, Rankine cycle efficiency is 13%, and the theoretical thermal efficiency is 22%.

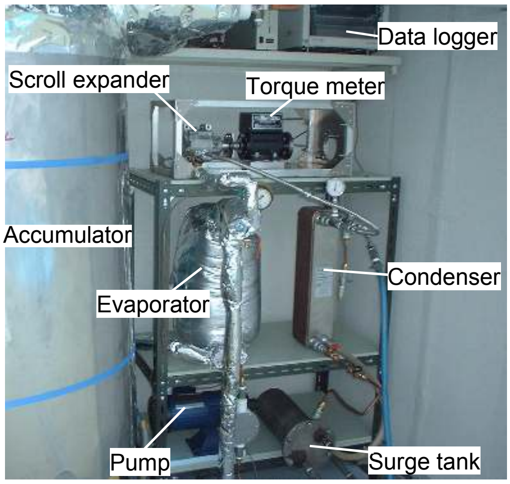

Fig. 4 Photograph of the SORCS

Table 3 Specifications of the SORCS

CPC Solar collector	Area	5.75 m^2
	Tilt angle	45°
	Azimuth angle	0°
	Glazing	Double glazing glass (filled with Kr gas)
Accumulator	Capacity	200 L
Evaporator and condenser	Heat transfer area	24 m^2 (Plate-type)
Pump	Flow rate	0.6 L/min
Working fluid	Collector circuit	Water
	Expander circuit	R113 ($C_2Cl_3F_3$)

Table 4 Experimental conditions and results of output characteristic test for scroll expander

Ambient temperature	T_a	30	˚C
Accumulator temperature	T_{tank}	140	˚C
Expander inlet temperature	$T_{t,in}$	136	˚C
Expander outlet temperature	$T_{t,out}$	80	˚C
Pressure difference at expander	Δp	0.9	MPa
Cooling water temperature	T_w	20	˚C
Flow rate of working fluid	G	0.016	kg/s
Output power (at 1800 rpm)	W	450	W
Expander efficiency	η_e	63	%
Theoretical Rankine cycle efficiency	η_{th}	22	%
Rankine cycle efficiency	η_{net}	12	%

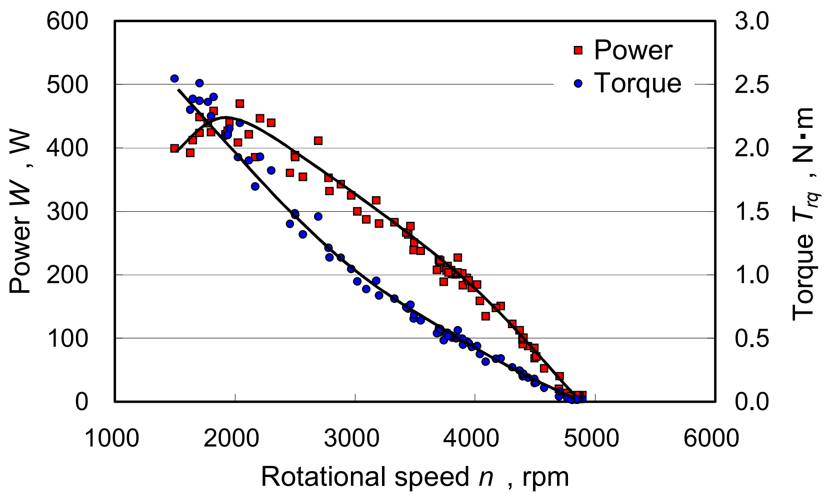

Fig. 5 Output power and torque curve of scroll expander

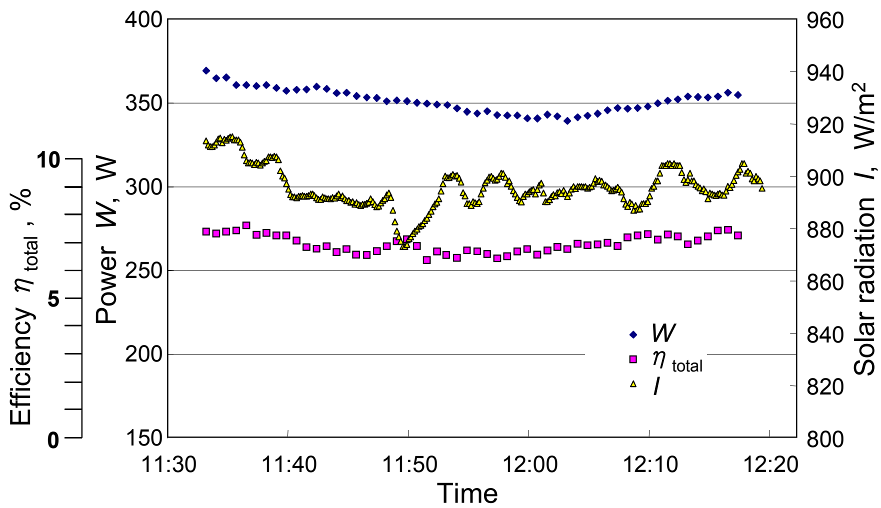

Fig. 6 Experimental thermal efficiency and output power for practical operation

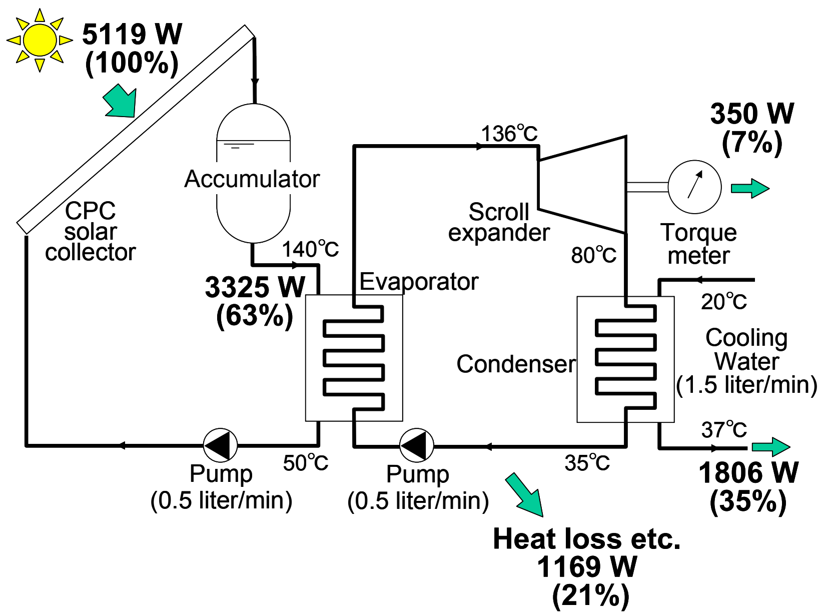

Fig. 7 Energy flow in the practical operation of SORCS

Table 5 Experimental results for the practical operation of SORCS

Ambient temperature	T_a	30	˚C
Average solar radiation at CPC solar collector surface	I	890	W/m^2
Inlet temperature of CPC solar collector	T_{in}	50	˚C
Outlet temperature of CPC solar collector	T_{out}	140	˚C
Accumulator temperature	T_{tank}	140	˚C
Expander inlet temperature	$T_{t,in}$	136	˚C
Expander outlet temperature	$T_{t,out}$	80	˚C
Pressure difference of expander	Δp	0.83	MPa
Cooling water temperature	T_w	20	˚C
Flow rate of working fluid	G	0.013	kg/s
Total solar radiation at collector surface	Q_s	5119	W
Power produced by scroll expander	W	350	W
Collector efficiency	η_c	63	%
Rankine cycle efficiency	η_{net}	11	%
Theoretical Rankine cycle efficiency	η_{th}	22	%
Expander efficiency	η_e	65	%
System efficiency	η_o	79	%
Total efficiency	η_{total}	7	%

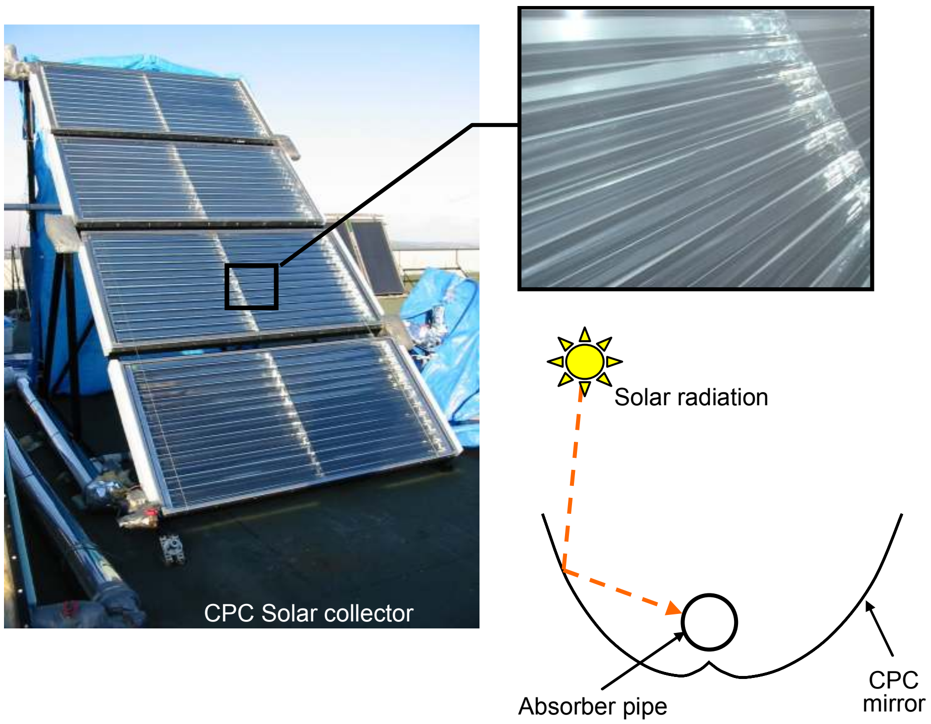

Fig. 8 Photographs of CPC solar collector

3.3 Autonomous Operation Test using Solar Radiation

An autonomous operation test was performed using actual solar radiation as the heat source. The test was conducted at Sendai City (Latitude 38° 17' 00") and continued from 11:30 to 12:20 on a typical summer day (July 12, 2002). During the period of the experiment, nearly constant solar radiation was obtained; moreover, the heat collected at the CPC solar collector is supplied in a stable manner to the evaporator. The expander can be continuously operated by using the accumulator as an energy buffer. After the system achieves a stable state, the temperature at each point, the output power of the expander, the flow rate and other data were recorded.

Figure 6 shows the time-varying results during the test, i.e., the solar radiation I collected at the CPC solar collector, W and η_{total} for the SORCS. The average energy flow during the operation is also presented in Fig. 7. The experimental conditions and results pertaining to the efficiencies are summarized in Table 5. The average solar radiation obtained by using the CPC solar collector during the test is approximately 890 W/m^2, the ambient temperature T_a is 30°C and T_{tank} is approximately 140°C. While the heat collected by the solar collector is 5119 W, the expander can yield an average power output of 350 W. The total system efficiency on the basis of the solar radiation is approximately 7%. During the test, the collector efficiency is approximately 65%, the Rankine cycle efficiency is 11% and the system efficiency is 79%. The output power of the expander is lower than that observed in the previous output characteristic test. This is because during the autonomous operation test, the flow rate of the working fluid decreases when the system is in a stable condition. The temperature of the cooling water released from the condenser is 37°C and the heat absorbed by the cooling water is estimated to be 1806 W. The total efficiency of the system is calculated to be 42% when the abovementioned waste heat is used for cogeneration.

3.4 Discussions

The proposed SORCS achieved a total efficiency of 7% on the basis of the use of solar radiation as the heat source. On the other hand, photovoltaic (PV) cells are already used widely as electric power generators employing solar energy. The annual average efficiency of commercial PV cells is reported to be approximately 7.8% [1].The present result indicating a total efficiency of 7% is obtained from for a limited number of experiments that were conducted only during summer. Hence, the efficiency should not be compared with the annual average efficiency of the commercial PV cells; however, the feasibility of the SORCS using a scroll expander as a small distributed power generation system was shown, which is simply a modified form of an air conditioning system installed in an automobile.

For higher η_{th}, T_{tank} should be higher, but increasing T_{tank} will decrease η_c. Hence, balancing both the efficiencies is very important and must be optimized. From the present experiments using two dimensional CPC solar collector, we observe that T_{tank} value for which the system efficiency is the highest is 140°C.

In the future, when using components such as the three-dimensional CPC solar collector [17] with a high concentration ratio, η_c can possibly be increased up to 80% and T_{tank} can be more than 200°C during summer when the radiation amount is more than 1000 W/m^2 for an inclined-plane collector. Furthermore, η_{total} can possibly be increased further. However, we should also mention that the increase in the system operation temperature is currently regulated by the Japan high-pressure gas regulation. When the temperature of the hot water reaches 180°C, the internal pressure of the accumulator will exceed 1.0 MPa, which is the limit set by the law.

Moreover, the proposed system can easily use waste heat not only from solar energy but also from exhaust heat from conventional micro gas turbine systems and fuel cells; additionally, the combustion heat of biogases and hydrogen can also be used. This feature is not present in PV cells. Thus, the proposed SORCS has the possibility of becoming a promising system for small distributed power generation systems in the future. The next tasks for obtaining higher efficiency and the popularization of the system are to select and develop an organic working fluid that is harmless to the environment, design an optimal

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1 Averaged power generation efficiency from the actual measurements at HARBEMAN HOUSE[18] during the period of 2002.2.1–2003.1.31

scroll expander, and to enable compact packaging of the components. Furthermore, if solar energy is being used as the heat source, efficiency improvement, cost saving of the solar collector and downsizing of the accumulator are also necessary.

4. Conclusions

In this study, a new and unique solar organic Rankine cycle system has been developed. The conclusions drawn from the experiments and measurements are summarized as follows:

(1) The organic Rankine engine system has been developed using a scroll expander and the organic working fluid R113. The expanding efficiency was 63% and proved to be an effective expander for retrieving the output power from the results of the output performance tests.

(2) The solar organic Rankine cycle system was constructed using solar energy as the heat source and the autonomous operation test was conducted under summer solar radiation. The total power generation efficiency based on the solar radiation at the aperture of the CPC solar collector attained 7%. When the cogenerative utilization of cooling water was considered, the total efficiency was 42%.

(3) The proposed system is capable of using waste heat from sources such as the combustion heat of biogases and hydrogen and the exhaust heat from other energy systems. This feature is not unrealizable in PV cell systems. Hence, the SORCS is expected to be used for small distributed power generation systems in the future.

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