Desalination 353 (2014) 91–97

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Analysis of a mechanical vapor recompression wastewater distillation system

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HIGHLIGHTS

- A design model of MVR system for wastewater treating was developed.
- The unit with a capacity of 20 kg/h is installed in the laboratory.
- The operational features of the unit were investigated.
- The effect of parameters on power consumption and heat transfer area was analyzed.
- The specific power consumption increases linearly with temperature difference.

ARTICLE INFO

Article history:
Received 25 May 2014
Received in revised form 28 August 2014
Accepted 11 September 2014
Available online 29 September 2014

Keywords:
Mechanical vapor recompression
High salinity wastewater
Horizontal tube falling film evaporation
Design and analysis

ABSTRACT

This paper presents a comprehensive design model of single-effect mechanical vapor recompression (MVR) system. The analysis focuses on the prediction of the specific power consumption of the compressor and the heat transfer areas of the evaporator. The MVR unit, with a capacity of 20 kg/h and horizontal tube falling film evaporation, is designed and installed in the laboratory. The performance of the system was investigated using high salinity wastewater containing Na_2SO_4. Except for the compressor consumption, experimental data shows good agreement for the predictions. The specific power consumption for the vapor compressor is 55.6 kWh/m^3. The experimental and theoretical results indicated that the evaporation rate increases by increasing the evaporate temperature from 70 °C to 85 °C. The evaporation rate, compressor consumption and heat transfer area of evaporator depend strongly on the temperature difference of heat transfer. The evaporation rate and specific power consumption increase linearly with temperature difference. On the other hand, the heat transfer area of evaporator goes down with the increase of temperature difference. This inferred that there is an optimum value of temperature difference that will lead to the optimum system with lower power consumption and smaller heat transfer area.

1. Introduction

Distillation-based water treatment is a conventional technology in the field of wastewater treatment. Especially in the process of high salinity wastewater treatment, which contains salts with Cl^-, SO_4^{2-}, Na^+, Ca^{2+} and the mass concentration is more than 1% [1,2]. Distillation mainly includes single effect evaporation (SEE), multiple effect evaporation (MEE), multi-stage flash (MSF), thermal vapor compression (TVC) and mechanical vapor recompression (MVR). MEE is considered to be more effective than SEE and MSF [3,4]. However, the MEE method requires a large amount of external heating vapor, the system is complicated, and its operation is complex. MVR is an alternative method for the treatment of high-salinity wastewater [5–7]. The characteristic of MVR is the reuse of the energy of vapor produced in the evaporator. The efficiency of MVR is higher than that of MSF, MEE and TVC [8].

Recently, the MVR system is mainly used in the process of seawater desalination. The major part of literature study of the MVR system is focused on description of system characteristics and performance [9–18]. Veza [9] reported on the reliability of two single-effect MVC units installed in the Canary Islands in 1987 and 1989. Aly and Fiqi [10] investigated thoroughly the thermal performance of a 5 m^3/d MVC system. Bahar et al. [11] conducted an experimental study on a 1 m^3/d MVC desalination plant. Shen et al. [12] presented a comprehensive analysis of a single-effect MVR desalination system using water injected twin screw compressors. Tuan et al. [13] combined a vacuum evaporator with MVR technology to recover and reuse blow-down (BD) water and waste heat in a fire-tube boiler system. Karameldin et al. [14] proposed wind-driven MVR system, which has been used in windy area of the Red Sea.

A number of mathematical models of the MVR system have been developed. Darwish [15] developed a simple mathematical model with

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http://dx.doi.org/10.1016/j.desal.2014.09.013

provides a useful and quick estimation of various system properties. Al-Juwayhel et al. [16] improved the model to provide performance evaluations for various single-effect vapor compression systems, including the MVR system. Ettouney et al. [17] further improved the model by incorporating more details for calculating the heat transfer area of the evaporator, the plate pre-heaters, and the compressor power. Aybar [18] developed a mathematical model using mass and energy balance equations in addition to an LMTD method for heat transfer analysis. The study focused on the operational characteristics of low temperature MVR system.

Literature studies concerning the MVR system design and analysis are limited to a small number [19–24]. Design and performance data for the MVR desalination system were first reported by Lucas and Tabourier [19] and Matz and Zimerman [20]. The reports include field data for single and multiple effect MVR systems. Ettouney et al. [21] developed a more detailed design model which studied the characteristic of the MVR system as a function of design and operating parameters. Al-Sahali et al. [22] discussed the features of the three thermal desalination processes MSF, MEE, and MVR with focus on design, energy, and economic aspects. Maborouk et al. [23] presented another design model which investigated the multi-stage flash-mechanical vapor compression (MSF-MVR) desalination process. Helal [24] presented a detailed model for the design of a hybrid solar-diesel powered MVR unit with a fresh water capacity of 120 m^3/d in the UAE.

Although the MVR system has been widely studied, it has not been widely applied in wastewater process. The MVR system used in the wastewater distillation with reliable and long-term operation is limited in China. One of the most pressing problems is the absence of design method. So, the purposes of this study were to develop a comprehensive design model of the single effect mechanical vapor compression process, and to analyze the performances focusing on the specific power consumption for the vapor compressor and the heat transfer areas of the evaporator. A laboratory prototype was built with vacuum evaporation and horizontal tube falling film evaporation design. The performance of the system was investigated using high salinity wastewater containing Na_2SO_4.

2. System process description and mathematical modeling

The building of the mathematical model is based on the relation of energy balance and mass balance in each part of the system. Compared with the actual working conditions, the mathematical model is based on the following simplification and assumptions: (1) the vapor compression process in the compressor is an adiabatic compression process; (2) the discharged condensate water contains a little of salt, and that can be ignored; (3) energy loss of the evaporator, preheater, pipeline and pumps is ignored; (4) the influence of non-condensable gas on the heat exchanger's heat transfer performance is not considered; (5) the state of the system is in a stable condition is assumed (Fig. 1).

2.1. Overall mass and salt balance

$$M_f = M_d + M_b \tag{1}$$

$$M_f X_f = M_b X_b \tag{2}$$

2.2. Process of preheat

The mass flow rate of the feed is M_f, with temperature T_i and concentration X_f. The feed is separated into two flows, one portion (M_{f1}, T_i, X_f) is sent to the HEX1 and the other portion (M_{f2}, T_i, X_f) to the HEX2, and exchanged heat with the condensate water (M_d, T_d) and the distillate (M_b, T_b, X_b) respectively. As a result, the outlet temperature of the feed is heated to T_{i1} and T_{i2}; meanwhile the condensate water and the distillate are discharged with the outlet temperature of T_{do} and T_{bo}.

Two plate heat exchangers are introduced to be the preheaters, and the feed exchanges the sensible heat with the condensate water and the distillate.

$$Q_{HEX1} = M_d C_{pd}(T_d - T_{do}) = M_{f1} C_{pf}(T_{i1} - T_i) \tag{3}$$

$$Q_{HEX2} = M_b C_{pb}(T_b - T_{bo}) = M_{f2} C_{pf}(T_{i2} - T_i) \tag{4}$$

The heat transfer balance equation is given by formula (5), where *CF* is the correction coefficient for plate combination.

$$Q_{HEX} = U_{HEX} \cdot A_{HEX} \cdot (\Delta T_{LM} \cdot CF) \tag{5}$$

The overall heat transfer coefficient U_{HEX} is given by the expression:

$$\frac{1}{U_{HEX}} = \frac{1}{h_{i\_HEX}} + \frac{1}{h_{o\_HEX}} + \frac{\delta}{k_{HEX}} + R_{i\_HEX} + R_{o\_HEX} \tag{6}$$

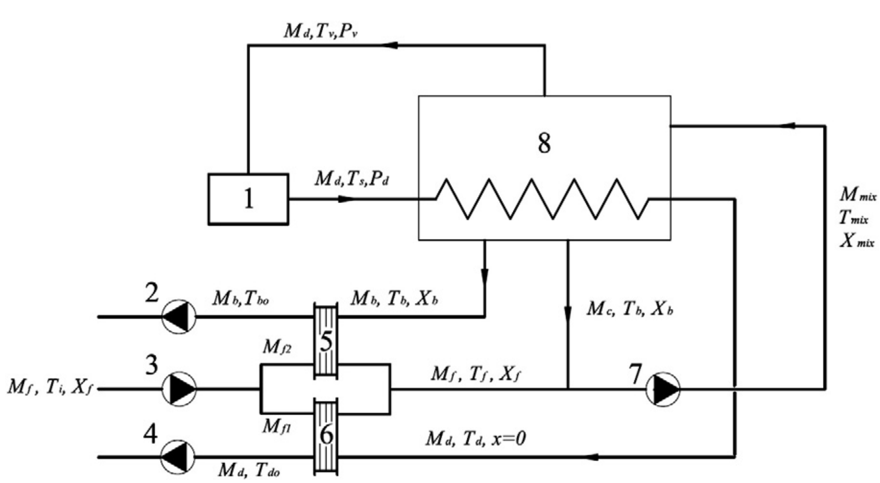

Fig. 1. System of the mechanical vapor recompression wastewater desalination. 1—vapor compressor; 2—pump of the distillate; 3—pump of the feed; 4—pump of the condensate water; 5—preheater 2 (HEX2); 6—preheater 1 (HEX1); 7—circulating pump; 8—horizontal-tube falling film evaporator.