



Experimental study on static flash evaporation of aqueous NaCl solution

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ABSTRACT

Experimental study on static flash of aqueous NaCl solution was present. Initial waterfilm concentration and superheat ranged between 0 and 0.15 (mass fraction), between 1.7 and 53.9 K respectively. Influence of factors, such as initial waterfilm concentration, initial waterfilm height and superheat on thermo-properties during flash, such as waterfilm temperature, non-equilibrium fraction (*NEF*), and volumetric heat transfer coefficient were analyzed and compared with that on flash of pure water. Results suggested that higher initial waterfilm concentration suppressed liquid–vapor phase change, reduced the rate of flash evaporating and weakened the intensity of boiling heat transfer. But the influences of superheat and initial waterfilm height on flash of aqueous NaCl solution were same as that on pure water. At last, *NEF* was fitted with relative error between -49.30% and 55.2% , upon which volumetric heat transfer coefficient could be calculated with relative error varying between -12.6% and 18.8% .

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1. Introduction

Flash evaporation defines the phenomenon of rapid evaporation when a given waterfilm is exposed to a sudden pressure drop below its saturated pressure, leading to significant drop of temperature. The sensible heat of waterfilm released during the process is transferred into the latent heat of flash steam. Particularly, static flash defines the case that waterfilm remains static in horizontal direction during flash.

Flash received world-wide attention due to its remarkable capacity on separation, such as desalination [1], and energy recycle, like geothermal power plant [2]. Miyatake et al. [3] carried out experimental study on static flash of pure water with superheats varied between 3 and 5 K. They examined the waterfilm temperature evolution and suggested that flash can be divided into fast evaporation stage and gradual evaporation stage according to the speed of waterfilm temperature drop. The fast evaporation stage was the key process during static flash. They also suggested the saturated temperature under final equilibrium pressure of flash chamber was the theoretical final equilibrium temperature that the superheated waterfilm can reach after flashing, but experiment results suggested that actual waterfilm temperature cannot drop to that value. The margin between the actual and theoretical equilibrium temperatures was defined as non-equilibrium temperature difference (*NETD*). They further introduced non-equilibrium fraction (*NEF*) to measure the degree of completion for flash, and found that higher superheat or lower waterfilm height led *NEF* to drop

more quickly and equalized at lower value [4]. Besides, Miyatake et al. also investigated the influence of waterfilm concentration on the bubble growth in stable pool boiling, and set up a simple calculation model [5,6]. Saury et al. [7] also carried out static flash experiments with pure water as working fluid, but enlarged the range of superheats to between 1 and 35 K. Results suggested that the sensible heat released from the temperature drop of waterfilm could be considered to all change into the latent heat of generated steam. Saury et al. further examined the influences of waterfilm height and depressurization rate on *NEF* elevation and evaporated mass [8]. Gopalakrishna et al. [9] studied the static flash of aqueous NaCl solution, superheat varying between 0.5 and 10 K, concentration ranging from 0 to 0.035 (mass fraction). By measuring the drop of waterfilm height, they proposed a calculating formula for final evaporated mass. Liu et al. [10] carried out experiments on flash evaporation of aqueous NaCl droplet. Results suggested that evaporation rate can be minimized by higher concentration or environment pressure. Comparatively research between static and circulatory flash of pure water was carried out by our research team [11]. *NEF* evolution was newly fitted by error function with relative error ranging between -17.2% and 23.1% . Upon this fitting formula, a unified calculating model for both flashes was set up. At the same time, volumetric heat transfer coefficient was proposed by our research team to measure the intensity of boiling heat transfer during flash. Besides, results of our experiments also indicated that part of liquid was directly carried out by upward flowing flash steam during flash, which was defined as steam-carrying effect. This effect was also examined and a calculation model for it was built [12]. In addition, there were also many works on industrial application of flash. Miyatake et al. [13], Jin and Low [14] and

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Nomenclature

c_p	specific heat of water at constant pressure ($\text{kJ kg}^{-1} \text{K}^{-1}$)	ΔT	superheat (K)
e	error (-)	ρ	density (kg m^{-3})
f_m	mass fraction of aqueous NaCl solution (-)	σ	surface tension (N m^{-1})
h	volumetric heat transfer coefficient ($\text{kW m}^{-3} \text{K}^{-1}$)	τ	time (s)
H	waterfilm height (m)		
m_{ev}	evaporated mass (kg)		
NEF	non-equilibrium fraction (-)	Subscripts	
$NETD$	non-equilibrium temperature difference ($^{\circ}\text{C}$)	0	start of flash
p	pressure (MPa)	B	aqueous NaCl solution (brine)
q	quantity of heat transfer during flash (kJ)	e	equilibrium
r	latent heat of vaporization (kJ kg^{-1})	f	flash chamber, fit, fitting value
R	radius of vapor bubble (m)	r	reference
T	temperature ($^{\circ}\text{C}$)	s	saturated
		w	pure water
		v	vacuum chamber
Greek symbols			
θ	boiling point elevation ($^{\circ}\text{C}$)		

Hassan [15] also did research on multi-stage flash (MSF). An improvement for custom MSF was proposed and analyzed by our research team [16].

Former studies have revealed the basic mechanism for flash evaporation, but two limitations are still obvious. First, former works mainly use pure water or dilute aqueous NaCl solution (concentration in most study is no more than 0.035) as working fluid. But nowadays the concentration of waterfilm in salt chemical industrial becomes even higher, (e.g. flash is considered to be used to take salt crystal (like NaCl crystal) out of blackish water or thick brine water whose concentration is even reach saturation) and thus process characteristics during flash of thick aqueous NaCl solution should be investigated. With the increasing of waterfilm concentration, the changes of its thermal properties, e.g. boiling point elevation, induce the process characters in flash to be significantly different from those of pure water. Second, former studies mainly focus on mass transfer properties, hardly on heat transfer properties (e.g. heat transfer coefficient). But heat transfer properties are even more important in industrial application. For example, the energy released during flash evaporation can be recycled and further used in industrial system to enhance its efficiency, and thus research on it is urgently needed.

Therefore, this paper presents static flash experiments with aqueous NaCl solution as working fluid. The initial waterfilm concentration and superheat range between 0 and 0.15 (mass fraction), between 1.7 and 53.9K respectively. Temperature evolution of waterfilm, non-equilibrium temperature difference (NETD), non-equilibrium fraction (NEF), heat transfer coefficient were measured. Their dependence on governing factors, particularly on initial waterfilm concentration, were examined and compared with our former results of pure water static flash. According to the results, a set of calculation formulae for NEF evolution and volumetric heat transfer coefficient in static flash of aqueous NaCl solution was present.

2. Experimental system and uncertainty analysis

2.1. Experimental system

The experimental study is carried out based upon the same experimental system (Fig. 1) used in our former works [12]. This system mainly contains high and low pressure part. High pressure part includes heater and flash chamber; low pressure part includes vacuum chamber, vacuum pump and auxiliary condensing system.

Two parts are connected by electromagnetic valve. The structure of each component and information of measurement equipments are clearly stated in Ref. [12] and do not repeat here again.

In this experimental study, aqueous NaCl solution with different concentration was firstly heated to given temperature in heater and then was filled into flash chamber to create waterfilm with certain initial height. The waterfilm height is monitored by a cathetometer (Fig. 1) attached outside the front glass of flash chamber, and the height could be adjusted by filling through valve 13 (Fig. 1) or drain from valve 15 (Fig. 1) on flash chamber. At the same time, pressure of vacuum chamber was reduced to given value by vacuum pump. After preparations on both sides were finished, the electromagnetic valve was disclosed, and then the flash took place. During flash, waterfilm temperature and flash chamber pressure were real-timely measured for 20 s (the reason would be discussed in Section 3.1.2). After flash, the equilibrium waterfilm height was read by cathetometer, and the equilibrium waterfilm concentration was measured by float densimeter after being drained out from flash chamber.

All the thermocouples used in system are stainless-steel sheathed copper-constantan (in order to avoid corrosion) thermocouples with diameter of 0.5 mm, precision of 0.2 K and time constant of 0.04 s. Pressure transducers in use are MSI-US5100 with range of 0–0.15 MPa and precision of 0.75% in full scale. The precision of the float densimeter is $5.0 \times 10^{-4} \text{ g mL}^{-1}$. The precision of cathetometer is $5.0 \times 10^{-4} \text{ m}$.

2.2. Uncertainty analysis

The ranges of main parameters in experiment are listed in Table 1. Table 2 lists uncertainty analyses results for all directly and indirectly measured values according to method of *constant odds-product form* proposed by Moffat [17].

3. Result and analysis

3.1. Waterfilm temperature

3.1.1. Waterfilm temperature evolution during flash

Static flash is an unstable boiling process in which both waterfilm temperature (T_B) and flash chamber pressure (p_f) quickly decay with time (Fig. 2). In order to compare T_B and p_f in same figure, p_f is converted into corresponding saturated temperature of pure water (T_s) and is also drawn into the subfigure of temperature in Fig. 2.

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