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Experimental study on equilibrium waterfilm concentration in static flash evaporation of aqueous NaCl solution

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HIGHLIGHTS

- An experimental system of static flash evaporation was built.
- Equilibrium waterfilm concentration was significantly influenced by superheat.
- A peak value of waterfilm concentration increment existed.
- Minimum crystallization superheat was affected by initial concentration or separating height.
- A calculating formula of equilibrium waterfilm concentration with an empirical constraint was set up.

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ABSTRACT

Experimental study on equilibrium waterfilm concentration in static flash evaporation of aqueous NaCl solution was presented. Equilibrium waterfilm concentration was defined as the concentration of aqueous NaCl solution in a flash chamber at equilibrium time after each flash. Experiments were carried out with the initial waterfilm concentration varied from 0 to 0.264 (saturation), separating height from 0.115 to 0.415 m, and superheat from 1.8 to 43.4 K. Results indicated that both evaporation and steam-carrying effect influenced the change of equilibrium waterfilm concentration. Equilibrium waterfilm concentration gradually increased with rising superheat until saturation. Meanwhile, minimum crystallization superheat was defined as the minimum superheat that made NaCl crystals separated out from waterfilm during the process of static flash evaporation when the equilibrium waterfilm concentration was in a saturated state. Results showed that the minimum crystallization superheat decreased with the rising initial waterfilm concentration or the decreasing separating height. Finally, a calculating formula of equilibrium waterfilm concentration with an empirical constraint was set up, and the relative error between experimental and calculating equilibrium waterfilm concentrations varied between −14.6% and 8.7%.

1. Introduction

Flash evaporation stands for the phenomenon that, when a superheated waterfilm is exposed to a sudden pressure drop below its saturated pressure, it evaporates suddenly, leading to a quick temperature drop and huge vapor generation. This phenomenon could be classified into circulatory flash or static flash according to whether the waterfilm has a velocity in the horizontal direction.

Flash evaporation is widely used in industrial applications, such as seawater desalination plants [1,2], cooling of hot parts of a shuttle by water spraying under low pressure conditions [3,4], geothermal power plant [5] and salt chemical industries [6,7].

In recent years, disposal of saline effluent from desalination plants and industrial wastewater is an increasing problem worldwide. Highly concentrated inorganic salt wastewater is a form of pollution if the wastewater is directly discharged to the environment; in particular, wastewater that contains dissolved salts that could be recycled. Therefore, the treatment and recovery of such wastewaters are necessary [8].

At present, although there are several basic techniques that can remove dissolved salts from water, the flash evaporation technique is usually used as a final stage for the recovery of salts and disposal of the brine produced from different desalting processes due to its remarkable capacity in material separation and concentration, such as multi-stage flash (MSF), multi-effect evaporator (MEE) and reverse osmosis (RO) methods [9–11]. And the flash evaporation technique has been used to take salt out of wastewater or brine water in salt production industries (like co-production of salt and Glauber's salt) [12,13].

The process of wastewater disposal is often accompanied by the change of solution concentration, even crystallization, and so study on the change of solution concentration during flash evaporation is necessary. Hence, experimental study on equilibrium waterfilm concentration

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Nomenclature

C	steam-carrying coefficient (s^6 kg^{-1} m^{-1})
c_p	specific heat of water at constant pressure (kJ kg^{-1} K^{-1})
f_m	concentration of aqueous NaCl solution (–)
H	waterfilm height (m)
Ja	Jacob number (–)
K	steam-carrying ratio (–)
m	mass (kg)
NEF	non-equilibrium fraction (–)
p	pressure (MPa)
r	latent heat of vaporization (kJ kg^{-1})
T	temperature (°C)

Greek symbols

Δf_m	waterfilm concentration increment
ΔH	waterfilm height drop (m)
Δp	pressure difference between flash and vacuum chambers (MPa)
Δp_m	mean pressure difference between flash and vacuum chambers (MPa)
ΔT	superheat (K)
ρ	density (kg m^{-3})
τ	time (s)

Subscripts

0	start of flash
B	aqueous NaCl solution
cal	calculating
cry	crystallization
e	equilibrium
f	flash chamber
ev	evaporated mass
exp	experimental
l	liquid
sp	separating
sc	steam-carrying
st	steam
v	vacuum chamber

in static flash evaporation of aqueous NaCl solution was presented. Influences of some parameters such as initial waterfilm height, superheat or initial waterfilm concentration on equilibrium waterfilm concentration were analyzed.

2. Literature review

2.1. Effects of initial waterfilm height and superheat on evaporated mass

It was well known that flash evaporation could improve the solution concentration due to the evaporation effect, thus, influences of some key parameters on the evaporation effect were introduced in a row.

Miyatake et al. [14,15] first carried out experimental study on static flash evaporation of pure water to examine its basic mechanism with superheat varying from 2.5 to 5.5 K, initial waterfilm height ranging from 100 to 225 mm and equilibrium temperature ranging from 40 to 80 °C. They defined superheat (ΔT), flashing time, non-equilibrium fraction (*NEF*) and non-equilibrium temperature difference (*NETD*). Superheat and non-equilibrium fraction were respectively introduced to measure unstable energy contained in waterfilm and the degree of completion for flash. It was found that higher superheat or lower waterfilm height led flash to take place faster and evaporate more completely. A correlation between the evaporated mass and waterfilm temperature was obtained. Meanwhile, the process of static flash evaporation was divided into fast evaporation stage and gradual evaporation stage according to the drop speed of waterfilm temperature.

Saury et al. [16] conducted an experimental investigation on static flash evaporation of pure water with an initial waterfilm height of 15 mm, superheat varying from 1 to 35 K and initial waterfilm temperature between 30 and 75 °C. They highlighted the influence of superheat on final evaporated mass. A correlation between water mass evaporated by flashing and superheat was proposed. Then Saury et al. [17] further studied the effect of initial waterfilm height and depressurization rate on the final evaporated mass. The results suggested that final evaporated mass increased with the rising initial waterfilm height and was almost independent of depressurization rate.

Gopalakrishna et al. [18] presented experiments on static flash evaporation of pure water and aqueous NaCl solution with the initial waterfilm concentration ranged from 0 to 0.035, superheat between 0.5 and 10 K, and initial waterfilm height at 165, 305, and 457 mm respectively. Evaporated mass increased with the Jacob number and decreased with the liquid Prandtl number. Meanwhile, by measuring the drop of waterfilm height, a calculation formula for final evaporated mass was proposed.

Our research team [19] conducted a comparative work on the heat and mass transfer characteristics of static and circulatory flash evaporation. In this article, a unified calculating model was established for both flashes, including the evaporated mass and boiling heat transfer coefficient. The evaporated mass for both flashes were found to increase with rising superheat, but drop with rising of initial waterfilm height. In addition, Kim and Lior [20] examined static flash of pure water revealing several critical transition points in waterfilm temperature evolutions.

2.2. Effect of steam-carrying effect on equilibrium waterfilm concentration

Primary research on equilibrium waterfilm concentration was studied by our research team [21] and results indicated that equilibrium waterfilm concentration was significantly influenced by steam-carrying effect. Equilibrium waterfilm concentration increased gradually with incremental mean pressure difference, but the growth rate had no significant dependence on initial concentration or separating height of waterfilm in current experiments. But the higher initial waterfilm concentration (more than 0.15) was not involved in this research. With the increasing of concentration, the changes of thermal properties, e.g. boiling point elevation, induced the process characters in flash to be significantly different from those of low concentration.

2.3. Effect of initial waterfilm concentration on flash evaporation

Lior and Greif [22] studied the heat, mass and momentum transport characteristic of vapor in a horizontal stage flash evaporator using aqueous NaCl solution as working fluid with a concentration of 41,575 ppm. It was found that the flashing of NaCl solutions was accompanied by strong foaming, mainly in the submerged sluice gate flow region. As a working fluid, the aqueous NaCl solution could reduce the fractional non-equilibrium allowance, but not weaken the purity of the distillate. Then, Lior and Nishiyama [23] indicated that air concentration in working liquid significantly influenced the equilibrium of flash.

Our research team [24] enlarged the aqueous NaCl solution concentration into 0–0.15 (mass fraction) in static flash evaporation of aqueous NaCl solution. Results showed that higher initial waterfilm concentration could hamper liquid–vapor phase change. Moreover, Liu et al. [25] did experiments on the flash evaporation process of aqueous NaCl solution droplet. Increasing of the droplet concentration and pressure in a flash chamber can weaken the intensity of flash evaporation and lead the evaporation rate to decrease.