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A humidification–dehumidification process for produced water purification

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ABSTRACT

Deployment of humidification–dehumidification process for produced water purification was investigated in this study. The produced water from natural gas production has a total dissolved solid of 1.98×10^4 mg/L and total organic carbon of 470.2 mg/L. The water purification was carried out in a lab-constructed humidification–dehumidification unit with an effective surface area of 1.2 m^2. The feed water temperature and flow rate were varied to investigate their influence on purified water quality, productivity, and water recovery. Both salt and dissolvable organics in the produced water were removed efficiently by the humidification–dehumidification process: the total dissolved solid was reduced from 1.98×10^4 to 76.75 mg/L while the total organic carbon declined from 470.2 to 17.83 mg/L. A built-in capillary bundle was deployed as dehumidifier for the enhancement of water productivity and heat efficiency. A water productivity of 0.31 kg/m^2.h with water recovery of 20.7% was achieved at 80°C. The study suggested that both salt and dissolvable organics could be removed by a humidification–dehumidification process. The purified produced water is suitable for beneficial uses, such as agriculture irrigation and industry processing.

Keywords: Produced water; Purification; Humidification-dehumidification; Desalination; Organics removal

1. Introduction

Produced water is the primary waste stream of oil, natural gas and coal bed methane production, containing large variation of contaminants, such as floating oil, particulates and dissolved salt and organics (i.e., fatty acid and phenol). Currently, over 90% of produced waters are treated by deep-well injection which is expensive and helds potential to contaminate groundwater system [1]. The increased regulatory restrictions and economical burden posed by produced water purification have shortened the lifetime of producing wells, particularly the high water-cut marginal wells in remote regions. On the other hand, many oil/gas production communities have reached the limits of their available water supplies. Reclamation of produced water could be a valuable asset for agricultural and industrial applications, which typically requires deployment of advanced technologies for purifying produced water to substantial quality.

Conventionally, produced waters are treated by oil/water separation or filtration process which can only remove the floating particulates and large oil droplets [2,3]. Advanced demineralization technologies must be deployed to remove salt and dissolvable organics for attaining surface water discharge standards or reuse criteria [4]. Unfortunately, most of desalination technologies are inefficient for produced water desalination because of the large variety in the source of contaminants. The presence of free oil and organic hydrocarbons is believed to be the main challenging factor limiting the deployment

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of membrane technologies, such as reverse osmosis and electrodialysis [5]. Other technologies such as multistage flash desalination (MSF), multiple-effect evaporation with thermal vapor compression (MEE–TVC) and mechanical vapor compression (MVC) are energy intensive and need sophisticated operating equipment, restricting their deployment in produced water purification [6].

Humidification–dehumidification is a heat-based desalination process involving enhanced water evaporation in the presence of flowing air and water condensation upon subsequent cooling or capillary condensation. The typical characteristics of the humidification–dehumidification process include flexibility in capacity, atmospheric pressure operation, and use of low-temperature energy such as solar energy, co-produced geothermal energy, and waste heat from industries. Such water desalination process is based on the fact that air can carry large amount of water vapor at elevated temperatures. For example, by increasing the temperature from 30 to 80°C, 1 kg air can carry 0.52 kg water vapor; about 500 g clean water could be collected upon subsequent cooling [7]. Taking into consideration the general humidification and dehumidification process for producing 1.0 kg clean water, the energy consumption of water heating, evaporation, and air blowing are 209 kJ, 2260 kJ and 8 kJ respectively, wherein over 90% of energy consumption is for the phase conversion. To overcome the high energy consumption during the phase conversion process, latent heat released by the dehumidification process could be deployed for feed water preheating [7]. A limitation of the referenced desalination process is low water recovery and high sensitivity to heat loss [8]. Recently, Beckman and coworkers reported a new humidification–dehumidification process named dewvaporation for enhancement in latent heat recovery and improvement in energy efficiency [9]. In the dewvaporation process, humidification and dehumidification occur continuously in two chambers with an internal liquid heat exchanger on the evaporation side. High ion removal efficiency was reported from 42,000 to 500 mg/L on a dewvaporation tower with a surface area of 7.9 m^2. More recently, a similar process named AltelaRain™ technology has been deployed by Altela, Inc. for produced water purification [10]. Water was evaporated in the presence of flowing air, forming humidified air. Purified water was then collected as the air was subsequently cooled.

As analyzed by Beckman and coworkers [11], the capital cost of dewvaporation ranges from \$264/m^3/d to \$2113/m^3/d depending on the scale of a plant. The operating cost ranges from \$0.13/m^3 to \$1.08/m^3 as a fuel or waste heat were deployed, respectively. Compared to the conventional RO process, the humidification–dehumidification process (HDP) shows great advantages for both initial capital investment and operating cost. Table 1 summarizes the economic data of these two technologies for a water treatment plant with a capacity of 1,000 m^3/d.

In this study, produced water purification by the humidification–dehumidification process was investigated on a lab-constructed separation system. Separation performance on both ion and dissolved organics was investigated at different operation conditions. Also, a built-in capillary condenser was deployed for enhancement of water productivity and improved heat efficiency.

2. Experimental

2.1. Air-enhanced humidification–dehumidification process

Similar to the conventional humidification–dehumidification process [8,9], the produced water purification in this experiment was carried out through three steps: (1) heating produced water to elevated temperatures; (2) water evaporation in a water–air contactor; and (3) clean water creation by condensation. Fig. 1 gives the schematic diagram of the produced water purification process. First, produced water samples were heated to elevated temperatures at 60, 70, or 80°C in a water bath (17 L, Polystat®). Further, the heated produced water was directed to a humidification–dehumidification chamber through a Masterflex® pump. The draining down water formed a thin water film which further contacted the up-flowing air stream, generating humidified air and concentrated wastewater. The up-flowing air was supplied by a centrifugal blower (Cole-Parmer). Subsequently, the resultant humidified air was directed to the condenser and exited to atmosphere through a gas/water separation unit. Both the feed and condensed water were collected in a time interval of 3 h and stored in a refrigerator at 5.0°C for chemical composition analysis. The temperatures of feeding water, concentrated water and purified water were monitored during the whole experimental process.

Table 1
Comparison of economic projection of HDP process with conventional RO process

Technology	Energy deployed	Unit capital cost, \$/m^3/d	Unit energy cost, \$/m^3	Unit chemical cost, \$/m^3	Water cost, \$/m^3	Reference
RO	Electricity	924	0.52	0.11	1.51	[6,12]
HDP	Natural gas	264	3.0	N/A	1.08	[11]
HDP	Waste heat	264	0.05	N/A	0.13	[11]

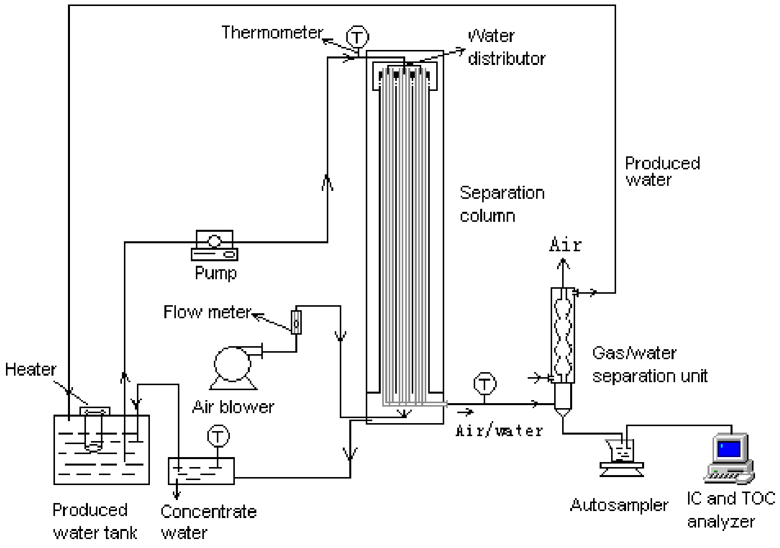

Fig. 1. Schematic diagram of air-enhanced humidification–dehumidification process for produced water desalination.

2.2. Separation column and built-in capillary bundles

The produced water desalination was first carried out in a column with shell and tubes described in the literature [13]. A tube bundle comprising 124 copper tubes with outside diameter of 6.35 mm and length of 1.8 m was embedded in a plastic column and deployed as humidifier and heat exchanger. The total heat exchange area was 4.5 m^2. The heated produced water was directed to the interior spaces of the copper tubes through 124 microbore tubes (ID = 0.25 mm). The draining down water formed a thin water film on the interior surface of the copper tubes and contacted the upward flowing air, generating humidified air. The humidified air was further directed to a chamber between the copper tube and the column. Clean water condensed on the external surface of the copper tubes was collected for chemical analysis.

To enhance the water productivity and heat efficiency, capillary tubing bundles were embedded in the copper tubes and functioned as built-in condensers. The capillary tubing used here had an inside diameter (ID) of 0.56 mm and outside diameter (OD) of 1.06 mm. Each copper tube contained three built-in capillary tubes, giving an overall heat exchange surface area of 1.2 m^2. Fig. 2 schematically shows the built-in capillary tubing bundle embedded in a copper casing.

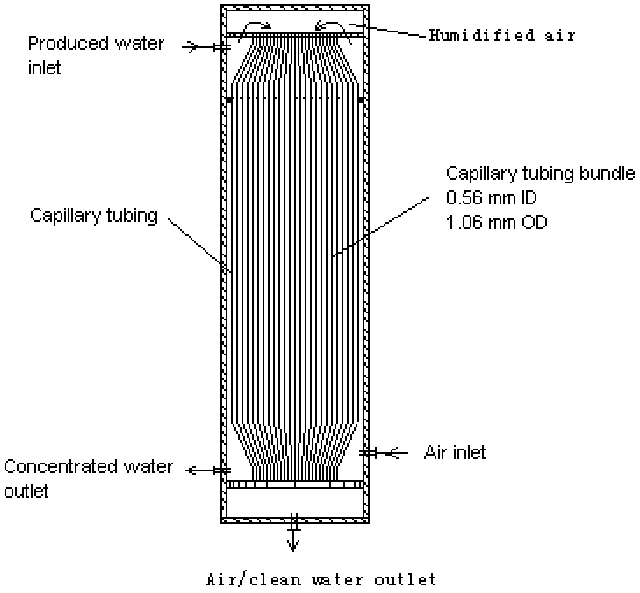

Fig. 2. Schematic diagram of built-in capillary bundle tubing for enhanced water.

As shown in Fig. 2, the feeding water formed a thin water film on the external surface of the built-in capillary tubing. The air was forced to flow in the interspacing of capillary tubing in a countermovement by a centrifugal air blower. The up-flowing dry air further contacted the water film generating humidified air stream. The humidified air was then directed to the interior cavities of capillary tubing and moved downward. In that process, water condensed inside the cavities of capillary tubing upon cooling and capillary condensation. The purified produced water was collected at the bottom air/water outlet port.

2.3. Produced water

A coal bed methane produced water sample was obtained from a local water disposal facility at Farmington of New Mexico. The original produced water contained a large number of suspended particulates, floating oil droplets and dissolved components. Coarse filtration with a 100-mm filter was first carried out. The purpose of coarse filtration is to remove the large particulates and oil droplets which can potentially block the microbore water distributor. The filtrate produced water with light yellow color had a high concentration of particulate suspension. A dynamic light scattering particle analyzer was deployed for the study of particle size distribution of the produced water. Fig. 3 gives the particle size distribution of the filtrated produced water.

The produced water had total dissolved solids (TDS) of 1.98×10^4 mg/L and total organic carbon (TOC) of 470.2 mg/L. Table 2 gives the chemical composition of dissolved components in the produced water and the total suspended particles.

2.4. Chemical analysis

Ion concentration of both feed and purified water samples was analyzed by an ion chromatograph (IC, DX-120, Dionex). A sterilizing filter (0.2 µm, Fisher) was deployed to remove any suspended particulates before the IC analysis. The water samples were diluted to desirable concentrations (~50 mg/L) and manually injected for cation and anion analysis. Concentrations of dissolved organics were represented by TOC and analyzed by a TOC analyzer (Shimadzu, TOC-V). Particle size distribution of the produced water was analyzed by a dynamic light scattering particle analyzer (Nanotrac NPA 150). Metal ions were analyzed by flame atomic absorption (Varian Model 110).

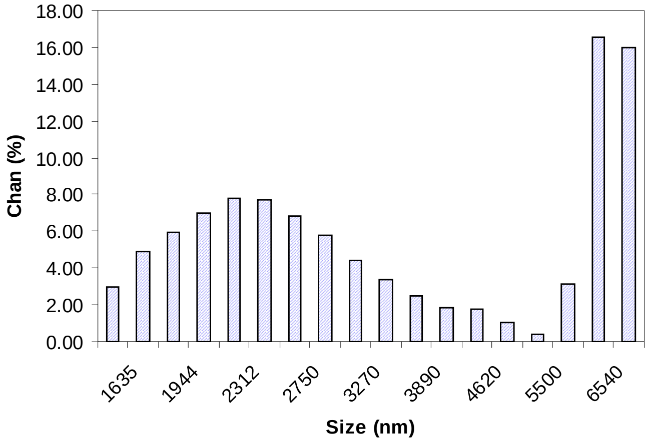

Fig. 3. Particle size distribution of suspensions in produced water.

3. Results and discussion

3.1. Water productivity

Water productivity of the humidification–dehumidification process was investigated with the two condensers: (1) copper tubing condenser and (2) built-in capillary bundles. The flow rate of carrying air was set at 1000 liter per hour (LPH). Produced water purification tests were first tested at a constant temperature of 80°C and varied feed water flow rate ranging from 10 to 30 ml/min. Each separation test was running for over 12 h until three consecutive water samples gave the same water productivity. It usually takes ~3.0 h to warm up the purification system and reach a stabilized operating condition. The water productivity is defined as the amount of water collected from a dehumidifier with the surface area of 1.0 m^2 in a unit time. Fig. 4 shows the water productivity and humidity at the top of the humidifier as a function of feed water flow rate.

The water humidity at the top of the copper tubing humidifier increased from 10.8% to 41% as the feed flow rate was increased from 10 ml/min to 30 ml/min, resulting in a monotonous increase in clean water productivity. The deployment of built-in capillary tubing bundle shows considerable enhancement in water evaporation and subsequent water productivity. The water humidity increased from 41% to 60.7%, resulting in higher water productivity upon subsequent cooling from 0.048 to 0.311 $kg/m^2.h$. We

Table 2
Chemical composition of CBM produced water in Farmington, NM

Ion species	Concentration, mg/L	Trace metal ions	Concentration, mg/L
Na^+	6765.7	Barium (Ba)	10.9
NH_4^+	350.0	Copper (Cu)	0.21
K^+	427.9	Iron (Fe)	0.27
Mg^{2+}	32.7	Lithium (Li)	4.7
Ca^{2+}	46.1	Silica (SiO_2)	11.7
Cl^-	10542.9	Strontium (Sr)	8.9
SO_4^{2-}	1590.7	Nickel (Ni)	0.16
Total dissolved solid (TDS), mg/L			19,792.8
Total suspended particulates, mg/L (0.22 mm < dia.< 100 mm)			99.6
Total organic carbon (TOC), mg/L			470.2

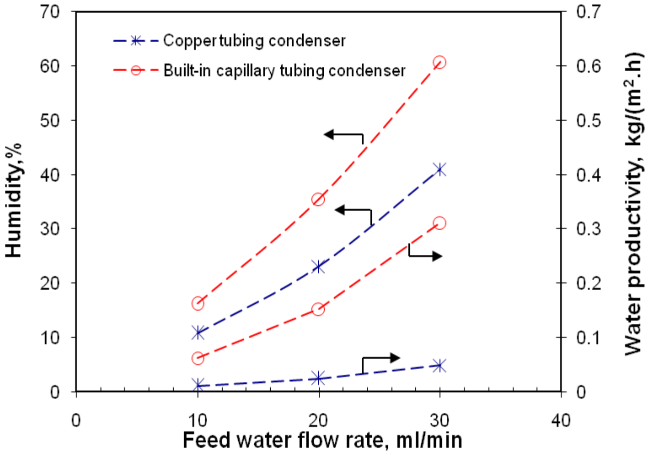

Fig. 4. Water productivity as a function of feed water flow rate for copper tubing and built-in capillary tubing condensers.

attributed such an improvement in water productivity to the fast heat transfer and enhanced energy efficiency. The condensation-released latent heat at the internal surface of capillary tubing will transport across the thin walls to the external surface and compensate the evaporation-provoked cooling effect. Apparently, a large air–water contact surface area and direct heat reuse will benefit the energy efficiency.

A few more experiments were carried out on the evaporator with built-in capillary tubing bundles. The feed water temperatures were varied from 60 to 80°C while the feed flow rate was increased from 10 to 30 ml/min. Figs. 5 and 6 show the water productivity and water recovery as a function of feed water temperature. Increasing feed water temperature and feed flow rate increases water humidity at the top of the humidifier, resulting in enhancement in water productivity [9]. It was observed that the water recovery increased with the increase of both feed water temperature and flow rate. Apparently, the unit energy consumption of produced water purification declines with the increase of operating temperature, suggesting the preferred operating conditions at high temperature and high water flow rate within the experimental range.

3.2. Heat efficiency

Fig. 7 schematically shows the mass flow and energy balance of the produced water purification unit. To quantify the energy input during the operating process, dehumidified air at 25°C was used as carrier gas. The feed water was heated to elevated temperature at 60 and 80°C. The gas and liquid exiting the system include: (1) concentrated wastewater, (2) purified clean water, (3) water vapor, and (4) air. Temperatures at each exiting port were recorded for energy efficiency analysis.

The water evaporation and condensation occurred

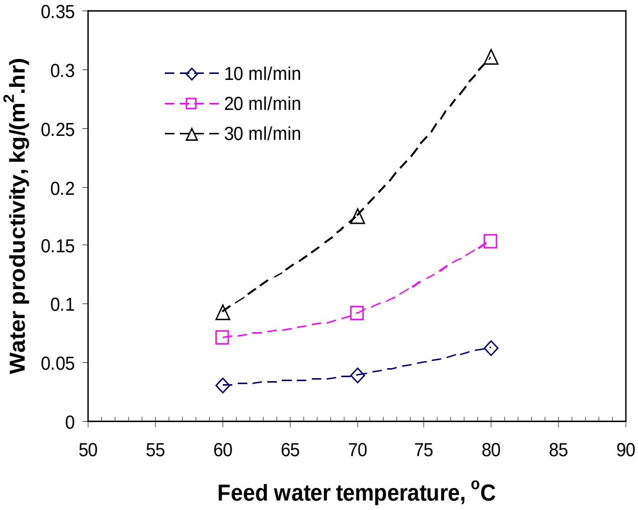

Fig. 5. Water productivity at varied feed water temperature.

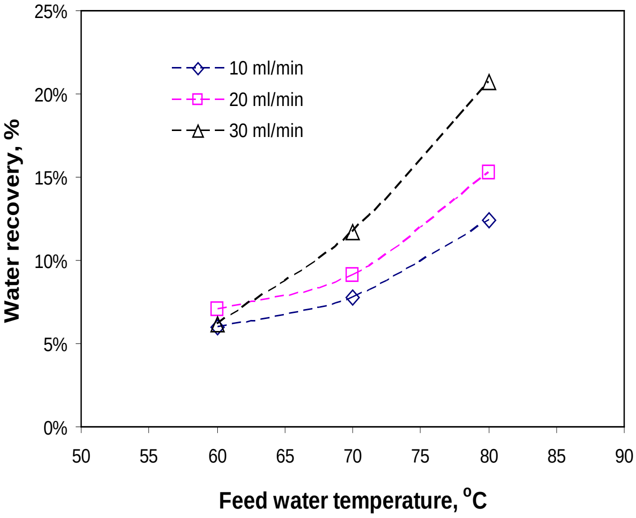

Fig. 6. Water recovery at varied feed water temperature.

inside the separation unit, resulting in a direct reuse of latent heat released by water condensation. The energy of the system was calculated by performing energy balance with the following equation:

$$\begin{aligned}&F_{w-feed}\cdot C_w\cdot\left(T_{w-in}-T_{w-ref}\right)+G_{air}\cdot C_{air}\left(T_{air-in}-T_{air-ref}\right)\\&=F_{w-conc}\cdot C_w\cdot\left(T_{w-conc}-T_{w-ref}\right)+F_{w-pure}\cdot C_w\left(T_{w-pure}-T_{w-ref}\right)\\&\quad+\left(F_{w-feed}-F_{w-conc}-F_{w-pure}\right)\cdot\lambda_w\cdot\left(T=T_{air-out}\right)\\&\quad+G_{air}\cdot C_{air}\left(T_{air-out}-T_{air-ref}\right)\\&\quad+Q_{loss}\end{aligned}\tag{1}$$

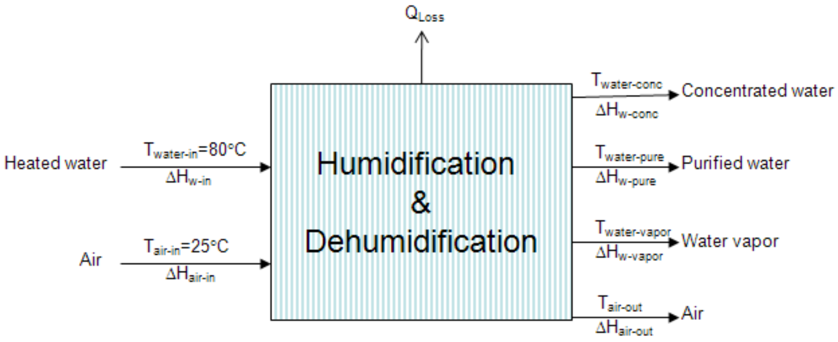

Fig. 7. Schematic diagram of mass flow and energy balance in produced water purification by a humidification–dehumidification process.

where F is the water flow rate, kg/min; G_{air} is the flow rate of carry air, LPH; C_w is specific heat capacity of water, 4.18 kJ/(kg.°C); C_{air} is specific heat capacity of air, 1.006 kJ/(kg.°C); T is temperature, °C; l is specific heat of vaporization of water, 2260 kJ/kg; Q_{loss} is defined as heat loss rate during the operation process, kJ/h. The $T_{w\text{-}ref}$ and $T_{air\text{-}ref}$ are the reference temperature of water and air respectively, both at 25°C in this study.

The heat balance was calculated from Eq. (1) and the results are summarized in Table 3.

The humidification–dehumidification operation results the formation of a temperature gradient along the separation unit: the top has the highest temperature while the bottom has the lowest temperature. The temperature gradient varies with the feed water temperature and feed flow rate. As shown in Table 3, in circumstances of low water flow rate or low operating temperature, the outlet temperatures are lower than those at the inlets because of the evaporation-provoked cooling effect. Increasing feed water temperature or feed flow rate increases the temperature of the whole system as well as outlet air and liquid. As a consequence, the heat loss caused by water evaporation and radiation will increase. Even though, the energy consumption for purifying unit produced water will decrease, resulting enhanced energy efficiency and water recovery.

3.3. Ion removal efficiency

Produced water desalination by humidification–dehumidification process was carried out at an air flow rate of 1000 LPH and water flow rate of 10 mL/min. The water temperatures were varied from 60 to 80°C. The purified water samples were collected at a time interval of 3 h. Each separation was running for over 12 h until three consecutive water samples showed identical water productivity. The ion removal efficiency is defined as ion concentration difference of the feed and purified water vs. feed ion concentration. Fig. 8 gives the individual ion removal efficiency of the produced water as a function of feed water temperature. The ion removal efficiency of NH_4^+ declined from 97.4% to 95.4% as water temperature increased from 60 to 80°C. In aqueous solution, ammonium ions exist at equilibrium with ammonia ($NH_3 + H_2O \leftrightarrow NH_4^+ + OH^-$). As an exothermic reaction, increasing temperature drives the reaction to the left side and forms free

Table 3
Energy balance of produced water desalination by the humidification–dehumidification process with different heat exchangers

No.	$F_{w\text{-}in}$, ml/min	$T_{w\text{-}in}$, °C	$T_{w\text{-}conc}$, °C	$T_{w\text{-}pure}$, °C	F_w, kg/m².h	Heat balance, kJ/h				
						$\Delta H_{w\text{-}conc}$	$\Delta H_{w\text{-}pure}$	$\Delta H_{air\text{-}out}$	$\Delta H_{w\text{-}vapor}$	Q_{loss}
Cu-1	10	60	19	22	0.006	–14.34	–0.35	–3.91	54.47	51.92
Cu-2	10	80	20.5	23	0.011	–10.38	–0.40	–2.60	58.16	93.17
Cu-3	20	80	29.5	33	0.025	20.50	3.69	10.42	106.59	134.68
Cu-4	30	80	35	39	0.049	66.09	12.82	18.23	151.63	165.06
Cp-1	10	60	23.8	22.7	0.030	–2.83	–0.35	–3.00	58.87	36.08
Cp-2	10	80	27.1	24.3	0.062	4.52	–0.25	–0.91	63.86	70.72
Cp-3	20	80	30.5	30	0.152	23.38	3.82	6.51	89.09	153.07
Cp-4	30	80	35.5	36	0.311	62.62	17.16	14.33	127.47	192.24

Cu-x: experiments on copper tubing condenser; Cp-x: experiments on capillary tubing condenser.

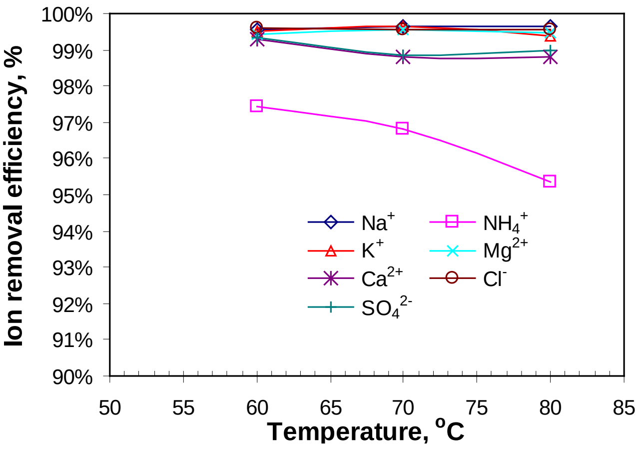

Fig. 8. Ion removal efficiency of individual ions in produced water at temperatures of 60°C, 70°C and 80°C, respectively.

ammonia molecules which will evaporate with air and condensate to the clean water upon subsequent cooling. All other ions showed >98% removal efficiency, resulting in a decline in total dissolved solids from 1.98×10^4 mg/L to 92.1 mg/L at 60°C.

The presence of ions in the purified produced water is explained by the mist formation during air-enhanced water evaporation process. Small water droplets will be carried with by the counter-flowing air stream and precipitate in the purified water upon cooling [9]. Increasing the feed water temperature increases the water partial pressure at the top of the humidifier while the mist formation is independent to water humidification. As a result, the ion concentration declines slightly with the increase in operating temperature, as shown in Fig. 9.

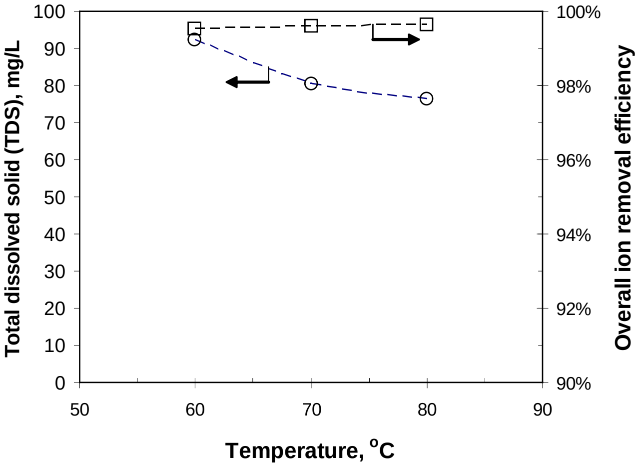

Fig. 9. Total dissolved solid in purified water and overall ion removal efficiency at different operating temperatures.

3.4. Organic removal efficiency

The presence of organics in produced water was quantified by the concentration of total organic carbon. The produced water sample treated by coarse filtration had TOC of 470.2 mg/L. Over 95% of organic carbon was removed by the humidification–dehumidification process with a decline of TOC from 470.2 mg/L to 21.5 to 17.8 mg/L at 60°C and 80°C, respectively. Fig. 10 gives the TOC of purified water and TOC removal efficiency at different operating temperatures.

The organic components in produced water typically contain fatty acid (~300 mg/L), polycyclic aromatic hydrocarbons (PAHs, ~5 mg/L), phenols (~10 mg/L), and volatiles such as benzene, toluene and xylene (BTX, ~8 mg/L) [3,14]. The organic composition varies over the lifetime of oil/gas production. Other factors such as temperature, production history, and type of produced water also show influence on organic composition in produced water. Generally, produced waters from gas field or CBM production have a higher concentration of volatile hydrocarbons than those in oilfield [1]. During the humidification process, organics will evaporate accompanying the water evaporation, forming organics-containing humidified air. Generally, the organics concentration in humidified air is far below the saturation, particularly for the volatile organics. The subsequent cooling for water condensation forms purified water while the organic vapor will exit to the atmosphere. All experiments show high organics removal efficiencies (>95%) with slightly variation at different operating conditions. For example, the organics removal efficiency increased from 95.4 to 96.2% as feed water temperature was increased from 60 to 80°C. The influence of feed water temperature on organics removal efficiency has the same trend as that on inorganic salts, which can be explained by the small water droplet formation in the presence of strong air flow.

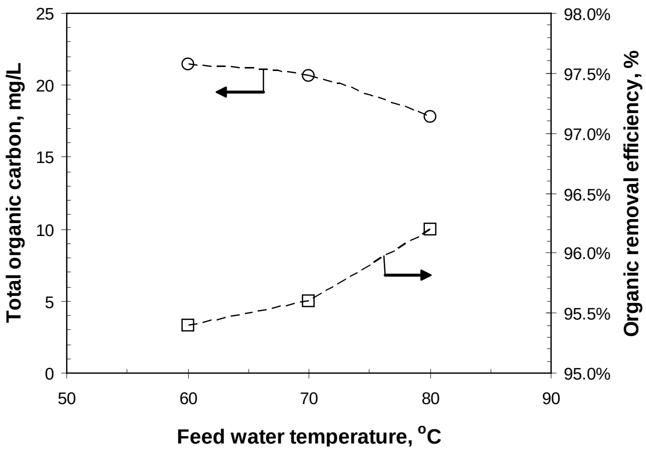

Fig. 10. Total organic carbon of purified waters and organic removal efficiency as a function of feed water temperature.

3.5. Water quality and beneficial use

Produced water contains large varieties of inorganic salts, heavy metals and organic contaminants. Direct disposal of produced water poses the potential for groundwater contamination and thus may not be discharged to groundwater system unless they are being purified to substantial quality [3]. Quantity and quality of purified produced water are the most important factors governing the beneficial uses when produced water is substituted for conventional water resource. Generally, beneficial use of produced water, such as irrigation, livestock watering, and power cooling, must satisfy all special considerations necessary for water quality requirement. Table 4 summarizes the general requirement of reclaimed water quality for the industry or agriculture applications.

Fig. 10 shows the produced water sample as received, filtrated, and purified by the humidification-dehumidification process. A large number of oil droplets and particulates was observed on the produced water as received. Coarse filtration with 100 μm Whatman® filter removed the oil droplets and large particulates, but left all dissolved components and fine particles with typical TDS of 19,792.8 mg/L and suspended particulates of 99.6 mg/L. The purification by the humidification–dehumidification removed majority of salts and organics. The detailed chemical composition of the purified water is shown in Table 5.

The purified produced water has the TDS of 76.35 mg/L and TOC of 17.83 mg/L. All trace metal ions in the purified water are below the detection limit. The purified produced water show much higher quality than the criteria for general irrigation, tower cooling and chemical processing.

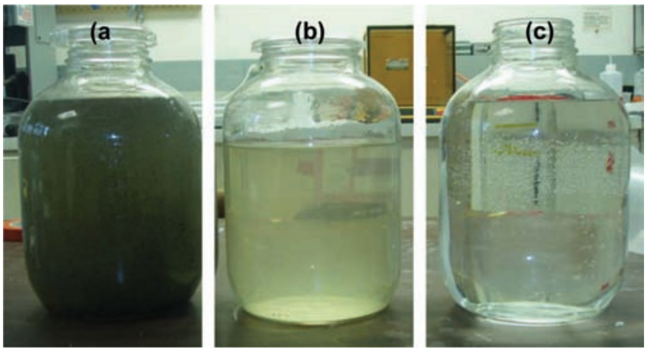

Fig. 10. Produced water and purified water samples. (a) produced water as received, (b) produced water with large particle and oil droplet removal (particle size >100 μm), (c) purified produced water.

Table 5
Chemical composition of purified produced water

Composition	Concentration, mg/L
Na^+	17.23
NH_4^+	13.95
K^+	5.08
Mg^{2+}	0.19
Ca^{2+}	0.51
Cl^-	29.07
SO_4^{2-}	10.3
Total dissolved solid (TDS), mg/L	76.35
Total organic carbon (TOC), mg/L	17.83

4. Conclusions

Humidification–dehumidification is an efficient desalination process for produced water purification. A bench scale experiment with coal bed methane produced water indicated that over 99.5% of dissolved salt can be removed with the total dissolved solid decline from 1.98×10^4 to 76.3 mg/L. The humidification–dehumidifica-

Table 4
Beneficial use of reclaimed produced water and quality requirements

Beneficial use	Water quality requirements					Main concerns
	TDS, mg/L	Hardness or trace elements	pH	Cl^-	Alkalinity	
Irrigation [15]	500–2000	Boron <0.75 Cu <0.2 Fe <5.0 Ni <0.2 Zn <2.0	6	NA	NA	Salinity, trace elements, chlorine residual, and nutrient
Cooling water [16]	<2700 (conductivity)	Hardness <450	6.5–7.5	350	280	Corrosion, biological growth, and scalling
Chemical process [16]	1000	Hardness <250 Fe <0.1 Mn <0.1	6.2–8.3	500	125	Low turbidity, suspended solids and silica

tion process also showed a remarkable organics removal efficiency by reducing the total organic carbon from 470.2 to 17.8 mg/L. The water productivity is insensitive to the feed water quality and chemical composition and thus is particularly useful for purification of concentrated- or particulate-enriched produced waters.

A built-in capillary tubing bundle was deployed as condenser for enhancement of water productivity and heat efficiency. The water productivity was increased from 48 to 311 ml/(m^2.h). The influence factors, such as feed water temperature and feed water/air ratio, on the water productivity were also investigated. Increasing feed water temperature or feed flow rate increases the heat loss, but the water productivity and recovery increase as a result of more efficient heat use.

The purified produced water has a higher quality than most of the requirements of agriculture and industry uses. Humidification–dehumidification shows promise for reclaiming produced water for beneficial uses such as irrigation, tower cooling and chemical processing.

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References

[1] J.A. Veil, M.G. Puder, D. Elcock and R.J. Redweik, A White Paper Describing Produced Water from Production of Crude Oil, Natural Gas, and Coal Bed Methane, ANL report under DOE (NETL), Contract W-31-109-Eng-38, 2004.

[2] A. Zaidi, K. Simms and S. Kok, The use of micro/ultrafiltration for the removal of oil and suspended solids from oilfield brines, Wat. Sci. Technol., 25 (1992) 163–176.

[3] S. Santos and M.R. Wiesner, Ultrafiltration of water generated in oil and gas production, Wat. Environ. Res., 69 (1997) 1120–1127.

[4] L. Dallbauman and T. Sirivedhin, Reclamation of produced water for beneficial use, Separ. Sci. Technol., 40 (2005) 185–200.

[5] C. Visvanathan, P. Svenstrup and P. Arlyamethee, Volume reduction of produced water generated from natural gas production process using membrane technology, Wat. Sci. Technol., 41 (2000) 117–123.

[6] H.M. Ettouney, H.T. El-Dessouky, R.S. Faibish and P.J. Gowin, Evaluating the economics of desalination, Chem. Eng. Progress, 12 (2002) 32–39.

[7] K. Bourouni, M.T. Chaibi and L. Tadrist, Water desalination by humidification and dehumidification of air: State of the art, Desalination, 137 (2001) 167–176.

[8] S. Parekh, M.M. Farid, J.R. Selman and S. Al-Hallaj, Solar desalination with a humidification–dehumidification technique — A comprehensive technical review, Desalination, 160 (2004) 167–186.

[9] B.M. Hamieh and J.R. Beckman, Seawater desalination using dewvaporation technique: Theoretical development and design evolution, Desalination, 195 (2006) 1–13.

[10] M.J. Bruff, AltelaRain produced water treatment technology, International Petro. Environment Conference, San Antonio, Texas, October 17–20, 2006.

[11] J.R. Beckman, Dewvaporation Desalination 5000-gallon-per-day Pilot Plant, Desalination and Water Purification Research and Development Program, Report No. 120, US Department of the Interior, 2008.

[12] R. Matz and U. Fisher, A comparison of the relative economics of sea water desalination by vapour compression and reverse osmosis for small to medium capacity plants, Desalination, 36 (1981) 137–151.

[13] R.H. Xiong, S.C. Wang, L.X. Xie. Z. Wang and P. Li, Experimental investigation of a baffled shell and tube desalination column using the humidification–dehumidification process, Desalination, 180 (2005) 253–261.

[14] B.R. Hansen and S.R.H. Davies, Review of potential technologies for the removal of dissolved components from produced water, Trans. IChE, 72 (1994) 176–188.

[15] D.R. Rowe and M.I. Abdel Magid, Handbook of Wastewater Reclamation and Reuse, Lewis Publishers, 1995.

[16] EPA/625/R-04/108, Guidelines for Water Reuse, US Environmental Protection Agency, 2004.