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Study on steam-carrying effect in static flash evaporation

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ABSTRACT

Study on steam-carrying effect in static flash of both pure water and aqueous NaCl solution was present. Properties, including steam-carrying ratio, waterfilm height drop and equilibrium concentration of waterfilm, were measured in experiments. Their dependences on separating height, initial waterfilm concentration and mean pressure difference were analyzed. Particularly, steam-carrying ratio was defined as the mass ratio of be-carried liquid and generated steam. Results suggested that this ratio increased with the decreasing of separating height or the rising of initial waterfilm concentration, and a peak value existed in its evolution versus mean pressure difference. At last, according to experimental results and basic principles a calculating model for steam-carrying effect in static flash was built.

1. Introduction

Flash evaporation defines the phenomenon of rapidly vaporizing when a given liquid is exposed to a sudden pressure drop below its saturated pressure, leading to significant drop of waterfilm height as well as its temperature. Particularly, static flash stands for the case that during flash process the waterfilm remains static in horizontal direction.

Flash evaporation has received world-wide interests primarily due to its application in seawater desalination. Miyatake et al. [1] carried out experimental study on static flash of pure water with superheats varied between 3 and 5 K. Results suggested that the sensible heat released in the temperature drop of waterfilm could be consider to all change into the latent heat of generated steam. He also defined coefficient of evaporation rate and gave its empirical formula by considering the pressure difference between saturated pressure at liquid temperature and final equilibrium pressure as the main driving force for flash evaporating. After further experiments, Miyatake et al. [2] suggests that evaporated mass and coefficient of evaporation rate were influenced significantly by waterfilm height. Saury et al. [3] carried out static flash experiments with initial waterfilm height being maintained at 15 mm but superheats being enlarged to between 1 and 35 K. Results validated that final evaporated mass was proportional to superheats and could be calculated by the heat balance with relative error less than 10%. Besides, Saury et al. [4] also examined the influence of depressurization rate to the final evaporated mass. Gopalakrishna et al. [5] studied the static flash of NaCl solution. They carried out experiments with superheat varying between 0.5 and 10 K, initial waterfilm height at 165, 305 and 457 mm, and concentration of NaCl ranging from 0% to 3.5%. By measuring the drop of waterfilm height with a cathetometer, they proposed a calculating formula for final evaporated mass. Liu et al. [6] presented experiment on flash evaporation of aqueous NaCl droplet. Results suggest that evaporation rate can be minimized by higher concentration or environment pressure. Mutair and Ikegami [7] examined flash evaporation from superheated water jets and found that higher initial water temperature or superheats can improve the intensity of flash and increase evaporated mass. Comparative study of static and circulatory flash was carried out by our research team [8,9]. A unified calculating model was set up for heat transfer characters of both flashes, including the evaporated mass and heat transfer coefficient. Besides, Miyatake et al. [10] and Jin et al. [11] also carried out experiments on multi-stage flash (MSF) and indicated the methods to enhance evaporating. An improvement for custom MSF was proposed by our research team [12] and theoretical analysis was present for evaporated mass before and after this improvement.

Former studies have clarified the basic mechanism for flash evaporation and revealed the dependence of evaporated mass with various factors, such as superheats, pressure drop and initial waterfilm height. But with the expansion of experimental range, two new problems emerge. First, evaporated mass in former studies is directly measured by waterfilm height drop, but larger superheat or pressure drop makes the flash process more intensive, part of the liquid phase is carried out from waterfilm bulk by severely overflowing steam, this phenomenon is defined as steam-carrying effect. This effect leads to significant waterfilm height drop, generating false appearance that evaporated mass is increasing. Second,

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Nomenclature

A	cross-section area of flash chamber (m^2)
C	steam-carrying coefficient ($s^6\ kg^{-1}\ m^{-3}$)
C_f	drag force coefficient (–)
c_p	specific heat of water at constant pressure ($kJ\ kg^{-1}\ K^{-1}$)
d	diameter (m)
F	buoyancy (N)
f	drag force (N)
f_m	concentration (mass fraction) of NaCl solution (–)
g	acceleration of gravity ($m\ s^{-2}$)
G	gravity (N)
H	waterfilm height (m)
Ja	Jacobi 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)
u	velocity ($m\ s^{-1}$)

Greek symbols

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

Subscripts

0	start of flash
drp	droplet
e	equilibrium
f	flash chamber
l	liquid
max	maximum
s	steam
sc	steam-carrying
sp	separating
v	vacuum chamber

in flash of NaCl solution, part of salt water is carried directly into vacuum chamber by the steam-carrying effect and thus makes the product water contain salt. In other words, desalination is not completely achieved.

Therefore, experimental study on steam-carrying effect in static flash was carried out based on newly built experimental system for both pure water and aqueous NaCl solution. Properties (steam-carrying ratio, waterfilm height drop and equilibrium concentration of waterfilm) and their dependence on factors such as mean pressure difference, initial height and concentration of waterfilm were examined. At last, a calculating model for steam-carrying effect was set up.

2. Experimental system

2.1. Experimental apparatus

Experimental system for static flash of NaCl solution (Fig. 1) is composed of high and low pressure parts. The high pressure part includes heater and flash chamber. The heater is a cylindrical tank made of stainless steel. Its volume is 0.03 m^3 and maximum heating power is 9 kW. The flash chamber is a rectangular tank with cross section of 0.20 × 0.20 m and height of H_f = 0.50 m. To achieve visualization, its front and rear faces are made of tempered glass, the other four faces are made of stainless steel and are finely insulated by asbestos layers. Besides, a cathetometer is attached outside front glass to read waterfilm height. The low pressure part mainly includes vacuum chamber, vacuum pump and condenser (5). The vacuum chamber is a 4.75 m^3 steel cylindrical tank and its inside is painted to avoid rusting. The ultimate pressure of the water-ring vacuum pump is 6.0×10^{-2} Pa and its capacity is 0.030 $m^3\ s^{-1}$. Condenser is a shell-and-tube heat exchanger being used to minimize the steam that otherwise would be sucked into vacuum pump. Both vacuum chamber and condenser are inclined with 0.4° to horizontal surface, making it easier for the condensed water to flow back into vacuum tank and finally drain out. The high and low pressure parts are connected by electromagnetic valve (3). The diameter of the electromagnetic valve is 80 mm. The inner surface of the connecting pipe between flash and vacuum chambers is finely polished.

In experiment, distilled water or NaCl solution in certain concentration was firstly heated in the heater to given temperature and then was channeled into the flash chamber to achieve designed waterfilm height. At the same time, condenser and vacuum pump were turned on successively to generate the required pressure in vacuum chamber. The pressures of flash chamber could be finely adjusted by valve (17). After these preparations on both parts, data acquiring system was started up and static flash phenomena took place in the chamber as soon as the electromagnetic valve (3) was turned open, the temperature of waterfilm and steam as well as pressure of both flash and vacuum chambers were real-timely sampled for 20 s (the reason for sampling 20 s is discussed in Section 3.1) and stored. Then the electromagnetic valve was shut down and waterfilm height drop was read from cathetometer. For trials that used aqueous NaCl solution as working fluid, after each flash, residual waterfilm was drained out from flash chamber and its equilibrium concentration was measured by float densimeter.

To avoid corrosion, all the thermocouples used in system are stainless-steel sheathed copper-constantan thermocouples with diameter of 0.5 mm, precision of 0.2 K and time constant of 0.04 s. A set of 12 thermocouples horizontally arranged along symmetrical axis of flash chamber, being used to measure temperature of steam and waterfilm. Their arrangement is displayed in Fig. 1. In trials, the samples from submerged thermocouples are averaged to obtain waterfilm temperature; while samples from not submerged ones are averaged as steam temperature. All the three pressure transducers in use are MSI-US5100 with range of 0–0.15 MPa and precision of 0.75% in full scale. The data acquisition system is controlled by PC with sampling rate of 40 S/s. Specifically, the temperature signals are sampled by NI-PCI6221 with 16 channels. Pressure signals are sampled by NI 4472 card with 8 channels. The precision of the float densimeter is 5.0×10^{-4} g mL^{-1}. High-speed camera is MotionXtra HG-100 K. The frame rate is 500 fps and record resolution is 1024 × 1024 pixels.

2.2. Determination for steam-carrying ratio

Considering that the flash process is quick and short, and the flash chamber is carefully insulated, thus all the sensible heat re-