Thesis for the Degree of Master of Engineering

An Experimental Study on Heat Transfer Characteristics of Plate Absorber

by

Dong-Hwi Kim

Department of Refrigeration and Air-Conditioning Engineering

The Graduate School

Pukyong National University

February 2003

An Experimental Study on Heat Transfer Characteristics of Plate Absorber

(플레이트 흡수기의 흡수 열전달 특성에 관한 실험적 연구)

Advisor : Professor Jung-In Yoon

by

Dong-Hwi Kim

A thesis submitted in partial fulfillment of the requirements
for the degree of

Master of Engineering

in the Department of Refrigeration and Air-Conditioning
Engineering, Graduate School, Pukyong National University

Feburuary 2003

김동휘의 공학석사 학위논문을 인준함

2002년 12월

주 심	공학박사	금종수	인
위 원	공학박사	오후규	
위 원	공학박사	윤정인	인

An Experimental Study on Heat Transfer Characteristics of Plate Absorber

A Dissertation
by
Dong-Hwi Kim

Approved as to style and content by :

Jong-Soo Kum
Chairman

Hoo-Kyu Oh
Member

Jung-In Yoon
Member

February 25, 2003

CONTENTS

TABLE OF CONTENTS i

LIST OF FIGURES AND TABLES iii

NOMENCLATURE v

ABSTRACT vi

CHAPTER 1. INTRODUCTION 1

1.1 BACKGROUND AND OBJECTIVES 1

1.2 REVIEW OF PREVIOUS STUDY 3

CHAPTER 2. EXPERIMENTAL THEORY 6

2.1 OPERATING PRINCIPLE OF ABSORPTION CHILLER/HEATER AND BASIC COMPOSITION 6

CHAPTER 3. EXPERIMENTAL APPARATUS AND METHOD 12

3.1 COMPOSITION OF EXPERIMENTAL APPARATUS 12

3.2 EXPERIMENTAL METHOD 23

3.3 EVALUATION METHOD OF ABSORBER PERFORMANCE 26

3.3.1 Calculation of heat balancing 26

3.3.2 Characteristic of absorption heat exchange 28

CHAPTER 4. EXPERIMENTAL RESULTS AND DISCUSSION 32

4.1 CHARACTERISTICS OF ABSORPTION HEAT EXCHANGE OF PLATE TYPE ABSORBER 33
4.1.1 Conditions of absorption experiment 33
4.1.2 Temperature distribution in absorber 34
4.1.3 Characteristics of absorption heat exchange 39

CHAPTER 5. CONCLUSIONS 50

REFERENCE 52

ACKNOWLEDGEMENT 55

LIST OF FIGURES AND TABLES

Figures

page

Fig. 2.1 Mechanism of vapor absorption in absorber 9

Fig. 2.2 Mechanism of vapor generation in generator 10

Fig. 2.3 Basic composition of absorption chiller/heater 11

Fig. 3.1 Schematic diagram of experimental apparatus 14

Fig. 3.2 Photograph of experimental apparatus 15

Fig. 3.3 Schematic diagram of conventional horizontal tubes bundle type and plate type absorber 16

Fig. 3.4 Plate absorber/evaporator set 17

Fig. 3.5 Plate layout 17

Fig. 3.6 Plate type exchanger 18

Fig. 3.7 Photograph of vacuum pump 18

Fig. 3.8 Photograph of high pressure transducer 19

Fig. 3.9 Photograph of low pressure transducer 19

Fig. 3.10 Photograph of constant temperature bath for chilled water 20

Fig. 3.11 Photograph of constant temperature bath for cooling water 20

Fig. 3.12 Photograph of gear pump 21

Fig. 3.13 Photograph of LiBr solution flow meter 21

Fig. 3.14 Heat balancing of absorber and evaporator 31

Fig. 3.15 Calculation model of heat balancing 31

Fig. 4.1 Temperature of solution by distance ($Re_f = 6.3$) 35

Fig. 4.2 Temperature of solution by distance ($Re_f = 12.6$) 35

Fig. 4.3 Temperature of solution by distance ($Re_f = 18.6$) 36

Fig. 4.4 Temperature of solution by distance ($Re_f = 19.42$) 36

Fig. 4.5 Temperature of solution by distance ($Re_f = 24.21$) 37

Fig. 4.6 Temperature of solution by distance ($Re_f = 25.97$) 37

Fig. 4.7 Temperature of solution by distance ($Re_f = 27.74$) 38

Fig. 4.8 Comparison of Temperature by film Reynolds number 38

Fig. 4.9 Refrigerating capacity by film Reynolds number 40

Fig. 4.10 Overall heat transfer coefficient by film Reynolds number 41

Fig. 4.11 Refrigerating capacity by concentration 43

Fig. 4.12 Heat transfer coefficient by concentration 44

Fig. 4.13 Refrigerating capacity by flow rate of cooling water 46

Fig. 4.14 Overall heat transfer coefficient by flow rate of cooling water 47

Fig. 4.15 The comparison of the other studies 49

Tables page

Table 3.1 Specification of the measuring instrument 22

Table 4.1 Standard conditions 33

Table 4.2 Experimental conditions 33

Table 4.3 Experimental conditions of absorber from literature survey 49

NOMENCLATURE

A : Heat transfer surface area [m^2]

a : Circulation ratio of solution [-]

c : Concentration [wt%]

c_p : Specific heat with constant pressure [kJ/kg · K]

D : Absorption rate of water vapor [kg/s]

G : Mass flow rate [kg/s]

h_r : Evaporation latent heat of refrigerant vapor [kJ/kg]

L : Length of plate [m]

P : Pressure [mmHg]

Q_r : Refrigeration capacity [kW]

Re : Reynolds number [-]

ΔT_{lm} : Logarithmic mean temperature difference [℃]

Greek letters

Γ : Flow rate of film [kg/m · s]

Subscripts

f : Liquid film

i : Inlet

o : Outlet

s : Solution

w : Water

An Experimental Study on Heat Transfer Characteristics of Plate Absorber

Dong-Hwi Kim

Department of Refrigeration and Air Conditioning Engineering,
Graduate School, Pukyong National University

Abstract(In Korean)

생활수준의 향상으로 보다 쾌적한 생활공간을 추구함에 따라 냉난방기의 설치율이 날로 증가되고 있는 가운데, 특히 냉방기의 설치가 매년 급격히 증가하고 있는 실정이다. 이에 따라 프레온계 냉매에 의한 오존층 파괴와 하절기의 전기냉방기 사용급증에 의한 피크전력 및 가스에너지의 동고하저 문제에 대한 대안으로 천연가스를 이용한 흡수식 냉난방기의 기술개발 및 보급에 대한 요구가 높아지고 있다. 현재 국내에서 보급되고 있는 흡수식 냉난방기는 주로 냉매로 물, 흡수제로 LiBr 수용액이 사용되고 있다. 또한 국내에서는 30RT 이상의 중 · 대형 수냉 흡수식 냉난방기가 단위 건물 냉방을 위하여 급속히 보급되고 있으나 상당부분 선진외국의 기술도입에 의해 생산되고 있다.

현재 흡수식 냉온수기는 소형경량화, 공냉화, 개별유니트화, 인텔리전트화 및 고성능화가 중요한 테마를 이루고 있으며 이를 위한 활발한 연구개발이 이루어지고 있다. 흡수식 냉온수기의 소형경량화를 위한 연구 중의 하나로 고성능 전열관의 개발과 함께 플레이트 열교환 방식을 이용하여 고밀도화 하는 것이 제안되고 있다. 기기 전체를 크게 하지 않고 전열면적을 크게 증대시키기 위해서는 단위용적당의 전열면적을 증대시킬

필요가 있다. 이러한 관점에서 흡수기와 증발기에 종래의 수평관군형 열교환기방식 대신에 플레이트형 흡수기/증발기에 대한 연구가 이루어지고 있다. 지금까지 플레이트형 흡수기에 대한 연구는 일본을 중심으로 최근 활발하게 연구되고 있으며 상용화 단계에 이르고 있지만 아직 발표된 연구결과는 극히 미미하다.

본 연구에서는 흡수기·증발기에 종래의 수평관군방식 대신 단위용적당의 전열면적을 증대시킬 수 있는 플레이트형 흡수기의 보다 상세한 특성을 조사하기 위하여 평판형 플레이트 흡수기를 제작하여 흡수실험을 수행하였다.

플레이트 흡수기의 사이즈는 0.392×0.564 m^2 이고, 냉동능력 설계치는 1RT였다. 그 실험결과들은 설계조건이 아닌 실험조건에서 본 장치의 문제점들로 인해 예상보다 작은 결과값으로 냉동능력이 최대 1.221kW, 열통과율이 최대 0.767kW/m^{2}K를 보였다.

CHAPTER 1. INTRODUCTION

1.1 BACKGROUND AND OBJECTIVES

In 1777, Gerald Nairne had discovered a phenomenon that H_2SO_4 absorbs water vapor , and in 1810, John Leslie in Scotland made a refrigerator applying this principle. This was the first refrigerator as absorption chiller/heater.

In 1850, Edmond Carre of France invented water-H_2SO_4 absorption refrigerator, and Ferdinand Carre of France made absorption refrigerator using NH_3 as a refrigerant and water as an absorbent and acquired the special right.

Absorption refrigerator drawn attention at the beginning of the 20th century, but it had not been taken notice until 1925. But, in the 1930's, keeping an eye on absorption refrigeration cycle of the recently used water as a refrigerant and LiBr as an absorbent had started.

Besides, recently, CFC (Chloro Fluoro Carbon) abolished by determination in accordance to the 3rd agreement of international conference of Montreal' protocol about the problem of ozone depletion. And HCFC (Hydro Chloro Fluoro Carbon) , having a little damage, would also be banned in 2020. So these are being helpful information to a diffusion of absorption refrigerator.

In case of the internal need of the country, installation rate of chiller/heater is increasing for pursuit of the comfortable living place, and among the rest, installation rate of cooler is augmenting yearly. Accordingly, imbalance problem of supply and demand of electric power is being a serious issue because air-conditioning demands using the other energy excepting electric power to solve disproportion problem of supply and demand of electric power. It's gas that is clean energy to solve this problem.

We are paying for importing gas in summer season, because we can't only depend on a concentrative import in winter and have to import it as a fixed quantity all the year round.

So, absorption chiller/heater is being in the spotlight because it has a big advantage to solve a burning problem of electric power in summer season and using gas as clean energy for air-conditioning. But absorption chiller/heater inside the country is being mainly supplied by means of air-conditioning more than 30RT. [1-5]

Absorption chiller/heater is consisted of main apparatus of absorber, generator, condenser and solution heat exchanger, and the absorber occupies about 33% for heat transfer area and 27% for it's volume. Accordingly we need to make a investigation about the absorber for a smaller size, lighter weight and higher efficiency of absorption chiller/heater.[16-19]

Now-a-days, researches is required to make high density by plat heat exchange method by developing high efficiency heat pipe to make the absorption chiller/heater smaller in size and lighter in weight.[12]

For increasing heat transfer area, we need to make an enlargement of heat transfer area per unit of volume, and can make a high density by plate type heat exchange method instead of heat exchange method of horizontal tubes bundle type.

In this study, I have done absorption experiments with plate type absorber for detailed investigation of properties of plate absorber, which can increase heat transfer area per a unit of volume.

1.2 REVIEW OF PREVIOUS STUDY

Recently, studies on plate absorber are going on, researches are being carried out actively, and attained to common grade, but results of published research are little.

Strenger et al.[6] carried out experiment on the absorption of water vapor into a LiBr solution film falling outside vertical plate with cooling water flowing inside. The plate used was 3m in height, 0.3m in width and 0.005m in thickness. The effect of system pressure, solution temperature and concentration on the overall heat transfer coefficient were investigated, with the result that the overall heat transfer coefficient was changed from $0.3kW/m^2 \cdot K$ to $1.8kW/m^2 \cdot K$.

Grossman et al.[7,14,15] analyzed absorption process of refrigerant vapor in a steady liquid film falling down over an incline plane on the assumption that uniform temperature and heat flux at wall, and the physical properties of liquid solution are constant and independent of temperature. The model can predict the temperature and concentration profiles. The heat and mass transfer coefficients were determined from the Nusselt and Sherwood numbers, which were expressed in terms of the operating parameters.

Morioka et al.[8] performed an experimental study on the absorption of water vapor into a LiBr solution film falling outside a vertical tube which was considered as vertical plate because of 84mm outer diameter and 4m length analyzed the effect of system pressure and coolant temperature. They proposed the optimum thickness of solution film for a maximum absorption mass transfer rate.

Homma et al.[10] analyzed a falling film of LiBr solution of vertical plate wall cooled by water, however the thermal effect due to diffusion was neglected. Besides, the operating conditions were chosen on the assumption that the mass flow rate of cooling water has already known.

It does not match with an actual designing and operating conditions of plate absorber where the temperature difference between the inlet and outlet cooling water temperature are chosen first and controlled to steady during operation of absorption chiller/heater whereas the mass flow rate of cooling water is determined and changed later.

CHAPTER 2. EXPERIMENTAL THEORY

2.1 WORKING PRINCIPLE OF ABSORPTION CHILLER/HEATER

Absorption is a phenomenon that refrigerant is entered to solution by vapor pressure difference of solution and refrigerant.[11]

We are required to absorb refrigerant vapor in evaporator to solution more and more for advancement of refrigerating capacity.

If we compare with condensation contacted directly to water vapor, vapor pressure is dropped by decrease of water temperature in condensation, but vapor pressure is fallen by melting of salts like LiBr to water in absorption. So, essentially condensation and absorption is the same principle

However, when refrigerant vapor is absorbed to absorption solution in absorption process, more complex phenomenon arises because of coexistence of heat transformation by latent heat and concentration distribution by substance transformation.[13]

Fig. 2.1 shows conceptual absorption process. Pressures of evaporator and absorber are maintained by P_1 and temperatures of water and absorption solution became T_1 and $T_1+\Delta T_1$ that are equilibrium temperature (saturated temperature) to P_1.

In here, ΔT_1 is a boiling point increasement by melting of water to salts like LiBr, and temperature in absorber must be maintain temperature as high as ΔT_1 that is a increasement value of boiling increasement than T_1 which is the temperature in evaporator. In here, if absorber is cooled, solution temperature is decreased, and pressure in absorber become more low than P_1 which is a equilibrium state because of saturated pressure. So, refrigerant vapor is flowing in absorber from evaporator by pressure difference ΔP_1, and refrigerant is evaporated in evaporator. If refrigerant is evaporated, temperature in evaporator is descended, and saturated pressure is also descended.

Accordingly, quantity of heat corresponded to evaporation latent heat needs to be supplied for maintenance of temperature T_1 and pressure P_1 that are initial conditions in evaporator. It has to take a heat from a heat source of low temp. By the way, refrigerant vapor is absorbed to absorption solution in absorber, discharges a latent heat and becomes a liquid phase. If this latent heat and heat corresponded to dilution heat of solution is discharged out of system by cooling water and solution temperature is maintained as a little lower temperature, absorption happens continuously because pressure in absorber can be kept as lower pressure as ΔP_1 than saturated pressure P_1.

Absorption solution is gradually weakened due to progress of absorption and absorption capacity is dropped because, quantity of absorption solution in absorber is limited. So, concentration of absorption solution needs to be generated on high concentration. It's a generation to concentrate absorption solution by evaporation of refrigerant in absorption solution, conception diagram is showed in Fig. 2.2. Here is being maintained P_2 as pressure in system, T_2 the temperature in condenser, and $T_2+\Delta T_2$ that is temperature in generator. In this condition, if generator is heated by urban gas etc., temperature of solution is increased, so vapor pressure is also increased. Under this circumstances, refrigerant vapor produced in generator is transferred to condenser because it is produced at a pressure difference as ΔP_2 between condenser and generator. In this time, if temperature and pressure is maintained as T_2 and P_2 that is initial conditions by cooling of the inside of condenser, produced vapor is in liquid phase.

From the energy view point, heating quantity in generator is used on evaporating latent heat for producing vapor and to concentrate absorption solution and is removed by cooling water as heat quantity by liquefaction of produced vapor.

In absorption and generation process, evaporation, absorption, generation and condensation is similar while operate separately, however actually these processes made absorption cycle by connecting consecutively.

Absorption solution weakened by refrigerant absorption, is sent to the inside of generator by solution pump. Absorption solution concentrated by heating is returned to absorber again, refrigerant vapor of high temperature and pressure produced in this time discharges latent heat, is liquefied, and forms cycle supplied to evaporator. These processes are showed to Fig. 2.3.

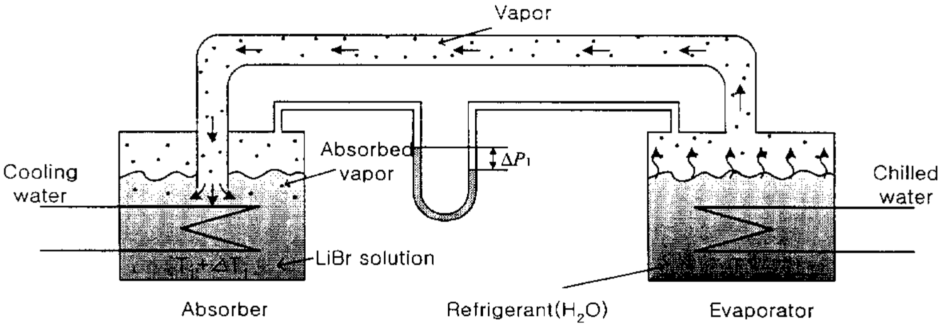


Fig. 2.1 Mechanism of vapor absorption in absorber

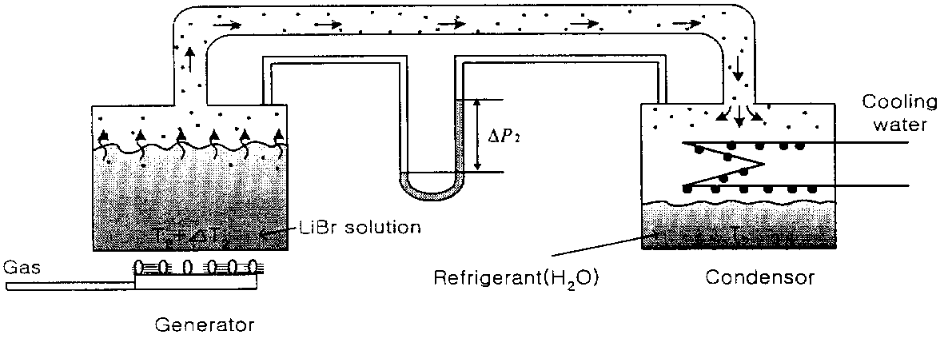


Fig. 2.2 Mechanism of vapor generation in generator

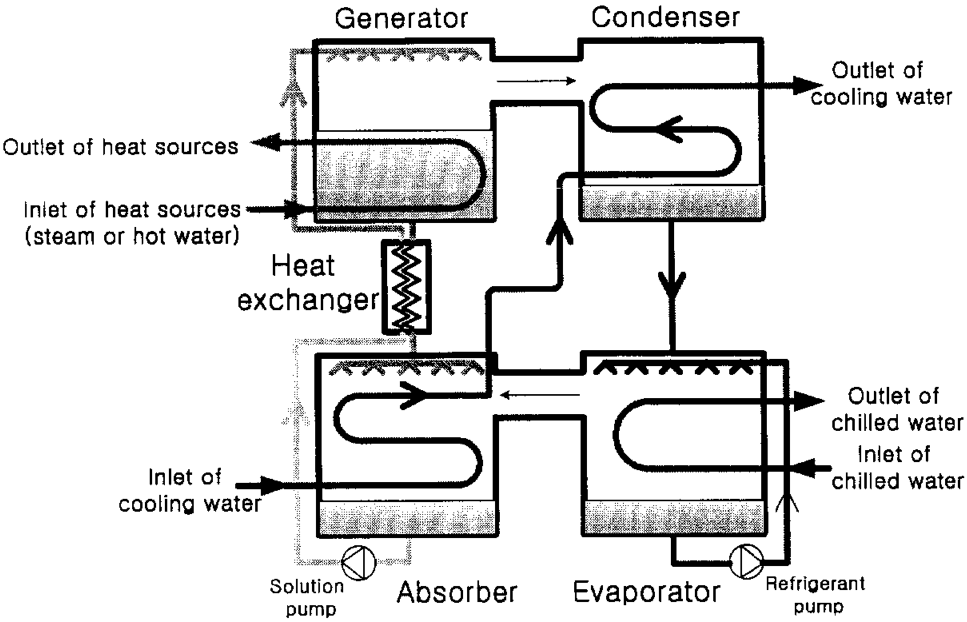


Fig. 2.3 Basic composition of absorption chiller/heater

CHAPTER 3. EXPERIMENTAL APPARATUS

3.1 COMPOSITION OF EXPERIMENTAL APPARATUS

Experimental apparatus composed in this study is designed and produced as batch type, and batch type has following advantages more than sequence type.

i) Operation of system is simple.

ii) Experimental conditions (parameters) namely, control of temperature, concentration of supply solution, supply flow rate, pressure of absorber and temperature of cooling water etc. can be controlled independently.

iii) By controling each parameters independently, we can grasp easily about effects of absorption phenomenon by each parameters.

But, batch type has defects like these

i) It is difficult to continue operating for a long time.

ii) Each component's size of system required to be large to increase the operating time of system.

Fig. 3.1 shows the schematic diagram of experimental apparatus used in this study, it's composed as absorber, evaporator, strong solution tank, generator, weak solution tank, refrigerant tank, heater and tubes etc. for connection of apparatus.

Fig. 3.2 shows the wetted plate exchanger and the entire picture of this experimental apparatus, Fig. 3.3 shows the conventional horizontal shell and tube type and the schematic diagram of plate type heat exchanger used in this experiment, and Fig. 3.4～3.6 shows the plate used to plate type heat exchanger.

Fig. 3.7～Fig. 3.13 give the pictures of attached machinery and equipments for measurement, and the specification are showed in Table 1.

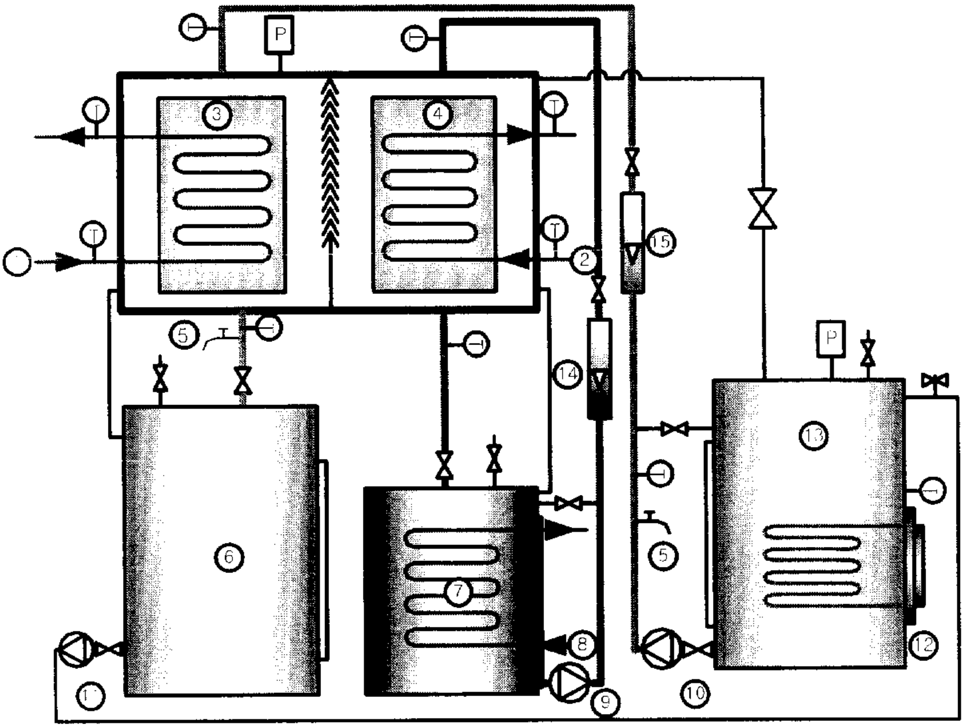
The experimental apparatus installed include a vacuum pump to maintain the vacuum of system, a digital pressure sensor for high pressure at the top of generator to know pressure of apparatus and a digital manometer for low pressure at the top of absorber.

Tubes are also installed for water circulation to supply cooling water from constant temperature bath of 2HP/5kW grade at absorber and chilled water from constant temperature bath of 3HP/8kW grade.

Sheath type thermocouples are installed to measure temperature of inlet and outlet of each water and solution tubes of absorber, evaporator, generator and tanks.

Flow meters are installed to measure the flow rate of cooling water, chilled water and solution.

And Sample valves are installed to measure solution concentration of inlet and outlet of absorber and the gear pumps are installed for constant flow rate of refrigerant and solution.



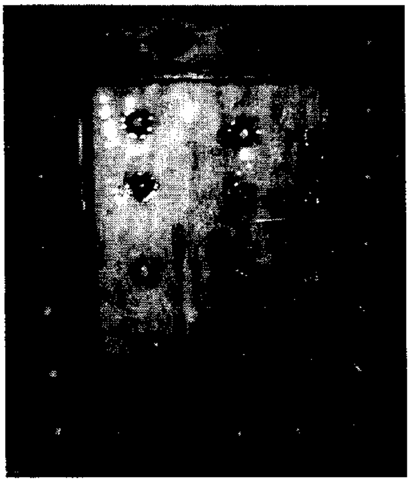
①Cooling water ②Chilled water ③Absorber ④Evaporator ⑤Sampling valve

⑥Weak solution tank ⑦Refrigerant tank ⑧Chiller ⑨Water pump ⑩Solution pump

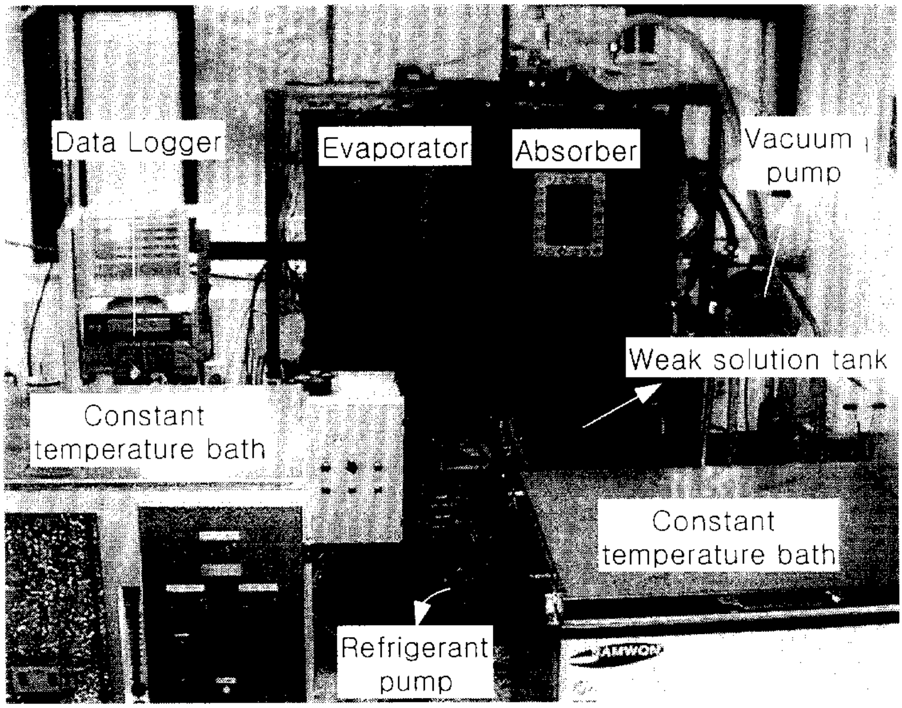
⑪Solution circulation pump ⑫Heater ⑬Strong solution tank ⑭Refrigerant flow meter

⑮Solution flow meter P Pressure gauge Ⓣ Thermometer

Fig. 3.1 Schematic diagram of experimental Apparatus

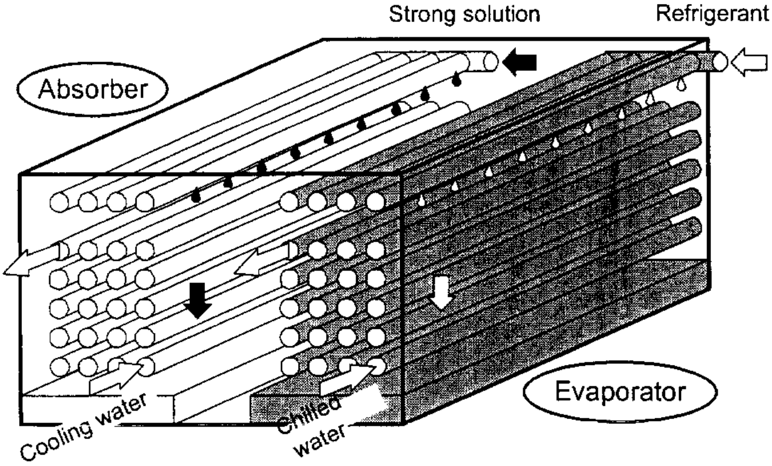


(a)The wetted plate exchanger



(b)Experimental apparatus

Fig. 3.2 Photograph of experimental apparatus



Conventional horizontal shell and tube type

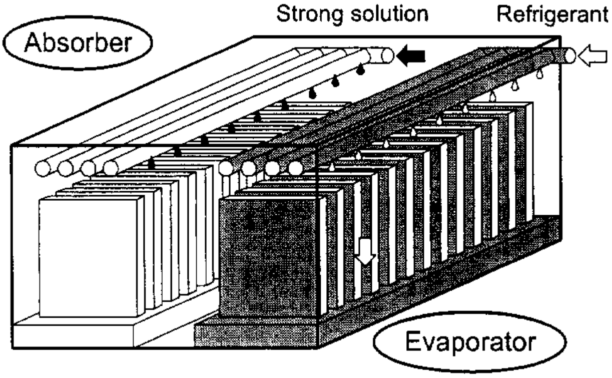


Plate type

Fig. 3.3 Schematic diagram of conventional horizontal tubes bundle type and plate type absorber

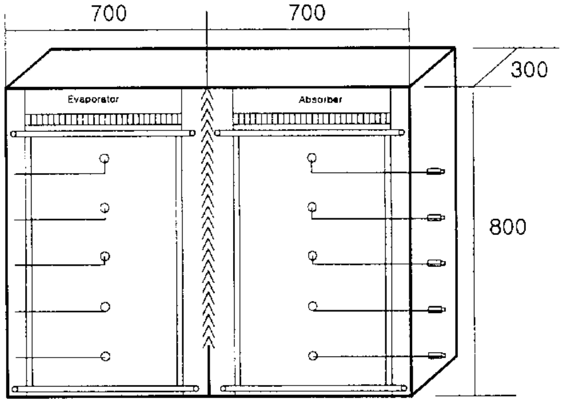


Fig. 3.4 Plate absorber/evaporator set

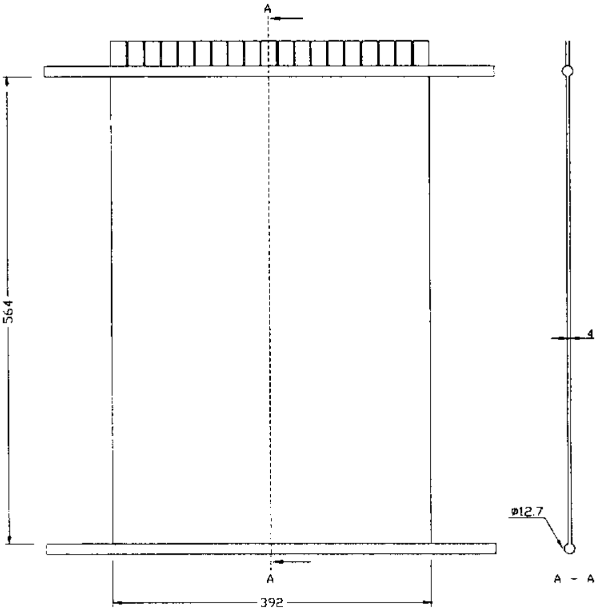


Fig. 3.5 Plate layout

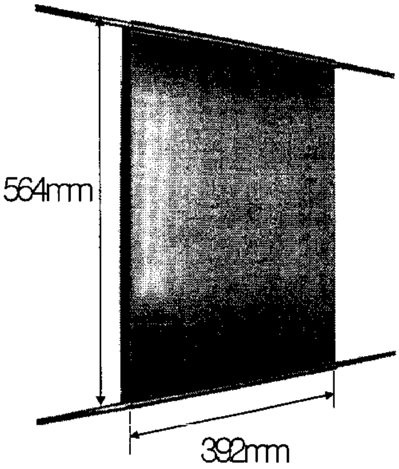


Fig. 3.6 Plate type exchanger

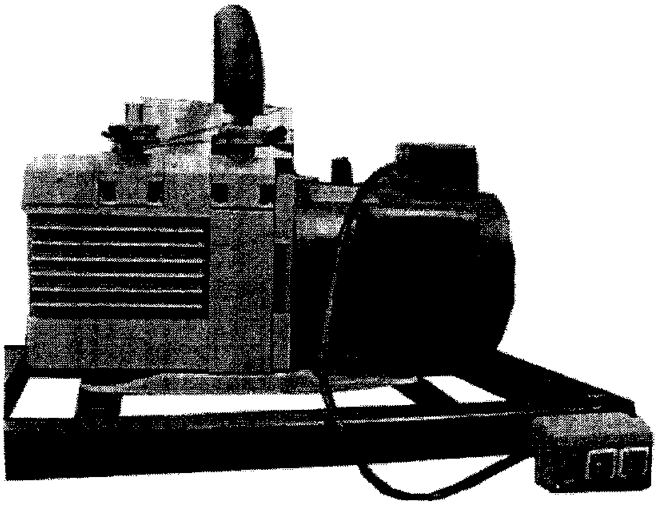


Fig. 3.7 Photograph of vacuum pump

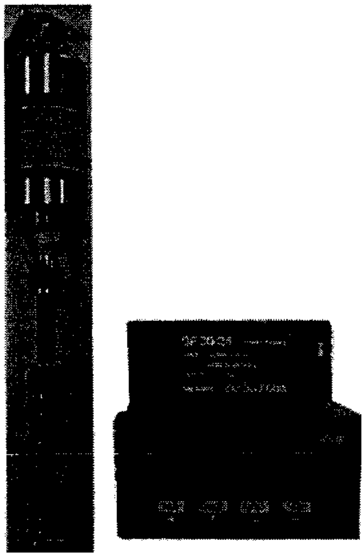


Fig. 3.8 Photograph of high pressure transducer

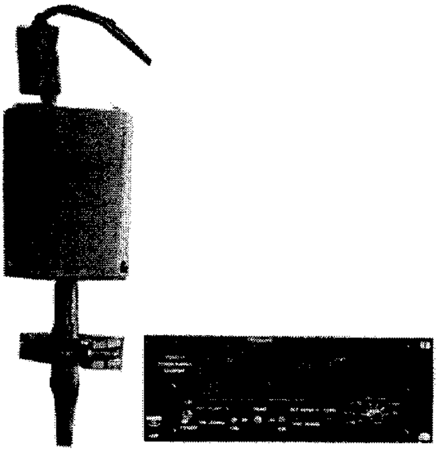


Fig. 3.9 Photograph of low pressure transducer

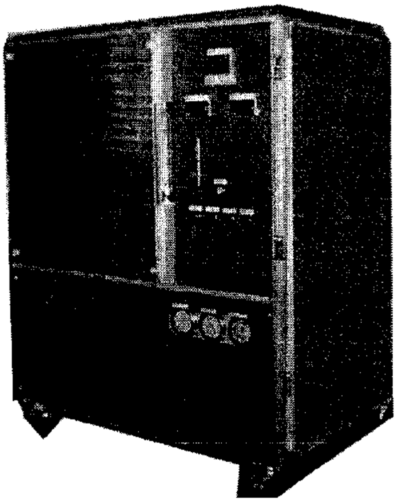


Fig. 3.10 Photograph of constant temperature bath for chilled water

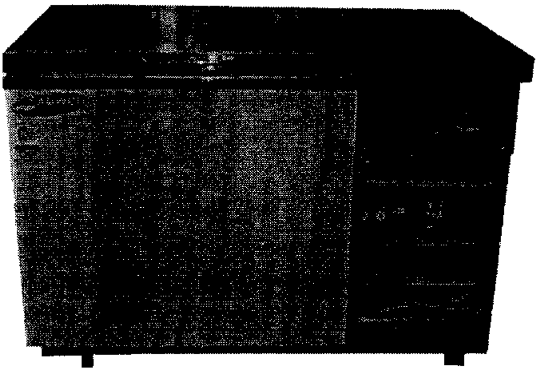


Fig. 3.11 Photograph of constant temperature bath for cooling water

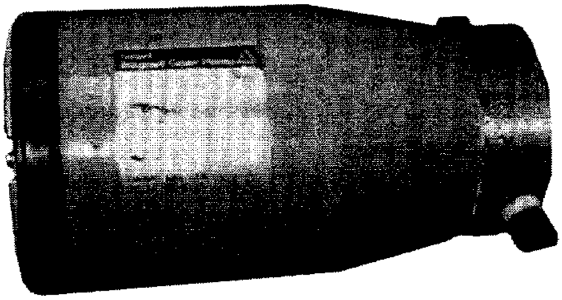


Fig. 3.12 Photograph of gear pump

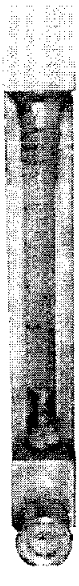


Fig. 3.13 Photograph of LiBr solution flow meter

Table 3.1 Specification of the measuring instrument

Measuring instrument	Specification	Maker	Model No.	Error bound
Vacuum pump	0.5 PS 5×10^{-4} Torr	SHINMYUNG	D10A	-
High pressure tranducer	14.7~35 PSIG	SETRA	280E	±0.5%
Low pressure transducer	0~100 Torr	MKS	128AA-00100D	±0.25%
Constant temperature bath for cooling water	4~40 l/min -10℃~60℃	AR	AR 3RT	±0.2%
Constant temperature bath for chilled water	4~40 l/min -10℃~60℃	SAMWON	M9911	±0.2%
Magnet gear pump	3.9~4.5 l/min	IWAKI	MDG -M4T6A100	-
LiBr solution flow meter	0~2 l/min	FLOW CELL	NO.002959	±0.8%

3.2 THE METHOD OF EXPERIMENT

Experiment was progressed in batch type divided by processes of establishment of experimental conditions measurement of performance and generation of solution to perform the experiment in stable state.

(1) The process of establishment of experimental conditions

The process of establishment of experimental conditions have to take a vacuum inside the system that is enough for the proper experimental conditions and controls the temperature conditions of solution in string solution tank, cooling water for absorber chilled water for evaporator and refrigerant tank.

Cooling water and chilled water supplied to absorber and evaporator is supplied after establishing of the temperature in constant temperature bath. And refrigerant in refrigerant tank is cooled to saturated temperature corresponded to experimental pressure by chilled water to prevent that the pressure in evaporator be affected by refrigerant vapor pressure in refrigerant tank.

(2) The process of performance measurement

In the process of performance measurement, first of all strong solution in strong solution tank is sent to absorber by solution pump, and this strong solution in the top of absorber is flowing as liquid film by spilling on plate. In this time, we measure the solution flow rate and the temperature of inlet and outlet of absorber. And refrigerant saved in refrigerant tank is evaporated in evaporator by sending through refrigerant pump.

The evaporated refrigerant flowing down on evaporator is absorbed to flowing down solution in absorber, and refrigerant not evaporated is flowing again in refrigerant tank. The solution weaken by absorption of refrigerant is saved in weak solution tank and is measured the solution concentration by taking weak solution in sampling valve. Cooling water and chilled water is sent to absorber and evaporator by water pump of constant temperature bath, and absorption solution and refrigerant is flown as counter flow. Cooling water taken heat in absorber and chilled water lost heat in evaporator is maintained again as setting temperature in constant temperature bath. In this time, the flow rate of evaporator and absorber inlet is measured separately, and the solution temperatures of inlet and outlet of absorber and absorber plate are measured in 5parts.

(3) The process of solution generation

In the process of solution generation, first the weak solution from weak solution tank is sent to strong solution tank (generation tank) by weak solution pump. If all weak solution is sent to strong solution tank, weak solution in strong solution pump is circulated by strong solution pump, and is heated by heater (3kW) in generator. So, refrigerant in the heated weak solution is separated, the solution became the strong solution, the separated refrigerant is gone to evaporator by pressure difference and is saved to refrigerant tank as being cooled and condensed by cooling water in evaporator.

Concentration of the strong solution is checked by taking it in sampling valve, and solution is generated continuously to be in the proper concentration state. strong solution made as constant concentration is circulated in heat exchanger that is flowing cooling water, and is saved to strong solution tank after adjusting to proper temperature for experimental conditions. The heat transfer plate used in this study is 392mm in width and 564mm in length as plate type.

3.3 THE METHOD OF PERFORMANCE EVALUATION OF ABSORBER

In the absorber of absorption chiller/heater, heat transfer phenomenon is very complex due to heat transfer accompanying mass transfer is occurred by absorption of refrigerant vapor in contrary to normal heat exchanger.

Absorption model is established to evaluate heat transfer property in absorption process.

3.3.1 THE CALCULATION OF HEAT BALANCING

Fig. 3.14 shows the heat balancing of absorber and evaporator about the system of experimental apparatus, and Fig. 3.15 shows the brief calculation model of this heat balancing.

The next equation is composed from that LiBr mass of absorber inlet is equal to that of absorber outlet.

$$(G_{s,o} - D)\, c_{s,i} = G_{s,o}\, c_{s,o} \qquad (3.1)$$

Here, if this equation is arranged by $a = G_o / D$,

$$a = \frac{G_{s,o}}{D} = \frac{c_{s,i}}{c_{s,i} - c_{s,o}} \qquad (3.2)$$

Which is showing the solution circulation ratio of refrigerant vapor per unit flow rate.

(a) The heat balancing in absorber

First of all, the heat exchange rate Q_w with cooling water is given like as follows.

$$Q_w = G_w c_{pw}(T_{w,o} - T_{w,i}) \tag{3.3}$$

By the way, quantity of heat radiated in absorption solution Q_s by the difference of enthalpy in inlet and outlet of absorber can be given like this.

$$\begin{aligned} Q_s &= (G_{s,o} - D)\, h_{s,i} - G_{s,o}\, h_{s,o} \\ &= D\,\{(a-1)\, h_{s,i} - a\, h_{s,o}\} \end{aligned} \tag{3.4}$$

Here, enthalpy $h_{s,i}$ and $h_{s,o}$ in inlet and outlet is

$$h_{s,i} = h(T_{s,i}\ ,\ c_{s,i}) \tag{3.5}$$

$$h_{s,o} = h(T_{s,o}\ ,\ c_{s,o}) \tag{3.6}$$

So, if latent heat quantity of absorbed water vapor is Q_r', the heat balancing in absorber is

$$Q_w = Q_r + Q_s \tag{3.7}$$

Here, if enthalpy of refrigerant vapor is h_r', it would be

$$Q_r = Dh_r' \tag{3.8}$$

(b) The heat balancing in evaporator

If the gotten heat quantity of refrigerant evaporated is supplying heat quantity Q_e and is transferred to all refrigerants, the next equation is composed to

$$Q_E = Q_H \qquad (3.9)$$

Because this heat quantity in normal state become evaporation latent heat of refrigerant vapor released to the inside of the entire absorber, it must be

$$Q_E = Dh_r' \qquad (3.10)$$

(c) Refrigeration capacity Q_r

Up to now, we considered heat balancing in absorber and evaporator, but if we think in a view point of refrigeration capacity, it's the point that absorber in normal state can take very well the heat quantity from the evaporator. So, refrigeration capacity Q_r is the heat quantity Q_r' transferred to absorber, and it can be seen in the next equation.

$$Q_{r1} = Q_w - Q_s \qquad (3.11)$$

$$Q_{r2} = Dh_r' \qquad (3.12)$$

3.3.2 THE PROPERTIES OF ABSORPTION HEAT EXCHANGE

(a) Refrigeration capacity Q_{r1}

In (c) of 3.3.1, refrigeration capacity in absorber and evaporator is defined, but we use Q_r, as refrigeration capacity to have an eye to the performance evaluation of absorber in plate type heat exchanger.

(b) Overall heat transfer coefficient K

Overall heat transfer coefficient K of absorber is shown in the next equation by using the received heat quantity of cooling water Q_w and heat transfer area A.

$$K = \frac{Q_w}{A \Delta T_{lm}} \tag{3.13}$$

In here, ΔT_{lm} is the logarithmic mean temperature difference defined by using the inlet and outlet temperature of absorption solution and cooling water, normally it is shown as follows.

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} \tag{3.14}$$

but, $\Delta T_1 = T_{s,i} - T_{w,o}$ (3.15)

$\Delta T_2 = T_{s,o} - T_{w,i}$ (3.16)

But, $T_{s,i}$ and $T_{s,o}$ is each the equilibrium temperature about solution concentration in inlet and outlet of absorber. Thus, if we use the logarithmic mean temperature difference, inside temperature of absorber has to take the ideal state of the equilibrium of air and liquid. But, ΔT_{lm} in absorber is certainly not equal to the logarithmic mean temperature difference. Because, although cooling water is equally heated, flowing down solution is not equally cooled certainly.

So, actually we have to calculate the overall heat transfer coefficient by logarithmic mean temperature difference of the proper type as comparing with the temperature distribution in absorber.

(c) Film Reynolds number Re_f

Film Reynolds number Re_f is defined like equation (3.17), and flow rate of film Γ_s per unit width is defined as given in equation (3.18)

$$Re_f = \frac{4\Gamma_s}{\mu_s} \tag{3.17}$$

$$\Gamma_s = \frac{G_s}{2L} \tag{3.18}$$

Here, $G_{s,i}$ is shown mass flow rate of absorption solution.

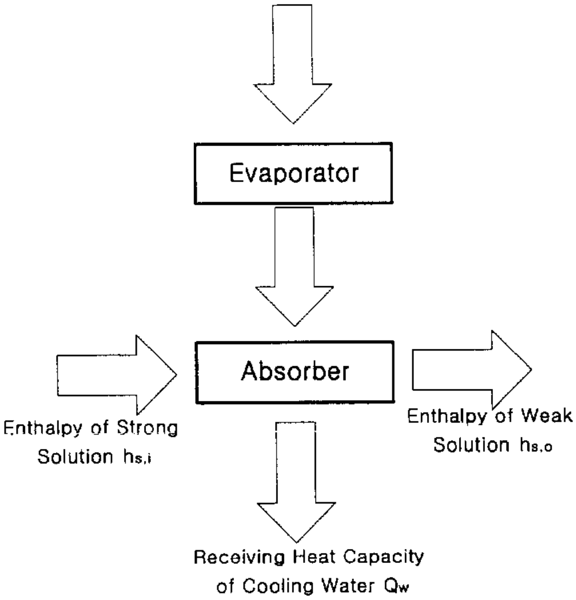


Fig. 3.14 Heat balancing of absorber and evaporator

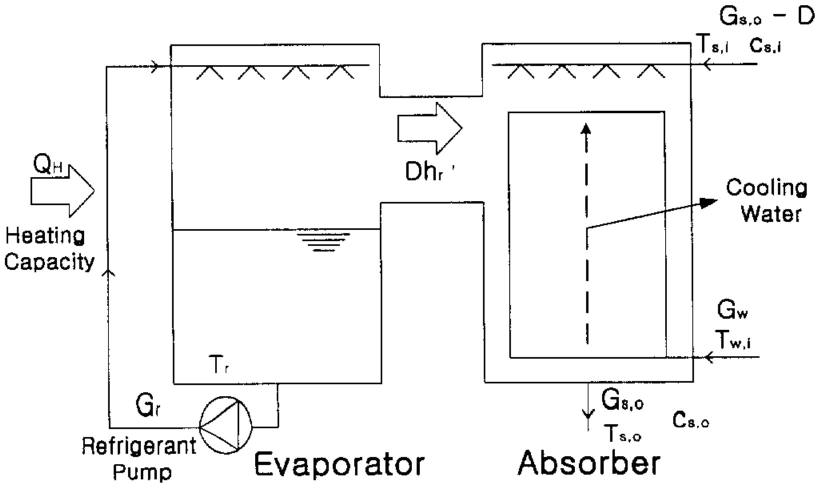


Fig. 3.15 Calculation model of heat balancing

CHAPTER 4. EXPERIMENTAL RESULTS AND DISCUSSION

The property evaluation of absorption heat exchange in absorber is calculated as effective experimental value, that is, data when temperature, concentration and flow rate of each parts of experimental apparatus have became normal state.

4.1 ABSORPTION HEAT EXCHANGE CHARACTERISTICS OF PLATE TYPE ABSORBER

4.1.1 The conditions of absorption experiment

The standard experimental conditions are shown in Table 4.1.

Table 4.1 Standard conditions

Pressure of Absorber P mmHg		6
LiBr solution	Temperature of Inlet $T_{s,i}$ (℃)	48
	Concentration of Inlet $c_{s,i}$ (wt%)	62
	Film Reynolds Number Re_f	18.4
cooling water	Temperature of Inlet $T_{w,i}$ (℃)	32
	Flow Rate (ℓ/min)	15

Absorption experiment measured temperature distribution and concentration of solution outlet in absorber by changing solution flow rate, concentration of solution inlet and pressure P in absorber under standard experimental conditions. Experimental conditions were shown in Table 4.2.

Table 4.2 Experimental conditions

Pressure of Absorber P mmHg		9±0.5
LiBr solution	Temperature of Inlet $T_{s,i}$ (℃)	45
	Concentration of Inlet $c_{s,i}$ (wt%)	60~62
	Film Reynods Number Re_f	6.3~34.6
cooling water	Temperature of Inlet $T_{w,i}$ (℃)	32±0.5
	Flow Rate (ℓ/min)	10~18

4.1.2 The temperature distribution in absorber

The temperature distribution in plate type absorber are shown in Fig. 4.1~Fig. 4.8. We could see that temperature of solution flowing on plate absorber is suddenly decreased in the upside of plate and is slowly reducing as flowing of solution. Because in the first time, if solution is flown in absorber, decreasing width of temperature is increased by large heat exchange due to big temperature difference with cooling water and latent heat quantity of refrigerant vapor.

And as solution flow rate increases temperature decreasing width of the first time is reduced. Because as solution flow rate increases in constant conditions, temperature change width is reduced by big thermal capacity.

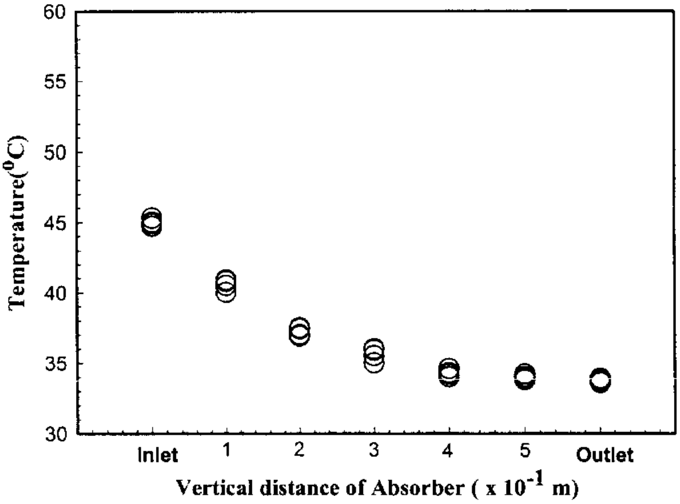


Fig. 4.1 Temperature of solution by distance ($Re_f = 6.3$)

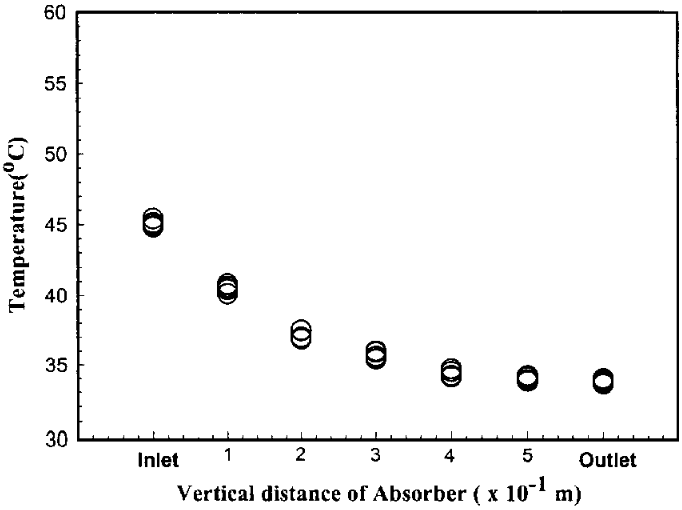


Fig. 4.2 Temperature of solution by distance ($Re_f = 12.6$)

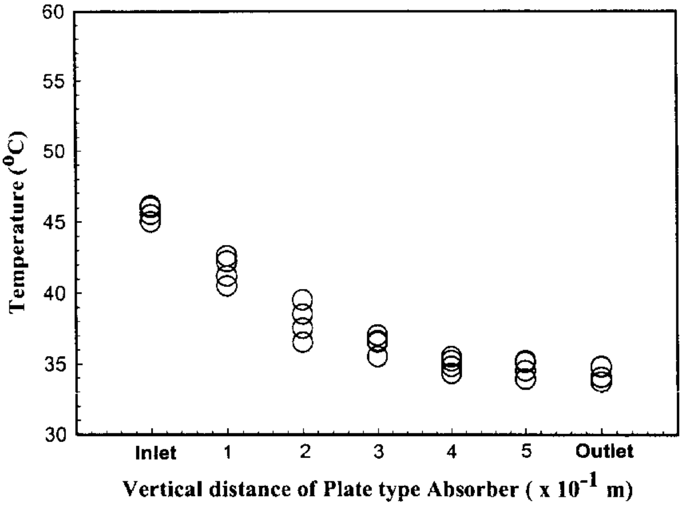


Fig. 4.3 Temperature of solution by distance ($Re_f = 18.6$)

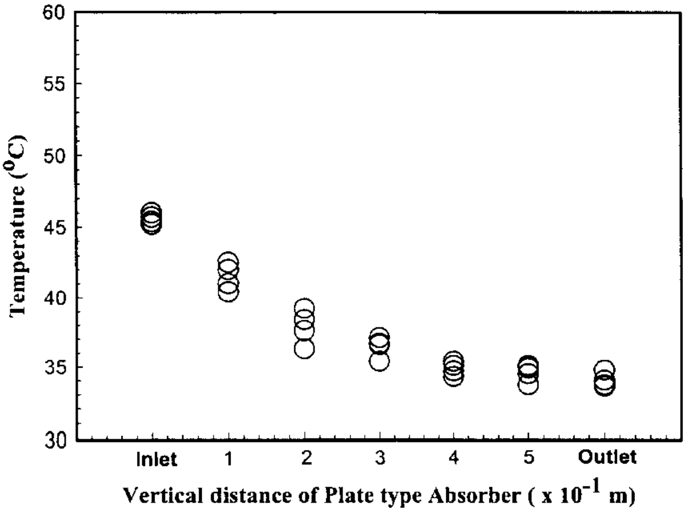


Fig. 4.4 Temperature of solution by distance ($Re_f = 24.2$)

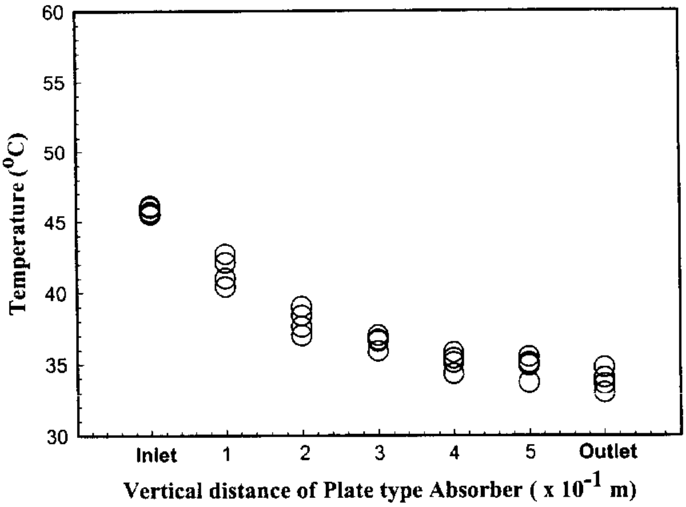


Fig. 4.5 Temperature of solution by distance ($Re_f = 30$)

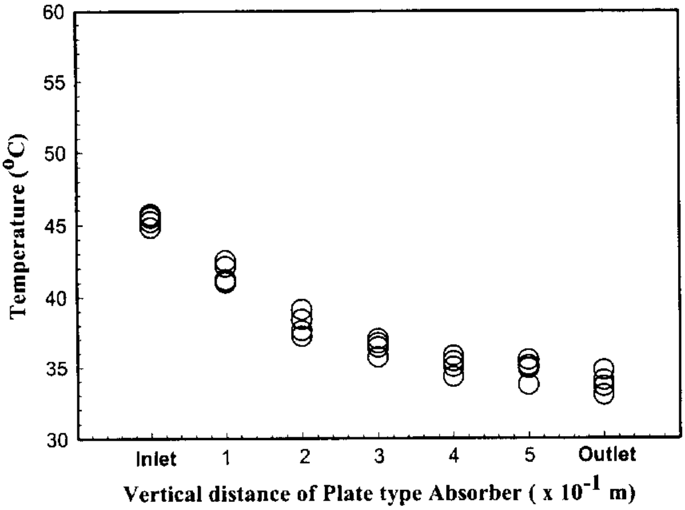


Fig. 4.6 Temperature of solution by distance ($Re_f = 32.3$)

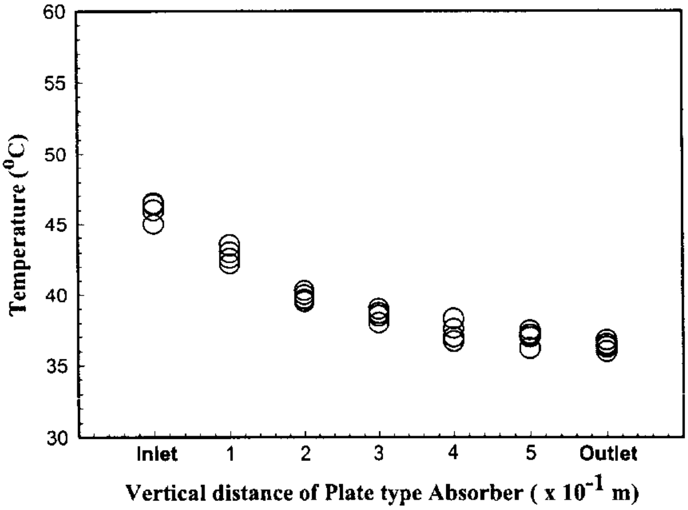


Fig. 4.7 Temperature of solution by distance ($Re_f = 34.6$)

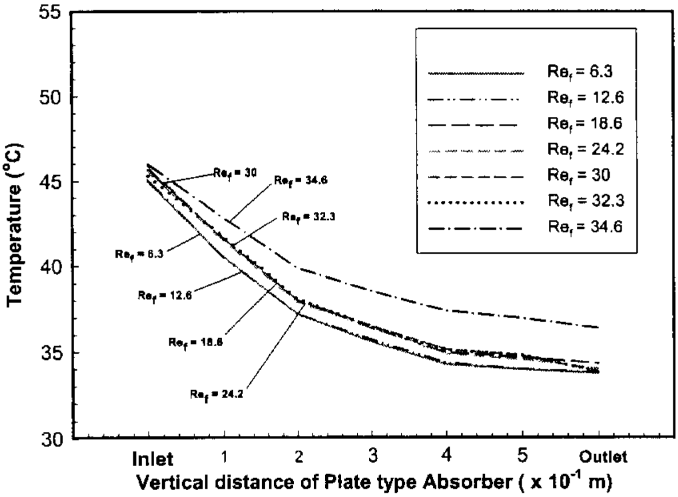


Fig. 4.8 Comparison of temperature by film Reynolds number

4.1.3 The characteristics of absorption heat exchange

Performance comparison was done using refrigeration capacity and over all heat transfer coefficient K in each experimental conditions about plate type absorption heat exchanger

(A) The comparison by solution flow rate

In pressure of experimental conditions, the comparison of refrigeration capacity Q_r by changing solution flow rate showed in Fig. 4.9. Through figure, we can know that as solution flow rate increases, in this apparatus, we can know that maximum refrigeration capacity is 1.221kW, it's unattainable to standard design capacity 1RT.

And overall heat transfer coefficient K by change of solution flow rate showed in Fig.4.10. Through figure, we can know that as solution flow rate increases, overall heat transfer coefficient is increased.

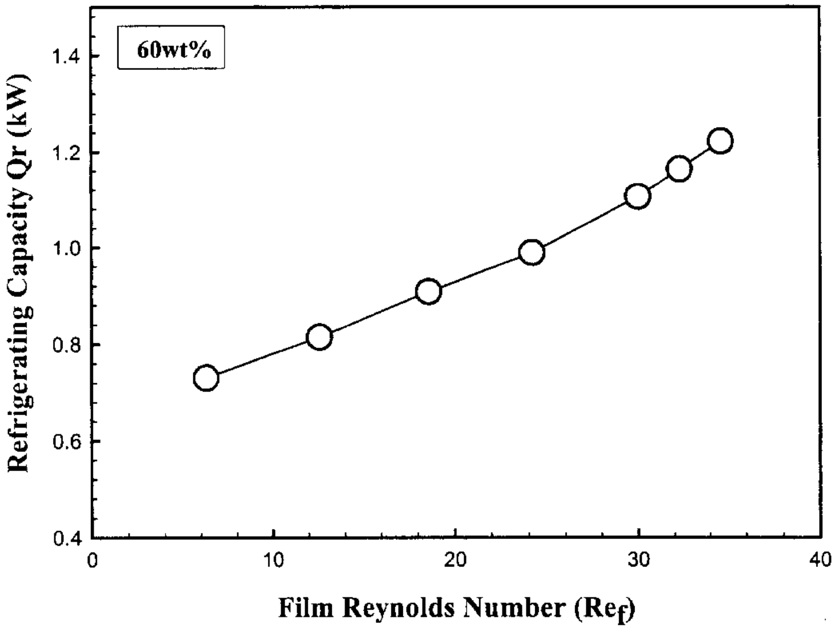


Fig. 4.9 Refrigerating capacity by film Reynolds number

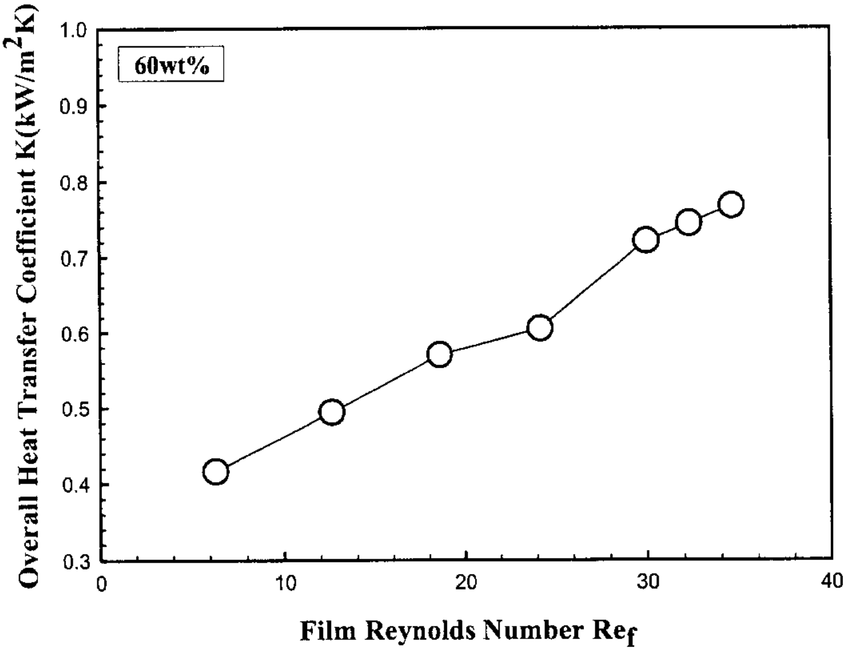


Fig. 4.10 Overall heat transfer coefficient by film Reynolds number

(B) The comparison by concentration

Here we are giving refrigeration capacity Q_r and over all heat transfer coefficient K by changing solution flow rate about solution inlet concentration $c_{s,i} = 60wt\%$ and 62wt%. Through Fig. 4.11, we can know that refrigeration capacity Q_r of $c_{s,i} = 62wt\%$ is higher than that of $c_{s,i} = 60wt\%$ by changing solution flow rate.

And through Fig. 4.12, We can know that overall heat transfer coefficient of $c_{s,i} = 62wt\%$ is better than it of $c_{s,i} = 60wt\%$ by increasing solution flow rate.

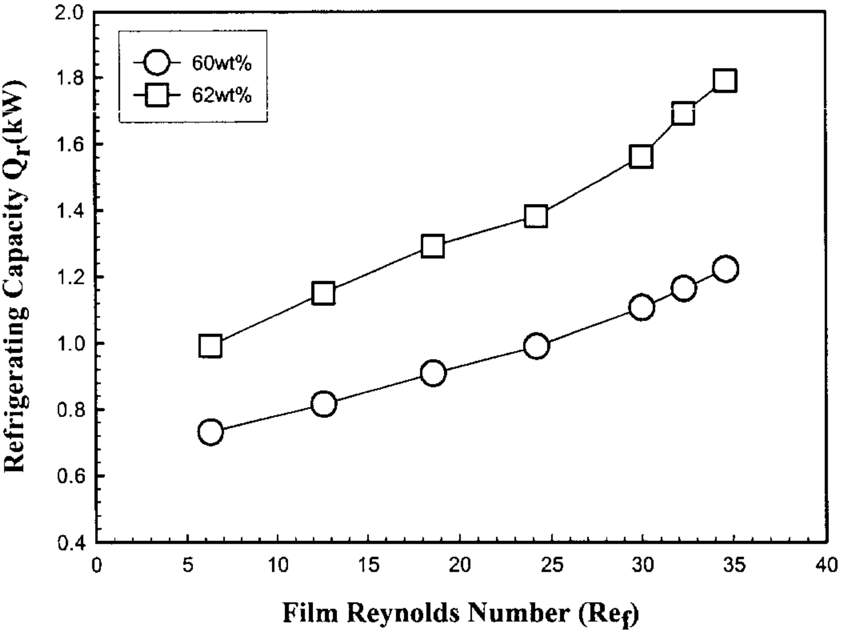


Fig. 4.11 Refrigerating capacity by concentration

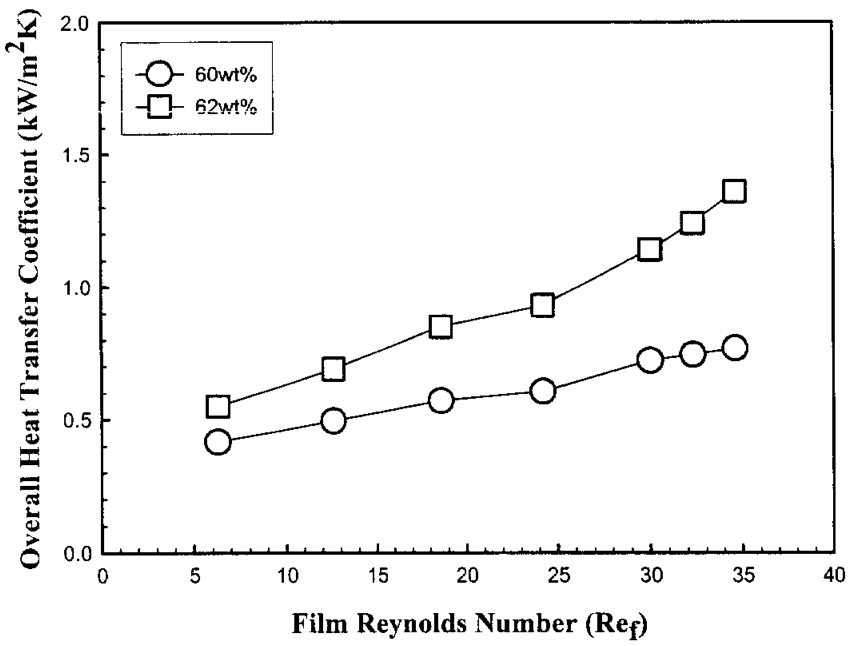


Fig.4.12 Heat transfer coefficient by concentration

(C) The comparison by cooling water flow rate

The comparison of refrigeration capacity Q_r and overall heat transfer coefficient K by changing cooling water flow rate in experimental conditions are showed in Fig 4.13 and Fig. 4.14.

We can know through Fig. 4.13 that as cooling water slow rate increases, refrigeration capacity is increased. But, we can also know through Fig. 4.14 that change of overall heat transfer coefficient by increasing cooling water flow rate is not remarkable

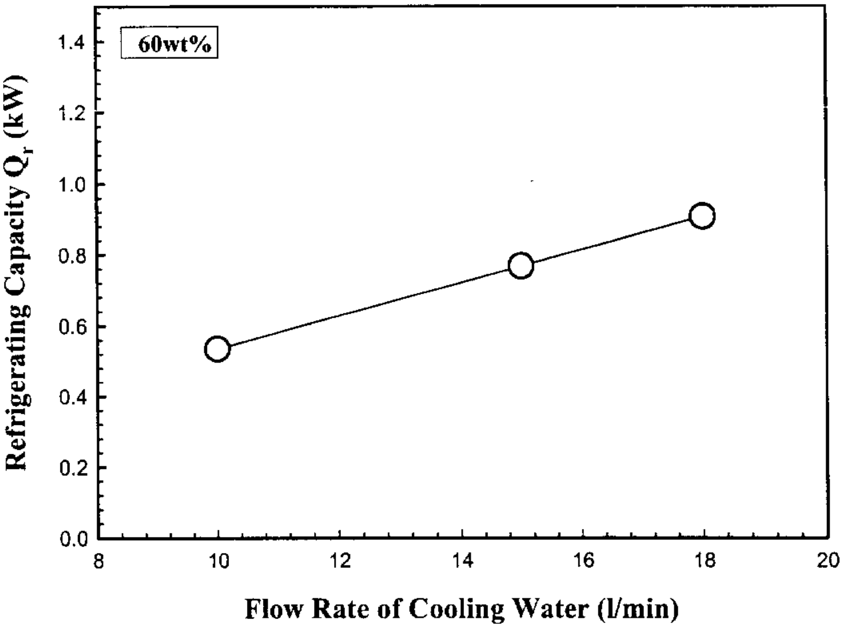


Fig. 4.13 Refrigerating capacity by flow rate of cooling water

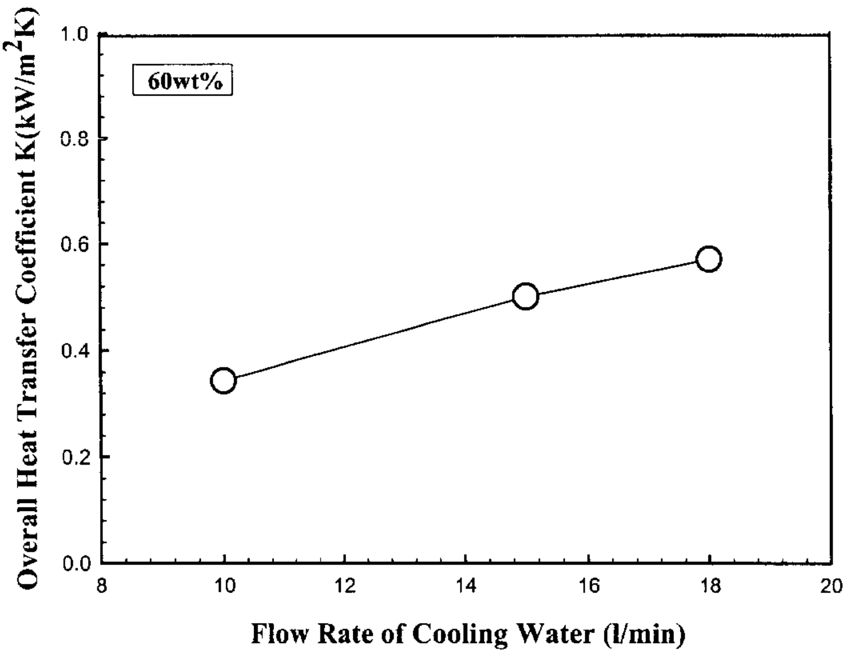


Fig. 4.14 Overall heat transfer coefficient by flow rate of cooling water

(D) The comparison with the other research results

As result in this study, overall heat transfer coefficient is compared with different study for comparison of performance of plate type heat exchanger.

Through the figure, overall heat transfer coefficient is a little smaller than that produced in the horizontal tubes bundle because of problem of plate surface in the experimental apparatus. Because the surface is not fully wetted when small flow is flowing down, surface cleaning of plate backside is difficult due to the difficulty of maintenance and management of apparatus and cooling water flow rate is not reached more than standard design value. If cooling water flow rate is fully maintained like standard design value and plate surface is always kept clean like the first time, overall heat transfer coefficient will be large values more than that from the horizontal tubes bundle type.

We need to develop the better technology for the even better solution flow on plate surface from the tray.

The lower part of the plate which was not wetted at the beginning was also not wetted well. We confirmed this through the experiment. So, I think we have to develop the ability for improving the wetting rate when solution flows at a low flow rate.

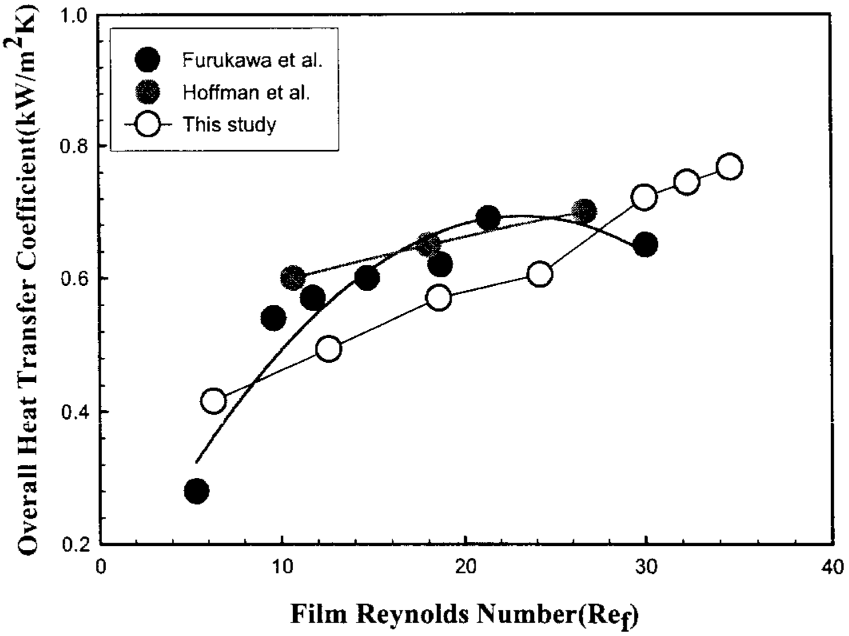


Fig. 4.15 The comparison with the other studies

Table 4.3 Experimental conditions on absorber from literature survey

Authors	Solution concent.	Solution temp.	Cooling water temp.	Cooling velocity	Solution flow rate (kg/ms)	Remarks
This study	60wt%	45℃	32℃	1.0m/s	6.3 ~ 34.2(Re_f)	Width :392mm Length:564mm
Furukawa et al.	58wt%	40℃	28℃	1m/s	0.013 ~ 0.042	1 row and 5 stages, d_o= 19.05mm
Hoffmann et al.	57wt%	42℃	30℃	-	0.007 ~ 0.045	1 row and 24 stages, bare tube

CHAPTER 5. CONCLUSIONS

Following conclusions can be reached based on the results of heat transfer characteristics from absorption experiment of plate absorber.

1. Temperature distribution in absorber, reveals that temperature of solution flowing in plate absorber is decreased suddenly in the top part of plate, and as solution flows down, reduction width of temperature is diminished

   Since temperature difference of the first solution flowing in absorber and cooling water is very high, so reduction width is increased due to large heat exchange.

   And as solution flows for the downward, reduction width of temperature is diminished due to temperature difference reduction of solution and cooling water and latent heat quantity of refrigerant vapor.

   And as solution flow rate increases, reduction width of the first temperature of refrigerant vapor is decreased. As solution flow rate increases in constant cooling water temperature and cooling water flow rate, temperature change due to heat exchange is decreased by large heat capacity.

2. Through the comparison by solution flow rate, we can know that refrigeration capacity is increased by increasing the solution flow rate.

   It can be note that as solution flow rate increases, overall heat transfer coefficient is increased.

3. From the comparison by concentration, we can know that refrigeration ca

pacity and overall heat transfer coefficient of the high concentration of solution is better than those of the low concentration of solution.

4. Through the comparison by cooling water flow rate, it is evident that refrigeration capacity increases when cooling water flow rate is increased.

REFERENCE

[1] J. I. Yoon, H. K. Oh and T. Kashiwagi, "Characteristics of heat and mass transfer for a falling film type absorber with insert spring tubes", Transaction of the KSME, Vol. 19, No .6, pp. 1501-1509, 1995

[2] J. I. Yoon and T. Kashiwagi, "Computer simulation of triple absorption cycles", Transaction of the JSME, B, Vol. 60, No. 578, pp. 304-309, 1994

[3] J. I. Yoon, H. K. Oh and T. Kashiwagi, "Characteristic simulation of the waste-heat utilization absorption cycles", Trans. of the JAR, Vol. 12, No. 1, pp. 43-52, 1995

[4] O. K. Kwon, J. K. Lim, and J. I. Yoon, "Characteristic of heat and mass transfer on helical absorber using new working fluid", Trans. of the KSME, B, pp. 228-233, 2000

[5] C. G. Moon, E. P. Kim and J. I. Yoon, "Analysis of performance in plate absorber", Winter trans. of Sarek, pp. 483-488, 2000

[6] U. Strenger and F. Setterwall, "Investigation on lamellas in an absorption heat pump", Proceeding of the International Absoption Heat Pump Conference ASME, AES-Vol.31, pp.149-153, 1993.

[7] G. Grossman, "Simultaneous heat and mass transfer in film absorption under laminar flow" , Int. J. Heat and Mass Transfer, Vol. 26, No.3, pp. 357-371, 1983.

[8] I. Morioka and M. Kiyota, "Absorption of water vapor into a lithium bromide water solution film falling along a vertical plate" , Transaction of the Japan Society of Mechanical Engineering, Vol.53, No. 485, pp. 236-240, 1987.

[9] S.C. Kim, M.D. Oh and J.H. Lee, "A numerical study on heat and mass transfer in a falling film of vertical plate absorber cooled by air ", Transaction of the KSME, Vol. 19, No. 4, pp. 1071-1082, 1995.

[10] R. Homma and S. Fujimaki, "Numerical simulation of plate absorber (Part 1: Analysis by the basic laminar model)" , Tokyo Research Center, Vol. 7, pp. 95-98, 1997.

[11] T. Kashiwagi, Y. Kurosaki and I. Nikai, "Heat and mass diffusions in the absorption of water vapor by aqueous solution lithium bromide", Transaction of the JAR, Vol. 1, No.1, pp.89-98, 1984.

[12] H. Becker and C.H.M. Machielsen, "Performance of a compact heat and mass transfer of the plate type as an absorber", XVIIth International Congress of Refrigeration, Proceeding, Wien87, Vol. B, pp. 144-109, 1987.

[13] E.S. Jeong, "Approximate solution of absorption process in an air-cooled vertical plate absorber", Trans. of the Sarek, Vol.6, No. 4, pp. 453-462, 1994.

[14] G. Grossman, "Simultaneous heat and mass transfer in film absorption under laminar flow", Int. J. Heat and Mass Transfer, Vol. 26, No.3, pp. 357-371, 1983.

[15] G. Grossman, "Heat and mass transfer in film absorption , Handbook of Heat and Mass Transfer", Gulf Publishing Company, Vol. 2, Chapter 6, pp. 211-256, 1986.

[16] O. K. Kwon and J. I. Yoon, " Heat and mass transfer of helical absorber on household absorption chiller/heater", Trans. of the Sarek, Vol. 11, No. 5, pp 570-578, 1999

[17] J. I. Yoon, O. K. Kwon and C. G. Moon, "Influence of surfactant on

heat transfer of air-cooled vertical absorber", Trans. of the Sarek, Vol. 11, No. 6, pp 740-748, 1999

[18] J. I. Yoon, O. K. Kwon and C. G. Moon, "Experimental study of heat and mass transfer on an absorber with several enhancement tubes", Heat transfer-asian research, Vol. 28, No. 8, 1999

[19] J. I. Yoon, O. K. Kwon and C. G. Moon, "Experimental Investigation of heat and mass transfer in absorber with enhanced tubes", KSME International journal, Vol. 13, No. 9, pp 640-646, 1999

[20] S. Y. Jeong and S. Garimella, "Falling-film and droplet mode heat and mass transfer in a horizontal tube LiBr/water absorber", Int. journal of heat and mass transfer, Vol. 45, pp. 1445-1458, 2002

[21] Hoffman, L, I. Greiter, A. Wagner, V. Weiss and G. Alefeld, 1996, "Experimental investigation of heat transfer in a horizontal tube falling film absorber with aqueous solutions of LiBr with and without surfactants", Int J. Refrig. Vol. 19, No. 5, pp. 331-341.

[22] Furukawa, M., Sasaki, N., Kaneko, T., Nosetani, T., 1993, “Enhanced Heat Transfer Tubes for Absorber of Absorption Chiller/Heater”, Trans. of the JAR, Vol.10, No.2, pp.219～226.

ACKNOWLEDGEMENTS

I would like to express my gratitude and respect to Professor Jung-In Yoon under whose supervision this research was performed. Although extremely busy, the professor always found the time for professional discussions, continued encouragement and support. I also thank Prof. Jong-Soo Kum, Prof. Hoo-Kyu Oh, Prof. Jong-Soo Kim, Prof. Kwang-Hwan Choi, Prof. Young-Soo Kim, Prof. Eun-Pil Kim, Prof. Seok-Kwon Jeong Kim of Department of Refrigeration and Air-Conditioning, Pukyong National University and Prof. Jae-Dol Kim of Tongmyong College.

Especially, I thank Mr. Choon-Geun Moon, Ho-Saeng Lee, Sung-Ho Song and Yong-Sik Jang for their help and support. And I also thank Mr. Md. Manirul Alam Sarker, Seung-Moon Baek, Thanh-Tong Phan, Dong-An Cha, Byung-Jin Kim, Ki-Suk Bang, Kyung-Hyun Min, Keun-Tae Lee and Dong-Hoon Lee for giving sincere help, encouragement and valuable advices wherever I have got trouble.

I deeply appreciate my parents and sisters for their support and encouragement.

Dong-Hwi Kim