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## Analysis on Hollow Fiber Membrane Heat Exchanger applying to the Lithium Bromide Absorption Refrigeration System

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### ABSTRACT

The aim of this work is to bring forward a new style heat exchanger about hollow fiber membrane module, and to analyze the performance which can expectantly be applied in the lithium bromide absorption refrigeration system. Polyvinylidene fluoride hollow fiber membrane module was adopted as the new style solution heat exchanger, hot feed solution from the generator flowed into the lumen side of membranes while cold feed solution from the absorber flowed away the shell side. Heat transfer and water vapor mass transfer occurred simultaneously in the membrane module, only water vapor can diffuse across the membrane pore from one side to the other side according to the water vapor pressure difference between the both sides of the membrane.

Mathematical equations of distributed parameter for heat transfer and mass transfer process in membrane heat exchanger was built, parameters of solution heat exchanger for traditional 10kw cooling capacity absorption refrigeration system was adopted as the simulation parameters, and the parallel-flow process and the counter-flow process was compared by numerical simulation.

The simulation result shows that the counter-flow process was the better flow mode because the mean temperature difference was larger and the mass transfer process were more steadily from the lumen side to the shell side. The heat caused by mass transfer may be one third of the total heat transfer.

### 1. INTRODUCTION

Solution heat exchanger played an important role in the absorption refrigeration system, it can recovery the heat energy, enhance the COP of the system, and can reduce the heat loading of the generator and the absorber. Many researchers studied the different type of solution heat exchanger for improving the performance of the system<sup>[1-3]</sup>. However, the traditional solution heat exchanger has large volume and weight for the steel material, and the steel surface will formed the deposition owing to the corrosive characteristic of lithium bromide solution, as a result, the COP will decrease, and the cooling capacity will weakening.

Hollow fiber membrane module was usually used in the membrane separation field, especially in water purification, solution concentration, and saline desalting etc.; it can provide maximum specific area in limited space. The material of membrane has many merits such as corrosion resistant, high-temperature, and pollution tolerant. The hollow fiber membrane module was made of hundreds of membrane threads which has well hydrophobic property so as to ensure only water vapor can diffuse across the membrane pore while the liquid solution can not. The driving force of water

vapor mass transfer depends on the water vapor pressure difference between the both sides of membrane. Although the heat conductivity of membrane was low, the specific area was great and the membrane diameter was small, the total heat quantity of heat transfer will improve effectively, on the other hand, the water vapor mass transfer may transfer the latent heat of water vapor from one side to the other side. Thus it is possible to apply the hollow fiber membrane module to the new style solution heat exchanger for the absorption refrigeration system.

## 2. MATHEMATICAL MODEL OF MEMBRANE HEAT EXCHANGER

### 2.1 Principle of Membrane Heat Exchanger

Traditional heat exchanger belongs to dividing wall type heat exchanger, no mass transfer happens, As for the lithium bromide absorption refrigeration system, if the solution heat exchanger can not only act as the thermal converter, but can concentrate the strong solution and thinning the weak solution at the same time while need not extra heat energy input, the heat loading in the generator and in the absorber will reduce and the COP of the system will improve remarkably. That is, the mass transfer process must happen along with heat transfer process in the solution heat exchanger.

The membrane heat exchanger has the characteristics of both heat transfer process and mass transfer process. Figure.1 shows the hollow fiber membrane heat exchanger module, hundreds of membrane threads were filled in the shell and the shell was sealed stably. Generally, the hot feed flowed into the lumen side, the cold feed flowed away the shell side. Hollow fiber membrane module was widely used in membrane separation field, in order to removal the water from the feed solution, Microporous hydrophobic membranes like Polythene(PE), polypropylene(PP), polytetrafluoroethylene(PTFE), and polyvinylidene fluoride(PVDF) were adopted as the material of membrane. The membrane pore size may be equal to the molecular free path, and the contact angle between the liquid drop and the membrane pore was so great that only water vapor can diffuse across the pore while the liquid drop can't. The membrane flux depended on the membrane property (porosity, membrane thickness, tortuosity etc.) and the operating parameters such as the feed temperature, feed flux, and the flow mode. In short, it depends on the water vapor pressure difference in both sides of membrane. The heat transfer and mass transfer process in membrane was quite complicated, and it was almost impossible to study the microscopic flow process on experimental method since the membrane diameter was too small, therefore, mathematical model become the popular means to study the heat and mass transfer process. Figure.2 shows the well-know principle of membrane heat and mass transfer process. The heat transfer including two parts: one was the thermal conduction between the membrane sides; the other was latent heat owing to the water vapor mass transfer process. As shows in Figure.2, temperature polarization and concentration polarization affect the membrane flux because the temperature difference between the membranes would reduce.



Fig.1. Hollow fiber membrane heat exchanger module

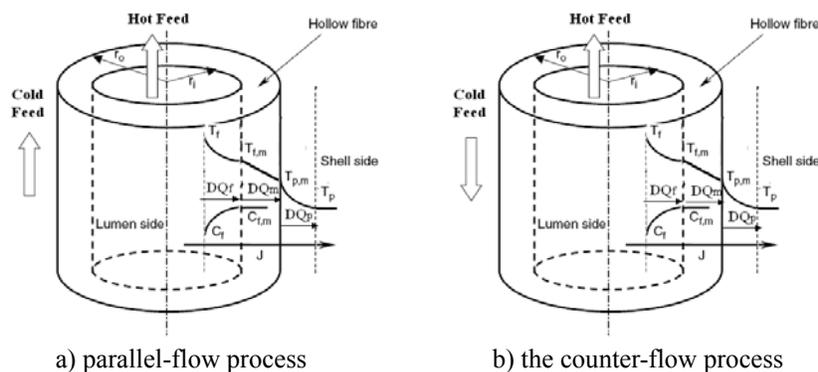


Fig.2. Principle of microscopic view heat transfer and mass transfer process in membrane

2.2 Mathematical Model of Heat and Mass Transfer process

Figure.3 shows the microscopic model of heat and mass transfer process of membrane heat exchanger. In Figure.3 (a), 3-4 means parallel-flow process, 3'-4' means counter-flow process. The flow process was in steady state, the quantity of thermal conduction along the membrane length direction was ignored, there were no thermal loss in the flow process, and the membrane pore had no residual air. The affection of concentration polarization was ignored since the temperature polarization affects the mass transfer process more obviously.

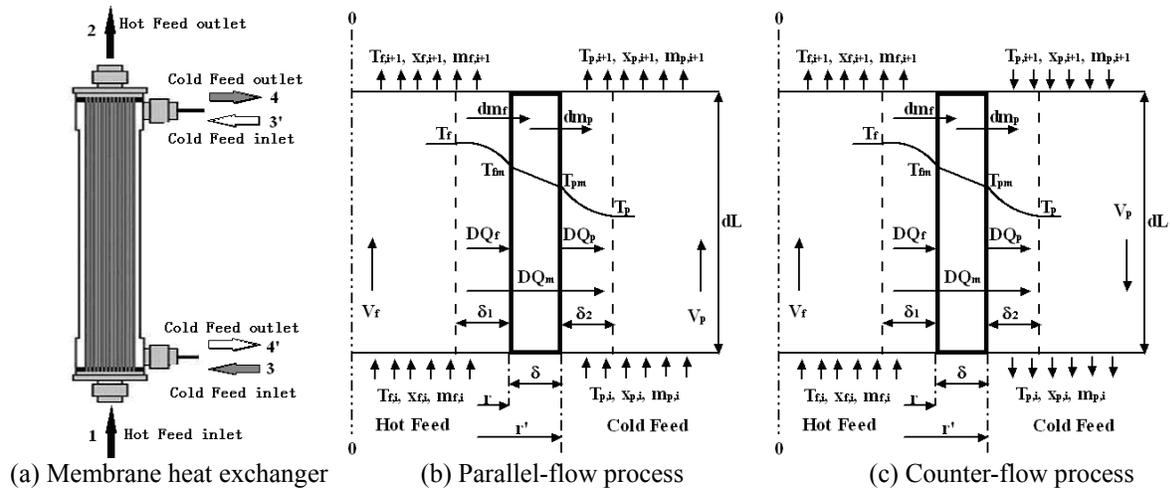


Fig.3. microscopic model of heat and mass transfer process in membrane heat exchanger

2.2.1 Simulation parameters

The parameters of membrane material and hollow fiber membrane module were showed in table 1 and in table 2; the parameters of solution heat exchanger were showed in table 3.

Table 1 Parameters of PVDF membrane thread

Membrane material	Average aperture / $\mu\text{m}$	Porosity	Inner diameter /mm	Wall thickness /mm	Outer diameter /mm
polyvinylidene fluoride	0.16	85%	0.8	0.15	1.1

Table 2 Parameters of hollow fiber membrane module

outer diameter /mm	Inner diameter /mm	Effective length /mm	Number of membrane thread	Membrane area / $\text{m}^2$
50	42	400~100	600	0.6~1.51

Table 3 Parameters of solution heat exchanger

Cooling capacity /kW	Chiller water flux / $\text{kg s}^{-1}$	Strong solution Mass concentration	weak solution Mass concentration	Strong solution Flux / $\text{kgs}^{-1}$	weak solution flux / $\text{kgs}^{-1}$	Hot feed inlet temperature / $^{\circ}\text{C}$	Cold feed inlet temperature / $^{\circ}\text{C}$
10	$4.26 \times 10^{-3}$	55%	50%	$4.26 \times 10^{-2}$	$4.69 \times 10^{-2}$	99.8	40

2.2.2. Mass conservation equations

$$m_{f,i} = m_{f,i+1} + dm_f \tag{1}$$

$$m_{p,i} = m_{p,i+1} \mp dm_p \tag{2}$$

$$m_{f,i} \cdot x_{f,i} = m_{f,i+1} \cdot x_{f,i+1} \tag{3}$$

$$m_{p,i} \cdot x_{p,i} = m_{p,i+1} \cdot x_{p,i+1} \tag{4}$$

Where in equation (1) and (2),  $dm_f = dm_p$ .

The minus in equation (2) means the flow process was in Parallel-flow mode, the plus means in counter-flow mode.

### 2.2.3. Energy conservation equations

$$m_{f,i} \cdot H_{f,i} = m_{f,i+1} \cdot H_{f,i+1} + DQ \quad (5)$$

$$m_{p,i} \cdot H_{p,i} = m_{p,i+1} \cdot H_{p,i+1} \mp DQ \quad (6)$$

The minus in equation (6) means the flow process was in Parallel-flow mode, the plus means in counter-flux mode.

### 2.2.4. Heat transfer equations

$$DQ_{f,i} = h_{f,i} \cdot (T_{f,i} - T_{f,m,i}) \cdot (2\pi r dL) \quad (7)$$

$$DQ_{m,i} = (2\pi h_{m,i} dL) \frac{T_{f,m,i} - T_{p,m,i}}{\ln(r'/r)} + J_i \cdot Hr_i \cdot (2\pi r dL) \cdot \frac{r'/r - 1}{\ln(r'/r)} \quad (8)$$

$$DQ_{p,i} = h_{p,i} \cdot (T_{p,m,i} - T_{p,i}) \cdot (2\pi r' dL) \quad (9)$$

Where in equation (7), (8) and (9)

$$DQ = DQ_{f,i} = DQ_{p,i} = DQ_{m,i}, \quad dm_f = dm_p = J_i \cdot (2\pi r dL) \cdot \frac{r'/r - 1}{\ln(r'/r)}$$

According to table 3, the hot feed solution and the cold feed solution flowed in laminar flow state. Then the involved count parameters needed in the equation were showed in table 4 and table 5.

Table 4 Parameters in lumen side

Parameter	$h_{f,i}$	$Nu_{f,i}$	$Re_{f,i}$	$Pr_{f,i}$
Formula	$(Nu_{f,i} d) / \lambda_{f,i}$		$u_{f,i} d / \nu_{f,i}$	$\mu_{f,i} Cp_{f,i} / h_{m,i}$
Value	$d = 2r$	$Nu_{f,i} = 4.36^{[4]}$	$d = 2r$	$h_{m,i} = 0.14^{[5]}$

Table 5 Parameters in shell side

Parameter	$h_{p,i}$	$Nu_{p,i}$	$Re_{p,i}$	$Pr_{p,i}$
formula	$(Nu_{p,i} d_e) / \lambda_{p,i}$	$Nu = (0.53 - 0.58\phi) Re^{0.53} Pr^{0.33}$ [6]	$u_{p,i} d_e / \nu_{p,i}$	$\mu_{p,i} Cp_{p,i} / h_{m,i}$
Value	$d_e = \frac{2(1-\phi)}{\phi} r'^{[6]}$	$\phi = n \times \left( \frac{\pi r}{\pi R} \right)^2$	$d_e = \frac{2(1-\phi)}{\phi} r'$	$h_{m,i} = 0.14$

### 2.2.5. Mass transfer equations

Local mass transfer equation:

$$J_i(x) = K_i(x) \cdot [P_{f,m,i}(x) - P_{p,m,i}(x)] \quad (10)$$

Average membrane flux:

$$J = \frac{1}{L} \int_0^L J(x) dx \quad (11)$$

$K$  was the coefficient of membrane distillation; it was quite complicated to test or to obtain the accurate value, the article [7] analyzed the coefficient of membrane distillation of  $K$  for different type of membrane and different operating conditions in detail, Knudsen diffusion and molecular diffusion was the basic diffusion factor in the membrane pore. In the lithium bromide absorption refrigeration system, the solution was deaerated before filling in the system, so the membrane pore had no residual gas and the molecular diffusion can be ignored.  $K$  can be estimated as equation (12).

$$K = \frac{\varepsilon}{\xi \delta} \cdot \frac{M}{RT} \cdot \frac{2}{3} \eta \left( \frac{8R\bar{T}}{\pi M} \right)^{1/2} \quad (12)$$

Where  $\xi = \varepsilon^{-2.6}$ , and  $\bar{T} = (T_{fm} + T_{pm}) / 2$ .

### 3. RESULTS AND DISCUSSION

Parallel-flux mode and counter-flux mode were calculated as comparison. Solving the differential equations of (1) ~ (12) and calculating the water vapor flux of local length unit of membrane module by iteration; then counting the next local length unit until the whole length of the membrane module was completed.

#### 3.1 Temperature and concentration distribution in Parallel-flow mode

When the hot feed solution and the cold feed solution were disposed as parallel-flow mode, the temperature in hot feed and in cold feed varied quickly in the nearby inlet. As showed in Figure.4 (a), the temperature curve tended to flat fleetly and could hardly change in nearby outlet. This can be explained according to Figure 4(b). The concentration of the hot feed solution and in the cold feed solution changed because water vapor mass transfer happened from one side to the other. As a result, the latent heat of water vapor was transferred from one side to the other side. The direction of mass transfer depends on the water vapor pressure difference between the sides of the membrane. As shows in Figure 4(b), the concentration of hot feed solution rise and the concentration of cold feed solution descend before the 300mm length from the inlet of the membrane module, this means the water vapor transferred from the lumen side to the shell side, after the 300mm length of the membrane, the concentration of hot feed solution descend and the concentration of cold feed solution rise, it means the water vapor transferred from the cold shell side to the lumen side, and the latent heat of water vapor transferred too, it counteracted part of the heat conduction until the temperature in both sides could not change.

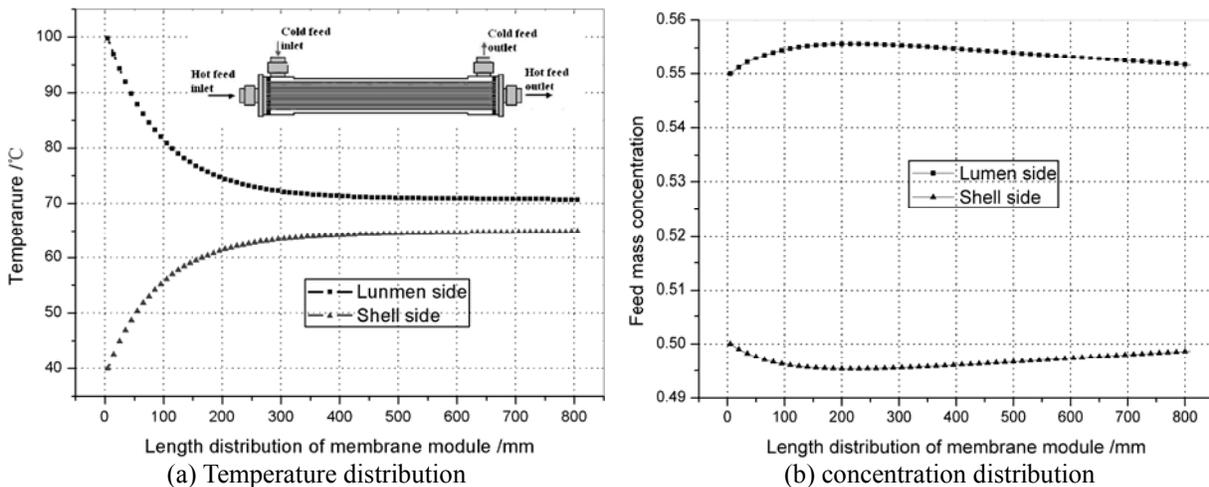


Fig.4. Temperature and concentration distribution in Parallel-flow mode

#### 3.2 Temperature and concentration distribution in Counter-flow mode

When the hot feed solution and the cold feed solution were disposed as counter-flow mode, the temperature of the hot feed solution fell gently while the temperature of the cold feed rise gradually. Moreover, the temperature difference between the lumen side and the shell side almost kept uniformity; both the temperature rise of cold feed solution and the temperature drop of hot feed solution were great, this means the heat transfer in counter-flow mode were operated adequately, As Figure.5 (b) shows, the strong solution was concentrated all the time in the membrane module and the weak solution was diluted at all times in the flow process. This is because the water vapor pressure in the lumen side was always greater than in the shell side, the water vapor transferred from the lumen side to the shell side in the whole length membrane module, and the latent heat of water vapor enhanced the heat transfer from lumen side to shell side. It was beneficial for the lithium bromide absorption system absolutely; it would diminish the heat loading of the generator and the absorber apparently.

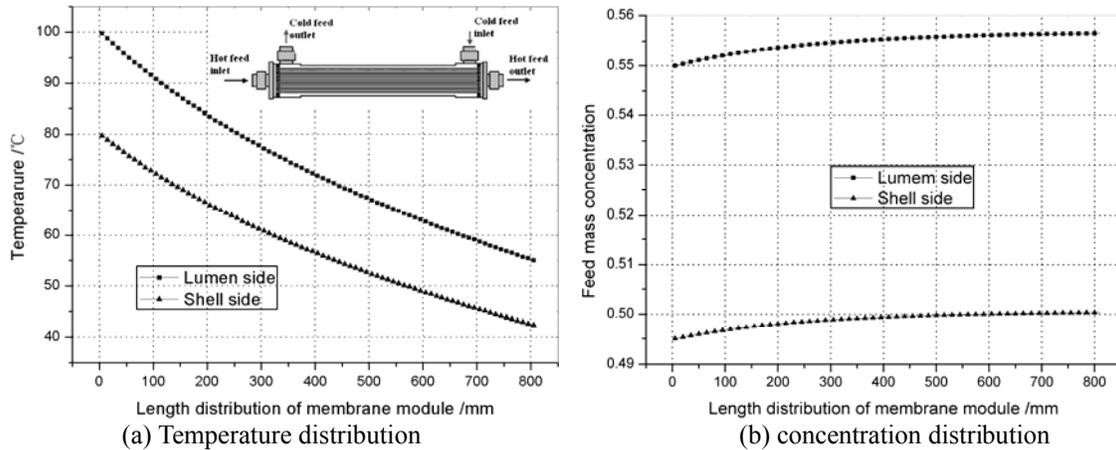


Fig.5. Temperature and concentration distribution in Counter-flow mode

**3.3 Heat transfer distribution in Counter-flow mode and in parallel-flow mode**

Figure.6 shows the heat transfer distribution in different flow mode, the latent heat transfer was enumerated to represent the mass transfer process. In counter-flow process, the latent heat transfer from the lumen side to the shell side all the while, it consisted with the heat transfer of thermal conduction, moreover, the concentration in hot feed solution was increased and the cold feed solution was decreased. In parallel-flow process, the latent heat of water vapor from the lumen side to the shell side was great in the beginning phase, but it declined sharply in the later phase, then it transferred from the shell side to the lumen side. Therefore, the latent heat transfer changed from the beneficial process to the harmful process, because it counteracted the heat conduction effect, and formed internal dissipation.

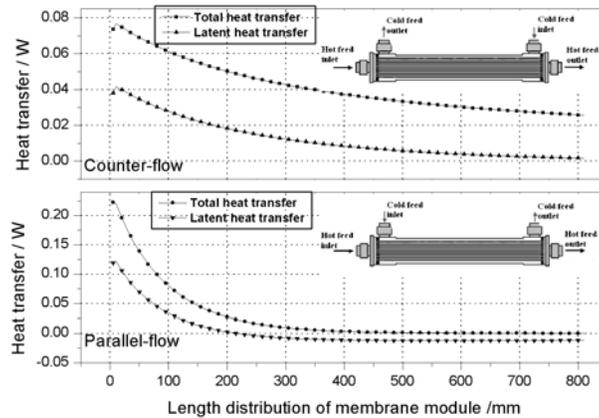


Fig.6. Heat transfer distribution in membrane heat exchanger module

Table 6 shows the simulation result of the heat transfer and latent heat transfer in parallel-flow and counter-flow process. It can be seen that the total quantity of latent heat transfer in parallel-flow was larger than in counter-flow process, however, the beneficial latent heat transfer was quite low and the total quantity of heat transfer was lower than in counter-flow process. Moreover, the quantity of latent heat transfer in counter-flow may be one third of the total quantity of heat transfer. It can conclude that the efficiency in counter-flow process was better than in parallel-flow process.

Table 6 Heat transfer and latent heat transfer in different flow mode

	Parallel-flow		Counter-flow		
Total quantity of heat transfer / kW	Total quantity of latent heat transfer / kW	Beneficial Latent heat transfer / kW	Total quantity of heat transfer / kW	Total quantity of latent heat transfer / kW	Beneficial Latent heat transfer / kW
2.605	1.794	0.285	3.998	1.196	1.196

### 3.4 Flow resistance distribution in counter-flow mode and in parallel-flow mode

The flow resistance was an important factor of the heat exchanger. Figure.7 shows the simulation results of the flow resistance distribution in the membrane module, the flow resistance in the lumen side was greater because the diameter of the membrane thread was too small. In shell side, the flow resistance seems lower because the equivalent diameter was relative bigger. The total flow resistance in the membrane module was showed in table 7. It seems that the flow resistance of membrane heat exchanger in both parallel-flow mode and counter-flow mode were greater than the traditional solution heat exchanger; it may cost greater bump work. However, it still looks quite low compared with other parts of energy cost and what's more important is that the outlet concentration of hot feed solution and cold feed solution were more benefit for the absorption refrigeration system. Thus it was worth consuming extra bump work for counter-flow process.

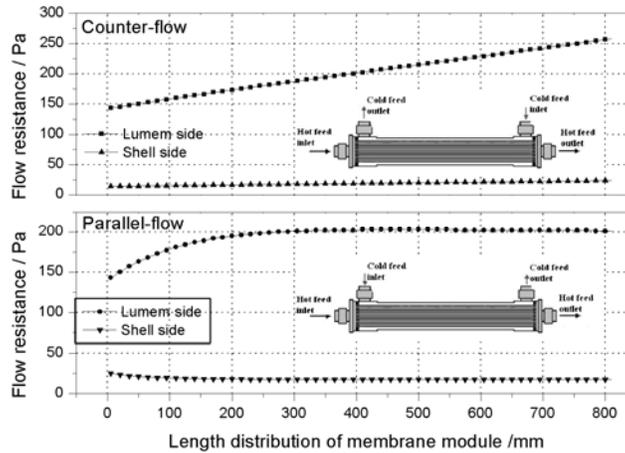


Fig.8. Flow resistance distribution in membrane heat exchanger module

Table 7 Flow resistance in the membrane module

Flow mode	Parallel-flow		Counter-flow	
	Lumen side	Shell side	Lumen side	Shell side
Flow resistance / Pa	31608.5	2896.6	32669.9	3116.4

### 3.5 Analysis of refrigeration cycle with membrane heat exchanger

In Figure 9, the cycle process 2-7'-5'-4-8'-6'-2 means the refrigeration cycle with traditional solution heat exchanger. The cycle process 2-7-5-4-8-6-2' means the refrigeration cycle with membrane solution heat exchanger. The circulation rate in generator and in absorber will reduce because the concentration range in 5-4 and in 6-2 increased. As a result, the generator heat loading and the absorber cooling load decreased, and the COP increased.

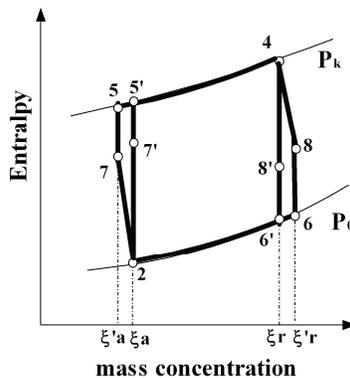


Fig.9. Refrigeration cycle with membrane heat exchanger

#### 4. CONCLUSIONS

- A new type of heat exchanger about hollow fiber membrane module was proposed, heat transfer and water vapor mass transfer happens at the same time in the heat transfer process, and it is possible to substitute the traditional solution heat exchanger for the membrane heat exchanger in the lithium bromide absorption refrigeration system.
- Numerical simulation about the heat transfer process was set up, parallel-flow process and counter-flux process was simulated and compared, the result shows that counter-flux process was the better flow mode for the heat exchanger.
- The water vapor mass transfer in counter-flow process can enhance the effect of the heat transfer process remarkably; the quantity of the latent heat transferred may be one third of the total quantity of heat transfer.
- The simulation result shows that the flow resistance may increase compared with the traditional heat exchanger, and the pump work may increase, but it is worth doing since the heat loading of the generator and the absorber may reduce and the COP of the system may increase obviously.

#### NOMENCLATURE

m	mass flux	kg/s
x	mass concentration	
T	temperature	°C
P	pressure	Pa
Q	heat quantity	W
H	enthalpy	kJ/kg
h	coefficient of heat transfer	W/(m <sup>2</sup> °C)
r	radius in inner side of membrane thread	m
r'	radius in outer side of membrane thread	m
h <sub>m</sub>	conductivity factor of membrane thread	W/(m°C)
n	quantity of membrane	
L	Length of membrane module	m
J	Membrane flux	kg/(m <sup>2</sup> s)
d <sub>e</sub>	equivalent diameter	m
ε	porosity	
ξ	tortuosity	
δ	wall thickness	m
M	mole mass of water	g/mol
R	gas constant	J/(mol K)
φ	packing density	
H <sub>r</sub>	Latent heat of water	kJ/kg
K	coefficient of membrane distillation	kg/(m <sup>2</sup> sPa)
η	pore radius	m

#### *Subscripts*

f	hot feed
p	cold feed
m	membrane
i	length unit

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