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Experimental study on energy transformation and separation characteristic of circulatory flash evaporation

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ABSTRACT

Flash evaporation efficiency and steam-carrying ratio under low superheat were introduced to investigate energy transformation and separation characteristic of circulatory flash evaporation in present paper. Experiments were carried out with flow rates of 400, 600, 800, 1000, 1200 $L \cdot h^{-1}$, initial water film heights ranging from 100 to 300 mm, initial water film concentration of 0, 5%, 10% and at pressures of 7.4, 12.3, 19.9, 31.2, 47.4 kPa, respectively. Results indicated that flash evaporation efficiency increased with increasing flow rate and flash chamber pressure, but decreased with increasing initial water film height and initial water film concentration. Since upward steam carries the droplets out of the flash chamber, the value of experimental flash vapor mass was larger than the theoretical one which not considering the steam-carrying effect. Steam-carrying ratio under low superheat decreased with increasing of superheat and mass flow rate, but increased with increasing water film height. Moreover, there was a peak value in steam-carrying ratio curve for static flash evaporation while the steam-carrying ratio for circulatory flash evaporation decreased monotonically.

1. Introduction

Flash evaporation is a kind of pool boiling. Liquid become superheated and the surplus heat is transformed into the latent heat of vapor when it is exposed to an environment below its saturate pressure. It's widely used in industrial processes, such as cooling of hot parts of a shuttle by water spraying under low pressure conditions [1,2], salt disposal [3,4], grape cooling in wine manufacturing process [5] and seawater desalination [6,7]. It's classified as circulatory and static flash evaporation due to whether the liquid bulk has a horizontal velocity or not.

Basic understanding about static flash evaporation was firstly performed. Miyatake et al. [8,9] carried out a static flash evaporation experiment on pure water with superheat ranging from 3 to 5 K and equilibrium temperature from 40 to 80 °C. It was found that flash evaporation underwent two exponential decay processes. Non-equilibrium temperature difference (NETD) and non-equilibrium fraction (NEF) was proposed in this article. Fath [10] undertook a study to measure the non-equilibrium factor and correlate the flashing evaporation rate inside the flash chamber of a Multi-stage flash (MSF) desalination plant. The flash evaporation stage efficiency was defined to evaluate the performance of each flash evaporation stage. They found that an increase in the superheat and the residence time in the flash chamber had promoted the evaporation. Study on static flash evaporation of aqueous NaCl solution at different pressures and water film heights were presented in Zhang et al.'s work [11,12]. Higher initial water film concentration suppressed liquid–vapor phase change, reduced the rate of flash evaporating and weakened the intensity of boiling heat transfer. Influences of superheat and initial water film height on flash of aqueous NaCl solution were same as that on pure water. Moreover, with the rising of flash speed, a minimum value of NEF at turning point existed. Zhang et al. [13,14] investigated circulatory flash evaporation on pure water and NaCl solution with different initial water film concentrations. NEF decreased with increasing flow rate and flash chamber pressure but increased with increasing initial water film height and initial water film concentration. Secondly, heat and mass transfer in flash evaporation process became another focus. Gopalakrishna et al. [15,16] investigated seawater flash evaporation with superheats ranging from 0.5 K to 10 K, initial water film heights of 165,305 and 467 mm and solution concentration from 0 to 3.5%. They proposed a correlation of mass evaporated on the parameters mentioned above. Saury et al. [17] conducted a study on distilled water flash evaporation with superheats of 1–35 K, initial water film height of 15 mm and initial water temperature from 30 to 75 °C. A

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correlation between the water mass evaporated by flashing and the superheat was then obtained. Yan et al. [18] conducted a comparative work on the heat and mass transfer characteristics of static and circulatory flash evaporation. A unified calculating model for these two flash evaporation patterns was set up as well as a new volumetric heat transfer coefficient. Volumetric heat transfer coefficient decreased with increasing water film concentration but increased linearly with the rising of flash speed in Zhang et al.'s work [11,12]. With the rising of superheat, the ratio of flash evaporating increased and the intensity of pool boiling got strengthened. Large-size droplets would be carried away from the flash chamber. Investigations about solvent–solute separation process become an issue. Zhang et al. [19] investigate the steam-carrying effect in static flash evaporation of both pure water and NaCl solution. Steam-carrying ratio increased with decreasing separating height or rising initial water film concentration, and a peak value existed in its evolution versus mean pressure difference. Other researches on the flow characteristics and optimization of multi-stage plants were presented. Mandil and Ghafour [20] proposed a new approach to the optimization of multi-stage flash evaporation plants. Jin and Low [21,22] performed experimental and simulation work on the single stage of multi-stage flash evaporation system at saturated pressure 0.023 MPa and 75, 97, 177 mm high water film. Factors, such as bubble size, distribution of the vortex number and water film height influencing flash evaporation, were analyzed under different superheats. They found the multiphase flash flow was dependent on the superheat and the nucleation distribution. El-Dessouky et al. [23] developed correlations including discharge coefficient, non-equilibrium allowance, and overall heat transfer coefficient. The key parameters in former studies are summed up in Table 1.

It is concluded from Table 1 that the previous studies mainly focused on non-equilibrium and heat transfer characteristics of static flash evaporation and low velocity circulatory flash evaporation. However, three limitations are obvious. Firstly, the water film concentration was limited to a low value in former circulatory flash evaporation investigations. Circulatory flash evaporation with higher concentrations should be conducted. Secondly, the non-equilibrium fraction, ratio of outlet superheat to inlet superheat, is a traditional indicator explaining complete degree of flash evaporation. To some extent, it reveals energy transformation characteristic from residual temperature difference aspect. Nevertheless, thermophysical properties of NaCl solution such as latent heat of vaporization and specific heat vary dramatically in different temperatures, pressures and mass concentrations, which strongly affected the energy transformation process. It's necessary to define a new parameter to evaluate the energy transformation of circulatory flash evaporation. Thus, flash evaporation efficiency, which means the ratio of flash vapor latent heat to the max superheat of liquid, was introduced. Thirdly, quality of flash vapor is a critical parameter in flash evaporation, especially in MSF desalination. When the inlet superheat increased, the upward flash steam would carry some liquid droplets away from the flash chamber. It's called steam-carrying effect, illustrating the separation characteristic of flash evaporation. The steam-carrying effect would cause deterioration of flash vapor quality. It's important to introduce a parameter to illustrate separation characteristic of circulatory flash evaporation.

Thus, a circulatory flash evaporation system for high velocity circulatory flash evaporation was built up. Range of water film concentration was enlarged to 10% to study circulatory flash evaporation of higher concentration NaCl solution. As to reveal energy transformation characteristics of circulatory flash evaporation, flash evaporation efficiency was defined and studied under different flash chamber pressures, flow rates, initial water film heights and concentrations. On the other hand, in order to describe the separation characteristic, theoretical and experimental analysis about flash vapor mass variation in high velocity circulatory flash evaporation was conducted in the present work and steam-carrying ratio was proposed. Furthermore, variation of steam-carrying ratio was also studied.

2. Experiment system and method

2.1. Experimental system

A test rig for circulatory flash evaporation is designed and constructed as showed in Fig. 1(a). The apparatus contains four circulatory loops: a basic hydrothermal loop, a flash steam loop, a primary condensing loop and an auxiliary condensing loop. The basic hydrothermal loop is composed of a circulating pump, an electrical heater, two metal rotameters, a flash chamber and a heat exchanger. The electrical heater has 20 groups heating outside the tube. Each group has a power of 3 kW. To get concise temperature regulation, 3 groups of them are controlled by a voltage regulator. The flash chamber is a rectangular cavity with a height of 0.66 m and a cross section of 0.1 m × 0.1 m. The front of the flash chamber is covered with glass plate for visualization. Two 25 mm-diameter adjusting valves with two thermocouples are arranged at the inlet and outlet of the flash chamber, respectively. Water in this loop is driven by a circulating pump. A shell-tube heat exchanger is placed near the outlet of the flash chamber to cool down the flashed water so as to protect the circulating pump from cavitation. The flash steam loop consists of a shell-tube heat exchanger and a mass flowmeter with a range of 0–110 $\mathrm{kg{\cdot}h^{-1}}$ and a precision of 0.2%. The primary condensing loop includes a centrifugal pump, a water tank and a heat exchanger which ensures the flash steam com-

Table 1
Main parameters in former investigations.

Authors	f_{m0}	$Q/\mathrm{kg{\cdot}h^{-1}}$	$T_e/^\circ\mathrm{C}$	$T_0/^\circ\mathrm{C}$	$\Delta T/^\circ\mathrm{C}$	H/mm	p_0/kPa
Miyatake O	0	0	40–80	–	3–5	196–255	0.73–47.3
Miyatake O	0	0	40–80	–	2.5–5.5	100, 200	0.73–47.3
Kim	0	0	–	40–80	2–7	380	0.66–35.4
Saury D, Harmand S	0	0	–	30–75	1–35	15	0.5, 10, 15, 20
Saury D, Harmand S	0	0	–	45–85	2–44	25–250	0.5–15
Gopalakrishna	0, 3.5%	–	–	25–80	0.5–10	165, 305, 457	0.3–31.0
Lior N	0	–	–	99.2	1.76	100	–
Fath H	–	23, 300		41–112	10–17	–	–
Jin W X	–	2592, 3168, 3564	–	–	–	70–100	–
Junjie Yan	0	0–300	–	44.0–89.0	1.5–48	20, 40, 60, 800, 100, 150, 200, 300	3–50
Dan Zhang	0, 5%, 10%, 15% NaCl solution	0	–	63.3–141.8	1.7–53.9	50–300	9.3–123.7
Dan Zhang	0, 5%, 10%, 15% NaCl solution	0	–	46.5–141.8	1.7–53.9	50–300	8.68–213
Yousen Zhang	0	400–1400	–	42–120	2–30	100–300	7.4–70
Yousen Zhang	0, 5%, 10% NaCl solution	400–1200	–	42–120	2–30	100–300	7.4–70