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DEMONSTRATION OF A HYBRID POWER AND REFRIGERATION AMMONIA-WATER CYCLE

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ABSTRACT

This paper reports on the demonstration of a hybrid power generation and refrigeration cycle in a turbine system which employs ammonia-water mixture as the working fluid. The hybrid cycle is the one in which the ammonia-water mixture turbine cycle and the ammonia absorption refrigerator are combined. To demonstrate the performance enhancement of the hybrid cycle, its steady state characteristics were experimentally investigated. The increase of the coefficient of performance (COP) and the performance improvement of the cycle are mainly due to a reduction of the heat of rectification at the ammonia absorption refrigerator. Therefore, the authors especially focused on the COP, the heat source steam consumption rate, and the heat of rectification when the ammonia mass fraction at the rectifier inlet increased. Results showed the COP and heat source steam consumption rate improved about 20% in hybrid operation, compared with normal operation which drives the ammonia absorption refrigerator and the ammonia-water mixture turbine cycle separately.

INTRODUCTION

Co-generation and the use of un-utilized thermal energy are attractive ways to effectively generate power and heat. The key is utilization of low temperature heat sources, a technology which is common to both ways. The authors recommend power generation and refrigeration bottoming cycles which employ an ammonia-water mixture (AWM) as the working fluid, because AWM is a low temperature bubbling medium considered to be suitable for energy recovery from low temperature heat sources. Concretely, this work focused on the AWM turbine cycle and the ammonia absorption refrigerator cycle. This suggestion is based on the knowledge of the low-boiling medium turbine cycle we had investigated[1, 2].

NOMENCLATURE

P	: Pressure	[MPa]
Q	: Heating rate	[kW]
Q_{R}	: Heat of rectification	[kW]
T	: Temperature	[°C]
W	: Output power	[kW]
z	: Mass fraction	[kg/kg]

Subscripts:

1-127	: State point in fig.4
D	: Desorber
E	: AAR evaporator
EV	: AWMTS evaporator
SYS	: SYSTEM

Abbreviations:

AAR	: ammonia absorption refrigerator
ACGS	: Advanced Co-Generation System
AWM	: ammonia-water mixture
AWMTS	: AWM turbine system
COP	: Coefficient of performance
DCSS	: Distillation/condensation subsystem
HPC	: High pressure condensation
LPC	: Low pressure condensation
VGSS	: Vapor generation subsystem

AMMONIA ABSORPTION REFRIGERATOR

The absorption type of the ammonia absorption refrigerator (AAR) is single-stage, as illustrated in Fig.1. The COP is defined by the following equation.

$$COP = Q_{\mathrm{E}} / Q_{\mathrm{D}} \tag{1}$$

AMMONIA-WATER MIXTURE TURBINE SYSTEM

The schematic of the AWM turbine system (AWMTS) is illustrated in Fig.2. The AWMTS features two subsystems: a distillation/condensation subsystem (DCSS) and a vapor generation subsystem (VGSS). These two subsystems represent Kalina cycle. [3-6]

The DCSS is composed of a condenser, a pump, a recuperator and a separator. The subsystem leverages the thermal energy of the turbine outlet vapor and converts it to the mass fraction difference between two condensers. The turbine outlet vapor releases its thermal energy at the recuperator, and heats the condensed liquid from the low pressure condenser. The liquid is partially evaporated, then separated into ammonia-rich dry-saturated vapor and water-rich saturated liquid at Separator-2. The vapor is absorbed at the high pressure condenser and provides a higher mass fraction liquid. The liquid at Separator-2 flows into the low pressure condenser and reduces the condensing mass fraction at the low pressure condenser. One of the simplest Kalina cycle, KCS-1, has a DCSS. The area surrounded by dashed lines in Fig.2 corresponds to the DCSS.

The KCS-34 is another simple Kalina cycle with a VGSS. It is mainly utilized in geothermal source plants. In VGSS, liquid preheating, vaporization, and vapor/liquid separation are achieved with a preheater, an evaporator, and a separator. VGSS prevents the flow of wet vapor into the turbine. The area in Fig.2 surrounded by single dot chain lines corresponds to the VGSS.

The AWM turbine system configuration is designed to use low-pressure process steam as a heat source. There are six levels of ammonia mass fraction in the turbine cycle (see Table 1).

HYBRID CYCLE

The AAR and the AWMTS both employ AWM as their working fluid. Focusing on this point, the authors propose a system which combines the AAR and the AWMTS. This system, which we call a hybrid AWMTS/AAR system, achieves higher efficiency by sharing the working fluid between the two cycles.

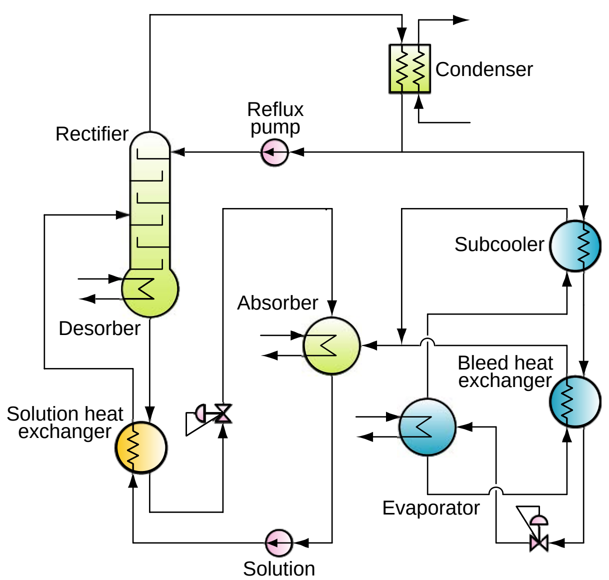

Fig.1 Schematic of the ammonia absorption refrigerator

REDUCTION OF THE HEAT OF RECTIFICATION

An AAR employs ammonia as the refrigerant and water as the absorbent. Water has a vapor pressure that is not negligible

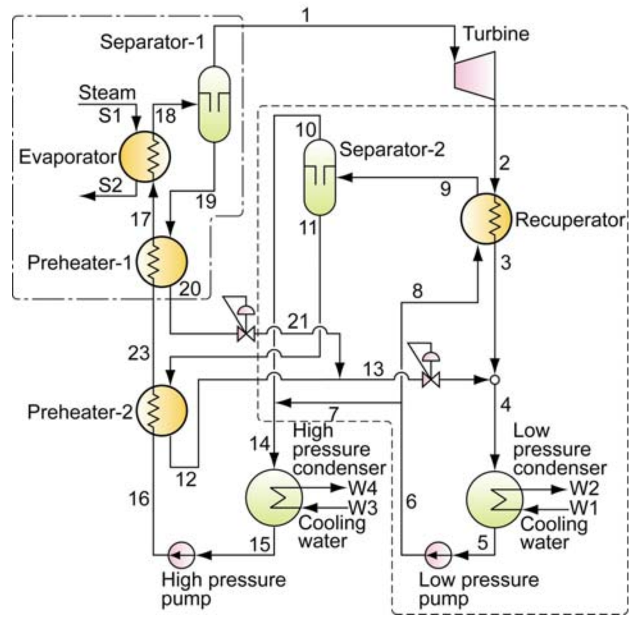

Fig.2 Schematic of the AWM turbine system

Table 1 Six levels of ammonia mass fraction in AWMTS

Spot	Ammonia mass fraction kg/kg
Separator 2 vapor region	0.97
Separator 1 vapor region (Turbine inlet vapor)	0.76
Outlet of the high pressure condenser	0.60
Outlet of the low pressure condenser	0.45
Separator 2 liquid region	0.36
Separator 1 liquid region	0.18

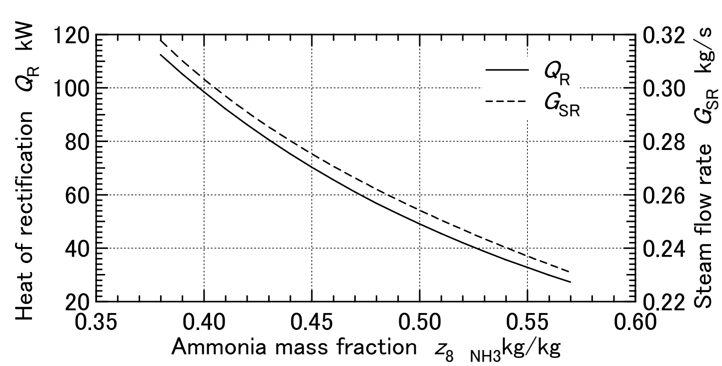

Fig.3 Relation between the heat of rectification, the steam consumption rate, and the ammonia mass fraction supplied to rectifier

relative to that of ammonia. Consequently, the vapor generated in the desorber contains a certain amount of water, and thus, the AAR requires an ammonia purification process. The performance of the rectifier is one of the major factors that determine the performance of the AAR, such as the COP (coefficient of performance). About 30 % of the thermal energy input at the desorber is spent as the heat of rectification. If a highly-concentrated AWM liquid can be fed to the rectifier, the COP will be improved due to the decrease of the heat of rectification.

Figure 3 shows the relation between the heat of rectification, steam consumption of the AAR, and the ammonia mass fraction supplied to the rectifier. As the mass fraction of the liquid supplied to the rectifier becomes higher, both the heat of rectification and the steam consumption of the AAR decrease.

HYBRID CONFIGURATION

As mentioned above, supplying a higher mass fraction AWM liquid leads to the performance improvement of the AAR. The hybrid cycle regards the AWMTS as equipment which is able to supply a higher mass fraction AWM liquid. On the other hand, the AWMTS increases output power by utilizing all of the steam that remains from the performance improvement of the AAR.

The hybrid cycle must fill the following conditions.

- The ammonia mass fraction of the feed liquid to the rectifier from the AWMTS must be higher than the AWM liquid at the outlet of the absorber.
- The ammonia mass fraction of the weak solution from the AWMTS to the absorber of the AAR must be lower than the AWM liquid at the outlet of the absorber.
- The mass of the ammonia constituent which flows into the AAR (or AWMTS) must be equal to that which flows from the AAR (or AWMTS). The same applies to the mass of the water constituent.

The hybrid system is illustrated in Fig.4. This hybrid configuration only exchanges liquid in the region between two cycles.

One of the pipelines from the AWMTS section to the AAR section, denoted “B line” in Fig.4 (point 125), feeds the liquid with a higher mass fraction than at the absorber outlet of the AAR. Feeding the higher mass fraction liquid leads first to a reduction of the heat of rectification and the steam consumption of the AAR. Finally, the AWM turbine output power increases if the AWMTS utilizes the excess steam from the AAR.

Another pipeline to the AAR section, denoted “A line” in the figure (points 121 and 122), supplies a weak solution to the absorber of the AAR.

The pipeline to the AWMTS section, denoted “C line” in the figure (point 123), maintains the mass balance of each cycle. An imbalance in both quality and quantity of the exchanged liquids leads to a shortage of working fluid and the stopping of the operation.

There are two spots which have a higher mass fraction than the absorber outlet, the low pressure condenser (LPC) outlet and the high pressure condenser (HPC) outlet. Therefore, two patterns of hybrid configuration are possible.[7] These two patterns are shown in Fig.4. “Pattern 1” takes liquid from the LPC and “Pattern 2” from the HPC.

DEMONSTRATION EXPERIMENT

The steady state characteristics of the hybrid cycle were investigated experimentally. This section describes the test facility, the methodology of the experiments, and the experimental conditions.

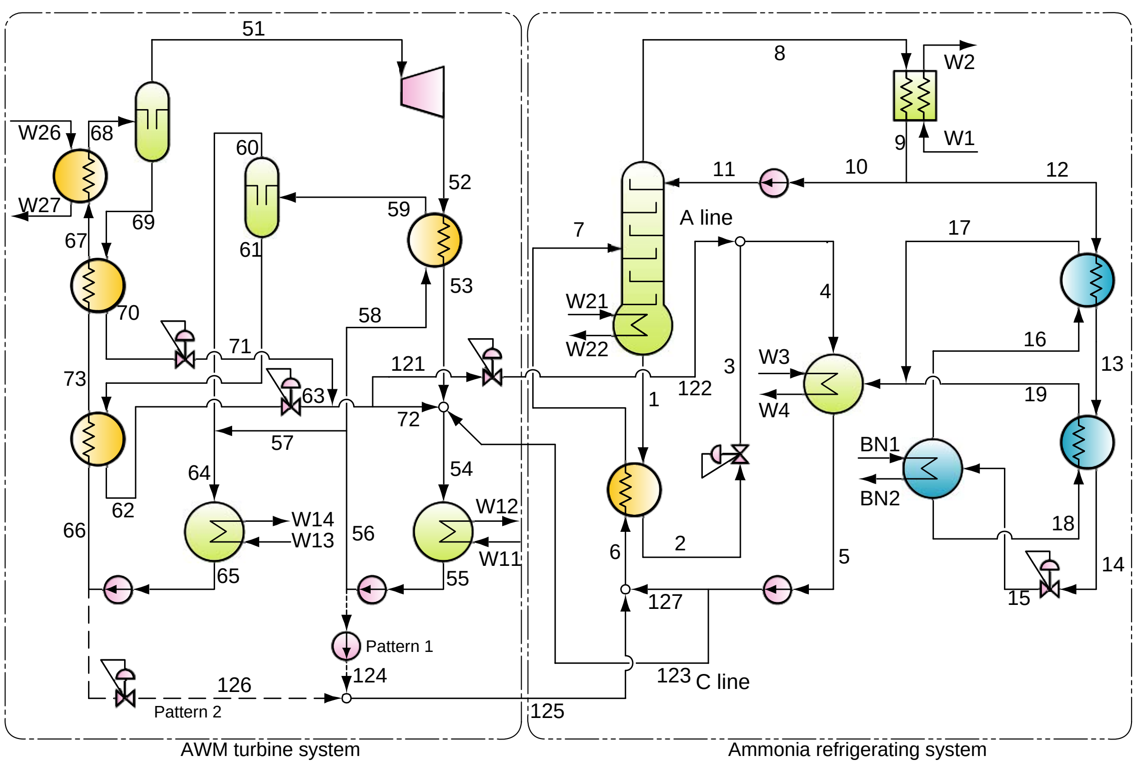

Fig.4 Schematic of the ammonia absorption refrigerator and its local control loop

TEST FACILITY

Both the AAR and the AWMTS are installed in the bottoming stage of a unique co-generation system which the authors constructed on the Waseda campus. The co-generation system is called the “Advanced Co-Generation System (ACGS)”.[8] ACGS is composed of a conventional combined cycle with the AAR, the AWMTS, and a water heater. The latter three components are arranged in a subordinate position at the combined cycle, utilizing exhaust steam from the steam turbine. The gas turbine and the steam turbine correspond to the topping stage and the middle stage, respectively.

Figure 5 shows the schematic of the ACGS. Tables 2 and 3 show the specifications of the AAR and the AWMTS.

METHODOLOGY OF THE EXPERIMENT

Table 4 shows the experimental conditions. “Main flow rate” means the flow rate of the AWM from the HPC to the evaporator. It corresponds to the flow rate at points 66~68 and 73 in Fig.4. “Average mass fraction” is the mass fraction which totals all of the AWM in the whole AWMTS.

The experiments were carried out with the “Pattern 2” hybrid configuration for the following reasons.

(1) The mass fraction difference between HPC and LPC is larger for pattern 2 than for pattern 1.
(2) The range of the average mass fraction which enables pattern 1 is very narrow.

The authors decided to focus on the COP, the heat source steam consumption rate, and the heat of rectification when the ammonia mass fraction at the rectifier inlet became higher. As mentioned in Section 3, the increase of the COP and the performance improvement of the cycle are mainly due to reduction of the heat of rectification at the AAR. Also, there are so many parameters to be set in the hybrid cycle that a long time would be needed to investigate the steady state of the whole cycle.

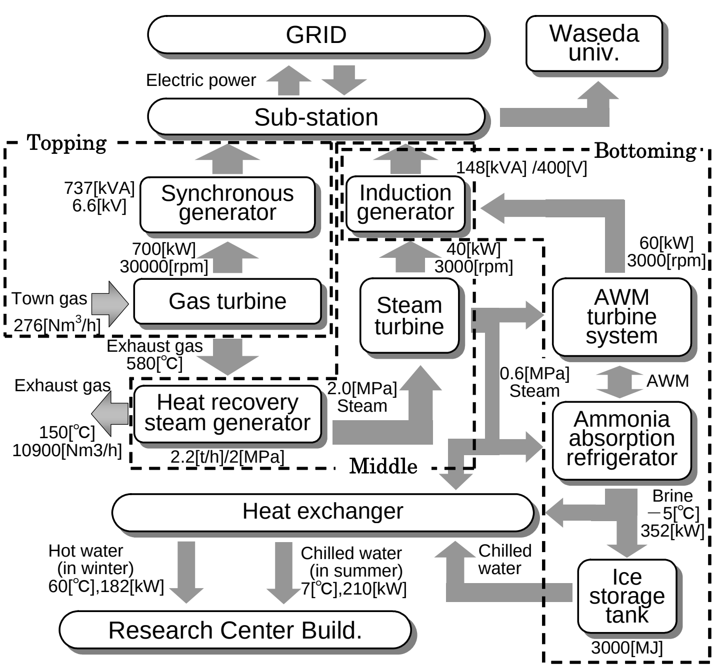

Fig.5 Schematic flow of the ACGS

A main parameter for the experiment is the B line flow rate, which mainly determines the mass fraction of the liquid fed to the rectifier. If the B line flow rate increases, the feeding mass fraction rises, and vice versa. Other flow rates (A line, C line, point 127) are adjusted in response to the B line flow rate.

Table 2 Specifications of Ammonia-absorption Refrigerator

Item		Unit	Spec.
Heat source	Fluid	Steam	
	Inlet temp.	°C	164
	Inlet press.	MPa(gage)	0.59
	Flow rate	kg/h	1140
Absorption Refrigerator	Type	Single-effect	
	Output	°C / kW	-5 / 352
	COP	-	0.55
	Cooling water inlet temp.	°C	30
	Condensing pressure	MPa(gage)	1.5
	Refrigerant mass fraction	$_{NH3}$kg/kg	0.998

Table 3 Specifications of AWM turbine system

Item		Unit	Spec.
Heat source	Fluid	Steam	
	Inlet temp.	°C	164
	Inlet press.	MPa(gage)	0.59
	Flow rate	kg/h	1800
Turbine	Type	Axial impulse	
	Output	kW	60
	Adiabatic efficiency	%	40
	Speed	rpm	3000
	Flow rate	kg/h	2480
	Refrigerant mass fraction	MPa(abs.)	1.5

Table 4 Conditions for experiments

Category	Item	Unit	Value
Whole system	Cooling water temp.	°C	25
	Heat source steam pressure	MPa(gage)	0.55
AAR section	Brine temp.	°C	−5.0
	Desorber outlet AWM temp.	°C	125
	Condensing pressure	MPa(gage)	1.25
	Rectifier outlet refrigerant temp. (Mass fraction of refrigerant)	°C ($_{NH3}$kg/kg)	55 (0.998)
	Reducing valve outlet refrigerant temp.	°C	−9.0
	Refrigerating capacity	kW	230
AWMT section	Evaporating pressure	MPa(gage)	0.8
	Separator 2 temp.	°C	90
	Main flow rate	m^3/h	1.5
	Average mass fraction	$_{NH3}$kg/kg	0.43

RESULTS

Figures 6-8 show the relation between the feeding mass fraction and the steam consumption rate, COP, and heat of rectification, respectively. Circles in the figures indicate the experimental results when the AAR and the AWMTS are operated separately (separate operation). Squares show the experimental results when the test facility works in hybrid operation. The results of simulation calculations[7, 9] are displayed as a solid curve. The thermodynamic properties of the AWM[10-13] are calculated with the PROPATH version 11.1[14] which is based on Ibrahim and Klein[15].

Data from previous experiments which investigated the steady state characteristics of the AAR are shown as small circles. The steam consumption rate and COP are not determined only by the feeding mass fraction, because of the effects of cooling water temperature, refrigerant mass fraction and so on. However, it does determine the performance of the rectifier, such as heat of rectification, if the desorber outlet AWM temperature and the rectifier outlet refrigerant temperature are regulated.

The figures show that the hybrid operation allows higher mass fraction AWM liquid to be fed to the rectifier; as the feeding mass fraction increases, the steam consumption rate and heat of rectification decrease, and COP rises. The steam consumption rate and COP improve up to 20 % when the rise of the feeding mass fraction becomes maximum. (The feeding mass fraction is 0.46 [$_{NH3}$kg/kg])

CONCLUSIONS

A hybrid power generation and refrigeration cycle was designed for an AWM turbine system and tested experimentally; the focus of the experiments was on the coefficient of performance, the steam consumption rate of the heat source, and the heat of rectification when the ammonia mass fraction increased at the rectifier inlet.

Several experiments with the hybrid configuration were conducted by changing the feeding mass fraction to the AAR rectifier, in order to demonstrate performance improvement of the AAR in the hybrid operation. The experimental results can be summarized as follows:

(1) The feeding mass fraction rises to 0.02[$_{NH3}$kg/kg].
(2) At that time, the steam consumption rate and COP improve about 20 %. This corresponds to an approximately10-% performance improvement for the whole cycle.
(3) Performance improvement of the AAR in the hybrid operation was confirmed by the experiments.

ACKNOWLEDGMENTS

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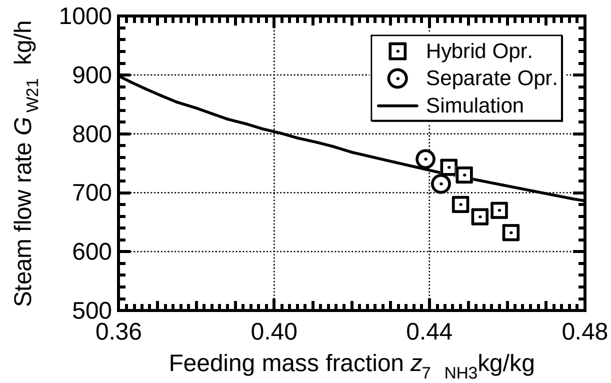

Fig.5 Reduction of steam consumption when the supplied liquid ammonia mass fraction rises

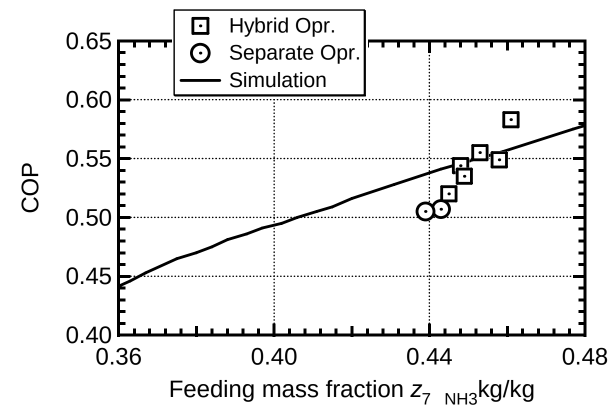

Fig.6 COP enhancement when the supplied liquid ammonia mass fraction rises

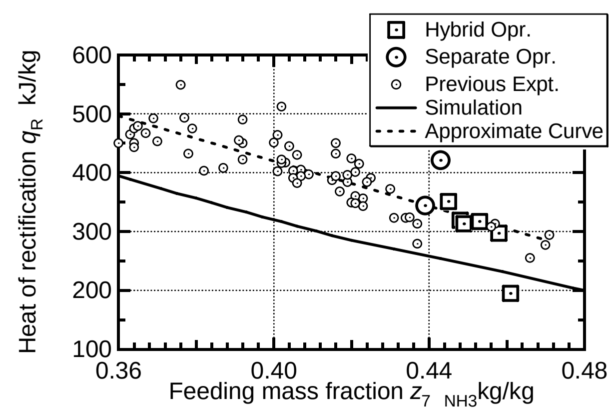

Fig.7 Reduction of heat of rectification when the supplied liquid ammonia mass fraction rises (P_8=1.25[MPa], T_8=55[°C])

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