Performance study of a pilot-scale low-temperature multi-effect desalination plant

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HIGHLIGHTS

- The performance of a 30 t/d LT-MED system is studied.
- We obtain a high heat transfer coefficient and a steady operation condition.
- The spray density of 240–300 L/(m h) should be adopted in actual design and operation.
- Vacuum pumping in the series mode had more advantages.

ABSTRACT

A 30 t/d low-temperature multi-effect evaporation seawater desalination (LT-MED) system was designed based on the mathematical model, and the corresponding pilot device was constructed in Tianjin, China. Whole-process tests were carried out, and the effects of key operating parameters, including motive steam pressure, maximum operating temperature, temperature difference, spray density, non-condensing gas extraction method, and steam ejector flow, on desalination performance were analyzed. Results showed that the device successfully met product water design requirements; total dissolved solids were less than 5 mg/L. Water production initially increased as motive steam pressure increased, then stabilized when pressure exceeded 21% of the design value. Water production reached its maximum when heat transfer temperature difference and spray density ranged from 3 °C to 4 °C and from 240 L/(m h) to 300 L/(m h), respectively. Unlike in parallel mode, water production increased by 3.64% when vacuum pumping was operated in series mode. Water production and gain output ratio increased, and system energy consumption reduced when a thermo-vapor compressor was introduced. The results provide a useful reference for the design of other large-scale seawater desalination systems.

1. Introduction

The demand for freshwater is increasing dramatically with the rapid growth of the global population and the general improvement of living standards. Limited freshwater resources obtained from surface water and groundwater are wasted in many regions. As a result, freshwater shortage has become a critical problem that limits long-term social and economic development [1]. Fortunately, freshwater can be obtained from seawater through desalination. China has a vast marine area with more than 150 coastal cities. Moreover, nearly 6500 islands, area larger than 500 m², are found in the Bohai Sea, Yellow Sea, East Sea, and South Sea. Therefore, seawater desalination is an important approach to solve freshwater shortage in coastal areas.

Different desalination methods have been developed during the past decades, such as RO and thermal processes (e.g., MSF and MVC). However, these conventional methods usually have high initial cost, operation cost, and energy consumption. Low-temperature multi-effect desalination (MED) has been developed many years ago [2]. A thermo-vapor compressor (TVC) is added to a typical MED system to reduce steam requirement (motive steam), boiler size, and cooling water; the TVC lowers power consumption and pre-treatment costs [3]. This method reaches a relatively high heat transfer coefficient because of phase changes in the heat exchanger and liquid in the tube wall film flow, thereby reducing the required heat transfer area [4–7]. At the same time, multiple-effect falling film evaporation on horizontal tubes is effective because of the small heat transfer temperature difference. Therefore, low energy consumption is reached, and low-temperature waste heat is fully utilized [8–9]. MED–TVC with a top brine...
temperature (TBT) lower than 70 °C is presently the subject of increased attention [10–12].

Several studies have recently focused on modeling and single optimization of MED–TVC systems. Bin Amer [13] optimized MED–TVC by using smart exhaustive search and sequential quadratic programming. Bin Amer [13] applied an approach that maximized the gain output ratio (GOR) of MED–TVC. Kamali et al. [11], El-Dessouky et al. [14], Zhao et al. [15], Alasfour et al. [10], and Al-Salahi and Ettouney [16] developed steady-state mathematical models to represent MED–TVC and used parametric techniques to determine the optimum operating and design conditions of the system. Sayyaadi et al. [17] performed thermodynamic and thermo-economic optimization of MED–TVC by using a hybrid stochastic/deterministic optimization approach. All the mentioned papers focused on single optimization; few theoretical and mathematical studies focused on the MED–TVC. Shakouri et al. [12], Lukic et al. [18], Choi et al. [19], Ansari et al. [20], and Sharaf et al. [21] developed mathematical and economic models for MED–TVC and performed exergy analysis. Shakouri et al. [12] optimized MED–TVC based on minimizing unit product cost. Piacentino and Cardona [22] analyzed the MED desalination process by using the thermo-economic approach and investigated the possibility of optimizing the six effects of MED as a case study. Sayyaadi and Saffari [23] thermoeconomically optimized a MED desalination system with TVC. Ameri et al. [24] presented a conceptual design for a four-effect MED system with TVC with the objective of using waste heat from a gas turbine power plant to produce potable water. The results showed that TBT has a minor effect on GOR, and the heat transfer surface significantly decreases as TBT increases. Aybar [25] presented the results of using waste heat from a North Cyprus steam power plant to produce make-up water for boilers. System production capacity increases because of the decreasing temperature difference between hot and cold side effects. El-Dessouky et al. [26] compared different configurations for MED systems. Two operating modes, namely, parallel and parallel/cross flow systems, were considered in the analysis. The parallel/cross feed MED system performed the best. However, the parallel flow system has similar performance characteristics, and its design, construction, and operation are simpler than that of the parallel/cross feed MED system. The effects of heating steam temperature and seawater salinity on GOR, specific heat transfer area, specific cooling water flow rate, and conversion ratio were also presented. El-Dessouky et al. concluded that specific heat transfer surface and GOR decrease with increasing heating steam temperature. Therefore, optimizations based on these parameters should be performed for various applications. Ashour [27] presented that GOR increases when the first effect temperature increases; this increase was mainly caused by the decrease in the required sensitive heat to warm the feedwater to saturation temperature.

Few studies focused on seawater desalination pilot tests. Most studies only focused on single-tube evaporation, atmospheric evaporation, or working fluid desalination, which is different from distillation. Consequently, the results proved unconvincing and difficult to use to guide the actual design and optimization of MED systems.

In this work, a 30 t/d low-temperature multi-effect evaporation seawater desalination system was designed based on a mathematical model, and the corresponding pilot device was constructed in Tianjin, China. Whole-process tests were carried out, and the effects of key operating parameters, including motive steam, maximum operating temperature, temperature difference, spray density, non-condensing gas extraction method, and steam ejector flow, on desalination performance were analyzed. The results are expected to provide a useful reference for the design of large-scale seawater desalination systems.

2. System design model

(1) The pilot test material balance flow is shown in Fig. 1.

Previous publications presented design procedures and mathematical models for different MED systems [24,26,28]. Mass and
(2) The mathematical definition of material and energy balance for each effect is given as follows:

\[ \Delta G_i = G_i - G_{i-1} \]

\[ (G_{i-1} - G_{i-2}) \times C_{i-1} = (G_i - G_{i-1}) \times C_i \]

(3) The mathematical definition of energy balance for freshwater flashing in each effect is given as follows:

\[ d_i \cdot \dot{\lambda}_i = \sum D_{i-1} \times \left[ \dot{c}_{p,i+1} \cdot (T_{i+1} - T_i) - \dot{c}_{p,i} \cdot (T_i + \Delta\text{NEA}_i) \right] \]

(4) The mathematical definition of energy balance for brine flashing in each effect is given as follows:

\[ g_i \cdot \dot{\lambda}^*_{i+1} = G_{i+1} \times \left[ \dot{c}_{p,i+1} \cdot \dot{\lambda}^*_{i+1} \cdot (T_i + \Delta\text{NEA}_i) \right] \]

(5) The heat transfer equation of each effect is shown as follows:

\[ Q_i = K_H \cdot A_H \cdot \text{LMTD}_i + K_2 \cdot A_2 \cdot (T_c - t_i) \]

(6) The rise in boiling point and temperature difference loss are defined as follows:

\[ T_i = t_i - BPE_i \]

\[ T_{ci} = T_i - \Delta T_i \]

(7) The GOR equation is given as follows:

\[ \text{GOR} = \sum D_i / D_0 \]

(8) Device thermal losses are calculated as follows:

\[ Q_a = q \times F \]

\[ q = a_{rec} \cdot (t_i - t_p) \times K_{12} \]

(9) TVC ejection ratio can be calculated as follows:

\[ \mu = \sum D_{hi} / D_0 \]

TVC ejection ratio represents the performance of second steam reuse, and the high ejection ratio, the large GOR.

3. MED pilot device

An MED pilot device was designed and constructed by the Institute of Seawater Desalination and Multipurpose Utilization based on the above mathematical model. The pilot was located at the Datang Lubei power plant in Tianjin, China. Fig. 2 shows a simplified schematic of the device. The device consists of three-effect evaporators, condenser, steam ejector, pumps, vacuum pumps, connecting pipes, valves, and electronic control instrumentation. Raw water was obtained from the cooling seawater of the power plant, with a temperature of 20–28 °C. The device successfully ran for more than two years since it began operating in October 2011. The device produces freshwater at an average rate of 30 t/day. Fig. 3 shows the experimental pilot device.

The test aimed to simulate operating conditions of large-scale, low-temperature, multi-effect distillation desalination devices. Another objective was to study the effects of key technical parameters and operating factors on device performance under large operating parameters. First, the device was initiated in cold-state operating mode when motive steam passed. The running parameters (i.e., evaporating pressure, operating temperature, heating transfer temperature difference, and spray density) were then gradually adjusted to a specified value. Second, the automatic operation mode was selected, and the system reached a steady state.
state after two hours of operation. Finally, the influencing parameters were tested. The pneumatic valve, electric valve, and transducer were accurately adjusted to alter the experimental parameters [i.e., temperature difference, spray density, vacuum pumping mode, and TVC (steam ejector)] by using the host computer system.

We used measuring parameters, including temperature, pressure, flow rate, fluid level, online conductivity, and pH. Sensors on the device body and pipes tested the temperature and pressure. Pipe-installed electromagnetic flow meters measured the flow rate of seawater, concentrated water, and product water. Motive steam temperature and pressure fluctuations affected the measurement accuracy of the steam flow rate. In our experiment, the Orifice plate flowmeter is used to measure steam flow rate with temperature and pressure compensation to ensure a measurement error of less than ±0.1%. Product water quality was monitored by using an online conductivity meter and a pH meter installed on the product pump outlet. The host computer records and stores all in situ operation data automatically.

4. Experimental results and discussion

4.1. Whole-process test results

The whole-process test included two procedures: cold-state test and hot-state test. The difference between the cold-state test and the hot-state test was based on the motive steam injected into the system. Cold-state tests were generally conducted first; hot-state tests were initiated when the regulated technical requirements were met. Adjusting vapor pressure, operating temperature, heat transfer temperature difference, and spray density to the corresponding design values enabled the main devices (i.e., vacuum pump, steam ejector, circulating pump, cooling water pump, brine pump, and product pump) to meet the technical requirements and remain stable for 168 h at a full operation load.

Figs. 4 and 5 show the variation of the specific conductance and temperature of raw water and the specific conductance of product water during stable operation, respectively. The specific conductance of raw water was within the range of 37,900–44,650 l/cm, while the specific conductance of product water gradually decreased and was maintained at 7.5 l/cm. Therefore, the present pilot test has a strong adaptive capacity to raw water and obtains good product water quality.

The analysis results of product water samples provided by the National Quality Supervision and Inspection Center for Seawater and Brackish Water Utilization Products indicate that the product water meets the national drinking water criterion. The total dissolved solids are less than the design valve of 5 mg/L [33], as shown in Table 1.

4.2. Variations of motive steam flow with pressure

The motive steam used in the pilot test was the industrial steam from the power plant; vapor pressure and flow can be adjusted by using valves. Fig. 6 shows the variation of motive steam flow with its pressure. The steam flow trendline shows that motive steam flow increases linearly on average with its pressure. Although the pressure and flow can be adjusted by using valves, they cannot be regulated individually.

4.3. Effects of motive steam pressure P1 on water production and GOR

Figs. 7 and 8 show the effects of motive steam pressure on water production and GOR, respectively. The experimental operating...
temperature was $T_0 = 72 \, ^\circ C$, temperature difference was $\Delta t = 6 \, ^\circ C$, and total spray density was $\Gamma = 300 \, L/(m \cdot h)$.

Water production increased along with increased motive steam pressure, as shown in Fig. 7. The motive steam pressure stabilized when steam pressure continued to increase and exceeded 0.95 MPa (i.e., 121% of the designed value).

The trend of GOR with motive steam pressure was similar to that of the TVC ejection ratio with the motive steam pressure (Fig. 8). However, the TVC ejection ratio and GOR exhibited a slight downward trend when the motive steam pressure exceeded the design value. This downward trend was due to the fact that the motive steam pressure increased beyond its optimum operating conditions, which do not match the TVC design parameters.

4.4. Effect of maximum operating temperature $T_0$ on water production and GOR

The maximum operating temperature for low-temperature MED is usually less than 70 $^\circ C$. This temperature is expected to increase with the development of anti-scaling and heat transfer technologies. Experiments on water production variation laws were performed at a higher operating temperature (above 70 $^\circ C$) to investigate the effects of maximum operating temperature on water production and GOR. The experimental conditions were as follows: $P_1 = 0.85 \, MPa$, $\Gamma = 300 \, L/(m \cdot h)$, and $\Delta t = 6 \, ^\circ C$. The highest operating temperatures used in the test were $T_0 = 78 \, ^\circ C$, 72 $^\circ C$, and 66 $^\circ C$. The results are shown in Figs. 9 and 10.

Fig. 9 shows that water production increased along with the maximum operating temperature because of the horizontal falling film evaporator; a high operating temperature resulted in low liquid viscosity and surface tension. Liquid film flow rate was increased, and liquid film fluctuation was enhanced. The liquid film inside and outside the tube was thinned and shed. Finally, the overall heat transfer coefficient of falling film evaporation was increased. As the highest operating temperature up to 78 $^\circ C$, the maximum water production is up to 1.42 t/h and the overall heat transfer is supreme, about 2618 w/(m$^2$ $^\circ C$).

As shown in Fig. 10, GOR increased from 7% to 12% when the maximum operating temperature increased by 6 $^\circ C$. Two possible reasons can explain this result. First, the overall heat transfer coefficient for the given motive steam parameters of falling film evaporation increases as operation temperature increases. Second, the ejected secondary steam pressure and temperature increase as operating temperature increases. Consequently, the TVC ejection ratio is increased. Moreover, the GOR can be enhanced because of the improved secondary steam utilization ratio.

4.5. Effect of temperature difference ($\Delta t$) on water production and GOR

It is tested that the effects of temperature difference ($\Delta t$) on water production, GOR, and ejection ratio $\mu$. The experimental
operating temperatures were $T_0 = 72^\circ C$, $P_1 = 0.85$ MPa, and $I = 300$ L/(m h). Temperature differences $\Delta T$ that were used were 3 $^\circ C$, 4 $^\circ C$, 5 $^\circ C$, and 6 $^\circ C$. The results are shown in Figs. 11 and 12.

The effect of temperature difference increases on the falling film evaporator heat transfer coefficient has two aspects. First, the superheat degree increases, and liquid viscosity decreases when temperature difference increases; this reduction in viscosity plays a role in enhancing heat transfer [35]. Second, the temperature difference increase results in a great heat flux density and condensation liquid flow, which increases liquid film thickness. The condensation heat transfer coefficient is obviously reduced, whereas condensation liquid flow is increased. The proportion of the condensation liquid heat transfer area (at the bottom of the tubes) to the total heat transfer area increases as the condensation flow increases; the average heat transfer coefficient on the surface decreases [36–38]. The total heat transfer coefficient decreases and product water flow gradually reduces with the increase of $\Delta T$ because of the influence of the two aspects (Fig. 11). However, the brine boiling point elevation and flow resistance cause a loss in temperature difference when the temperature difference is too small, which results in poor device stability. Therefore, temperature difference should be restricted to the range of 3–4 $^\circ C$, which is critical to obtaining a high heat transfer coefficient and a steady operating condition.

The ejection ratio and GOR decrease as temperature difference increases, as shown in Fig. 12. A great temperature difference results in a low secondary steam pressure in the third-effect and small TVC ejection ratio under certain operating temperatures and motive steam pressure. Consequently, secondary steam and GOR utilization decrease accordingly.

4.6 Effect of spray density $I$ on water production and product conductivity

The effect of spray density $I$ on device performance was measured under steady conditions to select the spray density basis for the MED plant design. The experimental conditions were as follows: $P_1 = 0.85$ MPa, $T_0 = 72^\circ C$, and $\Delta T = 6^\circ C$. Spray density was adjustable within the range of 147–425 L/(m h). Figs. 13 and 14 show the effect of spray density on water production and product conductivity. The experimental results indicate that spray density is an important factor that influences the evaporation surface heat transfer coefficient under falling film horizontal tube evaporation.

The evaporation surface heat transfer coefficient and total heat transfer coefficient increased as spray density increased. This increase can be attributed to the fact that the average thickness of the liquid film increases with increased liquid load. Thus, more preheat steam will be consumed, which is unfavorable for the heat transfer process. Moreover, liquid flow velocity outside the tube increases, which aggravates the fluctuation of the liquid film. Thus, the convective heat transfer is strengthened [39]. Based on Fig. 13, the largest water production was obtained when spray density was 290 L/(m h); beyond this value, water production decreased.

Fig. 14 shows that the product conductivity stabilized at 10 $\mu$S/cm when the spray density was within the range of 240–300 L/(m h). Moreover, product conductivity increased gradually with increased spray density. The nozzle outlet pressure increased, and spray splash and droplet atomization intensified when spray density (which is greater than the design value) increased, which resulted in increased steam-entrained droplets. Consequently, product conductivity was increased. A spray density value between 240 L/(m h) and 300 L/(m h) should be adopted for the actual design and operation. Installing a baffle before the steam passage inlet prevents seawater droplet splashing, which greatly affects product water quality.
4.7. Effect of vacuum pumping modes on water production and GOR

The operation performances were conducted when the vacuum pump was in the parallel and in the series modes. Experimental conditions are similar to the relationship between water production and GOR with the different NCG extraction modes, as shown in Figs. 15 and 16.

Comparisons between the effects of vacuum pumping in series mode and in parallel mode on water production and GOR are presented in Figs. 15 and 16, respectively. The results demonstrate that vacuum pumping in the series mode had stronger adaptability to steam fluctuation compared with that in the parallel mode. The pressure difference between effects was easily maintained, and the operational conditions were stable because every evaporator and condenser depended on vacuum pumping methods. Non-condensable gas (NCG) is extracted from the former effect to the next through pressure difference between the two effects. Finally, the NCG is extracted by the vacuum pump in the condenser. However, in the case of vacuum pumping in parallel mode, every evaporator and condenser was independent, which resulted in inconsistent pressure change. Thus, motive steam pressure fluctuations easily affected the device, which made steady operation difficult.

Furthermore, vacuum pumping in the parallel mode facilitated steam extraction from the system. Condensation inside NCG flow meters of one- to three-effect evaporators appeared during the test process, which reduced system efficiency. However, steam that was extracted from the former evaporator is reused in the next effect evaporator for vacuum pumping in the series mode, thereby improving system efficiency, water production, and GOR. Vacuum pumping in the series mode increased water production and GOR by 3.64% and 3.28%, respectively, on average.

4.8. Effect of TVC valve openings on water production and GOR

Figs. 17 and 18 show the effects of the TVC valve openings (i.e., TVC ejection ratio \( \mu \)) on water production and GOR, respectively. The experimental motive steam pressure was \( P_1 = 0.85 \) MPa, \( T_0 = 72 \) °C, and \( \Delta t = 6 \) °C. The TVC ejection ratio was adjusted during the test by changing the different TVC valve openings.

As shown in Figs. 17 and 18, the TVC ejector flow affects water production, GOR, and ejection ratio. For the given motive steam pressure, water production was about 0.8 t/h and GOR was 3.2 when the ejector flow was zero. Water production increased from 0.923 t/h to 1.32 t/h when secondary TVC steam flow increased; the GOR and ejection ratio also increased. The GOR had a higher value when TVC was used compared with using standalone MED systems [7,28]. However, water production, GOR, and ejection ratio stabilized when the TVC valve opening exceeded 44°.

5. Conclusion

In this paper, a 30 t/d low-temperature multi-effect evaporation seawater desalination system was designed based on the mathematical model, and a corresponding pilot device was constructed. Whole-process tests were conducted, and the effects of key operating parameters were analyzed. The following conclusions can be drawn from the test results:

(1) Motive steam pressure fluctuations strongly influence the stability of the device, water production, and GOR. Water production increased as motive steam pressure increased. However, the motive steam pressure stabilized when steam pressure continued to increase and exceeded 0.95 MPa (i.e., 121% of the designed value).

(2) Device water production increases as the maximum operating temperature increases. The tests indicate that water production increased by 7–12% when the maximum operating...
temperature increased by 6 °C. Hence, the set value of the maximum operating temperature should be slightly increased, which is dependent on the progress of anti-scale and heat transfer technologies.

(3) Water production increases as heat transfer temperature difference decreases. However, water production can no longer increase when the temperature difference decreases to a certain value. Temperature difference was restricted to the range of 3–4 °C in this paper; this limited range was critical to obtaining a high heat transfer coefficient and a steady operating condition.

(4) Device maximum water production was obtained when spray density was between 240 L/(m·h) and 300 L/(m·h). These values should be adopted for actual design and operation. Installing a baffle in front of the steam passage inlet prevents seawater droplet splashing, which can greatly affect the quality of product water.

(5) Vacuum pumping in the series mode had more advantages than vacuum pumping in the parallel mode. These advantages include good adaptability to motive steam fluctuations and high system efficiency, water production and GOR. Water production and GOR increased by 3.64% and 3.28% on average, respectively, in the series mode.

(6) TVC increases water production and GOR as well as reduces system energy consumption. An adjustable TVC nozzle is recommended to improve device stability and efficiency.

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