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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.

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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 m^2, 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

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Nomenclature

A_{1i}	the total heat transfer areas of preheating, m^2
A_{1i}	the total heat transfer areas of falling film evaporation, m^2
BPE_i	the rise in brine's boiling point rise, °C
C	the salt content percentage of brine, mg/L
c_p	the specific heat capacity, kJ/(kg °C)
D	the mass flow rate of evaporation, t/h
D_0	the flow of the motive steam, t/h
D_H	the flow of the TVC ejecting steam, t/h
d	the mass flashing flow rate of freshwater, t/h
F	the device surface area, m^2
G_0	the mass flow rate of the seawater feed to the effects, t/h
G_i	the mass flow rate of brine blow down, t/h
g	the mass flashing flow rate of brine, t/h
K_{1i}	the total heat transfer coefficient of preheating, W/(m^2 °C)
K_{2i}	the total heat transfer coefficient of falling film evaporation, W/(m^2 °C)
K_{l2}	the azimuth correction coefficient of the device surface when wind is present
$LMTD$	the logarithmic temperature difference in the heat transfer, °C
Q	the heat transfer rate, kW
Q_a	the thermal loss through the device surface per hour, kW/h
q	the thermal loss through the device surface per area, kW/m^2
T	the evaporator temperature, °C
t_0	the seawater temperature, °C
$T_{c,i-1}$	the secondary steam condensation temperature, °C
t_i	the brine temperature, °C
t_s	the outer wall surface temperature of the device, °C
t_a	the air temperature, °C
P	the pressure, MPa
Γ	the spray density, L/(m h)
Δt	the total temperature difference, °C
ΔT_i	the temperature difference loss caused by flow resistance, °C
$\Delta NEA_i'$	the unbalanced temperature rise caused by the freshwater flash, °C
$\Delta NEA_i''$	the heat transfer temperature difference loss caused by the concentration of brine, °C
a_{rc}	the heat transfer coefficient mixing radiation and convective of the device outside, kW/(m^2 °C)
λ	the latent heat, kJ/kg

superscripts

$'$	the fresh water
$''$	the brine flashing

Subscripts

i	the number of evaporator effects

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 thermoeconomic 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 thermoeconomic 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