Integration of direct contact membrane distillation and recirculating cooling water system for pure water production

Jun Wang, Bin Fan, Zhaokun Luan*, Dan Qu, Xianjia Peng, Deyin Hou

*State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences,
Chinese Academy of Sciences, P.O. Box 2871, Beijing 100085, PR China*

Received 4 September 2007; received in revised form 6 December 2007; accepted 7 December 2007

Available online 22 January 2008

Abstract

A novel cleaner production technology (CPT) using waste heat for pure water production was established by integration of direct contact membrane distillation (DCMD) and traditional recirculating cooling water (RCW) process. The effect of temperature difference and flow rate of fluid between the hot and cold sides in a membrane module on the membrane flux was investigated. The results of the study show that the membrane flux increases with an increase in the flow rate in both hot and cold sides and also increases linearly with the increase in fluid temperature difference between the hot and cold sides of the membrane module. Waste heat was utilized for pure water production, which will reduce the pure water production cost. The employment of DCMD in the RCW process may also reduce the amount of scale and corrosion inhibition additives needed in the CPT, the makeup water and blowdown quantity.

© 2007 Elsevier Ltd. All rights reserved.

Keywords: Membrane distillation; Recirculating cooling water; Cleaner production; Pure water production

1. Introduction

Worldwide there is huge potential and need for technologies of water saving and discharge reduction because of the water shortages in many regions and the situation is getting worse. Most industrial production sectors such as power plants, petroleum refineries, petrochemical and chemical plants usually include RCW system and pure water production system. The makeup water of RCW system and the water used for pure water production reach about 70–80% of industrial water in the world [1].

The main defects of the traditional RCW system are the additional protection needed from scaling and eroding attained through the use of a number of antiscalant additives, and huge blowdown production and big requirement for makeup water. At the same time, many industrial units have requirement for pure water. Relevant water purification techniques

used in the industry include the ion exchange process, reverse osmosis and nanofiltration/ultrafiltration, and so on [2]. However, there are several drawbacks that have been difficult to overcome for these technologies, such as low water recovery rate, cost of the chemical agents which also produce a secondary pollution, and have complicated pre-treatment/post-treatment and high operation/maintenance requirements [3].

Presently, in most industries, pure water production and the RCW are completely separate systems. However, it is not difficult to find the main purpose of both processes, that is desalination, when we analyse the essence of two water treatment systems. Therefore, alternative technology that can integrate closely two water treatment systems, which reduces the blowdown and makeup water of RCW system, produces high quality pure water with lower costs and better environmental performance, therefore, remains a priority.

The DCMD is a kind of thermally driven membrane separation process in which two solutions at different temperatures are separated by a microporous hydrophobic membrane. The driving force of DCMD is the formation of a vapour pressure difference across the membrane resulting from the temperature

* Corresponding author. Tel./fax: +86 10 62849198.

E-mail address: luanzk@rcees.ac.cn (Z. Luan).

Symbols

B	the blowdown flow rate of R_3 cycle as the final blowdown, L/min
D	blowdown flow rate of R_1 cycle, L/min
E	evaporation losses of the cooling tower, L/min
M	the makeup water flow rate in R_1 cycle, L/min
P	the production pure water flow rate of the CPT, L/min
T_m	temperature of the makeup water, °C
T_{11}	temperature of the hot side fluid at the membrane module inlet, °C
T_{12}	temperature of the hot side fluid at the membrane module outlet, °C
T_{21}	temperature of the cold side fluid at the membrane module inlet, °C
T_{22}	temperature of the cold side fluid at the membrane module outlet, °C
T_{31}	temperature of the recirculating cooling water at the cooling tower outlet, °C
T_{32}	temperature of the recirculating cooling water at the technologic condenser outlet in the R_3 cycle, °C
T_h	temperature of hot side fluid in the membrane module $[(T_{11} + T_{12})/2]$, °C
T_c	temperature of cold side fluid in the membrane module $[(T_{21} + T_{22})/2]$, °C
Q_{11}	the hot side fluid flow rate at the membrane module inlet in the R_1 cycle, L/min
Q_{21}	the cold side pure water flow rate at the membrane module inlet in the R_2 cycle, L/min
Q_{31}	the recirculating cooling water flow rate in R_3 cycle, L/min
Flux	the pure water production per square meter membrane area, $L\ m^{-2}\ h^{-1}$
K_1	the concentration factor calculated value of the fluid in R_1 cycle
K_2	the concentration factor calculated value of the fluid in R_3 cycle
K'_1	the concentration factor measured value of the fluid in R_1 cycle
K'_2	the concentration factor measured value of the fluid in R_3 cycle
γ	apparent membrane distillation efficiency
r	linear correlation coefficient
$[Cl^-]_{R_1}$	chloride concentration of the fluid in R_1
$[Cl^-]_{R_3}$	chloride concentration of the fluid in R_3
$[Cl^-]_{Makeup}$	chloride concentration of the fluid in makeup water R_3

In comparison with other separation operations, DCMD has obvious advantages: almost a complete rejection of dissolved and non-volatile species, lower operating pressure than pressure-driven membrane processes, reduced vapour space compared to traditional distillation, and low operating temperature of the feed enables the utilization of waste heat as a preferable energy source [2].

Although the DCMD technology has the advantages which other membrane technologies do not have, one of the main obstacles to the implementation of DCMD is its need for a heat supply. DCMD generally requires heating up the hot water side and cooling the cold water side because of the heat transfer involved in the process [16]. Therefore, the use of industrial waste heat to heat up the feeding water of DCMD process has an economical benefit in reducing the costs. There is a lot of low quality waste heat that can be used and a large requirement for pure water in industrial production sectors. So, DCMD technology has the application preponderance and foreground in the industrial water treatment field.

In this study, a novel CPT was established by integration of DCMD and traditional RCW process; this new process not only takes care of the cooling part of the process but also accomplishes pure water production. Furthermore, an experimental device simulating this was setup for elementary validation; the influences of temperature, velocity on the flux of DCMD and the makeup water flow rate on the CF of fluids in R_1 and R_3 cycles will be discussed here.

2. Principle of CPT

A schematic diagram of the proposed CPT which integrated DCMD with traditional RCW system is shown in Fig. 1. The CPT is established by addition of a DCMD unit and a technologic heat exchanger between the industrial heat exchanger and cooling tower in the traditional RCW system. The DCMD unit is made up of hollow fibre membrane modules. The technologic condenser is a kind of anticorrosive heat exchanger. Thus, it comes into being three series-wound sub-systems: R_1 , R_2 , and R_3 . In fact, if the dashed frame unit in Fig. 1 is deleted, then it forms the traditional RCW system.

- (1) No. 1 cycle (R_1) includes the industrial condenser or industrial heat exchangers and the hot side of DCMD modules. The low temperature makeup water was pumped into the hot side loop of DCMD modules as feed water after being heated up by heat exchange with industrial condenser. The vapour pressure difference across the membrane caused by the corresponding temperature difference provides the driving force that causes diffusion of vapours through the membrane pores from the hot side to cold side of membranes. The transmembrane heat of DCMD process includes vapour latent heat and heat conduction, so that the temperature of fluid out of membrane hot side will descend. The fluid out of the hot side returns to the industrial condenser for cooling medium after mixing with makeup water.

gradient in the boundary layers adjacent to the membrane surface. DCMD has been applied for water desalination, heavy metal recovery, water reuse and food concentration processing, and so on. The theory and application of DCMD have been described in many papers [4–15,18].

Fig. 1. A schematic diagram of the CPT.

- (2) No. 2 cycle (R_2) includes the cold side of DCMD modules and the hot side of technologic condenser. Pure water is the circulating medium in this cycle. Pure water in the cold side of DCMD modules will gain the vapour latent heat and conduction heat, so the temperature of pure water out of the cold side of DCMD modules will increase. After the heat exchange between the hot pure water and the cooler medium of R_3 cycle, the hot pure water is returned to the cold side of DCMD modules and circulated in R_2 cycle. The transmembrane vapour is cooled by the circulating pure water in the cold side of modules, and the condensate overflow R_2 cycle.
- (3) No. 3 cycle (R_3) includes the cold side of technologic condenser and the cooling tower. It resembles traditional open RCW system. The primary function of this water loop is to remove unwanted heat by evaporation losses. The cooling water is pumped through technologic condenser where the temperature of cooling water is increased. The warm water is then returned to the cooling tower where it flows into a distribution system located some height above the tower basin.
- (4) Because there is pure water produced flowing out of the R_1 cycle and evaporation losses in the R_3 cycle, the CF of fluids will increase in R_1 and R_3 cycles. Thus, some of the dissolved substances in the fluids will approach their solubility limit in water. To prevent the formation of scaling conditions, the concentration factors of fluids in R_1 and R_3 cycles are carefully controlled by discharging a portion of the concentrated recirculating water (blowdown) from the system and makeup water is pumped into the CPT process. The makeup water of R_1 cycle is industry tap water; the blowdown of R_1 cycle is fed into the R_3 cycle as the makeup water of the R_3 cycle. The blowdown of the R_3 cycle was discharged as the final blowdown of the entire cleaner production system.

The following relationship can be obtained from mass and salt balances of R_1 cycle:

$$M = \frac{K_1 P}{K_1 - 1} \quad (1)$$

$$D = \frac{P}{K_1 - 1} \quad (2)$$

where M is the makeup water flow rate, P is the pure water production flow rate, K_1 is the concentration factor (CF) of fluid in R_1 cycle, and D is the blowdown flow rate of R_1 cycle.

The following relationship can be obtained from mass and salt balances of R_3 cycle:

$$D = \frac{K_2 E}{K_2 - K_1} \quad (3)$$

$$B = \frac{K_1 E}{K_2 - K_1} \quad (4)$$

where E is the evaporation losses of cooling tower, K_2 is the CF of fluid in R_3 cycle, and B is the blowdown flow rate of R_3 cycle as the final blowdown.

Combining Eqs. (1)–(4) yields the following equation:

$$B = \frac{K_1 D}{K_2} \quad (5)$$

M , P , and B values can be obtained experimentally, and D , E , K_1 and K_2 values can be calculated using Eqs. (1)–(4). In this study, we use the chloride ion concentration variation as the criterion of CF [1], measured CF values, K'_1 and K'_2 , are measured from ratio of the concentration of chloride between the tower blowdown and the makeup. So, the CPT can be validated by comparing CF calculated values K_1 and K_2 with measured CF values, K'_1 and K'_2 .

$$K'_1 = \frac{[\text{Cl}^-]_{R_1}}{[\text{Cl}^-]_{\text{Makeup}}} \quad (6)$$

$$K'_2 = \frac{[\text{Cl}^-]_{R_3}}{[\text{Cl}^-]_{\text{Makeup}}} \quad (7)$$

where $[Cl^-]_{R_1}$, $[Cl^-]_{R_3}$, $[Cl^-]_{Makeup}$ are chloride concentration of the fluid in R_1 , chloride concentration of the fluid in R_3 and chloride concentration of the fluid in makeup water R_3 , respectively.

For the CPT, evaporation losses mainly depend on the cooling capacity and the atmospheric conditions which include air temperature, humidity and the air flow rate through the cooling tower. The evaporation losses are directly related to the fluid temperature difference across the tower. As a rough estimation, the rate of evaporation is approximately 1% of the recirculation flow rate for each 10 °C of rise between the outlet and inlet across the tower [17]. So, under fixed atmospheric conditions, circulating water flow rate and inlet water temperature, it can be presumed that the evaporation losses are certain.

Therefore, we can assume that the quantity of pure water production is equal to γE .

$$P = \gamma E \quad (8)$$

Combining Eqs. (2), (3) and (8) yields the following equation:

$$K_1 = \frac{1+\gamma}{K_2+\gamma} K_2 = (1+\gamma) - \frac{\gamma(1+\gamma)}{K_2+\gamma} \quad (9)$$

where γ is apparent MD efficiency. Usually, the evaporation losses are more than the requirement of pure water quantity, that is $\gamma < 1$.

The following relationship can be obtained from Eq. (9):

$$K_1 < 1 + \gamma < 2 \quad (10)$$

3. Experimental setup

Based on the CPT principle, an experimental device was setup. A schematic diagram of the experimental device is shown in Fig. 2. For the sake of clarity, each unit will be described separately.

3.1. Hollow fibre membrane and membrane module

The microporous polyvinylidene fluoride (PVDF) hollow fibre membrane was prepared by the authors using a dry/wet phase inversion process. The diameters of the membranes, nominal pore diameter and porosity were $d_{out}/d_{in} = 1/0.7$ mm, 0.18 μ m and 76%, respectively. The minimum pressure under which water will overcome the hydrophobic forces of the membrane and will penetrate the pores (LEP_w) is 150 kPa.

The module has a total length of 700 mm and an effective length of 500 mm. The number of fibres potted in one module was 1275 and the total area of the membrane was about 2 m². The shell of module was setup by gluing a polyester tube (diameter (mm), $D_i/D_o = 80/96$) to two ABS T-tubes, which have an “O” saw-toothed water distribution tube.

3.2. Membrane distillation unit

In Fig. 2, R_1 cycle is the hot side loop of the DCMD and R_2 cycle is the cold side loop of the DCMD. The fluids (tap water and pure water) were contained in two double-walled reservoir with a capacity of 80 L, and were driven by two magnetic circulation pumps (model MP-30R, purchased from Shanghai Seisun Bumps Co., Ltd.). The temperature of fluid in the hot side loop was controlled by pumping through the electric

Fig. 2. A schematic diagram of the experimental device.

heaters to simulate the heat gained in the condenser. The electric heater is an auxiliary heating system formed by an electrical resistance, connected to a circulation thermostat.

The feed flow rate through the lumen of membrane module (hot side) and the pure water flow rate through the shell side of membrane module (cold side) were monitored using two rotameters equipped with a back pressure valve for the manual regulation of the flow rate. Two pressure meters (model YJTF100, purchased from Nanjing Wanda Co., Ltd.) connected to the lumen and shell side of the module were used to measure the pressure at the inlet of both sides in the range 0–100 kPa. The flow rate and pressures were selected by taking into account that the pressure difference should not exceed the LEP_W (150 kPa). The temperature of both fluids was monitored at the inlet and outlet of the membrane module using four Pt-100, platinum resistance thermometers connected to a digital thermometer (Digit RTD, model XMT-808, purchased from Yuyao Changjiang Temperature Meter Instrument Factory) to provide an accuracy of ± 0.2 °C.

3.3. Technologic condenser and cooling tower

The technologic condenser and the cooling tower form the R_3 cycle. The condenser is a brazed plate heat exchanger (model D3-095B-2 m², stainless steel, purchased from Hangzhou Qinbao Refrigeration Equipment Co., Ltd.).

In the counter flow cooling tower, ambient air is pulled into the tower by means of an axial flow fan mounted on top of the tower. The diameter of column is 800 mm, height is 1800 mm and it was fabricated from clear PVC. It contains 600 mm height stuffing layer of polyhedral ball ($\varnothing 25$ mm) with a total transfer area of 100 m².

A circulation pump (mode MP-30R) draws the cooled water from the basin which is located at the bottom of the column at a rate adjusted by a hand operated water control valve and sends it to the brazed plate heat exchanger. After absorbing heat from the hot water stream in the heat exchanger, the water was pumped to the top of the cooling tower. A rotameter was fixed on the pipeline and four temperature meters were fixed at inlets and outlets of the plate heat exchanger. The UPVC pipeline and valves of the experimental setup were thermally insulated in order to reduce the energy loss towards outside.

3.4. Experimental procedure

The quality of water used in this study and experimental operation parameters are presented in Tables 1 and 2.

The experimental procedure is as follows:

1. Container at hot side of R_1 cycle and the basin of cooling tower were filled with tap water. The pure water container was filled with distilled water.
2. Starting the hot side circulation pump, connecting the auxiliary heating system and setting the temperature. Starting the cold side circulation pump, the circulation pump of the cooling tower and axial flow fan.

Table 1
The tap water quality parameter used in experiments

Parameter	Data
Sodium (mg/l)	78.44
Potassium (mg/l)	19.06
Calcium (mg/l)	54.51
Magnesium (mg/l)	26.24
Chloride (mg/l)	91.22
Sulfate (mg/l)	138.80
Nitrate (mg/l)	6.2
Silica (mg/l)	3
Bicarbonate (mg/l)	195.26
pH	8.07
Conductance (μ S/cm)	864
Total dissolved solids (mg/l)	540

3. Starting and adjusting the variable flow peristaltic pump for makeup water, and adjusting the flow rate of the hot side stream.
4. After running for 24 h, the system reached a steady state. Then the experimental measurements are made at regular time intervals.

The electrical conductivity of the pure water was measured using a hand-held meter (sensION 156™, Hach Company) at a temperature of 20 °C. Chloride concentration was measured using a Digital Titrator (Model 16900, Hach Company) with silver nitrate method.

4. Results and discussion

4.1. The CPT test

Variables in operation conditions include hot side temperature, transmembrane temperature difference and circulation flow rate of the feed water on the hot side of the membrane module. The ranges of these operation conditions are summarised in Table 2. The calculated values of D , K_1 , K_2 and measured values of P and B are listed in Table 3. P and B values are accurately measured using an electronic balance.

The performance of DCMD of CPT under different experimental conditions was tested. In this study, we present a summary of the most representative obtained results. The fixed

Table 2
Experimental operation parameters

Parameter	Data
Hot side water flow rate, nominal	12–80 L/min, adjustable
Cold side water flow rate, nominal	20–120 L/min, adjustable
Recirculating cooling water flow rate, nominal	50 L/min
Hot side water inlet temperature	50, 55, 60, 70 °C
Cold water inlet temperature	30–35 °C
MD cell membrane area, nominal	2 m ²
Heating power requirement	Max, 15 kW
Makeup water flow rate, nominal	0.8–1.5 L/min

Table 3
Experimental values and main results

T_{11} (°C)	T_{21} (°C)	T_{31} (°C)	M (L/min)	P (L/min)	B (L/min)	Q_{11} (L/min)	K_1	K'_1	K_2	K'_2
50.8	25.6	22.6	1.0	0.32	0.26	40	1.47	1.45	3.85	3.72
50.2	25.7	22.6	1.1	0.31	0.37	40	1.39	1.34	2.97	3.09
50.3	25.8	22.8	1.2	0.31	0.47	40	1.35	1.32	2.55	2.57
49.8	26.1	23.1	1.5	0.29	0.79	40	1.24	1.23	1.90	1.82
55.3	27.8	23.5	1.2	0.34	0.43	40	1.40	1.41	2.79	2.88
60.4	28.4	23.7	1.2	0.40	0.39	40	1.50	1.46	3.08	3.21
68.7	29.1	23.5	1.2	0.51	0.25	40	1.74	1.79	4.80	4.62
71.2	29.5	23.5	1.2	0.54	0.22	40	1.82	1.86	5.45	5.56
49.8	26.1	23.1	1.0	0.30	0.26	40	1.43	1.40	3.85	4.01
50.1	26.3	22.8	1.0	0.27	0.29	32	1.37	1.33	3.45	3.61
50.3	26.2	23.3	1.0	0.18	0.38	24	1.22	1.25	2.63	2.57
50.2	26.0	22.9	1.0	0.14	0.42	18	1.16	1.21	2.38	2.44

parameters are the temperature of makeup water $T_m = 15 \pm 0.3$ °C, cold side flow rate $Q_{21} = 50$ L/min and flow rate of cooling water in the R_3 cycle $Q_{31} = 50$ L/min, respectively. Atmospheric pressure was about 100.4 kPa, relative humidity was about 65% and wet bulb temperature was about 18.9 °C. The values of those experiments correspond to mean values obtained in steady state during a time interval greater than 24 h. In the experimental processes, the quality of the pure water does not deteriorate and the electrical conductivity remains stable at 3.5 μ S/cm.

A careful examination of the data appearing in Table 3 allows us to reach the following conclusions:

1. Pure water production increases with the increase in the feed flow rate Q_{11} , for a fixed value of cold side inlet temperature T_{21} .
2. Pure water production increases with the increase in the temperature at the MD hot side inlet T_{11} , for a given value of the feed flow rate, Q_{11} .
3. The K'_1 value decreases with the increase in makeup water flow rate M , for a given value of the feed flow Q_{11} and a fixed value of hot side inlet temperature T_{11} .
4. Better agreement can be seen between CF calculated values (K_1 and K_2) and CF measured values (K'_1 and K'_2), where the differences between them are in the range of ± 0.2 .
5. Under the experimental conditions, water temperatures in the basin of cooling tower are about 23 °C. This indicates that the cooling tower can meet the heat load of the system. When heat load of the cooling tower increases with the increase in water temperature (T_{32}) and the blowdown of R_1 (D), the evaporation losses of cooling tower also increase. That is, the evaporation losses of the system can be controlled by the makeup water quantity and MD process operation parameters. The heat load of the cooling tower in the CPT is less than that of conventional RCW process because the pure water out of the CPT takes out some heat. So the heat load for the cooling tower was reduced. Therefore, to meet the same cooling requirement, the RCW flow through the cooling tower can be reduced, which will result in less evaporation losses.

4.2. The influence of the temperature difference on membrane flux

Because the DCMD is a thermally driven membrane separation process, the flux of DCMD is greatly influenced by the temperature difference between the hot and the cold sides. In this study, the temperature difference between the hot side and cold side fluid ($T_h - T_c$) was obtained from the arithmetic mean values of the temperatures at the inlets and outlets of the membrane module, $T_h = [(T_{11} + T_{12})/2]$ and $T_c = [(T_{21} + T_{22})/2]$ respectively.

The influence of temperature difference on membrane flux was studied in this work by performing different experiments at different feed temperatures (35–70 °C), and the temperature difference is in the range of 5–40 °C. For the range of temperatures tested, the flow rate of the hot side fluid was held at 40 L/min, the flow rate of pure water in the cold side loop was held at 50 L/min, and the recirculating water in the R_3 cycle was nominally held at 50 L/min. The results are shown in Fig. 3, which shows the pure water flow produced

Fig. 3. Membrane flux as a function of the temperature difference of both sides.

per square meter of effective filtration area as a function of the temperature difference, $T_h - T_c$.

An almost linear relation was obtained between membrane flux and temperature difference. The temperature difference creates a vapour pressure difference, which leads to water vapour diffusion through the membrane. As the temperature difference increases, so does the vapour pressure difference and thus the membrane flux rises. Under the experimental conditions, it is possible to estimate the production of pure water for a given value of the imposed temperature difference using Eq. (11).

$$\text{Flux} = 0.5041(T_h - T_c) - 0.2392 \quad (11)$$

An easy calculation shows that the pure water productions at temperature difference of 10, 20 and 30 °C are 4.80, 9.84 and 14.88 L m⁻² h⁻¹, respectively. Membrane flux increases by 51.2% with an increase in temperature difference from 20 to 30 °C.

4.3. Influence of fluid flow rate on membrane flux

Fig. 4 shows the influence of flow rate of hot and cold sides on membrane flux. It can be seen that the membrane flux increases with the increase in flow rate of both hot and cold sides.

The effect of hot side flow rate on the membrane flux was studied at hot side temperature $T_{11} = 50$ °C and cold side flow rate $Q_{21} = 50$ L/min. The results, shown in Fig. 4, indicate that the membrane flux increases approximately linearly with the feed flow rate in the range of 12–78 L/min (feed velocity in the range of 0.2–1.3 m/s). Increasing hot side flow rate improved membrane fluxes and flux increases by 40.8% with the increase in hot side velocity from 12 to 30 L/min.

The effect of cold side flow rate on the membrane flux was studied at fixed hot side inlet temperature $T_{11} = 50$ °C and hot side flow rate $Q_{11} = 40$ L/min. From the results shown in

Fig. 4, it can be found that increasing of cold side flow rate has an obvious effect on membrane flux and the flux increases by 22.4% with the increase in cold side flow rate from 20 to 100 L/min (velocity in the range of 0.1–0.5 m/s). As the cold side flow rate exceeds 100 L/min, the flux decreases slightly.

At the hot side of MD, with increased flow rate, temperature polarisation and concentration polarisation effects will be decreased and higher membrane fluxes can be expected. Higher flow rate creates greater turbulence, which will lead to greater heat transfer.

At the cold side of MD, with the increase in flow rate, the turbulence will decrease the temperature polarisation effect. At the same time, with the increase of cold side flow rate, it may result in the vibration of flexible PVDF hollow fibre membrane, which will also reduce the temperature polarisation greatly. The vibration process results in a cross flow and parallel flow in the cold side. As for cross flow, pure water flows perpendicular to the axis of the hollow fibres to ensure a high heat transfer coefficient at a low Reynolds number. It is known that cross flow can enhance mass transport coefficients by a few times at quite low Reynolds numbers compared to parallel [18]. However, when cold side flow rate exceeds 100 L/min, the membrane flux will be decreased. This is due to increased air pressure in the pores of the membrane, which increases the resistance to vapour transport. The significance of these results implies that flux of DCMD processes can be optimized by adjusting the flow rate of the two sides.

4.4. CF variation of the fluids in R_1 and R_3

A range of experiments for the CPT were performed using different hot side flow rates and makeup water flow rates to assess the influence of concentration factors of R_1 and R_3 cycles (K_1 and K_2) on the CPT process. The following results are obtained: K_1 and K_2 stood directly related to the makeup water and pure water production. Under the experimental conditions, when the cold side water flow rate and R_3 cycle water flow rate are certain, K_1 and K_2 will increase with increase in hot side temperature and flow rate and decrease in makeup water. The K_1 and K_2 relationship meets the requirement for Eq. (9). Fig. 5 shows the relationship between γ and K_1 and K_2 values.

For example, if $\gamma = 0.7$, the final concentration factors are $K_2 = 4$ and $K_1 = 1.45$ (K_1 may be calculated through Eq. (9)). If the industrial tap water of R_1 cycle runs with this CF, anti-scaling is not necessary. Though the K_2 value reaches 4, the requirement for scale inhibition and corrosion inhibition is lower than R_1 cycle because industrial condenser in R_1 cycle is vital industrial equipment, but the materials of technologic condenser in R_3 cycle are anticorrosive materials such as stainless steel, engineering plastic, and so on.

4.5. The advantages of CPT

The DCMD process and traditional RCW system were combined in the CPT and waste heat was utilized as energy for pure water production by DCMD technology. So the CPT has many advantages compared to tradition RCW system.

Fig. 4. Transmembrane flux vs. hot side and cold side flow rate. Line, the flow rate of the hot side fluid was changed and Q_{21} and Q_{31} were fixed at the valve of 50 L/min. $T_{11} = 50$ °C. Curve, membrane flux vs. cold side pure water flow rate, the flow rate of the pure water was changed and Q_{11} was fixed at the valve of 40 L/min, Q_{31} was fixed at the valve of 50 L/min. $T_{11} = 50$ °C.

Fig. 5. The CF of R_3 cycle K_2 variation with apparent MD efficiency γ and the CF of R_1 cycle K_1 .

- Utilization of the industrial waste heat for pure water production by MD in CPT process will lower O&M costs and capital costs. Many studies have shown that the main problem impeding the application of MD technology is the heat energy needed to maintain the hot side temperature of MD process. In the CPT process, the utilization of waste heat reduces the energy costs significantly and results in lower O&M costs compared to traditional pure water production process, such as RO processes [19]. The hardware costs and total fixed costs for MD are much lower than those for RO due to the fact that no high-pressure pumps are required. The membrane cleaning costs are lower for MD than those for RO due to the low-pressure-operation of MD. Overall, the total water production costs for the MD process can be much lower than that for RO process.
- Requirements for the scale inhibition and corrosion inhibition were reduced in the CPT. CF of the traditional RCW is in the range of 3–5, but in the CPT process, the CF of R_1 cycle water is usually below 2.0 and the requirement for scale inhibition is reduced. By calculation, take $\gamma = 1$ for example, as for the CPT process, in order to control the final CF of blowdown to above 5.0, the requirement of CF of R_1 cycle is only 1.8. Although scale inhibition of R_3 cycle is still required, the requirement for the scale inhibition is much lower when compared to traditional RCW process. This is due to the following two facts. First, the water of the R_3 cycle has the lowest temperature in the circulatory systems of CPT, so, it can reduce the scaling trend of water. Second, the aim of R_3 cycle is cooling the pure water in the anticorrosive heat exchanger, rather than cooling industrial equipments which have high requirement for scale inhibition and corrosion inhibition. Therefore, a more simple method will be enough to meet the requirement of scale inhibition and corrosion inhibition.

- In many industrial water treatment fields, the industrial tap water quantity for the pure water production is more than the makeup water of the RCW system. If the industrial tap water was only used as makeup water of CPT process for pure water production, then, total makeup water, blow-down and evaporation losses will be reduced and higher water utilization efficiency can be obtained.

The comparison of water savings and costs of CPT process with that of the present pure water production and RCW system is shown in Table 4. In this table, a pure water production and RCW system with RCW quantity of 3000 m³/h, wet bulb temperature of 28 °C, T_{11} of 58 °C, T_{12} of 33 °C in a chemical plant in Shandong Province, China is given as an example. In this plant, “UF + RO” process with a water recovery rate of 70% was presently employed for 50 m³/h pure water production.

5. Conclusions

A CPT was established by integration of DCMD and RCW system for simultaneous cooling and pure water production. The new technology is a manoeuvrable, cleaner technology using waste heat for pure water production, which reduces the makeup water, blowdown and evaporation losses of the system.

A hollow fibre PVDF membrane module having a membrane area of 2 m² was experimentally investigated for pure water production of CPT with tap water. Temperature difference and flow rate of both sides in MD module have significant influence on membrane flux. A linear relation was

Table 4

The comparison of water savings and costs of CPT process with that of the present 50 m³/h pure water production and RCW system

	CPT process		Present pure water production and RCW system	
	DCMD	RCW system	UF + RO	RCW
system				
Pure water production, m ³ /h	50	—	50	—
Pure water quality, $\mu\text{S}/\text{cm}$	<5	18–25	—	—
RCW, m ³ /h	—	3000	—	3000
Concentration factor	1.4 (K_1)	4.2 (K_2)	—	2.5
Makeup water, m ³ /h	—	180	75	174
Blowdown, m ³ /h	—	42	22	65
Evaporation loss, m ³ /h	—	84	—	105
Total investment, ^a US\$	280,000	—	320,000	—
O&M cost, ^b US\$/m ³ pure water	0.139	—	0.504	—

^a Total investment is the summation of installation cost and equipments' investment. The equipments' investment includes membranes/membrane modules, heat exchangers, pumps, water tanks, measurement equipments, security and control system and others.

^b The O&M cost includes the cost of electricity, chemicals and labors. (1) Electricity price is US\$ 0.067/kWh. (2) The lifetime of facility and membranes is 15 and 3 years, respectively. (3) Labor price is US\$ 400/month/person.

obtained between flux and temperature difference. Membrane flux increases linearly with the increase in feed flow in the flow rate range of 12–78 L/min. Increasing hot side flow rate improved membrane flux and the flux increases by 40.8% with an increase in hot side flow rate from 12 to 30 L/min. Increasing of cold side flow rate also increases the flux and the flux increases by 22.4% with an increase in cold side flow rate from 20 to 100 L/min at $T_{11} = 50\text{ }^{\circ}\text{C}$ and $Q_{11} = 40\text{ L/min}$. When the cold side flow rate exceeds 100 L/min, the flux decreases slightly. When the cold side flow rate and R_3 cycle water flow rate are certain, K_1 and K_2 values will increase with increase in hot side temperature and flow rate and decrease in makeup water. The K_1 and K_2 relationship fits well to the equation: $K_1 = ((1 + \gamma)/(K_2 + \gamma))K_2$.

This CPT study shows that producing pure water from waste heat using DCMD integrated with an RCW system is a promising technology for future application. Nevertheless, more efforts should be towards the developing of the CPT. Areas for further study include:

1. Exploring the application field of the CPT. Looking into different system arrangements, possible integration with waste heat from industrial production sectors, such as power station and different chemical plants.
2. Experimental investigations considering rigorous testing with respect to water quality especially for the different industrial production sectors.
3. Exploring new module designs for optimized output, including membranes with higher membrane flux, membrane module configurations, heat recovery system, and cascade design of membrane modules.
4. Longer term tests are required to quantify the amount of membrane fouling. Larger-scale studies and detailed economic analysis.

Acknowledgments

Financial support provided by the National Natural Science Foundation of China (under Grant No. 50678169) and the National Science and Technology Support Program of China (under Grant No. 2006BAJ08B05) is gratefully acknowledged.

References

- [1] Lens P, Hulshoff PL, Wilderer P, Asano T. Water recycling and resource recovery in industry: analysis, technologies and implementation. UK: IWA Publishing; 2002.
- [2] El-Zanati E, El-Khatib KM. Integrated membrane-based desalination system. *Desalination* 2007;205:15–25.
- [3] Gryta M, Tomaszewska M, Karakulski K. Wastewater treatment by membrane distillation. *Desalination* 2006;198:67–73.
- [4] El-Bourawi MS, Ding Z, Ma R, Khayet M. A framework for better understanding membrane distillation separation process. *J Membr Sci* 2006;285:4–29.
- [5] Lawson KW, Lloyd DR. Membrane distillation. *J Membr Sci* 1997;124:1–25.
- [6] Cassano A, Conidi C, Timponi R, D'Avella M, Drioli E. A membrane-based process for the clarification and the concentration of the cactus pear juice. *J Food Eng* 2007;80:914–21.
- [7] Gilron J, Song L, Sirkar KK. Design for cascade of crossflow direct contact membrane distillation. *Ind Eng Chem Res* 2007;46:2324–34.
- [8] Curcio E, Drioli E. Membrane distillation and related operations – a review. *Sep Purif Rev* 2005;34:35–86.
- [9] Martinez L, Rodriguez-Maroto JM. Effects of membrane and module design improvements on flux in direct contact membrane distillation. *Desalination* 2007;205:97–103.
- [10] Li B, Sirkar KK. Novel membrane and device for direct contact membrane distillation-based desalination process. *Ind Eng Chem Res* 2004;43:5300–9.
- [11] Macedonio F, Curcio E, Drioli E. Integrated membrane systems for seawater desalination: energetic and exergetic analysis, economic evaluation, experimental study. *Desalination* 2007;203:260–76.
- [12] Ding Z, Liu L, Li Z, Ma R, Yang Z. Experimental study of ammonia removal from water by membrane distillation (MD): the comparison of three configurations. *J Membr Sci* 2006;286:93–103.
- [13] Hanemaaijer JH, Medevoort JV, Jansen AE, Dotremont C, Sonsbeek EV, Yuan T, et al. Memstill membrane distillation – a future desalination technology. *Desalination* 2006;199:175–6.
- [14] Gryta M. Long-term performance of membrane distillation process. *J Membr Sci* 2005;265:153–9.
- [15] Martinez L, Florido-Diaz FJ. Theoretical and experimental studies on desalination using membrane distillation. *Desalination* 2001;139:373–8.
- [16] Criscuolo A, Carnevale MC, Drioli E. Evaluation of energy requirements in membrane distillation. *Chem Eng Process* 2007; doi:10.1016/j.cep.2007.03.006.
- [17] Qureshi BA, Zubair SM. Prediction of evaporation losses in wet cooling towers. *Heat Transfer Eng* 2006;27:86–92.
- [18] Song L, Li B, Sirkar KK, Gilron J. Direct contact membrane distillation-based desalination: novel membranes, devices, larger-scale studies, and a model. *Ind Eng Chem Res* 2007;46:2307–23.
- [19] Meindersma GW, Gijjt CM, Haan AB. Desalination and water recycling by air gap membrane distillation. *Desalination* 2006;187:291–301.