RESEARCH AND DEVELOPMENT OF SMALL-CAPACITY ABSORPTION CHILLER USING WASTE HEAT FROM DISTRIBUTED POWER GENERATION

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ABSTRACT

In this research, a mixing-type absorber is proposed to be used in LiBr/H_2O absorption chiller in order to develop a new small-capacity system with high efficiency and compact structure. The mixing-type absorber is composed of an ejector and a cooler with subcooled LiBr aqueous solution as driving flow. The adiabatic absorption inside the ejector and the mixing of solution with water vapor are expected to promote the absorption efficiency. From the performance experiments of the mixing-type absorber, it is found that although the two-phase flow inside the ejector was not critical flow, the adiabatic absorption can be performed efficiently and the system can be composed compact. A cycle simulation was carried out to investigate the system performance of the absorption chiller using two mixing-type absorbers in series. As compared to a conventional absorption chiller, the COP is improved by 15%, and the volume of the mixing-type absorber is decreased by about 50% when compared to a conventional falling film type absorber.

Key words: ***absorption chiller, absorber, ejector, nozzle, simulation***

1 INTRODUCTION

In Japan, about 26% of primary energy is consumed in noncommercial use. In order to attain 6% cut down of greenhouse gas discharge from 2008 to 2012 compared to that in 1990, as regulated in COP3, further promotion of energy-saving technologies in noncommercial area is important. Considering the fact that half of the energy consumption in noncommercial area is used in heating/cooling, the spread of cogeneration systems with distributed power supply becomes important for energy saving. Because cooling demand stands high compared with heating and hot-water supply demand, development of the absorption chiller which generates cooling ability efficiently using waste heat from a micro gas turbine is important for introducing and extending the application of the distributed power system.

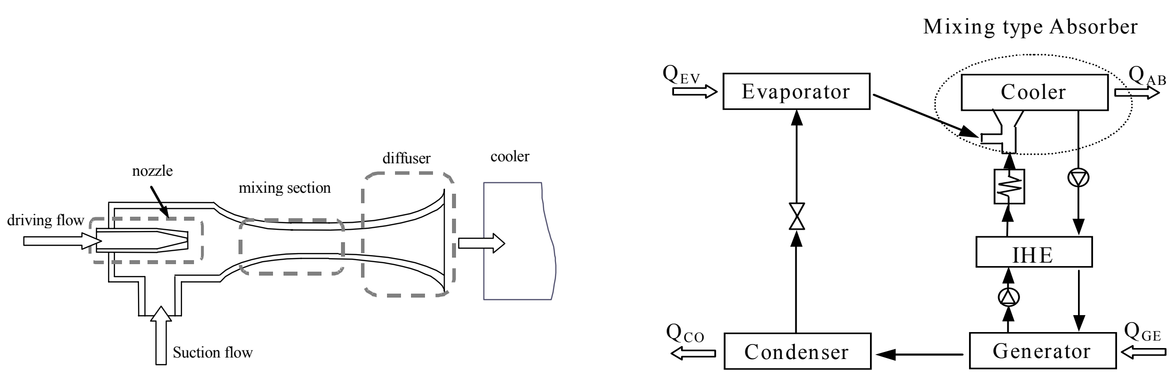
Although an absorption chiller is considered the most suitable facility to generate cooling ability from the waste heat recovery of a micro gas turbine, its large size and low efficiency as compared to vapor-compression system have limited the application in the plant, district heating & cooling system and large buildings. Researches on a compact and efficient system are needed to extend its application area. To develop a small-capacity absorption chiller, a joint research project, “named” Research and Development of Small-capacity Absorption Chiller Using Waste Heat from Distributed Power Generation” has been launched. This research is supported by the New Energy and Industrial Technology Development Organization, NEDO. Participants include The University of Tokyo, National Institute of Advanced Industrial Science and Technology, and HITACHI Air Conditioning system.

In order to enhance the absorption performance, it is necessary to accelerate the absorption rate and increase vapor-liquid interface. In this research, a mixing-type absorber is proposed, which introduces an ejector to increase the vapor-liquid interface area and promote the mixture between the vapor and solution (Dang et al. 2004). By separating heat and mass transfer process in absorption process, the compact heat exchanger can be introduced thus decreases heat transfer area significantly.

This report will introduce the concept of mixing-type absorber, measurement of the flow and absorption characteristics inside the mixing-type absorber, and the cycle simulation results of a LiBr/H_2O absorption refrigeration system using mixing-type absorber. At present, a prototype absorption chiller has been manufactured and the actual proof examination is being performed.

2 CONCEPT OF MIXING-TYPE ABSORBER

Figure 1 shows the concept of mixing-type absorber and the absorption refrigeration cycle. The mixing-type absorber is composed of an ejector and a cooler. The driving flow is subcooled LiBr aqueous solution from generator. It enters the mixing section of the ejector through a nozzle. The suction flow is entrained from the evaporator by the differential pressure between the mixing section and the evaporator or by the kinetic energy of the well-dispersed high speed solution droplets. At the mixing section the driving flow combines with the suction flow, and adiabatic absorption occurs. The mixed steam enters the diffuser to convert its kinetic energy into a pressure boost and finally enters the cooler to complete the absorption process.



(a). Mixing-type absorber **(b). Absorption refrigeration cycle with mixing-type absorber**

Fig. 1. Concept of mixing-type absorber system

For a conventional absorber, the absorption process is complex because both the heat and mass transfer processes take place simultaneously. By introducing the ejector, the mixing between the solution from the generator and the vapor from the evaporator takes place inside the ejector, and then the mixture enters into the cooler to be cooled and complete the absorption process. The mass transfer process (to be exact, the mixing process) is separated from the heat transfer process, thus the enhancement of each process can be performed independently. In addition, a well-designed ejector can facilitate the pressure recovery from a low evaporation pressure to a high pressure at inlet of the cooler, and improve the mixing between the solution and the refrigerant vapor, therefore enhance the system efficiency further.

3 FLOW AND ABSORPTION CHARACTERISTICS INSIDE THE MIXING-TYPE ABSORBER

3.1 Experimental Apparatus and Conditions

3.1.1 Experimental apparatus

Figure 2 shows the outline of experimental apparatus. Experimental loop consists of a solution condensation section, a vapor generation section, and a test section. The LiBr aqueous solution is pressurized with a pump and then flows through a Coriolis-type mass flow meter to measure its flow rate, density, and temperature. Concentration of the solution is calculated from the density and temperature using a thermophysics property table. Solution temperature is adjusted by a subcooler and a heater. Flow pattern observation and measurements of pressure distribution are conducted in test section. Back pressure of the test section is adjusted by a cooler connected to the ejector. The outlet solution concentration and flow rate is measured by another Coriolis-type mass flow meter. The diluted solution is then introduced into generator to generate water vapor and to be condensed into strong solution.

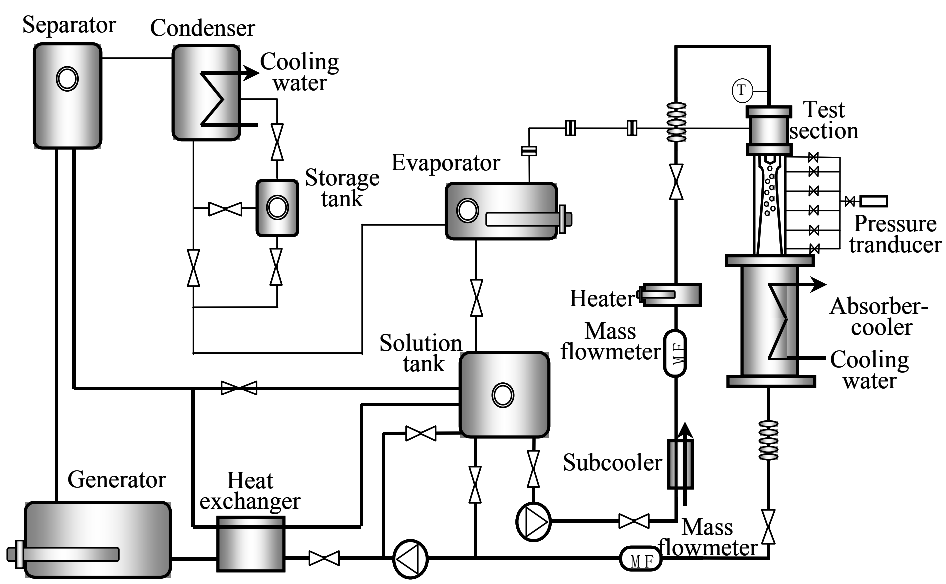


Fig. 2. Schematic of experimental apparatus

3.1.2 Test nozzle

In order to investigate the spray pattern and its effect on absorption capability, four nozzles were tested in this research, including a single-hole nozzle and three commercially available nozzles (Spraying Systems Japan Co.). The characteristic of the test nozzles are shown in Table 1.

Table 1. Nozzle properties (provided by Spraying Systems Japan Co.)

Nozzle	Orifice diameter (mm)	Flowrate (L/min)	Spray angle (°)	Pressure (MPa)
Single-hole nozzle	0.79	-	-	-
G-30	0.79	0.99	30.0	0.3
D2-35	1.0	0.99	44.0	0.3
D2-45	1.0	0.80	46.0	0.3

3.1.3 Test ejector

Figure 3 shows the photograph of the test ejector. Test ejector consisted of a nozzle, mixing section, diffuser and suction section. The mixing section and diffuser were made from acrylics to observe the flow pattern inside the ejector. Two mixing section, with throat diameter of 20mm and 40mm, were used in experiment. In order to examine the flow characteristic in ejector at various back pressures, a gas-liquid separator with cooling coil inside was attached at the ejector exit, and back pressure of ejector was adjusted by varying cooling water temperature and flow rate.

Fig. 3. Photograph of test ejector

3.1.4 Experimental conditions

Experimental conditions are summarized in Table 2. Inlet temperature of LiBr aqueous solution was 32ºC, with inlet concentration of 62 wt%. Back pressure of the ejector was kept to be 1.0 kPa. Solution flow rate was varied in the range of 0.0158-0.0256 kg/s to investigate the effect of nozzle spray on concentration difference between absorber inlet and outlet.

Table 2. Experimental parameter and conditions

Experimental parameter	Experimental conditions
Inlet temperature	32 ºC
Inlet solution concentration	62.0 wt%
Inlet solution flow rate	0.0158~0.0256 kg/s
Back pressure	1.0 kPa

3.2 Experimental Results

3.2.1 Flow characteristic inside ejector

Figure 4 shows the concentration difference $\Delta\zeta$ between the inlet and outlet of the absorber at various back pressures and solution mass flow rates. Nozzle G-30 (relatively narrow spray angle is formed) was used, with ejector throat diameter of 20mm. The back pressure was adjusted from 0.3kPa to 1.0kPa by changing the inlet temperature and flow rate of cooling water. It is shown that the concentration difference $\Delta\zeta$, corresponding to the absorption capability, varies with the back pressure under constant solution flow rate condition. It is also found from measurement of static pressures along flow direction that no sharp pressure rise due to the choke of two-phase flow was observed. Therefore the vapor-liquid two-phase flow in ejector is considered not a critical flow, which is the result of low operation pressure. The increase of concentration difference when decreasing the back pressure is the result of cooling the solution in the gas-liquid separator.

Figure 4 also shows the tendency that the $\Delta\zeta$ increases with the increase of flow rate at constant back pressure condition. It is found that the back pressure does not change with solution flow rate when the cooling water temperature and flow rate is kept constant. It is therefore concluded that the absorption of water vapor into LiBr aqueous solution occurs by the pressure difference of pressure of water vapor and LiBr saturation vapor pressure at the vapor-solution interface, since the solution was subcooled at the ejector inlet. The suction of water vapor from evaporator by the entrainment between water vapor and well-dispersed solution droplets are not significant. The increase of the concentration difference with increase in solution flow rate is considered due to change of the jet stream pattern under different solution mass flow rate conditions.

3.2.2 Influence of spray pattern on absorption capability

The influence of nozzle spray pattern on the absorption capability was compared using three nozzles at several mass flow rate conditions. Two full cone type spray nozzles (D2-35, G-30) and one hollow cone type spry nozzle (D2-45) were examined. All the three nozzles have almost the same injection angle on specification when the inlet pressure is set to be 300kPa. Ejector throat diameter was 40mm, and the solution inlet temperature and concentration were 32 ºC and 62.0 wt%. Vapor pressure at the evaporator was kept to be 1.0kPa. Figure 5 shows measured concentration difference $\Delta\zeta$ at various solution flow rates for the three nozzles. It is seen that for both hollow cone spray nozzle and full cone spray nozzle, $\Delta\zeta$ increases with increase of solution flow rate. As the $\Delta\zeta$ for different nozzles are compared, on the whole, the hollow cone spray nozzle shows larger $\Delta\zeta$ than the full cone spray nozzle at the same solution flow rate.

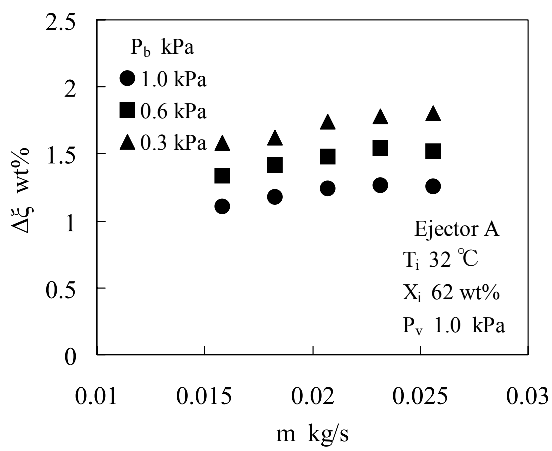


Fig. 4. Effect of solution flow rate on $\Delta\zeta$ at various ejector back pressures

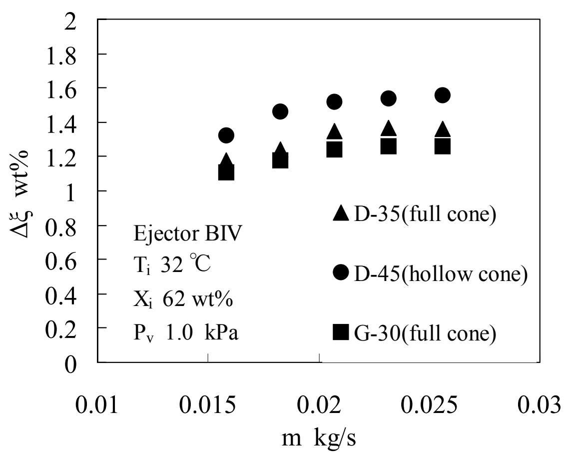


Fig. 5. Effect of spray pattern on $\Delta\zeta$

3.2.3 Comparison of Absorption Capability in Liquid Sheet region and liquid droplet region

From the comparison of concentration difference for different spray patterns, it is seen that the hollow cone spray showed the highest concentration difference. The spray pattern at the exit of a hollow cone spray nozzle consists of three regions, i.e., a liquid sheet region, a breakup region, and a liquid droplet region. A schematic drawing of the atomization process for a hollow cone nozzle is shown in Fig. 6. Under present experimental condition, the liquid sheet region is found occurs at the exit of the nozzle and last for about 10 to 15mm. After a short breakup region, the spray turns into a fully-dispersed droplets flow pattern. Very fine atomization spray is observed for hollow cone spray nozzle D2-45 as compared to that of full cone nozzle G-30. In addition, the spray seems to contract with reduction in spray angle when the absorption starts.

The absorption capability at different flow regions were investigated by varying the ejector length. Figure 7 shows the effect of distance between the ejector exit and nozzle exit on the concentration difference $\Delta\zeta$. Inlet solution temperature was 32 º C and the concentration 62%. Mass flow rate of the solution was 0.023kg/s. A dashed vertical line shows the location where the breakup of liquid sheet completes. It is seen from the comparison that within the 10mm distance form the nozzle exit $\Delta\zeta$ increases sharply with distance, which indicates an intense absorption is performed in the short liquid sheet region of about 10mm. The $\Delta\zeta$ acquired in this liquid sheet region is equivalent to 85% of the concentration difference acquired from the whole ejector. This intense absorption inside liquid sheet region is considered the result of turbulence generated within swirl chamber which promotes the mass transfer in the liquid sheet region significantly. Moreover, the concentration difference in 5mm distance from nozzle exit shows 70% of the whole concentration difference, this is due to the fact that the turbulence intensity reaches the largest at the nozzle exit, and then decreases sharply along the flow direction. The contribution of absorption in liquid droplet region only makes up 15% of the whole absorption capability. This result implies that by using a hollow cone spray nozzle, only a short mixing section is needed to complete the adiabatic absorption, thus the structure of the mixing-type absorber can be compact.

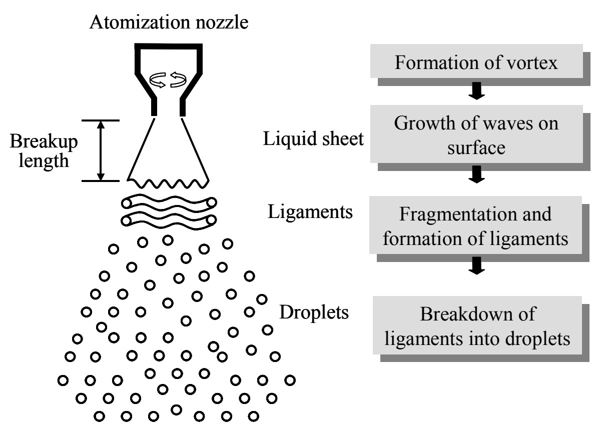


Fig. 6. Flow pattern near nozzle exit for hollow cone spray nozzle

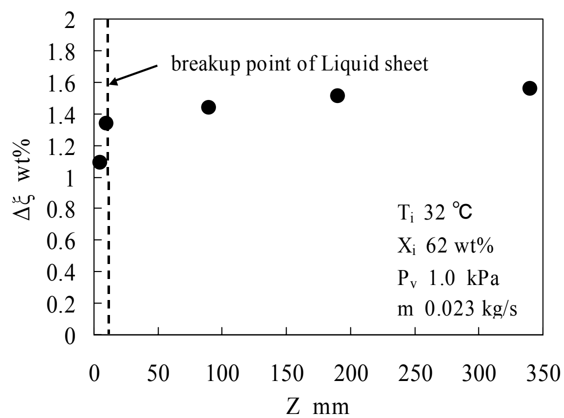


Fig. 7. Variation of $\Delta\zeta$ in the flow direction for hollow cone spray nozzle D2-45

4 SIMULATION OF ABSORPTION REFRIGERATION CYCLE

4.1 Absorption Refrigeration Cycle

The simulation object is a parallel flow double-effect H_2O/LiBr absorption chiller. Figure 8 shows the schematic drawing of simulated cycle and the thermodynamic property change of the LiBr solution in During diagram. The condensed absorption solution from the generator is pressurized by a solution pump and subcooled by a solution heat exchanger. It then enters two mixing-type absorbers which connected in series. The solution is introduced into the absorber through a venturi nozzle, and breaks up into small droplets at the mixing section where the adiabatic absorption occurs. The saturated solution droplets fall into the cooling section and continue the absorption process. To meet the desired absorption capacity and the structure compactness, the cooled solution is pressurized again and introduced into another mixing-type absorber. After the absorption process, the diluted solution is returned to the low and high temperature generators through solution heat exchanger to be condensed back into strong solution.

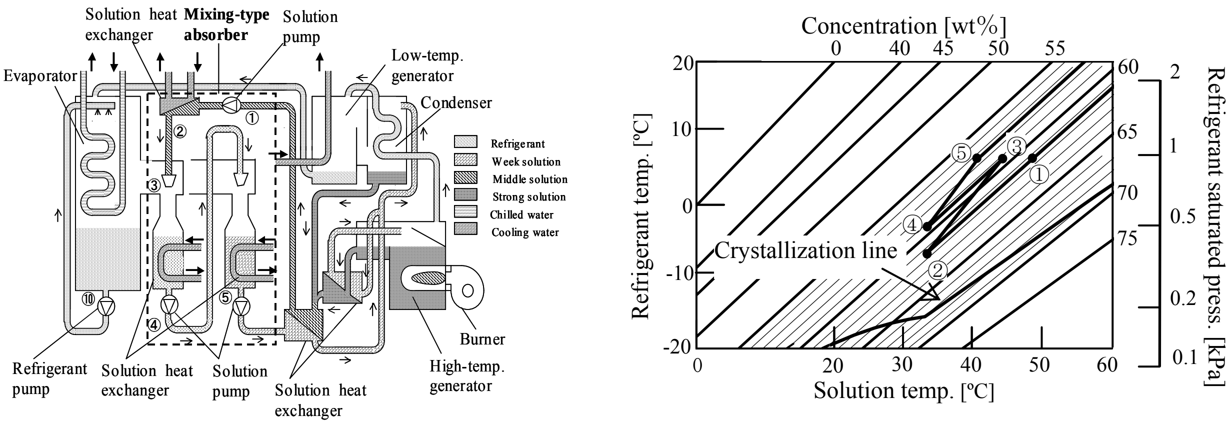


Fig. 8. Mixing-type absorption refrigerant cycle

4.2 Simulation Model

The heat balance of each heat exchanger is the same as that of Hihara et al. (1986). Coefficient of Performance COP is defined by the ratio of cooling capacity Q_E to input heat of high temperature generator Q_{HG}.

$$COP = Q_E / Q_{HG} \tag{1}$$

Table 3 shows the capacity of the absorption chiller, the inlet temperature and flow rate of cooling water and cooled water, together with the solution temperature and pressure at the inlet of first ejector. In addition, the absorption performance of mixing-type absorber used in the cycle simulation is described to be the function of inlet solution concentration, as shown in Fig. 9.

Table 3. Condition of simulation

Refrigerating capacity	2.0 usRT
Temp. of outlet chilled water	7.0 ºC
Temp. of inlet cooling water	32.0 ºC
Chilled water flow rate	1.2 m^3/h
Cooling water flow rate	2.0 m^3/h
Temp. at first ejector inlet	34.0 ºC
Pressure at first ejector inlet	240 kPa

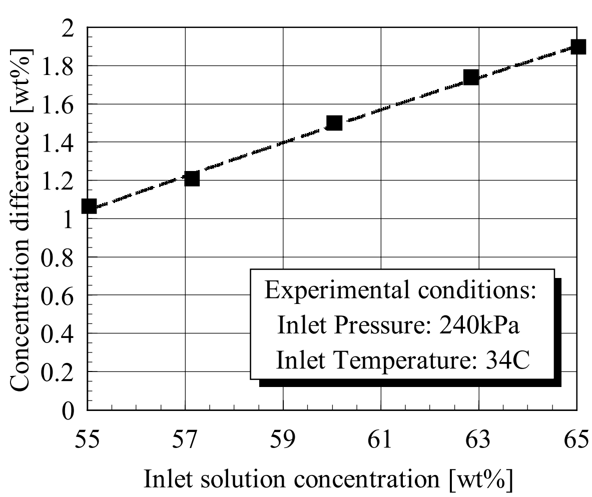


Fig. 9. Performance curve of mixing-type absorber

4.3 Simulation Result

Figure 10 shows the simulation results as compared with a conventional absorption chiller. The COP is compared under various solution concentration conditions of the first absorber inlet. Compared to a conventional absorption chiller, COP of the new system increases by about 10-15%. And the increase becomes much more significant as the concentration decreases. This is because that with the decrease of inlet concentration, the temperature of high-temperature generator decreases, thus the heat loss in generation can be reduced. The simulated variation of solution circulation ratio, concentration, pressure, and temperature of high-temperature generator are also shown in Fig. 10 versus the inlet concentration of the first absorber. Because the driving potential of absorption at low solution concentration such as 50% is weak, for a conventional absorption chiller, usually a high concentration such as 60% or more is used as inlet condition to decrease the volume of absorber. By using the mixing-type absorber, the volume of absorber can be reduced as the results of separation of heat and mass transfer process, and by the enhanced absorption performance. As a result relatively lower concentration solution can be used in absorption chiller, the risk of crystallization of solution and corrosion can be moderated.

The volume of mixing-type absorber and a conventional falling film absorber is also compared and the results are shown in Table 4. Because there is no real absorption chiller of 2.0usRt capacity available in comparison, an absorption chiller with 30usRt in capacity is used and the volume per cooling capacity is compared. It can be seen from Table 4 that the volume of mixing-type absorber per cooling capacity is about 50% of the conventional falling film absorber. Thus the mixing-type absorber can not only contribute to the enhancement of COP and decrease in solution concentration, but also contribute to the miniaturization of the system greatly.

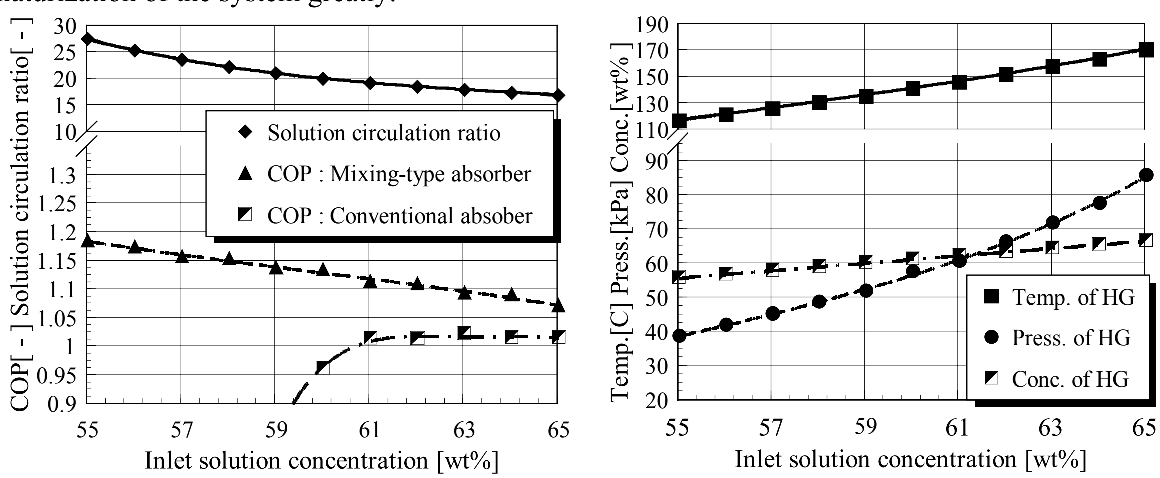


Fig. 10. Static characteristic of mixing-type absorption refrigeration cycle

Table 4. Comparison of absorber volume

	Volume	
Mixing-type absorber	$0.015m^3$/2usRT	$0.0075m^3$/usRT
Conventional absorber	$0.50m^3$/2usRT	$0.017m^3$/usRT

5 CONCLUSIONS

In this research, a mixing-type absorber has been proposed. The flow and absorption characteristics of the mixing-type absorber were experimentally investigated. Furthermore, a cycle simulation of LiBr/H_2O absorption chiller using mixing-type absorber was performed. Main conclusions are summarized as follows:

(1) From the observation of the flow characteristic within ejector, and measurement of absorption

capacity:

- It is difficult to obtain a two-phase critical flow in ejector because of the low pressure, and the absorption of water vapor into the LiBr aqueous solution is mainly driven by the pressure difference.
- The absorption capacity is affected greatly by the spray pattern at nozzle exit. The concentration difference between absorber inlet and outlet increases with increase of solution flow rate. The hollow cone spray nozzle shows a better performance than the full cone spray nozzle.
- Using a hollow cone spray nozzle, the adiabatic absorption can be completed within a very short contact time, which is the result of intense turbulence occurring inside the nozzle. This implies that the structure of mixing-type absorber can be very compact.

(2) From the cycle simulation:

- By using the mixing-type absorber, the COP is improved by 10% to 15% compared to a conventional absorption cycle. Moreover, the volume of the mixing-type absorber is cut down about 50% as compared to a conventional falling film type absorber.

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