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Energy and exergy analyses of circulatory flash evaporation of aqueous NaCl solution

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ABSTRACT

In present study, an experimental system for circulatory flash evaporation was designed and built. Energy and exergy analyses of circulatory flash process were carried out. Basing on the first law of thermodynamics, the gained output ratio of circulatory flash evaporation (GOR_{CFE}) was defined as an energy ratio between latent heat carried away by flash steam and input excess energy of working fluids. The performance ratio of circulatory flash evaporation (PR_{CFE}) was defined as the mass flow rate divided by exergy destruction rate. The Effects of main factors, namely, superheat degree, circulating flow rates, equilibrium pressure, initial water level and salinity on GOR_{CFE} and PR_{CFE} were studied. Results suggested that GOR_{CFE} decreased rapidly at the initial stage, then increased with the increase of superheat degree and became flat eventually. The optimal superheat degree was determined wherein the maximum performance ratio was reached. According to the comparison of gained output ratio and performance ratio, the maximum performance ratio was obtained when gained output ratio was great enough and temperature difference was minimal.

1. Introduction

The demand for fresh water is growing rapidly with the rising population and increasing standard of living. To alleviate water scarcity, several desalination technologies has been proposed and developed to produce fresh water [1–4]. Multi-effect distillation (MED) and multi-stage flash (MSF) are typical technologies of thermal desalination processes [5,6]. As the pioneer of thermal desalination, MED process is extensively used due to low specific power consumption [7]. Meanwhile, multi-stage flash (MSF) technology is also widely adopted because of the remarkable advantages, such as high fresh water yield, safety and reliability [8,9]. MSF still holds a certain share on desalination market [7,10]. The design procedure, construction practice and operation of MSF have been given considerable attention [11]. MSF process is also common in other industrial processes, such as energy and chemical industry [12]. Thus, research on energy and exergy analyses of MSF has great significance on design and optimization of flashing process.

MSF technology is an energy intensive process and numerous studies on energy and exergy analyses of MSF process and distillation plants have been performed to obtain the optimal working conditions [13,14]. Performance ratio was defined as the ratio of net product water flow to energy consumption. Exergy flow diagrams of MSF desalination plant were plotted. Results suggested that exergy destruction mainly occurs in the MSF section and increasing temperature gradient in the stage requires higher energy consumption. Mistry and Warsinger [15,16] analyzed the entropy generation of several desalination technologies powered by waste heat of various temperature to understand the generation of irreversibility. Performance ratio was defined as the ratio of the mass flow rate of product water to that of heating steam for a thermal desalination system. The exergetic efficiency was defined as the ratio of the process products to the input exergy of the process. Results suggested that entropy generation due to thermal disequilibrium is crucial in once-through MSF process and a lower temperature of waste heat leads to a greater entropy generation in MSF and MED process. Jin et al. [17] performed an exergy analysis for a vapor compression flash seawater desalination system and found that the greatest exergy destruction occurred in the flash tank. The selection and optimization of operation parameters in flash pot influence the performance of vapor compression seawater desalination system significantly. Hosseini Araghi et al. [18] carried out an exergetic analysis of the discharged thermal energy combined desalination system (DTECD). The irreversibility of each component was calculated. Results showed that evaporator was the most responsible for exergy destruction due to the large temperature difference between the inlet and outlet of evaporator. Eldean et al. [19] conducted the exergy analysis of a MSF desalination system powered by solar thermal cycles. Results showed that exergy destruction rate of MSF was quit high due to the massive

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thermal losses and great mass flow rate of working fluids. Chung et al. [20] conducted an energy analysis of MSF desalination plant and calculated the energy consumption of all parts of the process. Results showed that increasing the top brine temperature (*TBT*) can promote the productivity.

Flash evaporation is the core of MSF desalination process and has considerable influence on the energy and exergy efficiencies of the MSF desalination process. Extensive studies on both static and circulatory flash evaporation of water pool have been reported. Miyatake et al. [21,22] performed a series of experiments on the flash evaporation of pool pure water. And non-equilibrium temperature difference (*NETD*) is the difference between temperature at time *t* and the saturation temperature can be expressed as Eq. (1). The non-equilibrium fraction (*NEF*) is a dimensionless temperature to describe the liquid temperature and can be expressed as Eq. (2).

$$NETD = T_{\mathrm{t}} - T_{\mathrm{e}} \tag{1}$$

$$NEF\,(t) = \frac{T_t - T_e}{T_{il} - T_e} \tag{2}$$

where T_{t}, T_{e} and T_{il} are liquid temperature at time *t*, equilibrium temperature and initial liquid temperature, respectively. Gopalakrishna et al. [23] presented an experimental study on flash evaporation of quiescent water pool. Flashed mass increased exponentially with time and the non-dimensional number was adopted in correlations to predict flashed mass. Saury et al. [24,25] studied flash evaporation of quiescent water pool under various conditions. Evolution of *NEF* with time was obtained. *NEF* declined exponentially with time and a higher depressurization rate yielded a faster decay of *NEF*. Kim et al. [26] conducted a series of experiments on pool flash evaporation and found that cumulative number of bubbles increased with increasing superheat degree. When the initial water level was 100 mm, a minimum *NETD* existed with the increase of initial temperature of water. Augusto et al. [27,28] performed a comprehensive analysis of the influence of initial temperature and volume of liquid on low pressure vaporization in which water temperature decreased with time. Smaller initial volume and higher initial temperature of water yielded a faster decay of water temperature. The influence of various porous media on low pressure vaporization was also studied. NaCl solution was selected as the working fluid to study flash evaporation of quiescent liquid pool [29,30]. *NEF* decreases with the increase of superheat degree and decrease of initial water level. Lior et al. [31–33] studied the flash evaporation of flowing water pool in horizontal evaporator. Non-equilibrium allowance *NEA* was defined as the difference between average temperature at outlet of evaporator and vapor temperature. Moreover, *NEF* was expressed as the ratio between *NEA* and stage flashdown superheat degree. Results suggested *NEF* decreased as stage flashdown superheat degree and stage saturated temperature increased. NaCl solution was selected as the working fluids and boiling point elevate was considered. The correlations of the *NEF* were summarized. El-Dessouky et al. [34] studied the *NEA* of MSF desalination flash chamber wherein *NEA* defined by Lior [31] was adopted. Cipollina et al. [35] defined *NEA* as the difference between the outlet brine temperature and the theoretical boiling brine temperature, calculated according to stage pressure and brine salinity. Fath et al. [36] investigated the flash chamber efficiencies and non-equilibrium factor of a MSF desalination plant. They found that increasing the superheat degree, flashing surface area, evaporation cores and residence time inside the flash chamber can promote flash efficiencies. Non-equilibrium temperature difference *NETD*, non-equilibrium temperature loss Δ' and *NEF* were adopted to evaluate the thermal performance in a flash chamber. A smaller *NEF* or *NETD* indicated that flash process was closer to thermal equilibrium state [37–40]. Zhang et al. [38,39] defined *NEF* of circulatory flash evaporation as the ratio of exit superheat degree to inlet superheat degree. *NEA* defined by Cipollina et al. [35] is equal to superheat degree at the exit of flash chamber which is the numerator of *NEF* defined by Zhang et al. [38,39]. Boiling point elevation of NaCl solution was considered and the influence of main parameters such as circulating flow rate, initial water level and pressure of flash chamber on the non-equilibrium characteristics and thermal performance of flash process was analyzed [41,42].

Previous studies on the energy and exergy analyses of desalination systems showed that the flash process is most responsible for exergy destruction [13,14,17,43]. However, the non-equilibrium temperature difference of flash evaporation at the outlet of flash tank was not considered in these studies. As the core of MSF desalination, although fundamental flashing process was studied by many researchers, *NETD*, *NEA* and *NEF* were adopted as indictors to describe thermal equilibrium of flash evaporation. However, these indicators provided no information available on the degradation of energy.

Exergy analysis and parameter optimization of fundamental flashing process are important to promote the exergy efficiency of desalination processes. An experimental system for circulatory flash evaporation was established to test the actual flash process independently. Energy and exergy analyses of circulatory flash evaporation were performed to quantify the quality of heat content. The gained output ratio of circulatory flash evaporation (GOR_{CFE}) was defined as an energy ratio between latent heat carried away by flash steam and input excess energy of working fluids. The performance ratio of circulatory flash evaporation (PR_{CFE}) was introduced to evaluate the exergy efficiency. Moreover, PR_{CFE} under ideal and actual conditions was analyzed. The ideal condition means that *NETD* and *NEF* of circulatory flashing process are equal to 0. The influence of main factors on gained output ratio (GOR_{CFE}) and performance ratio (PR_{CFE}) of circulatory flash evaporation was also studied to determine the optimal design and operation conditions. Finally, the relationship between GOR_{CFE} and PR_{CFE} was analyzed.

2. Experimental system

Fig. 1 displays the schematic of experimental rig for circulatory flash evaporation. The experimental system can carry out experiments of circulatory flash evaporation of NaCl solution under various parameters. The experimental setup mainly includes a fundamental hydrothermal loop, a flash vapor cooling loop and two auxiliary cooling loops. The vacuum pump and two auxiliary loops are operated to found an environment under desired pressure during experiments. NaCl solution is heated up to desired temperature and pumped into the flash chamber by the circulating pump. Flash evaporation starts as soon as the working fluids enter the flash chamber. Data acquisition system starts recording experimental data at the same time.

Flash chamber is the key component of fundamental hydrothermal loop which has a rectangular cross-section of 0.1 × 0.1 m (length *L* × width *B*). The metal rotating flow meter with a full-scale of 1600 $\mathrm{L{\cdot}h^{-1}}$ is adopted in the experimental system with precision of 0.5%. The metal rotating flow meter was installed before the flash chamber to measure the volume flow rate of brine. And the working fluid is heated by the power-tunable electrical heater with the power rang of 0–90 kW. A series of T-type sheathed thermocouples with precision of 0.2 K are used to measure the temperatures of brine due to the satisfactory performance in vacuum and NaCl solution. The pressure transmitters with the full scale of 200 kPa are adopted to gauge pressure of flash and vacuum tanks. And its precision is ± 0.1% of its measure range. The data acquisition system is controlled by a PC. The pressure transmitters and flow meter are connected to a NI-9215 card and thermocouples and recorder are connected by a NI-9213 card. The details of instruments are listed in Table A.1 of Appendix A.

The uncertainty analysis of experiments is listed in Table 1.