MASS-TRANSFER CHARACTERISTICS OF THE RECTIFIER FOR ABSORPTION—REFRIGERATION CYCLE USING TFE/NMP AS A WORKING FLUID

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ABSTRACT

In order to design a rectifier of an absorption refrigerator or a heat pump, some experiments were performed in this study changing solution flow rate, solution concentration, and vapor flow rate using TFE/NMP as a working fluid. The experimental apparatus was manufactured to investigate the effect of the parameters mentioned above on the mass- transfer characteristics of the rectifier. The experimental apparatus consisted of the tower type rectification test section with a 47-mm inner diameter and 500-mm height, the generator, the condenser, and the solution reservoir. Local temperatures of vapor and solution along working fluid-flow direction were measured every 100 mm using type-K thermocouples to derive the distribution of temperature and concentration. Then experimental data were evaluated using the overall mass-transfer coefficient and the rectification efficiency. Experimental results showed that the overall mass-transfer coefficient became lower as the flow rate of vapor increased and higher as flow rate of solution increased.

Key words: *absorption, rectification, mass transfer*

1 INTRODUCTION

The absorption refrigeration cycle is widely used for air conditioning or refrigeration. This refrigerator or heat pump is driven mainly by heat. NH_3/H_2O and $H_2O/LiBr$ working fluid pairs are already commercially available. The NH_3/H_2O working fluid pair is considered suitable for refrigeration and heat pump use. And the $H_2O/LiBr$ working fluid pair may be suitable for air-conditioning (cooling). But the absorption refrigeration cycle, using the NH_3/H_2O working fluid pair, works in a high-pressure range (more than 2 MPa), and ammonia is combustible and toxic. The absorption refrigeration cycle using the $H_2O/LiBr$ working fluid pair has a narrow working range because of the crystallization in high concentration condition. In the point of view of using waste heat to energy, the absorption refrigeration cycle has a wide working and low pressure range and should work within a range of temperatures. This study focuses on the trifluoroethanol-n-methylpyrolidinone (TFE/NMP) working fluid pair[1),2),3] as a next-generation working fluid pair for the absorption refrigeration cycle with a wide working and low-pressure range, but it needs to be processed to accomplish pure refrigerant (TFE) from TFE/NMP mixed vapor generated in the generator.

The effect of the absorbent mixture in the refrigerant is derived using equation 1.[4]

$$Q_e / Q_{e0} = \frac{\left(\xi_R - \xi_{SR}\right)}{\left(1 - \xi_{SR}\right)} \qquad (1)$$

where Q_e is the heat rate of the evaporator in the condition that the concentration of refrigerant TFE is ξ_R , Q_{e0} is the heat rate of the evaporator in the condition that the concentration of refrigerant is 1, and ξ_{SR} is the concentration of solution that is not able to evaporate in the evaporator because of the refrigerant and solution equilibrium.

Fig 1 shows the calculation result of the ratio of the evaporator heat rate Qe/Qe_0. From this figure the higher the concentration of refrigerant, the greater the ration of the evaporator heat rate becomes. And only 3% absorbent mixture in the refrigerant makes the heat rate of the evaporator 20% decrease. So rectification process is very important in the absorption refrigeration cycle to improve the heat rate of the evaporator and the cycle performance.

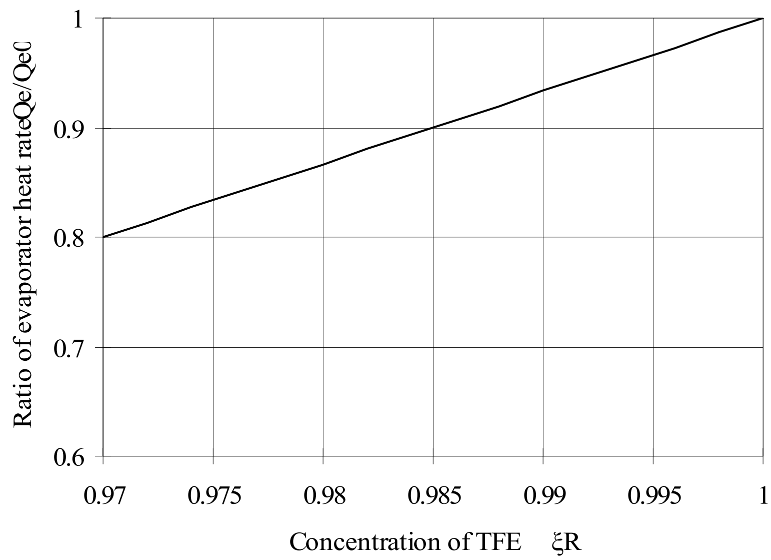

Fig. 1. Effect of the refrigerant concentration on the heat rate of the evaporator

Generally the mass transfer characteristics are improved as the solution flow rate sprinkled to the rectifier column increases, on the other hand the coefficient of performance of the absorption refrigeration cycle is reduced. Figure 2 shows the calculation result of the coefficient of performance of the absorption refrigeration cycle using TFE/NMP as a working fluid. Energy balance equations of the heat exchangers (the generator, the condenser, the evaporator and the absorber) are shown in table 1. Using these equations, the cycle simulation was made for the TFE/NMP absorption refrigeration cycle. In the calculation the flow rate of strong and weak solution, flow rate of refrigerant vapor, the concentration of strong and weak solution and the heat rate of the heat exchangers were derived.

From Fig. 2 the coefficient of performance ($=Q_e/Q_g$) increases about 14% as the concentration difference between strong and weak solution changes from 0.15 to 0.35. But the circulation ratio ($=G_s/G_r$) decreases from 3.8 to 2.1 in the same condition, which makes it more difficult to enhance the mass transfer in the rectifier column in the limited working condition in the absorption refrigeration cycle.

Table 1. Energy balance

Generator	$Q_g = G_w \cdot h_{wgo} + G_r \cdot h_{vrh} - G_s \cdot h_{sgi}$
Condenser	$Q_c = G_r \cdot (h_{vrh} - h_{lrh})$
Evaporator	$Q_e = G_r \cdot (h_{vrl} - h_{lrh})$

Absorber	$Q_a = G_w \cdot h_{wai} + G_r \cdot h_{vrl} - G_s \cdot h_{sao}$

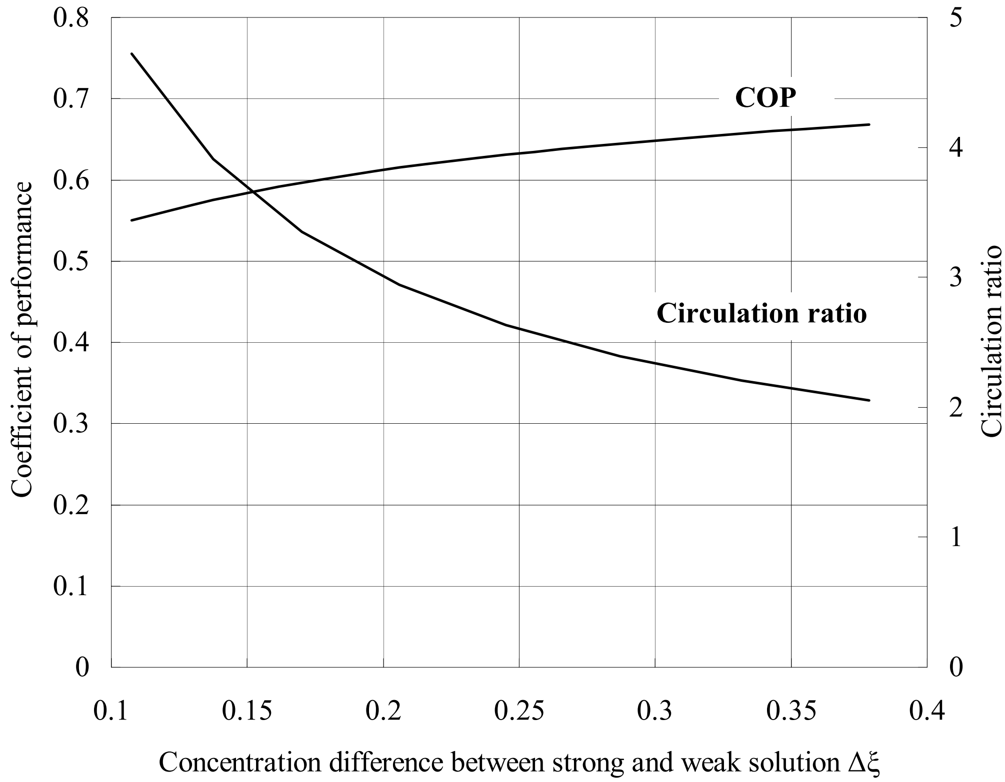

Fig. 2. Coefficient of performance of the absorption refrigeration cycle using TFE/NMP as a working fluid (calculation result)

To reduce the absorbent mixture in the refrigerant vapor flowing into a condenser and improve the cycle performance, the mass transfer characteristics of the rectifier column for the absorption refrigeration cycle using TFE/NMP as a working fluid were investigated in this study.

2 EXPERIMENTAL DESCRIPTION

2.1 Experimental Equipment

The experimental setup shown in Figure 3 consisted of the rectifier (main test section), the generator, the condenser, the solution reservoir, the solution pump. The main test section was the tower type rectifier column which had 47mm in inner diameter and 500mm in its height. The mixed vapor (TFE and NMP) is generated from the solution in the generator by heat input using the resistance heater. Then the mixed vapor goes up to the bottom of the rectifier column. The solution in the solution reservoir is pumped up and sprinkled to the top of the rectifier column. As the vapor temperature flowing into the rectification column from the generator is higher than the solution temperature sprinkled to it from the solution reservoir, the combined heat and mass transfer yields on the vapor and solution interface and the refrigerant component moves from the solution to the vapor. Thus the concentration of mixed vapor at the top side becomes higher than that of the bottom side by the rectification process. The both vapor and solution temperatures in the rectifier column were measured every 100mm using type-K thermocouples and the pressure in the rectifier column was also measured using digital manometer. The solution flow rate was controlled using the solution pump and the concentration is adjusted measuring the temperature and pressure in the solution reservoir.

2.2 Experimental Condition

The experimental conditions are shown in table 2. The solution concentration enclosed in the system was changed from 0.3 to 0.6. Flow rate of mixed vapor in the rectifier was changed from 0.15 to 0.36 kg/m^{2}s changing the heat input of the resistance heater in the generator. And flow rate of solution sprinkled to the top side of the rectifier was changed from 0.59 to 0.91 kg/m^{2}s using the solution pump. And these effects on the mass transfer characteristics in the rectifier were investigated.

Table 2. Experimental conditions

Enclosed solution concentration	0.3, 0.4, 0.5, 0.6
Flow rate of vapor kg/m^{2}s	0.15, 0.22, 0.29, 0.36
Flow rate of solution kg/m^{2}s	0.59, 0.69, 0.80, 0.91
Circulation ratio	1.63 ～6.28

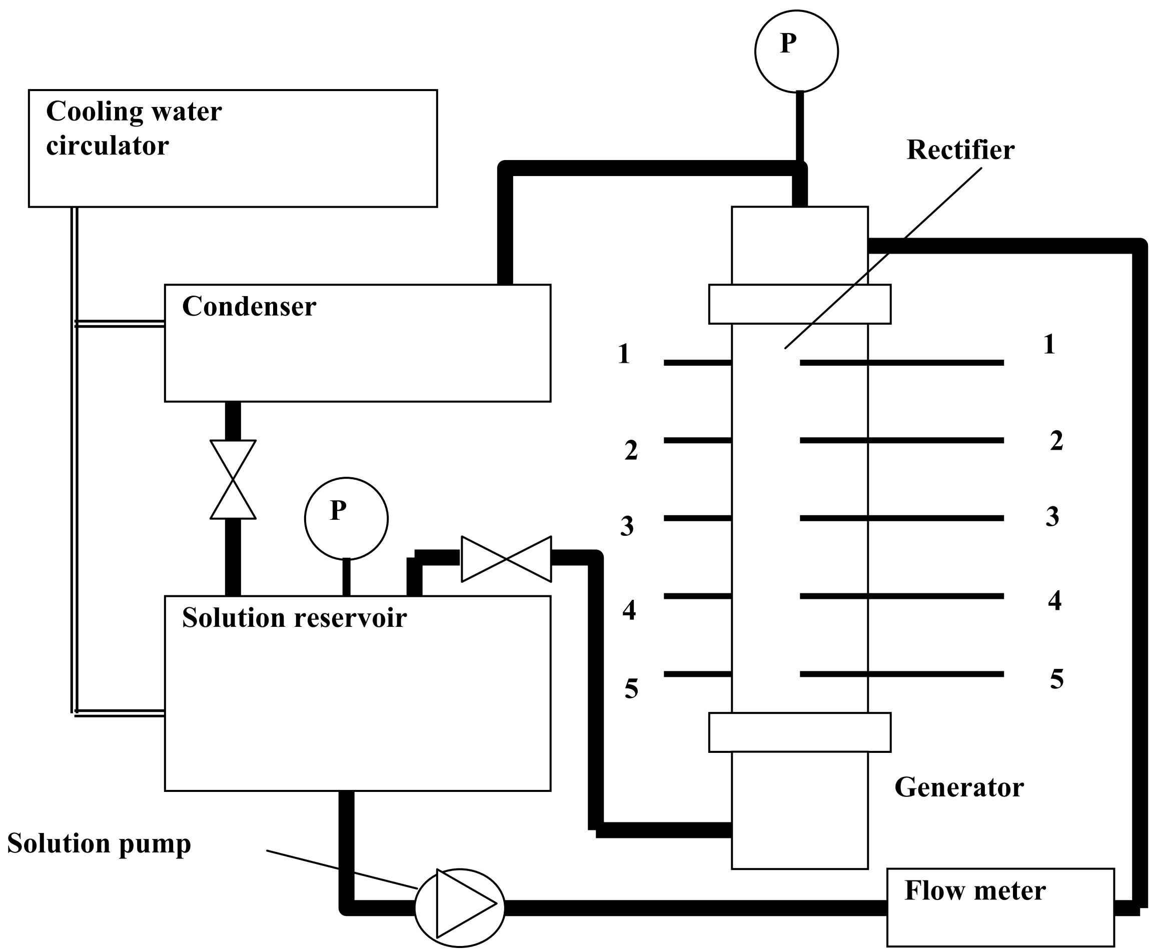

Fig. 3. Experimental setup

3 RESULTS AND DISCUSSION

3.1 Local Concentration in the Rectifier

Figure 4 shows the mixed vapor concentration along flow direction in the rectifier changing the enclosed solution concentration from 0.3 to 0.6. And Fig. 5 shows the solution concentration along flow direction in the rectifier changing the enclosed solution concentration. The measuring point numbers (1-5 mixed vapor and solution) are corresponding to the numbers in Fig. 3. Both mixed vapor and solution concentrations were calculated from the temperatures measured by type-K thermocouples and the pressure measured by digital manometer. From Fig. 4 the concentration of the mixed vapor increased along the flow direction by distillation process. This trend was more obvious in the case that the mixed vapor inlet concentration (point 5) was low. The inlet vapor concentration (point 5) in each condition was not equal to the vapor concentration equilibrating to the enclosed solution concentration. The mixed vapor concentration generated in the generator was higher than the vapor concentration equilibrating to the enclosed solution concentration in most case, so the solution sprinkled to the rectifier was considered to affect the generation process.

The concentration of the solution sprinkled to the rectifier shown in Fig. 5 decreased along the flow direction. Although the concentration of the solution from the solution reservoir (point 1) was expected to be same in every experimental condition, it was also affected by the enclosed solution concentration.
The concentration difference between vapor inlet (point 1) and outlet (point 5) varied from about 0.25(ξ encld=0.6) to 0.6(ξ encld=0.3). It means that the higher the inlet vapor concentration, the smaller the concentration difference by distillation becomes. These results show that the distillation process is more difficult in the high concentration range, though it is important for the rectifier in the TFE/NMP absorption refrigeration cycle which is expected to derive the pure refrigerant at the rectifier outlet point.

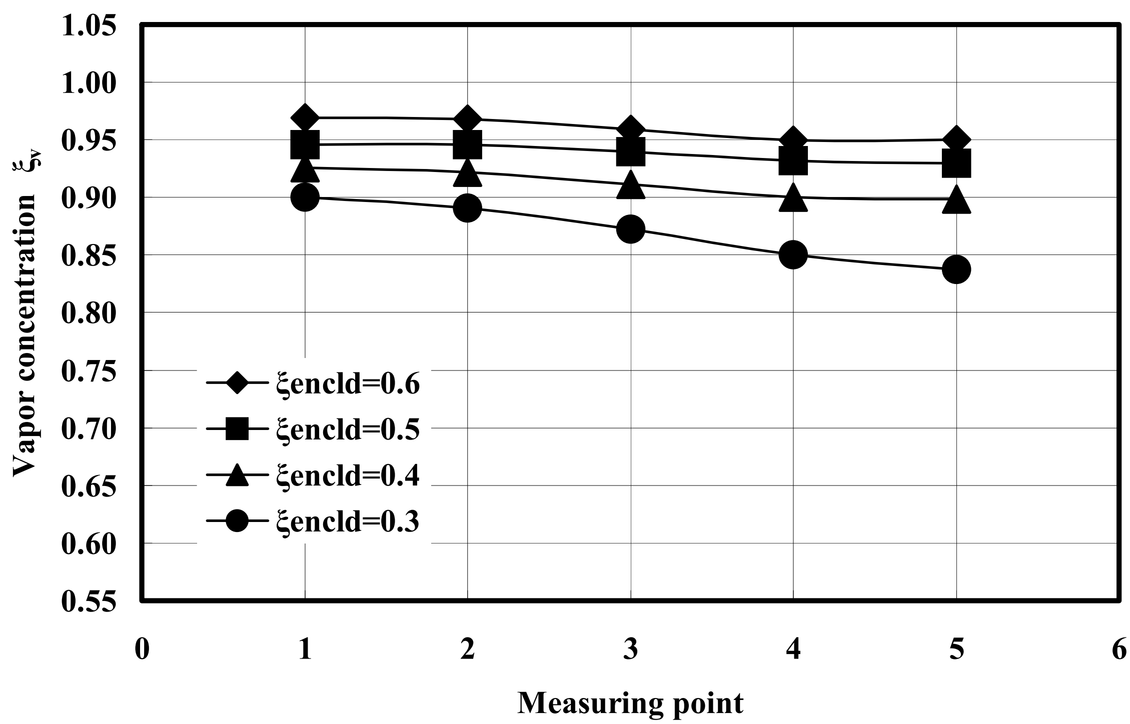

Fig. 4. Mixed vapor concentration along flow direction in the rectifier
(Gr=0.36 kg/m^{2}s, Gs=0.91 kg/m^{2}s)

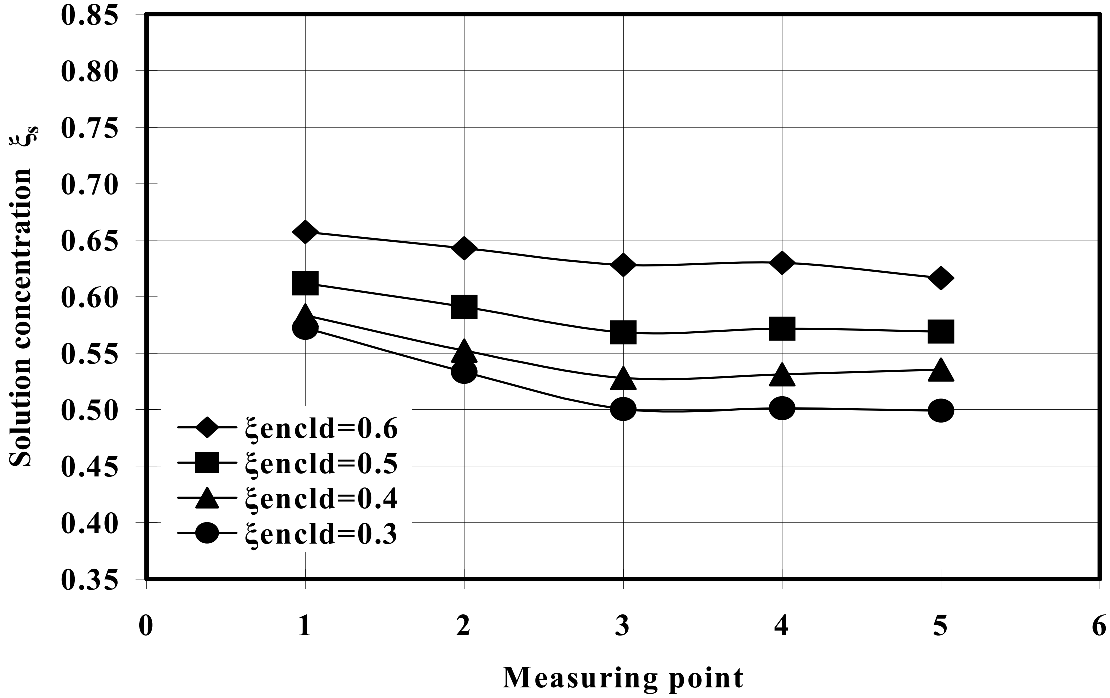

Fig. 5. Solution concentration along flow direction in the rectifier
(Gr=0.36 kg/m^{2}s, Gs=0.91 kg/m^{2}s)

3.2 Mass Transfer Characteristics

To evaluate the mass transfer characteristics of the rectifier column manufactured in this study, the over-all mass transfer coefficient was defined bellow.

$$m = \rho_s \cdot K \cdot \left(\xi_{vm}{}^* - \xi_{vm} \right) \qquad (1)$$

Where mass flux *m* is defined as follows (equation 2).

$$m = \frac{G_s \cdot \left(\xi_{\sin} - \xi_{sout} \right)}{A} \qquad (2)$$

Usually the mass transfer phenomenon exists in both vapor and solution phase. It is necessary to measure the temperature of both bulk and interface in both vapor and solution phase to evaluate both mass transfer characteristics separately. But it seems to be difficult to measure the vapor-solution interface temperature in the various experimental conditions, especially in the case of changing the solution flow rate. So the over-all mass transfer coefficient using the concentration difference between the vapor concentration equilibrating to the solution bulk and the vapor bulk concentration as a driving force was selected as the evaluation method.

Figure 6 shows the effect of mixed vapor flow rate on the over-all mass transfer coefficient. From this figure the over-all mass transfer coefficients were within about 0.3 to 0.8×10^{-4} m/s and decreased as flow rate of mixed vapor increased from 0.15 to 0.62 kg/m^{2}s in all experimental condition. And higher solution concentration generally showed higher over-all mass transfer coefficient. The heat transfer area in the rectifier relatively decreases as flow rate of vapor went up. And it was considered that this effect became dominant, though the disturbance effect went up in large flow rate condition. Figure 7 shows the effect of solution flow rate on over-all mass transfer coefficient. In this case the over-all mass transfer coefficients increased as flow rate of solution went up from 0.59 to 0.91 kg/m^{2}s and varied from about 0.1 to 0.6$\times 10^{-4}$ m/s. Thus higher flow rate of solution and/or higher solution concentration is required to enhance the mass transfer in the rectifier, though the theoretical coefficient of performance of absorption refrigeration cycle decreases in this condition.

3.3 Rectification Efficiency

To evaluate the distillation performance of the rectifier, the rectification efficiency was introduced which was defined as follows. The rectification efficiency expresses the ratio of the lift-up from inlet concentration to outlet concentration.

$$\phi_r = \frac{\xi_{vout} - \xi_{vin}}{\xi_{vout}{}^* - \xi_{vin}} \qquad (3)$$

Where $\xi_{vout}{}^*$ is the ideal vapor outlet concentration equilibrant to the inlet solution concentration. The over-all mass transfer coefficient and the rectification efficiency were used as an evaluation method in this study. The difference of these two is that the over-all mass transfer coefficient represents the mass transfer rate of the refrigerant per unit surface area, per unit concentration difference, on the other hand the rectification efficiency represents the increased rate of the concentration in the rectifier column compared with ideal increased rate.

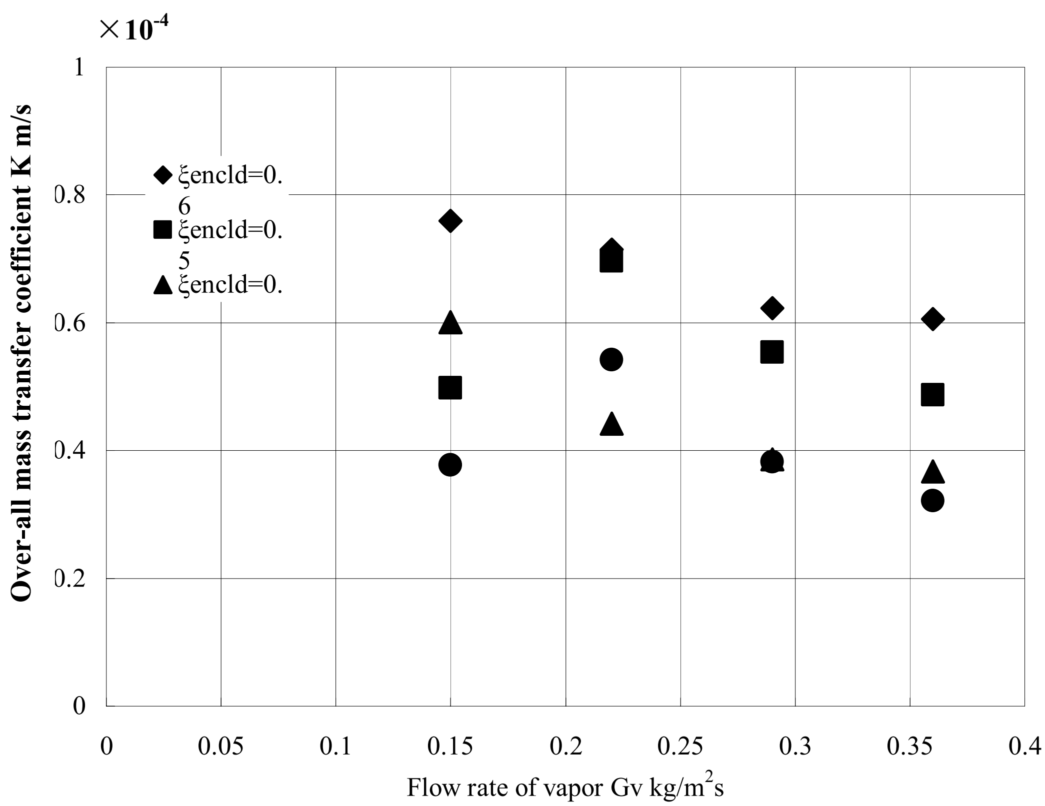

Fig. 6. Effect of flow rate of mixed vapor on over-all mass transfer coefficient (Gs=0.91 kg/m^{2}s)

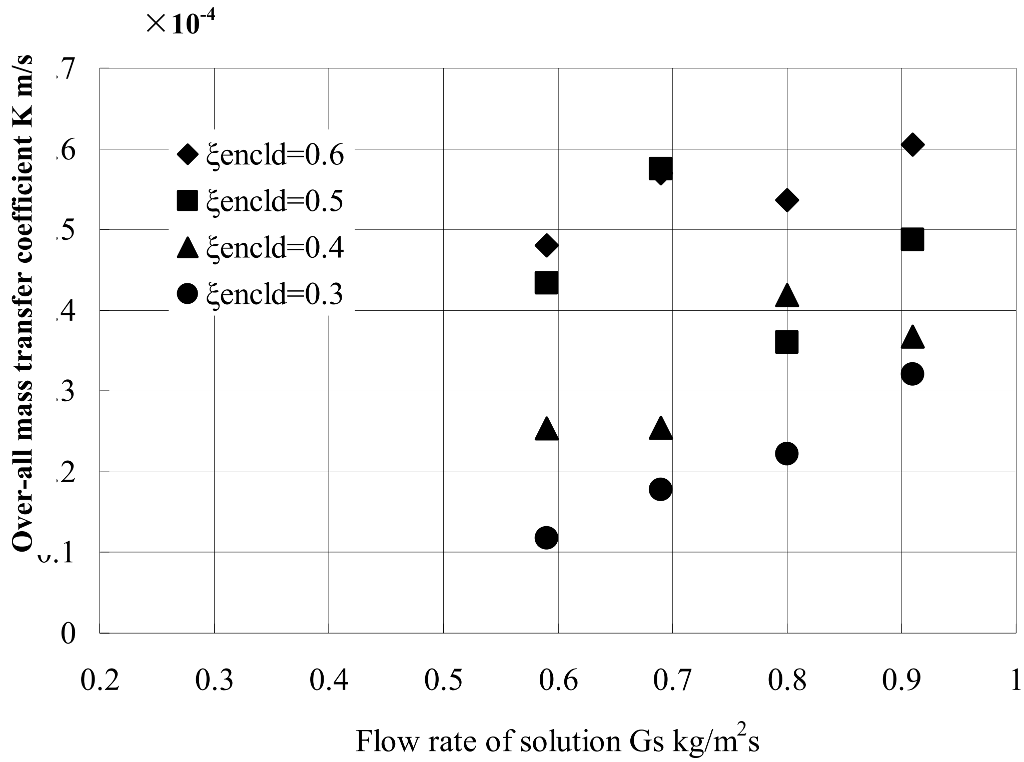

Fig. 7. Effect of flow rate of solution on over-all mass transfer coefficient ($Gr=0.36\ kg/m^2s$)

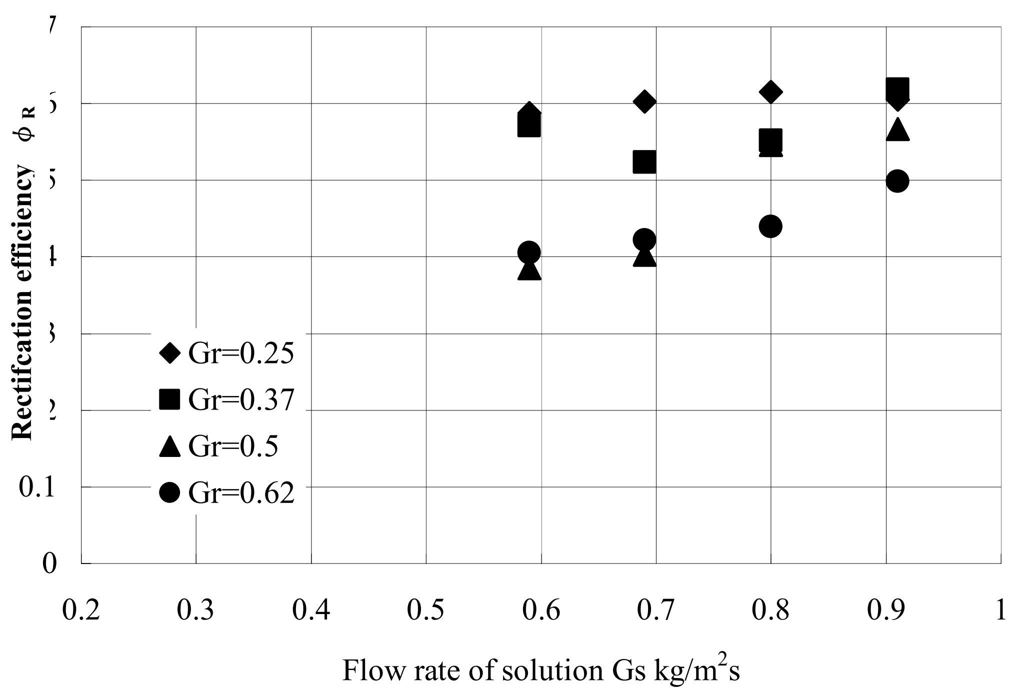

Fig. 8. Rectification efficiency (ξs=0.3)

From Fig. 8 the rectification efficiency increased as the flow rate of solution went up from 0.59 to 0.91 kg/m^2s. And lower flow rate of the mixed vapor showed higher rectification efficiency and also showed gradual inclination. The rectification efficiency in this experiment varied from 0.39 to 0.62, which was considered to significantly affect the cycle performance.

4 CONCLUSIONS

In order to design a rectifier of an absorption refrigerator or a heat pump, the experimental apparatus was manufactured and some experiment were performed in this study changing solution flow rate, solution concentration and vapor flow rate using TFE/NMP as a working fluid. From the above-described experimental results investing the mass transfer characteristics of the rectifier, several important conclusions are derived below:

1) The over-all mass transfer coefficient were almost from 0.1 to 0.8×10^{-4} m/s.
2) The over-all mass transfer coefficient became lower as the flow rate of vapor increased and higher as flow rate of solution increased.
3) The rectification efficiency increased as the flow rate of solution increased, and lower flow rate of the mixed vapor showed higher rectification efficiency and also showed gradual inclination.

In this study the mass transfer characteristics of the rectifier column was investigated. In next stage, the mass transfer characteristics of the packed type rectifier are going to investigate, which is expected to show high performance.

NOMENCLATURE

A: mass transfer area m^2
G_r: flow rate of vapor kg/s, m^3/s
G_s: flow rate of strong solution kg/s, m^3/s
G_w: flow rate of weak solution kg/s, m^3/s
Qa: heat rate of absorber kW
Qc: heat rate of condenser kW
Qe: heat rate of evaporator kW
Qg: heat rate of generator kW
h: enthalpy kJ/kg
K: over-all mass transfer coefficient m/s
m: mass flux kg/m^2s
ξ_R: concentration of refrigerant
ξ_{SR}: concentration of refrigerant not to evaporate
ξ_v: concentration of mixed vapor
ρ_s: density of solution kg/m^3
ϕ_R: rectification efficiency

Subscripts:

lrh: condenser outlet liquid
sao: absorber outlet solution
sgi: generator inlet solution
vrh: condenser inlet vapor
vrl: evaporator outlet vapor

wai absorber inlet solution
wgo generator outlet solution
*: ideal condition (equilibrating to the solution)

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