Opportunity and challenge of developing a hydrophobic membrane-based compact absorption system

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Abstract

Several attempts for the enhancement of heat and mass transfer in major components of vapor absorption re-frigeration system are described in the paper. As a promising measure to this purpose, a micro-porous hydropho-bic membrane based heat and mass exchangers are proposed. A micro-porous hydrophobic membrane acts as a selective barrier which allows vapor to pass through but blocks the passage of liquid, and therefore it is expected that the stream of working solution is narrowly confined by the membrane, and the refrigeration vapor is ab-sorbed into or desorbed from the solution across the membrane. We firstly reviews various attempts that have been proposed to enhance heat and mass transfer in the conventional absorption components, and proposes the potential of microporous hydrophobic membrane for novel membrane based compact desorber and absorber with the feasible single effect membrane based absorption cycle. The theoretical model for the heat and mass transfer is presented, and is also simulated to look into the heat and mass transfer characteristics of membrane based heat and mass exchangers. The absorption mass flux of various membrane based absorption components were re-viewed, and compared with absorption flux of conventional components.

1. Introduction

As global warming problem has come to the fore all over the world, there is a rising interest on the develop-ment of novel thermal engineering system that alleviates the environmental problem and the energy consumption in the air-conditioning industry. Vapor compression refrigeration system (VCRs) has widely been used owing to their small size, high performance-to-volume ratio, but it has two major disadvantages, such that: the large ener-gy requirement for compressor operation, and the use of hydrocarbon derivatives causing environmental prob-lems. To this purpose, vapor absorption refrigeration system (VARs) which uses the environmental working fluids has a great potential to substitute the CFC-based and ozone-depleting air-conditioning systems. Further, by using the low-grade waste heat energy, as opposed to the high-grade electrical energy for the operation of VCRs, the aforementioned drawbacks of VCRs can be eliminated.

The conventional VARs commonly uses two pairs of working fluids: (1) LiBr-water, or (2) water-ammonia pair. Since the single-effect VARs which uses LiBr-water pair was introduced in 1930, this thermally activated absorption system has been widely used for the industrial applications and numerous studies has been carried

out. Thermo-physical properties of aqueous LiBr solution were explored, and constructed [1-7]. Several extensive numerical and experimental researches on the single-effect VARs were also carried out [8-15]. This heat-actuated LiBr-water absorption system is basically consists of five components, a desorber, an absorber, a condenser, an evaporator, and a solution heat exchanger, as labeled in *Figure 1*. All the components and tubes are made of stainless steel and the system is maintained at vacuum to prevent the corrosion caused by the LiBr solution. The LiBr solution is circulated, and is pressurized by means of the solution pump in the heat-operated desorber. The heat energy is directly supplied (H1-H2) to a tube bundle installed in the desorber so that the refrigerant vapor (i.e. water vapor) is desorbed from the LiBr solution at high pressure. The desorbed water vapor is condensed in the condenser (1-2) by the cooling process (C2-C3), that is, heat is rejected out to the surroundings, and then is expanded to low pressure through an expansion valve (2-3). The refrigerant is evaporated at low pressure for the cooling purpose, and leaves the evaporator (4). The weak solution becomes stronger in the desorber as the water vapor escapes and the strong solution heads for the absorber via the solution heat exchanger (8-9). The strong solution is expanded through an expansion valve (9-10), and enters the absorber. In the absorber, the water vapor from the evaporator is absorbed into the strong solution at low pressure, releasing the heat of absorption by the cooling process (C1-C2). The solution heat exchanger (SHE) induces the higher coefficient of performance (COP) by the elimination of the irreversibility caused as the high temperature heat is conveyed to the absorber and condenser. For ammonia-water absorption system, a rectifier is located between the desorber and condenser so that the water vapor which is evaporated with ammonia is removed and only dried ammonia gas heads for the condenser since both working fluids are volatile.
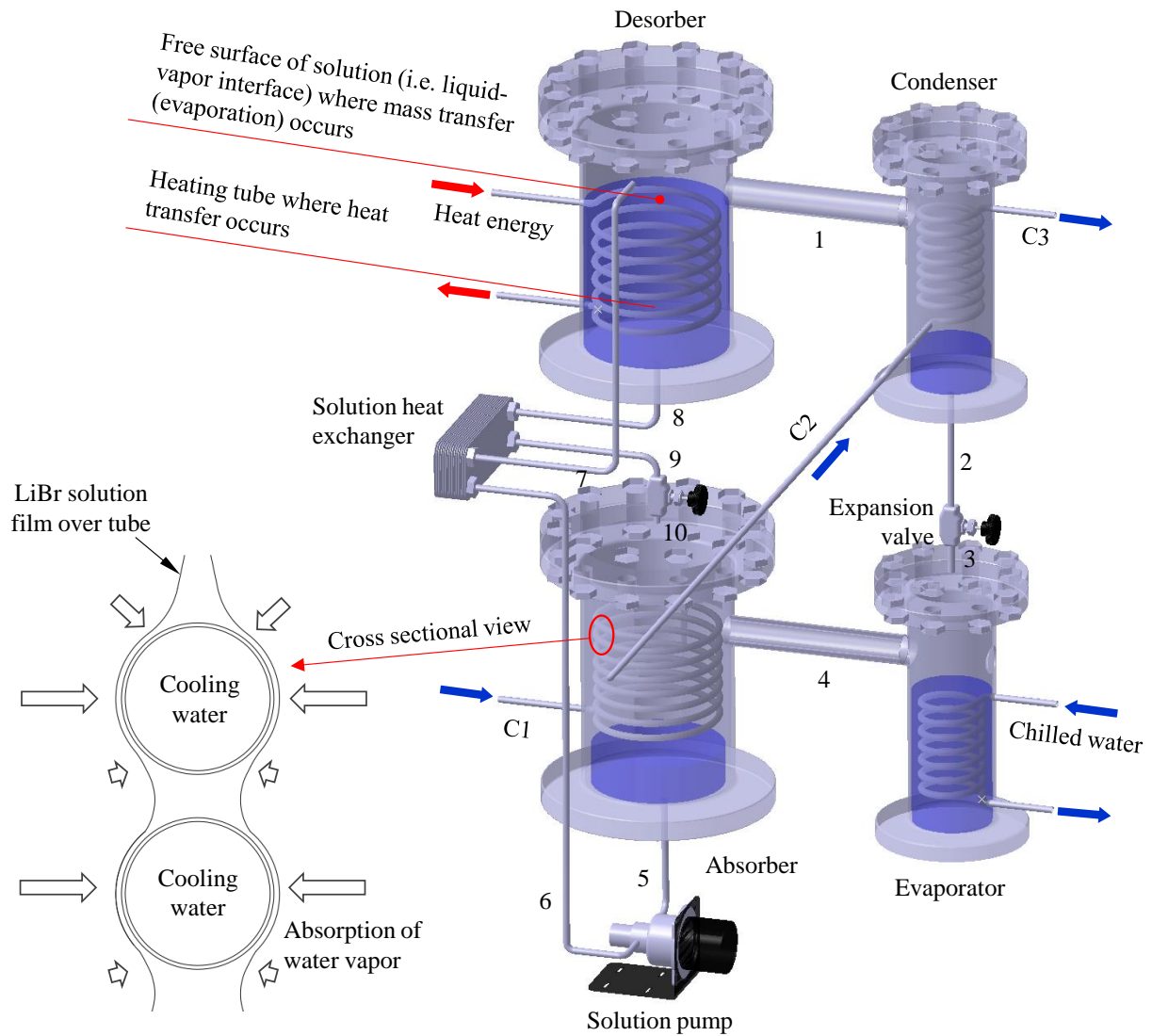
(b) Hydrodynamic of gravity-driven falling film of LiBr solution over cooling tube   (a) Conventional falling film absorption refrigeration system

Fig.1. (a) Schematic of conventional single-effect LiBr falling film absorption refrigeration system, (b) Cross sectional view of hydrodynamic of gravity-driven falling film of LiBr solution over cooling tube in absorber

The VARs has noteworthy advantages as aforementioned; yet, the system has much lower performance-to-volume ratio compared to VCRs. VARs has much more complex thermodynamic cycle than VCRs to achieve the high theoretical system performance that demands a number of heat and mass exchangers and control systems. All components of LiBr-water absorption cycle, including the heat and mass exchangers and tubing, are the stainless steel-based structures owing to highly corrosiveness of LiBr solution [16]. LiBr-water absorption system contains large heat and mass exchangers which are responsible for their high cost and large volume. The absorber and desorber, in particular, are major components that impact the system performance as well as their size and cost. In conventional gravity-driven falling film absorber, for example, a cooling tube bundle is installed to remove the heat of absorption and the strong LiBr solution is sprayed over the horizontal cooling tube (*Fig.1a*). Hydrodynamic of falling LiBr film over the horizontal tube develops the thick film layers that resist the heat and mass transfer (*Fig.1b*). LiBr-water absorption system runs at static vacuum pressure associated with a large specific volume of water vapor, and therefore it is hardly avoidable that the system is bulky and also weighty. A heating tube bundle is also equipped in the conventional desorber, and is immersed in the solution where heat transfer occurs to boil the solution (*Fig.1a*). The ill-spent space against heat transfer, however, exists because of structural demerit (i.e. shell and tube) and the desorption takes place only at the liquid-vapor interface

that impedes the mass transfer. It is also well known that the liquid phase of LiBr solution has considerably large mass resistance.

It is no exaggeration to mention that the enhancement of absorption rate in LiBr-water absorption system is one of the key stages to make the system minimize. Many attempts to this purpose have for a long time been made to exploit the additives, which is known as the most cost-efficient mechanism of improving the absorption performance. The thick LiBr solution film over the cooling tube, as aforementioned, impedes the heat and mass transfer in the absorption process. The additives, higher alcohols, induce the lower surface tension of the solution so that the thinner solution film is sprayed over the tube (i.e. enhanced wettability). The heat transfer becomes significantly boosted in the absorber, and as a result the overall heat and mass transfer area is diminished. Since *Kashiwagi et al.* [17] begun to the experimental work for more fundamental and quantitative understanding of the relationship between the additives and Marangoni instability, extensive experimental and theoretical works have been conducted. *Hozawa et al.* [18] reported that the increase in the concentration of LiBr solution leads to the increase in surface tension of the solution, but on the other hand, causes the decrease in that of solution when the additive is added. *E. Hihara and T. Saito* [19] reported the considerable enhancement of absorption rate by the additive, and well explained the mechanism of interfacial turbulence as Marangoni instability. The static surface tension data of LiBr solution with various additives [20-24] and dynamic data [25-26] were established and the numerical works were well performed using the established data. *H. Daiguji et al.* [27] conducted both the numerical and experimental works to investigate the prediction of the occurrence of Marangoni instability and the mass transfer enhancement, and well described Marangoni convection by the salting effect. *D. Glebov and F. Setterwall* [28] conducted two series of experimental works to look into the effect of 2-methyl-1-pentanol on the enhancement ratio, comparing the cooling effect with and without additive. In the first experimental series which injected the additive into LiBr solution, they found 20% of increase in the enhancement ratio at the optimum additive concentration; the enhancement ratio became 32.3% in the second experimental series that the additive is introduced to the refrigerant (i.e. evaporator). Their observation supported that the additive is volatile that travels around the cycle and even small amount of additives in vapor phase helps the heat and mass transfer in the absorber more successfully than the case of additive-in-solution. *W. Rivera and J. Cerezo* [29] reported the impact of the additives, 1-octanol and 2-ethyl-1-hexanol, on 2kW of single effect VARs in which the absorber temperature is in range of 70 to 110°C. They found that adding 1-octanol hardly influences the enhancement of system performance; however, 40% of enhancement is observed 40% by adding 2-ethyl-1-hexanol at the optimum operating condition. The absorber temperature increases about 5°C with 400 ppm of 2-ethyl-1-hexanol.

Wettability of solution film on the cooling tube is also major mean for the enhancement of heat and mass transfer in the absorber. Mechanical surface treatments, such as shape or roughness control of cooling tube surface, have been considered. The enhancement of absorption rate by coupling wires with the tube surface was reported by several works [30-31]. Many attempts had been established using various configurations, such that: constant curvature surface [32], grooved and wire-wound tube [33], porous surface [34], and tubular surface with pin-shaped fin, grooves, and twisted fins [35]. *J.K. Kim et al.* [36] and *C.W. Park et al.* [37] numerically and experimentally investigated the effect of roughness of cooling tube surface by using two different micro-scale helically grooved tubes in the roughness range of 0.386 to 6.968 micron and a bare tube, and confirmed that the increase in roughness promotes the wettability (i.e. heat transfer), further also enhances the absorption flux.

The microchannel based heat and mass exchangers, which have high heat transfer coefficient even in laminar flow regime, have been introduced by several researchers. Since *S. Garimella (1999)* [38] proposed his prototype microchannel based absorber in which short length of microchannel tubes are located in multiple square arrays, he and his group tested it for the absorption performance using ammonia-water pair [39-40]. They found the solution distribution and surface wetting problems in the prototype absorber, and thereafter proposed an improved absorber configuration, which has only 30% of surface area of the prototype absorber [41-42]. *J.M. Meacham and S. Garimella* [41] initiated the visualization test of solution flow along the array of microchannel tubes and the experiments on the heat transfer for ammonia-water absorption process using their improved absorber. 15 kW of absorption capacity was accomplished in a 16.2 X 15.7 X 15.0 cm of absorber with 0.456 m^2 of surface area. They found the significant enhancement of solution distribution and that of absorption rate as well. *S. Garimella et al.* [42] and *M.D. Determan* [43] made a minor modification of the absorber they proposed to convert to desorption process. The microchannel based desorber has a solution drip tray brazing 14.0 cm length of 648 microchannel tubes. Their analytical and experimental observation revealed that 17.5 kW of desorption capacity was transferred at overall heat transfer coefficients between 388 and 617 W/m^2K. Their heat and mass

exchangers were successfully minimized compared to the conventional components and it is expected that this miniaturization technology is universally applicable not only to absorber and desorber, but also to condenser and evaporator. *N. Goel and D.Y. Goswami* [44] and *N. Goel and D.Y. Goswami* [45] proposed the microchannel based falling film absorber with the flow guidance medium by screen mesh/fabric. They firstly presented the concept of conventional microchannel based absorber that has 3.175 mm outer diameter and 0.4 mm wall thickness of stainless steel tubes, and suggested a novel design with the screen mesh/fabric. The screen mesh/fabric is installed in contact with the horizontal cooling tubes, and guides the gravity-driven solution flow, and enables the solution flow rate retarded. Their numerical and experimental results pointed out that the heat load of the proposed mesh-enhanced absorber is improved about 17 to 26% compared to the conventional microchannel based absorber. This phenomenon supported that the screen guidance improves the liquid hold-up, wetting characteristics, and fin-effect of the mesh/fabric.

2. Micro-porous hydrophobic membrane based heat and mass exchangers

In recent years, microporous hydrophobic membranes, including hollow fiber membranes and flat sheet membranes, have been utilized for gas or water distillation from gas mixtures or aqueous binary solutions [46-49]. A hydrophobic membrane is defined as a selective barrier that enables a certain component to pass through, but blocks the passage of others. The membrane is generally categorized as two types with respect to its structure: porous and dense membrane. The porous membrane has micro- or nano-scale interconnected pores that characterize both the mass transfer and the selectivity of molecules. The pore size and porosity are primary factors directly related to the mass transfer. Less membrane thickness also leads to higher mass transfer performance by the reduction of molecular travel distance across the pore. The dense membrane, however, is non-porous media, and is used for the elimination of tiny molecules. The dense membrane has high selectivity, but has extremely low mass transfer performance since the molecules go through more mass resistances: diffusing to the membrane surface, dissolving into the dense membrane surface, diffusing through the solid membrane wall, and absorbing into or desorbing from the interface of downstream [50].

There is increasing interest in the use of microporous hydrophobic membrane in VARs due to its great advantages: compactness, small volume, reliability, high separation performance, large interfacial area to volume ratio, lower cost, fewer mechanical part demand, and relatively low energy consumption [50]. In the hydrophobic membrane based heat and mass exchanger in VARs, the stream of aqueous LiBr solution is in direct contact with hydrophobic membrane layer, and is mechanically confined due to the hydrophobicity and large surface tension of LiBr solution. The opposite side of membrane is kept at vacuum, that is, the saturation condition of condenser or evaporator. The driving force of mass transfer is the vapor partial pressure difference between the both sides of membrane. As long as the vapor partial pressure of LiBr solution is higher than the static equilibrium pressure at vapor side, the volatile component (i.e. water) is evaporated at the liquid-vapor interface, and is desorbed to the vapor side through the pores. On the contrary to this, the absorption of water vapor into the solution also occurs when the vapor pressure is higher than the vapor partial pressure of solution.

A micro-porous hydrophobic hollow fiber membrane (HFM) module has a great potential, particularly when introduced for potable application with its significant advantages; compactness, lightweight, small volume, low cost, large interfacial area to volume ratio, and the use of plastic material alleviating corrosion problem. In HFM based heat and mass transfer exchangers, the feed LiBr solution enters several hundreds of or thousands of HFM capillaries and the water vapor is transported across the HFM layers (*Fig.2a*). As a result, the total area for the heat and mass transfer becomes significantly enhanced, whereas the heat and mass transfer area in the conventional components is highly limited. *Fig. 2b* shows a schematic of feasible single effect VARs with HFM based absorber and desorber. HFM based heat and mass exchangers replace the conventional absorber and desorber and an axillary heat exchanger is installed to heat the weak LiBr solution up. As the hot weak solution enters HFM based desorber, a large temperature drop takes place due to the consumption of heat for the latent heat of vaporization, and as a result, the partial vapor pressure decreases in the flow direction (i.e. decrease in the driving force of mass transfer). As long as the partial vapor pressure is higher than the vapor pressure at condenser, the evaporation process keeps on. The weak solution becomes stronger as the water vapor escapes from HFM based desorber and the strong solution enters HFM based absorber via firstly the solution heat exchanger for the heat recovery and secondly an auxiliary heat exchanger for cooling process. The adiabatic absorption process occurs in HFM based absorber and thus temperature of solution increases in the flowing direction as the water

vapor is absorbed into the stream of LiBr solution. The weak solution is pumped back to HFM based generator to complete the refrigeration cycle.

(a) Hollow fiber membrane module, and description of absorption and desorption process

(b) Schematic of single effect absorption refrigeration cycle with hollow fiber membrane based absorber and desorber
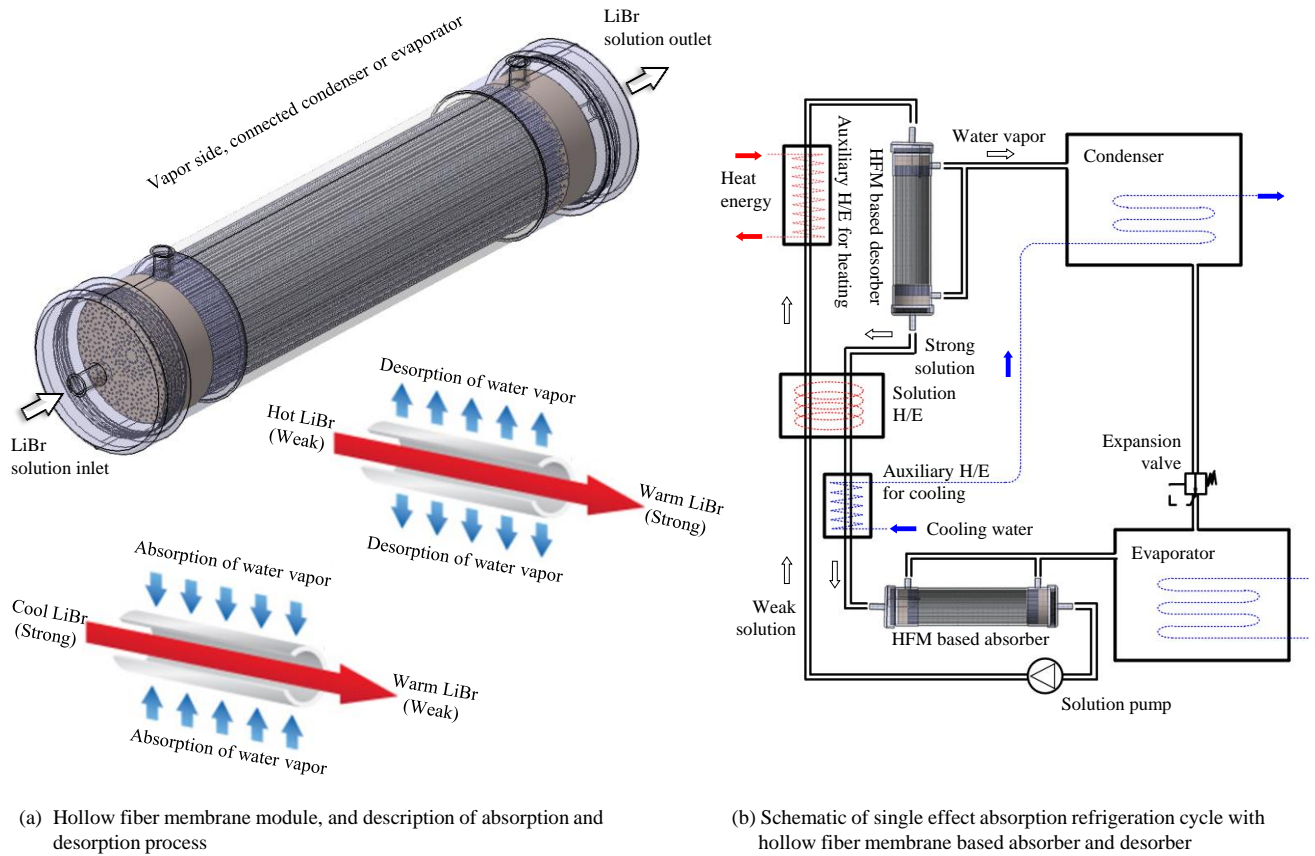
Fig. 2. (a) Hollow fiber membrane module, and description of absorption and desorption process through a string of hollow fiber membrane, (b) Schematic of single effect absorption refrigeration cycle with hollow fiber membrane based absorber and generator

A flat sheet hydrophobic membrane accompanied with microchannel is also highly recommended for the heat and mass exchangers. A feasible structural schematic of flat sheet membrane based heat exchangers is shown as *Fig. 3a*. A metallic plate which contains an array of microchannel and an array of mini-channel on other side is set so that the LiBr solution flows in microchannel and the heating or cooling source flows in mini-channel. Another metallic plate is also placed in direct contact with the membrane for the condensation or evaporation process. The solution is fed into the microchannel, and is mechanically constrained by the hydrophobic flat sheet membrane. This narrowly confined solution flow significantly increases the mass transfer area per unit volume. As the absorber configuration, for example, the non-adiabatic absorption of water vapor across the membrane takes place as the cooling source is applied so that the vapor partial pressure of solution is lower than the evaporation pressure. On the other hand, when heat source is applied to the solution, the desorption process occurs since the vapor partial pressure becomes higher than the vapor pressure determined by the condensation process at the opposite side of membrane.

The development for enhancement of the heat and mass transfer remains the ongoing challenge for the realization of widely available air-conditioning system. The microporous hydrophobic membrane presents much large interfacial area of heat and mass transfer. The size and weight of system becomes diminished with the enhanced heat and mass transfer performance. The microporous hydrophobic membrane was lately utilized for various configurations of heat and mass exchanger in VARs as summarized in *Table 1*.

(a) Flat sheet membrane module, and description of absorption and desorption process

(b) Schematic of single effect absorption refrigeration cycle with flat sheet membrane based absorber and generator
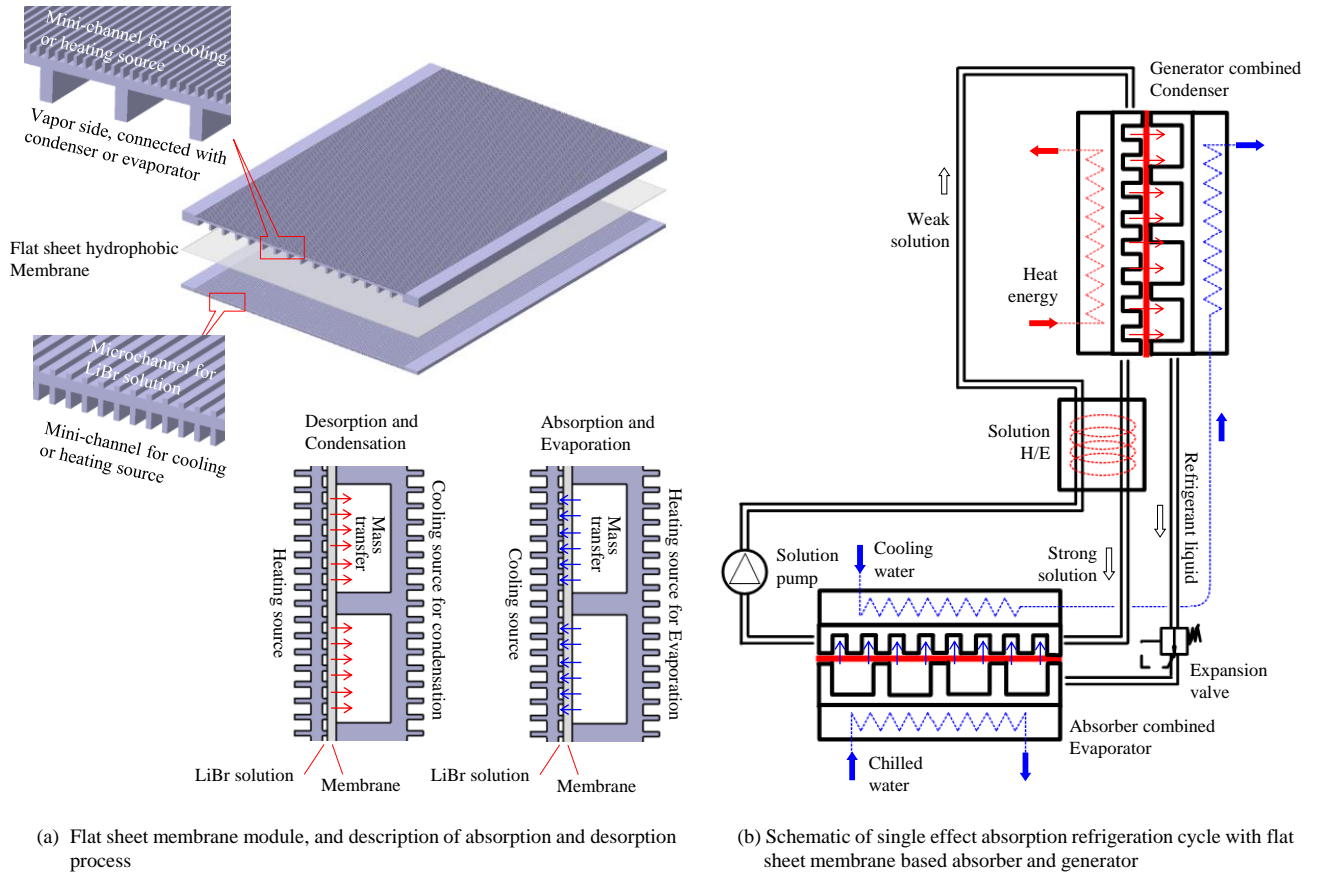
Fig. 3. (a) Flat sheet membrane module, and description of absorption and desorption process through flat sheet membrane based heat and mass exchangers, (b) Schematic of single effect absorption refrigeration cycle with flat sheet membrane based absorber-evaporator and desorber-condenser combinations

3. Theory on membrane-based heat and mass exchangers

3.1. Liquid entry pressure

Most important concept of the membrane-based heat and mass exchanger are (1) to make the solution confined by the hydrophobic membrane, and (2) to enable the passage of water vapor across the pores. By controlling the path and height of solution flow using the hydrophobicity of membrane, the heat and mass transfer is enhanced by minimizing the LiBr film thickness. When the solution flows in direct contact with the hydrophobic membrane, the curvature liquid-vapor interface is formed at the entrance of pores due to the large capillary actions (*Fig.4*). The liquid solution, therefore, cannot seep into the pores as long as the pressure difference across the membrane is kept at lower than a certain pressure called as the liquid entry pressure (LEP), expressed as,

$$LEP = -\frac{2\sigma\cos\theta}{d_p}$$

(1)

where σ, θ, and d_p are the surface tension of the liquid, the contact angle between the liquid and membrane surface, and pore size, respectively.

3.2. Coupled heat and mass transfer mechanism

Liquid LiBr solution, which has high surface tension, does not seep into the pores of hydrophobic HFM layer due the hydrophobic effect action and the liquid-vapor interface is formed as shown in *Fig 4*. Volatile component, water vapor, evaporates at the liquid-vapor interface, and passes through the pores as long as the pressure at vapor side is maintained below the equilibrium vapor partial pressure at the membrane surface (*Fig.4a*). In con-

trast, a higher pressure at vapor side than the vapor partial pressure at the membrane surface directly causes the absorption of water vapor across the membrane (*Fig.4b*). Thus, the driving force of water vapor mass transport across the membrane is the partial pressure difference between at the membrane surface and at the vapor side. Both the temperature and concentration polarizations between the bulk phase and the membrane surface are occurred due the simultaneous heat and mass transfer. The hydraulic characteristic in the boundary layer determines the temperature and concentration profiles. Diffusive heat and mass transfer resistances exist by both the temperature and concentration polarization. These polarization effects give rise to the decrease in the driving force of mass transfer. Non-volatile component (i.e. LiBr) is also accumulated at the entrance of pores, and obstructs the movement of volatile component to the liquid-vapor interface [61]. The frictional mass transfer resistance also exists inside the porous structure, and is generally explained by several transport mechanism related to collisions among molecules or of molecules with membrane wall in the pore, such that: the Knudsen diffusion, the Poiseuille flow, molecular diffusion. The Knudsen diffusion model is expected to evaluate the mass flux across the microporous membrane due to the size of water vapor molecules and membrane pores used in this study. The mass flux of water vapor across the membrane is evaluated as,

$$J_v = 1.064 \frac{d_p \, \varepsilon}{\tau \, \delta} \left(\frac{M}{RT_m} \right)^{0.5} (p_{p,ms} - p_v) \tag{2}$$

where J_v is the mass flux of water vapor across the membrane. d_p, ε, τ, and δ are the mean pore size of membrane, membrane porosity, membrane tortuosity, and membrane thickness, respectively; M, R, and Tm are the molecular weight of vapor, gas constant, and temperature of membrane pores, respectively. $p_{p,ms}$ and p_v are the partial pressure of water vapor at membrane surface, and pressure at permeate side, respectively. Mean pore size is the first approximation of mass transport, and is generally evaluated by the gas permeation experiment [62]. Porosity, defined as the fraction of voids in total volume of membrane, is also directly relevant to the mass transport performance. Higher porosity of membrane has less mass transfer resistance, but the mechanical strength of membrane becomes weaker [63].

Simultaneous heat and mass transfer takes place due to latent heat of water at the liquid-vapor interface. The confined solution flow develops a thermal boundary layer next to the membrane surface and the convective heat transfer takes place in the layer.

$$h_f (T_b - T_{ms}) = J_v \, \Delta H \tag{3}$$

where h_f is the convective heat transfer coefficient. T_b and T_{ms} are the solution temperature at the bulk phase, and at the membrane surface, respectively. ΔH_v is the latent heat of water vaporization. As the downstream of water vapor desorption is kept under vacuum and the water vapor and the air in the pores are withdrawn, the conduction of membrane layers is negligible [64-68]. Owing to coupled heat and mass transfer, a heat transfer coefficient in a thermal boundary layer next to the membrane surface directly influences both the heat flux and the mass flux of water vapor across the membrane. The Nusselt number has commonly been used for the evaluation of convective heat transfer coefficient. The empirical heat transfer correlations used in the membrane distillation
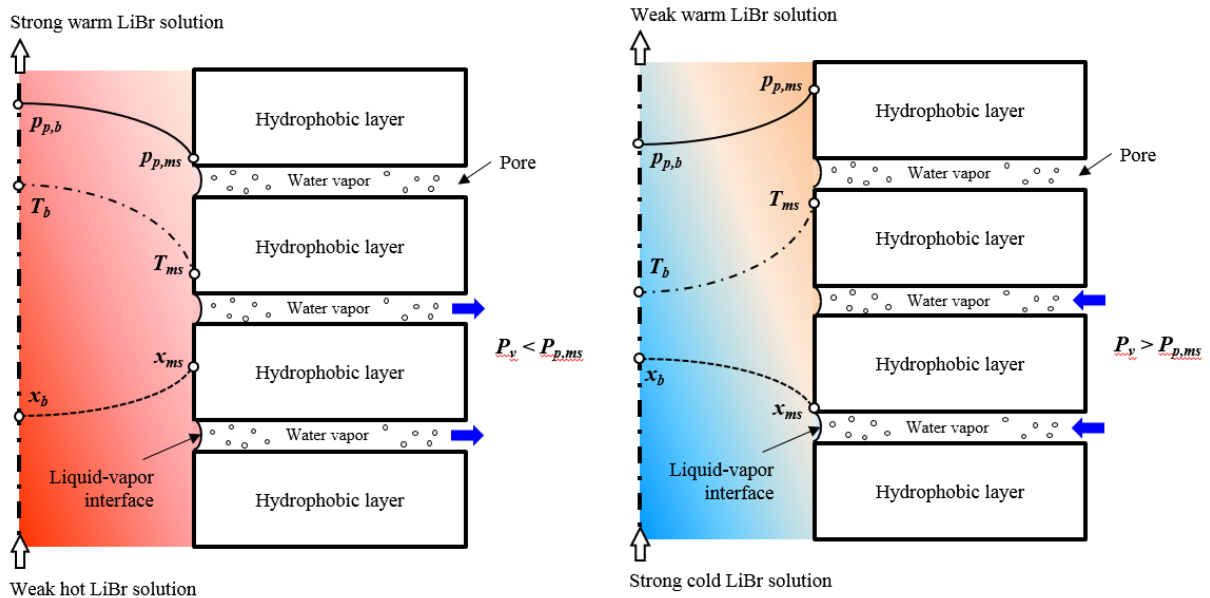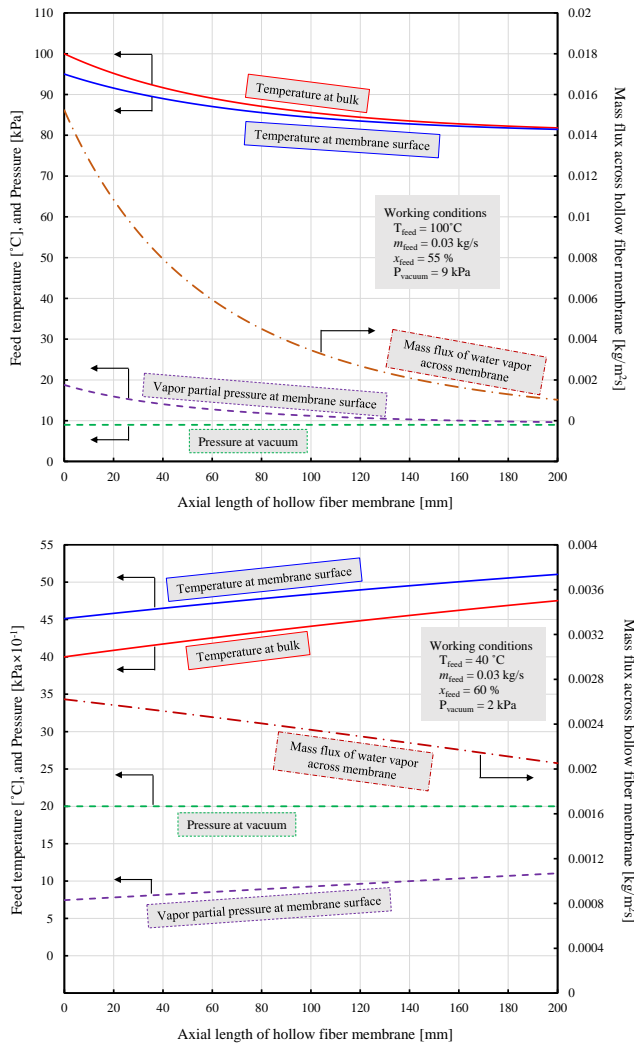
are summarized in *Table 2*.
Fig. 4. Heat and mass transfer for (a) water vapor desorption from, and (b) water vapor absorption into a thermal boundary layer of solution flow confined by micro-porous hydrophobic membrane

4. Theoretical analysis of membrane based heat and mass exchangers

4.1. Hollow fiber membrane based absorber and desorber

Fig. 5 describes the heat and mass transfer characteristics of water vapor desorption and absorption across the hollow fiber membrane along the flow direction. In the flow direction, as for the desorption configuration, temperature of solution drops as the water vapor evaporates at the liquid-vapor interface in the pores due to the latent heat of vaporization (*Fig. 5a*). The rate of temperature variation in the flow direction decreases as the amount of heat needed for the vaporization decreases. The driving force (i.e. difference between vapor partial pressure at membrane surface and pressure at vacuum side) is also reduced in the flow direction; yet, the desorption of water vapor takes place as long as the vapor partial pressure is higher than the pressure at vacuum side. *Fig. 5b* shows the heat and mass transfer characteristics of absorption process in the flow direction. The solution temperature increases due the heat of absorption as the water vapor is absorbed into the confined flow of solution. Thus absorption mass flux performance also decreases in the flow direction due to the reduction of driving force of mass transport. *Table 3* includes the membrane parameters used for the simulation.

Fig. 5. Heat and mass transfer for (a) water vapor desorption from, and (b) water vapor absorption into a thermal boundary layer of solution flow confined by micro-porous hydrophobic membrane

Fig. 6 present the effect of the number and length of hollow fiber membrane on the increase or the decrease

in concentration via hollow fiber membrane based desorber and absorber. As aforementioned, hollow fiber membrane based heat and mass exchanger has a great advantage that the number of HFMs is easily adjusted for a given volume of the module so that the contact area for desorption or absorption increases to enhance its performance. The increases in both the number and length of HFMs enhance the concentration difference. The results, however, shows the curve for the concentration difference becomes almost flat and hardly varies as the independent variables of hollow fiber membrane increase. The change in the number of HFMs is associated with the solution velocity and the change in length of HFMs is related with the decrease in the driving force in the flowing direction. That is, the driving force of mass transport drastically decreases as the solution temperature decreases, and thus the mass transfer across the membrane layers is hardly occurred in the flow direction.

Table 3. Comparison

Configuration	Pore size [μm]	Porosity [%]	Inner diameter [μm]	Thickness [μm]	Dimension of membrane
Hollow fiber membrane	0.16	85	800	300	200 [mm, Length] X 200 [NO*]
Flat sheet membrane	0.40	85	N/A	300	200 [mm, Width] X 300 [mm, Length]

* NO: The number of hollow fiber membrane

Table 1. Summary of hydrophobic membrane used in vapor absorption refrigeration configuration

Reference	Membrane module	Configuration	Working fluid	Membrane Material	Pore size [μm]	Porosity [%]	Thickness [μm]	Inner diameter or Height* [μm]	Study
J. D. Thorud et al. [51]	Flat sheet	Desorber	LiBr-water	PTFE	N/A	N/A	N/A	170, 745	Experimental
J. Chen et al. [52]	Hollow fiber	Absorber	NH_3-water	N/A	0.03	40	30	240	Numerical
Y. J. Kim [53]	Flat sheet	Desorber	LiBr-water	N/A	N/A	N/A	N/A	300	Numerical
Z. Wang et al. [54]	Hollow fiber	Desorber	LiBr-water	PVDF	0.16	85	150	800	Experimental
A. H. H. Ali et al. [55]	Flat sheet	Absorber	LiBr-water	PTFE	0.2 to 1.0	N/A	60 to 175	4,000	Experimental
D. Yu et al. [56]	Flat sheet	Absorber	LiBr-water	N/A	6	60	20	50	Numerical
R. N. Isfahani et al. [57]	Flat sheet	Absorber	LiBr-water	PTFE	1.0	80	N/A	100, 160	Experimental
R. N. Isfahani et al. [58]	Flat sheet	Desorber	LiBr-water	PTFE	0.45	N/A	50	N/A	Experimental
M. Venegas et al. [59]	Flat sheet	Absorber	LiBr-water	N/A	1.0	0.8	60	150	Numerical
S. J. Hong et al [60]	Hollow fiber	Desorber	LiBr-water	N/A	0.16	85	150	800	Numerical

* Inner diameter: Inner diameter of hollow fiber membrane, Height: Height of microchannel for flat sheet membrane configuration

Table 2. Summary of heat transfer correlations used in membrane distillation

| Heat transfer correlation	Reference	Membrane module	Flow regime	Note
$Nu = 1.86\left(\dfrac{Re\,Pr\,d_h}{L}\right)^{1/3}$	*L. Martinez-Diez et al.* [69]	Flat sheet	Laminar	$D_c = 55(L) \times 7(W) \times 0.45(H)$ mm
	F. A. Banat et al. [70]	Hollow fiber	Laminar	
	Y. Yun et al. [71]	Flat sheet	Laminar	
	J. G. Lee and W. S. Kim [72]	Hollow fiber	Laminar	$L = 64, 170$ mm, $d_i = 0.2, 0.28, 0.33$ mm
	S. J. Hong et al. [60]	Hollow fiber	Laminar	$L = 200$ mm, $d_i = 0.8$ mm
$Nu = 1.62\left(\dfrac{Re\,Pr\,d_h}{L}\right)^{1/3}$	*S. Kimura and S. I. Nakao* [73]	Flat sheet	Laminar	
	A. Criscuoli et al. [74]	Hollow fiber, Flat sheet	Laminar	$L = 470$ mm, $d_i = 1.8$ mm, $D_c = 10(L) \times 4(W) \times 3.5(H)$ mm
$Nu = 3.66 + \dfrac{0.0668\,(Re\,Pr\,d_h/L)}{1+0.045\,(Re\,Pr\,d_h/L)^{2/3}}$	*S. Bandini et al.* [75]	Hollow fiber, Flat sheet	Laminar	$L = 160, 270$ mm, $d_i = 0.4$ mm
	S. C. Sartu et al. [76]	Hollow fiber, Flat sheet	Laminar	$d_i = 0.4$ mm
$Nu = 4.36 + \dfrac{0.036\,(Re\,Pr\,d_h/L)}{1+0.0011\,(Re\,Pr\,d_h/L)^{0.8}}$	*M. Tomaszewska et al.* [77]	Hollow fiber	Laminar	$d_i = 1.8$ mm
	J. I. Mengual et al. [78]	Hollow fiber	Laminar	
$Nu = 0.023\,Re^{0.8}\,Pr^{0.33}$	*A. Criscuoli et al.* [74]	Hollow fiber, Flat sheet	Turbulent	$L = 470$ mm, $d_i = 1.8$ mm, $D_c = 10(L) \times 4(W) \times 3.5(H)$ mm
	F. A. Banat et al. [70]	Hollow fiber	Turbulent	
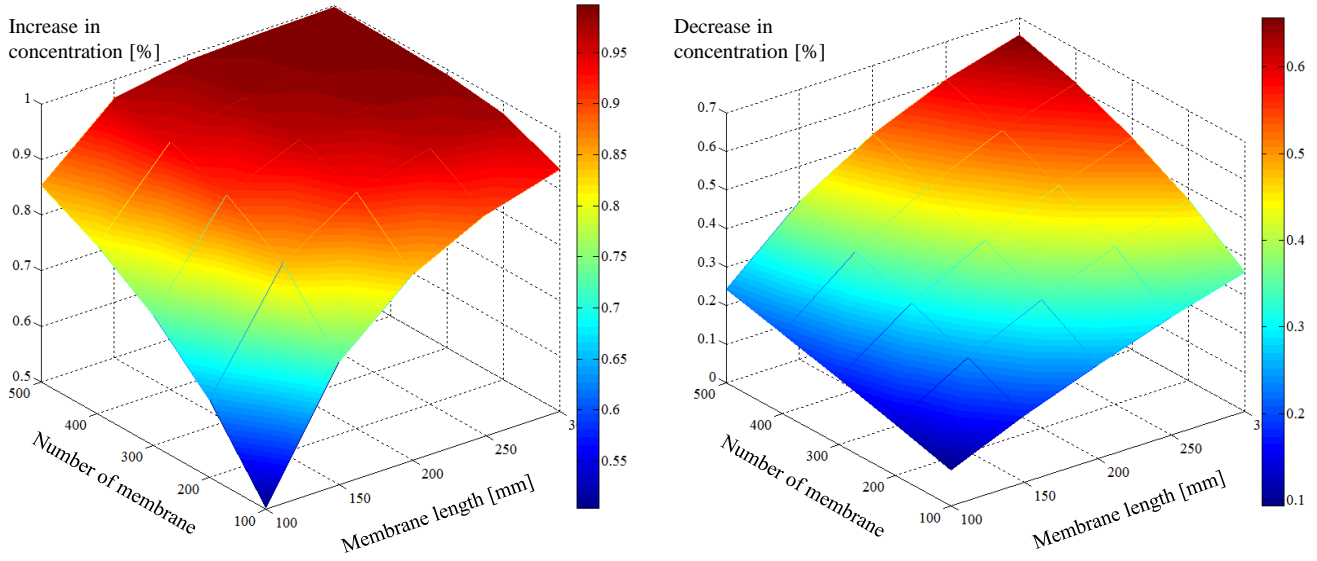
Fig. 6. (a) Increase in solution concentration by desorption process (T_{feed} = 100℃, m_{feed} = 0.03 kg/s, x_{feed} = 55 %, and P_{vacuum} = 9 kPa), and (b) Decrease in solution concentration via hollow fiber membrane based heat and mass exchanger (T_{feed} = 40℃, m_{feed} = 0.03 kg/s, x_{feed} = 60 %, and P_{vacuum} = 2 kPa)

4.2. Flat sheet membrane based absorber and desorber

Based on the flat sheet membrane parameters shown in *Table 3*, a whole cycle of flat sheet membrane based absorption system is simulated. *Fig 7* describes depicts the effect of the flat sheet membrane area on the cooling capacity and the system performance for two kinds of membrane pore size. A larger pore size directly influences the enhancement of both the cooling capacity and COP. Both the cooling capacity and COP, however, hardly increases as the membrane area significantly becomes larger. In other words, those do not increase beyond a certain value despite the further increase in the area because the membrane distillation efficiency, that is, the ratio of the mass transfer rate and membrane area decreases.
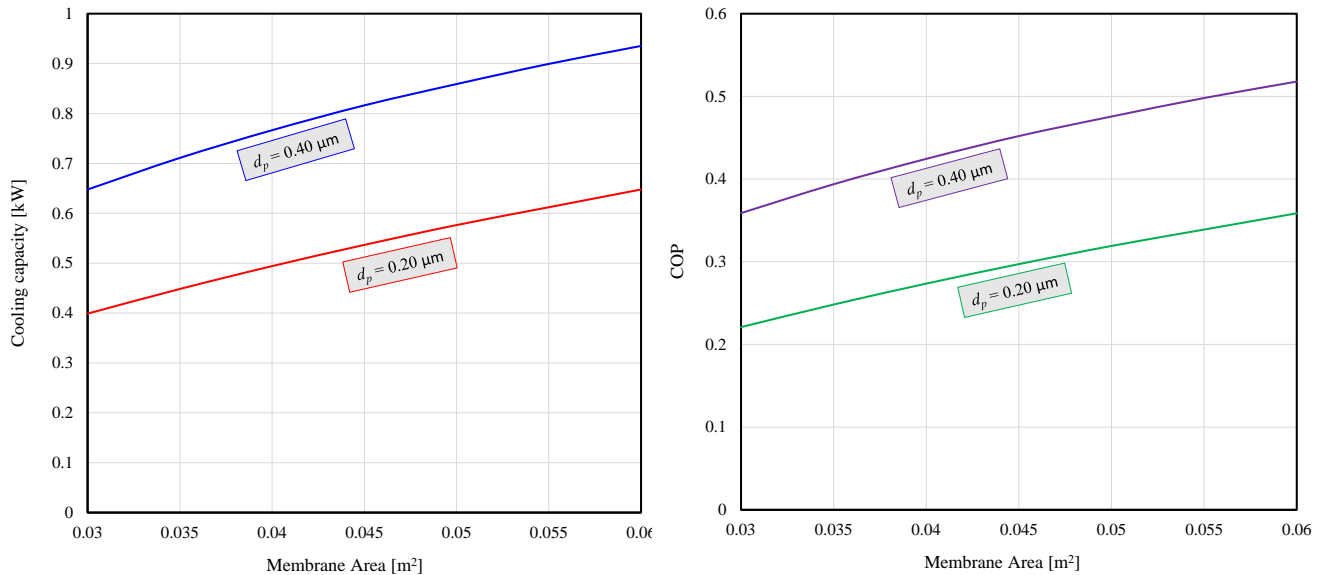

Fig. 7. (a) Effect of flat sheet membrane area on cooling capacity, and (b) on COP ($T_{heating\ source}$ = 100℃, T_{feed} = 60℃, $T_{cooling}$ = 40℃, $T_{evaporator}$ = 6℃, $m_{heating\ source}$ = 0.05 kg/s, m_{feed} = 0.03 kg/s, x_{feed} = 58.4 %)

4.3. Comparison of absorption flux by various conventional absorber and membrane based absorber

Table 4 shows the comparison data of absorption mass flux for various conventional falling film and membrane based absorber.

Table 4. Comparison of absorption mass flux in conventional LiBr falling film absorber and membrane based absorber

Reference	Absorption flux [kg/m²s]	Vapor pressure [kPa]	Inlet solution temp [°C]	Inlet concentration [%]	Inlet cooling water temp [°C]	Absorption mechanism	Study
Islam et al. [79]	0.0022	2.3	39.8	60.4	29.4	Horizontal tube	Experimental
Islam [80]	0.0021	2.62	39.8	60.4	26.5	Horizontal tube	Experimental
Yoon et al. [81]	0.0028	0.933	47	61	32	Horizontal tube	Experimental
Matsuda et al. [82]	0.0025	1.3	N/A	55	N/A	Vertical tube	Experimental
Medrano et al. [83]	0.0035	1.6	40	60	30	Vertical tube	Experimental
Karami et al. [84]	0.0027	1.0	45.6	60	32	Vertical wall	Numerical
Md. R. Islam et al. [85]	0.00209	N/A	N/A	60.4	35.2	Vertical wall	Experimental
Ali et al. [55]	0.00138	1.6	N/A	54	N/A	Flat sheet	Experimental
Yu et al. [56]	0.0065	0.87	55	60	N/A	Flat sheet	Numerical
Isfahani et al. [57]	0.0057	1.3	25	60	25	Flat sheet	Experimental
This study	0.111	0.933	60	58.4	40	Flat sheet	Numerical
This study	0.0024	2	40	60	N/A	Hollow fiber	Numerical

[55] $d_p = 0.45 \mu m$, $\varepsilon = 80\%$, $\delta = 60 \mu m$, [56] $d_p = 6 \mu m$, $\varepsilon = 60\%$, $\delta = 20 \mu m$, [57] $d_p = 1 \mu m$, $\varepsilon = 80\%$, $\delta = N/A$,

5. Conclusion

Literature investigation presented numerous attempts to enhance the heat and mass transfer in major components of vapor absorption refrigeration system. Additive, or surface treatment of heat and mass exchanging tubes was used for the improvement of heat and mass transfer in the conventional falling film absorber. Microchannel based heat and mass exchangers successfully reduced the size and weight of major components of absorption system.

The concept of membrane based heat and mass exchangers were described and the simulated results were included in this paper. The hydrophobic hollow fiber membrane module is in general made of plastic body which eliminates the concern of weight and corrosion, and has much larger interfacial area for mass transfer compared to the conventional one. The narrowly confined solution flow through the hollow fiber membrane or flat sheet membrane associated with microchannel also has a crucial point that the heat and mass transfer performance could be significantly enhanced. Absorption mass flux of the various membrane based heat and mass exchanger configurations were compared with the existing absorption data of conventional falling film absorbers, describing that the absorption flux is considerably improved by the membrane based absorption process.

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