Mathematical modeling and optimal operation condition analysis of heat pump two-effect direct contact membrane distillation system

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Abstract. Compared with traditional membrane distillation system, the heat pump two-effect direct contact membrane distillation system has an advantage of low energy consumption. However, affected by many kinds of parameters, such as materials, components and operation conditions as well as the complex coupling between these parameters, it is difficult to achieve the optimal operation conditions and high gained output ratio (GOR) by optimizing the parameters. Therefore, analyses of mathematical modeling and optimal operation conditions of heat pump two-effect direct contact membrane distillation system were carried out in this paper. According to the operating principle and physical characteristics of key components, such as membrane distillation system, heat pump system, intermediate heat exchanger and auxiliary cooler, the mathematical model of heat pump two-effect direct contact membrane distillation system was established, the process of system performance simulation was designed and system performance simulation software was compiled to analyze the effect of ten parameters on GOR and total water production (Wtot). The optimal operation conditions analysis method of heat pump two-effect direct contact membrane distillation system was proposed. Through the developed simulation software of the heat pump membrane distillation system, using the proposed optimal operation conditions analysis method, When Wtot was 10.0kg/h and heat pump compressor power was 688W, the GOR of the optimized system could reach 9.43

Keywords: Direct contact membrane distillation; heat pump; Polypropylene hollow fiber hydrophobic membrane; membrane flux; GOR.

1. Introduction

Membrane distillation (MD) has the advantages of low pressure on membrane surface, capability of treating high concentration liquid and separating liquid at low temperature under atmospheric pressure. [1-3]. MD has a great potential in treating waste water, concentrating temperature-sensitive feed liquid
and seawater desalination (especially in treating high concentration tail water of reverse osmosis desalination) [4-7].

Direct contact membrane distillation (DCMD) is a membrane distillation form which hot feed liquid and cold permeate respectively direct contact with hydrophobic membrane. In DCMD process, a large amount of heat energy needs to be input to vaporize volatile components in feed liquid side while permeate side needs cold energy to condensate vapor of volatile component crossing membrane pores. As a result, the large consumption of heat and cold energy is one of the main obstacles to large-scale application of membrane distillation [8-10].

Heat pump is a device that can produce multiple heat and cold energy simultaneously by consuming a little amount of electricity. The coupling of heat pump and membrane distillation is one of the important ways to reduce the energy consumption of membrane distillation process. [11,12]. The heat pump membrane distillation system is expected to achieve high GOR [13]. This technology has attracted the attention from many researchers. Its feasibility has been verified by manufacturing prototypes and experiments and it will have a great value on engineering application in the future. Zhang et al. [14] developed vapor compress heat pump membrane distillation system and proved the feasibility of providing heat and cold energy simultaneously for membrane distillation by heat pump. Yu [15] developed the direct contact membrane distillation system coupled with heat pump when the GOR was 2.0. Liu et al. [16] developed vacuum multi-effect membrane distillation process coupled heat pump and its GOR was 3.65. Liu et al. [17] developed heat pump two-effect direct contact membrane distillation system. In this system, heat pump provides heat and cold energy for membrane distillation process. The permeate of the first effect membrane distillation module was used to heat feed liquid of the second effect membrane distillation module. Heat energy had been used twice and system performance could thus be improved. However, affected by many kinds of parameters, such as materials, components and operation conditions as well as the complex coupling between these parameters, it is difficult to achieve the optimal operation conditions and GOR by optimizing the parameters. These problems retard system reliability and large-scale application of this system. Therefore, it is necessary to conduct a systematic and in-depth research of the system to reveal the change rules between parameters and system performance (GOR and $W_{tot}$) and seek for the further optimal operation condition analysis method of the system. Currently, there is few researches about the parameters and performance of heat pump membrane distillation system. Concerning many factors, such as many operating parameters involved, strong coupling of parameters and complex operating conditions, establishment of mathematical model based on operation principle and physical characteristics of key components may be an effective means to study on the optimal operation conditions of heat pump membrane distillation system.

This paper carries out the research on mathematical model establishment and optimal operation condition analysis of heat pump two-effect direct contact membrane distillation system. Firstly, the configuration of system and related parameters were sorted out. The mathematical model was built according to operation principle and physical characteristics of key components, such as membrane distillation system, heat pump system, intermediate heat exchanger and auxiliary cooler. Secondly, the simulation process was designed and by using the simulation software to analyse the effect of ten parameters on GOR and $W_{tot}$, the variation rules of system performance were achieved. Finally, further research on optimal operation conditions was carried out. The calculation results of the developed simulation software showed that the GOR of system could be improved.

1 Heat pump two-effect direct contact membrane distillation system

The configuration and working principle of heat pump two-effect membrane distillation system are presented in Fig. 1.
The working process of heat pump two-effect membrane distillation system is as follows: when the heat pump is running, heat energy carried by refrigerant is transferred to feed liquid entering the first effect membrane distillation module through the heater. The volatile component of feed liquid passes through membrane in the form of vapor into the permeate side. The temperature of cold permeate rises after absorbing the heat energy of vapor. Then, the cold permeate enters the intermediate heat exchanger to heat the feed liquid of the second effect module. After the feed liquid enters it, the second effect module will function as the first one. The cold permeate of the second effect module enters the cooler and is cooled by heat pump refrigerant. At the same time, condensation heat is taken away with heat pump refrigerant. Then the cold permeate is cooled to the setting temperature by the auxiliary cooler and goes back to the second effect module. In this system, the heat pump unit contains compressor, heater, expansion valve and cooler. The first and the second effect membrane distillation module as well as intermediate heat exchanger form the two-effect membrane distillation unit. The auxiliary cooler is used to adjust operation conditions of the system. The main parameters of the system are listed in Table 1.

### Table 1. Main parameters of the system

| Category                  | Main parameters                                                                 |
|---------------------------|---------------------------------------------------------------------------------|
| Membrane                  | Average pore diameter ($d_m$), Porosity ($\varepsilon$), Membrane thickness ($\delta_m$), Inner diameter of the hollow fiber membrane ($d_{hm}$). |
| MD module                 | Inner diameter of the module shell ($d_p$), Number ($N$) and Length ($L$) of the hollow fiber membrane |
| Heat pump & heat exchanger| Compressor power ($P_{com}$), Area of heater, cooler, intermediate heat exchanger ($A_h, A_c, A_{hec}$), Cooling power of auxiliary cooler ($Q_{ac}$). |
| Operation condition       | Mass flowrate of the feed and the permeate ($m_f, m_p$), Temperature of the feed and the permeate in the inlet and outlet of MD module ($T_{inh}, T_{iop}, T_{pnh}, T_{pop}$), Condensing and evaporating temperature of heat pump refrigerants ($T_{rc}, T_{re}$). |
| Performance               | Heat pump coefficient of performance ($COP_{hp}$), Water production ($W_{tot}$), Gained output ratio ($GOR$). |
2. Mathematical model and simulation process design of the system

Heat loss from the system to the environment is negligible. Cold and hot liquids are arranged in a counter flow in the membrane distillation modules, heater, cooler and intermediate heat exchanger. In MD modules, feed liquid flows in the hollow fibers while the permeate homogeneously flows outside the hollow fibers. All heat energy the hot liquid released is absorbed by the permeate. The feed liquid is NaCl solution. The influence of solute on boiling point and other thermophysical properties is not taken into consideration. Based on the above settings, the mathematical model of the device and its simulation calculation flow are constructed.

2.1. Mathematical model of the system

(1) Equations of the membrane distillation process

Equation of thermal load of the MD module:
\[ Q_m = m_f c_f (T_f - T_{fo}) = m_p c_p (T_{po} - T_{pi}) \]  \hspace{1cm} (1)

Equation of heat transfer in the feed and the permeate side [18-20]:
\[ Nu = 4.36 + \frac{0.036 Re Pr D}{1 + 0.0011 \left( Re Pr \frac{D}{L} \right)^{0.8}} \]  \hspace{1cm} (2)

Equations of mean temperature in the feed and the permeate side:
\[ T_{fm} = 0.5 (T_f + T_{fo}) \]  \hspace{1cm} (3)
\[ T_{pm} = 0.5 (T_{pi} + T_{po}) \]  \hspace{1cm} (4)

Equation of temperature of thermal side of membrane wall [21]:
\[ T_{nh} = T_{fm} - \frac{Q_m}{\alpha_{mi} A_{mi}} \]  \hspace{1cm} (5)

Equation of temperature of cold side of membrane wall:
\[ T_{nc} = T_{pm} + \frac{Q_n}{\alpha_{ma} A_{ma}} \]  \hspace{1cm} (6)

Equations of permeate flux [22-24]:
\[ J_m = \left( \frac{3.6}{R_m + R_k} \right) (p_{mh} - p_{me}) \]  \hspace{1cm} (7)
\[ R_m = \frac{\tau \delta_m RT_m (p_a - p_m)}{18 \varepsilon p_D \omega_a} \]
\[ R_k = \frac{\tau \delta_m \sqrt{2 \pi M_a RT_m}}{48 \varepsilon R_m} \]
\[ \tau = \frac{1}{\varepsilon} \]

Equation of effective thermal load:
\[ Q_{eff} = \frac{J_m r w A_{mi}}{3.6} \]  \hspace{1cm} (8)

Equations of ineffective thermal load [22,25-27]:
\[ Q_{lost} = A_{mi} k_{ma} (T_{mh} - T_{mc}) \]  \hspace{1cm} (9)
\[ k_{ma} = \varepsilon k_3 + (1 - \varepsilon) k_m \]

Equation of transmembrane heat transfer:
\[ Q_{ma} = Q_{eff} + Q_{lost} \]  \hspace{1cm} (10)
Equation of thermal efficiency of the MD module [27]:

$$\eta = \frac{Q_{\text{eff}}}{Q_{\text{eff}} + Q_{\text{lost}}}$$  \hspace{1cm} (11)

(2) Equations of heat pump unit

Equations of heat production:

$$Q_{\text{hp}} = Q_{\text{in}}$$  \hspace{1cm} (12)

Equation of COP [28,29]:

$$COP_{\text{hp}} = \frac{C_{\text{hp}}T_{\text{c}}}{T_{\text{c}} - T_{\text{re}}}$$  \hspace{1cm} (13)

Equation of compressor power:

$$P_{\text{com}} = \frac{Q_{\text{hp}}}{COP_{\text{hp}}}$$  \hspace{1cm} (14)

Equation of heater:

$$Q_{\text{hp}} = k_{\text{hp}}A_{\text{hp}}(T_{\text{c}} - T_{\text{m1}})$$  \hspace{1cm} (15)

Equations of cooler:

$$Q_{\text{c}} = P_{\text{com}}(COP_{\text{hp}} - 1)$$  \hspace{1cm} (16)

$$Q_{\text{c}} = k_{\text{c}}A_{\text{c}}(T_{\text{m2}} - T_{\text{re}})$$  \hspace{1cm} (17)

(3) Equations of intermediate heat exchanger and auxiliary cooler

$$Q_{\text{ihe}} = k_{\text{ihe}}A_{\text{ihe}}(T_{\text{m1}} - T_{\text{m2}})$$  \hspace{1cm} (18)

Equations of auxiliary cooler power when the system is running stably:

$$Q_{\text{ae}} = P_{\text{com}}$$  \hspace{1cm} (19)

(4) Equations of system performance

Equation of system water production rate:

$$M_{\text{tot}} = M_{\text{m1}} + M_{\text{m2}} = J_{\text{m1}}A_{\text{m1}} + J_{\text{m2}}A_{\text{m2}}$$  \hspace{1cm} (20)

Equation of GOR [30]:

$$\text{GOR} = \frac{M_{\text{ex}}P_{\text{c}}}{3.6P_{\text{com}}}$$  \hspace{1cm} (21)

2.2. Simulation process of the system

Simulation process of the system is shown in Fig. 2. The total circulation of simulation process consists of two sub-circulations in which $T_{fo1}$ and $T_{fo2}$ are assumed and $Q_{m1}$, $Q_{m2}$ are equal to $Q_{mz1}$, $Q_{mz2}$ respectively after cyclic calculation. $T_{pi}$ is assumed in the beginning of the total circulation. Through cyclic calculation, $Q_{m1}$ is equal to $Q_{m2}$ and then output parameters are obtained. The input and output parameters are listed in Table 2.
According to the simulation calculation process of the device shown in Fig. 2, in order to achieve change rules of system performance, data simulation research was carried out by changing the number size of parameters. The simulation conditions were set as follows: The feed liquid is 10% NaCl solution, the membrane material is polypropylene (PP), \(d_{mi}=0.700\text{mm}, \ d_{mo}=1.00\text{mm}, \ \delta_{m}=0.150\text{mm}, \ \epsilon_{m}=0.800, \ N_1=N_2=700, \ \eta_{pi}=50.0\text{mm}, \ L_1=500\text{mm}, \ L_2=700\text{mm}, \ \eta_{m1}=1.50\text{m}^2, \ \eta_{m2}=1.50\text{m}^2, \ \eta_{m}=1.50\text{m}^2, \ \eta_{mp1}=100\text{g/s}, \ \eta_{mp2}=100\text{g/s}, \ T_{fi1}=80.0^\circ\text{C} \ \text{and} \ T_{pi1}=50.0^\circ\text{C}.

**Table 2.** Input and output parameters of simulation process

| Input parameters | Output parameters |
|------------------|-------------------|
| \(d_{mi}\)      | \(A_{h}\)        |
| \(d_{mo}\)      | \(A_{c}\)        |
| \(d_{m}\)       | \(A_{he}\)       |
| \(\epsilon\)    | \(m_{f}\)        |
| \(N\)           | \(m_{p}\)        |
| \(d_{pi}\)      | \(T_{fi1}\)      |
| \(L_1\)         | \(T_{pi2}\)      |
| \(L_2\)         | \(T_{rc}\)       |
| \(T_{f}\)       | \(T_{re}\)       |
| \(T_{mc}\)      | \(COP_{hp}\)     |
| \(T_{fh}\)      | \(P_{com}\)      |
| \(T_{m}\)       | \(GOR\)          |
| \(M_{p}\)       | \(M_{tot}\)      |
3.1. Influence of membrane parameters on system performance

The change rules of system performance (GOR and \( W_{\text{tot}} \)) are shown in Fig. 3 when membrane pore diameter (\( d_m \)), membrane porosity (\( \varepsilon \)), membrane thickness (\( \delta_m \)) and inner diameter of hollow fiber (\( d_{mi} \)) are changed respectively. (When \( d_{mi} \) is changed, \( \delta_m \) remains unchanged and \( N \) should be changed to keep \( A_{mi} \) unchanged.)

![Graphs showing changes in system performance with varying membrane parameters.](image)

**Fig. 3** System performance when different membrane parameters are changed

It can be found in Fig. 3(a), (b) that GOR and \( W_{\text{tot}} \) increase with the enlargement of \( d_m \) or \( \varepsilon \). In Fig. 3(d), GOR and \( W_{\text{tot}} \) will be decreased once \( d_{mi} \) is raised. When \( \delta_m \) rises in Fig. 3(c), GOR and \( W_{\text{tot}} \) change little. Concern should be raised that it could cause the feed leakage and other problems if \( d_m \) is too large. Therefore, \( d_m \) ranges from 0.200 to 0.300\( \mu \)m in practical applications. The porosity of organic membrane limited by manufacturing process is usually in the range of 0.800 to 0.850.

With the increase of \( d_m \) or \( \varepsilon \), the transmembrane resistance of vapor rises and effective thermal load rises. Thus, GOR and \( W_{\text{tot}} \) are enhanced. The increase of \( \delta_m \) raises the thermal resistance of transmembrane heat conduction and mass resistance of vapor during the transmembrane mass transfer process. In the meantime, the change of thermal resistance and mass resistance redistributes the temperature difference on both sides of membrane. As the result of intersection of above factors, GOR and \( W_{\text{tot}} \) are changed slightly. When \( d_{mi} \) rises, the thermal resistance and mass resistance of membrane are basically unchanged, and the slight decline of feed liquid velocity decreases the heat transfer coefficient and transmembrane temperature difference. As a result, GOR and \( W_{\text{tot}} \) are reduced.
3.2. Influence of MD module parameters on system performance

The change rules of system performance (GOR and $W_{\text{tot}}$) are shown in Fig. 4 when number of hollow fiber ($N$), $A_{m1}/A_{m2}$ and inner diameter of module shell ($d_{pi}$) are changed respectively. (When $N$ is changed, $\delta_m$ remains unchanged and $d_{mi}$ should be changed to keep $A_{mi}$ unchanged.)

It can be found from Fig. 4(a) that GOR and $W_{\text{tot}}$ will be elevated once $N$ rises. GOR and $W_{\text{tot}}$ will be reduced once $d_{pi}$ is raised, but the range of change is not large in Fig. 4(c). GOR and $W_{\text{tot}}$ in Fig. 4(b) is not monotonous and both have peak values when $A_{m1}/A_{m2}$ equals 1.00.

When $N$ rises, the thermal resistance and mass resistance of membrane are changed little but the slight increase of feed liquid velocity enhances the heat transfer coefficient and transmembrane temperature difference. As a result, GOR and $W_{\text{tot}}$ are elevated. In the condition that the total area of membrane is fixed, the large difference between $A_{m1}$ and $A_{m2}$ will lead to the large difference of transmembrane temperature, which makes $COP_{hp}$ change. Then, GOR and $W_{\text{tot}}$ are influenced. The change of $d_{pi}$ has no effect on the heat and mass transfer process, but it could affect the permeate liquid velocity. When $d_{pi}$ is raised, the permeate liquid velocity will be reduced, which decreases the heat transfer coefficient and transmembrane temperature difference. As a result, GOR and $W_{\text{tot}}$ are reduced.

3.3. Influence of operation condition parameters on system performance

The change rules of system performance (GOR and $W_{\text{tot}}$) are shown in Fig. 5 when temperature of the permeate in the inlet of the 2nd effect MD module ($T_{p2}$), temperature of the feed liquid in the inlet of the 1st effect MD module ($T_{f1}$) and mass flowrate of the feed and the permeate ($m_f$, $m_p$) are changed respectively.
It can be found from Fig. 5(a) that \( GOR \) will be raised and \( W_{\text{tot}} \) will be reduced once \( T_{\text{pi2}} \) rises. In Fig. 5(b), \( GOR \) and \( W_{\text{tot}} \) will be elevated once \( T_{\text{fi1}} \) is raised. (The difference between \( T_{\text{fi1}} \) and \( T_{\text{pi2}} \) keeps the same.) In Fig. 5(c), \( GOR \) will be reduced and \( W_{\text{tot}} \) will be raised once \( m_f \) and \( m_p \) are raised. (\( m_f = m_p \))

When \( T_{\text{pi2}} \) is decreased, the difference between \( T_{\text{rc}} \) and \( T_{\text{re}} \) will be raised, which reduces the \( \text{COP}_{\text{hp}} \) that finally declined \( GOR \). At the same time, the decrease of \( T_{\text{pi2}} \) makes transmembrane temperature difference larger, which raises the permeate flux. Therefore, \( W_{\text{tot}} \) is elevated. Due to the increase of \( T_{\text{fi1}} \), temperature of the hot membrane surface is raised. Therefore, transmembrane pressure difference is enhanced, which leads to the increase of permeate flux that promotes the effective thermal load and thermal efficiency of the MD module. Consequently, \( GOR \) and \( W_{\text{tot}} \) are raised. When the value of \( A_{\text{tot}} \), \( A_h \), \( A_c \) and \( A_{\text{hhe}} \) are determined, raising \( m_f \) and \( m_p \) will have influence on two aspects. On one hand, heat transfer coefficient of the feed side and the permeate side are both elevated, which increases the transmembrane temperature difference. Therefore, permeate flux and \( W_{\text{tot}} \) is elevated. On the other hand, the difference between \( T_{\text{rc}} \) and \( T_{\text{re}} \) is raised, which reduces the \( \text{COP}_{\text{hp}} \) that finally declined the \( GOR \).

4. Optimal operation condition analysis of heat pump two-effect direct contact membrane distillation system

4.1. Analysis of key parameters for system performance optimization

Collating the research contents of the previous section and the data of Fig. 3-5, Table 3 shows the \( GOR \) ranges from 5.18% to 89.3% with the change of different parameters. System parameters are divided into three groups based on actual adjustment range of parameters and their influence on system performance: low impact parameter, low adjustment parameter and high sensitivity parameter. Low impact parameters are parameters which have little effect on system performance. Low adjustment
parameters are parameters which are limited by the actual technical conditions and thus the adjustment range is small. High sensitivity parameters are parameters which have significant influence on system performance, such as $T_{pi2}$ and $T_{fi1}$. The ranges of GOR are 0–89.3% and 0–63.8% respectively when $T_{pi2}$ and $T_{fi1}$ are changed in their adjustment range. Therefore, high sensitivity parameters are the key to the optimization of system performance.

| Table 3. Category of system parameters |
|----------------------------------------|
| **Category** | **Parameters** | **Adjustment range** | **Change range of GOR (%)** |
|---------------|----------------|----------------------|-----------------------------|
| Low impact parameter | $\delta_m$ | 0.150~0.400mm | <9.85 |
| | $d_{mi}$ | 0.500~1.00mm | <8.36 |
| | $N$ | 500~1000 | <8.34 |
| | $d_{pi}$ | 40.0~50.0mm | <6.42 |
| | $A_{mi}/A_{m2}$ | 0.400~1.40 | <6.31 |
| Low adjustment parameter | $\varepsilon$ | 0.800~0.850 | <9.13 |
| | $m_{ni}$ | 0.200~0.300μm | <5.35 |
| | $m_{f}, m_{p}$ | 0.350~0.450m/s | <5.18 |
| High sensitivity parameter | $T_{fi1}$ | 60.0~85.0°C | <63.8 |
| | $T_{pi2}$ | 35.0~60.0°C | <89.3 |

4.2. Analysis of optimal operation conditions of the system

Adjusting low-impact parameters and low schedulable parameters requires changing the original hardware of the device, and it has difficulties in the adjustment, small range and slow effect. Therefore, this paper focuses on how to adjust the high sensitivity parameters. However, the adjustment of high sensitivity parameters is also restricted by some conditions. The analysis is as follows.

From Equations (20) and (21),

$$GOR = \frac{M_{\text{tot}}r_w}{3.6P_{\text{com}}} \left( \frac{M_{mi} + M_{m2}}{3.6P_{\text{com}}} \right) r_w = \frac{M_{mi}r_w + M_{m2}r_w}{3.6P_{\text{com}}}$$

(22)

Then

$$GOR = \frac{Q_{hp}\eta_{mi} + Q_{hp}\eta_{m2}}{P_{\text{com}}} = COP_{hp}(\eta_{mi} + \eta_{m2})$$

(23)

Based on Equation (23), $COP_{hp}$ and thermal efficiency of two MD modules need to be improved to achieve higher $GOR$. In order to improve the thermal efficiency of MD modules, it is necessary to adjust the high sensitivity parameters reasonably under the condition of increasing $COP_{hp}$ as much as possible.

The constraints are that $A_{\text{tot}}$ and $M_{\text{tot}}$ are given the fixed value and $T_{fi1}$ need to be a value as high as possible because of its increase which is beneficial to $GOR$ and $M_{\text{tot}}$. The maximum $GOR$ of system decreases with the increase of $M_{\text{tot}}$ and it increases with the raise of $A_{\text{tot}}$. Thus, a reasonable $M_{\text{tot}}$ should be set according to $A_{\text{tot}}$ when optimizing $GOR$. On the premise of satisfying the constraints, the optimization methods of the system are as follows: (1) setting $T_{fi1}$ as the temperature resistance limit of the feed liquid; (2) giving fixed $A_{\text{tot}}$ and $M_{\text{tot}}$; (3) making $T_{pi2}$ increased as high as possible to obtain the highest $GOR$.

Using the above-mentioned optimization method and the simulation flow of the system shown in Fig. 2, the simulation software of heat pump two-effect membrane distillation system shown in Fig. 6 was developed. In the simulation, $A_{mi}/A_{m2}$ was set as 1.00 and other parameters were set as the same value in Section 3. When $T_{pi2}$ increased gradually from 20.0°C, $GOR$ was raised and $W_{\text{tot}}$ was decreased simultaneously. When $W_{\text{tot}}$ reached 10.0 kg/h, $GOR$ at this time is the highest one that met the
requirement of \( W_{\text{tot}} \). It is thus clear from Fig. 6 that \( T_{\text{pi2}} \) was 48.3℃, \( P_{\text{com}} \) was 688W and \( GOR \) could reach 9.43 in optimal operation condition of the system.

![Simulation software of heat pump two-effect membrane distillation system](image)

Fig. 6 Result of the simulation

5. Conclusion
In this paper, the change rules between different parameters and system performance were researched through the establishment of mathematical model of heat pump two-effect direct contact membrane distillation system. The adjustment method of system optimal operation condition was proposed. Conclusions are as follows:

1. According to the operating principle and physical characteristics of key components, the mathematical model of heat pump two-effect direct contact membrane distillation system was established. It laid theoretical foundation for further research and analysis of existing heat pump membrane distillation system.

2. The change rules between different parameters and system performance were revealed. According to the different degree of influence on system performance, the division of various adjustment parameters were realized, and high sensitivity parameters were the key parameters of system performance.

3. A specific optimization method for the system was proposed which was as follows: in the condition that the hardware of the system was guaranteed to be unchanged, \( T_{\text{fi1}} \) was set as the temperature resistance limit of the feed liquid. Then, \( T_{\text{pi2}} \) was raised from ambient temperature to higher temperature. When \( M_{\text{tot}} \) reached required value, the corresponding \( GOR \) was at the peak point where \( T_{\text{pi2}} \) was the optimum temperature and the system was running in the optimal operation condition.

4. When the MD module enlarges, it is unavoidable that the non-uniform distribution of hollow fiber, the existence of channel flow and short circuit in permeate side will have a great impact on the heat and mass transfer on the shell side. As the result of above problems, thermal efficiency of the MD module could be low and \( GOR \) could have difficulty in reaching the theoretical calculation value. How to overcome these problems will be the direction of further research and exploration in the future.
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