Experimental Study on the Expansion Law of Foam Layer in Static Flash Evaporation of NaCL Solution (Postprint)

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Date: 2017-11-07T00:00:00+00:00

Abstract

This study established a static flash evaporation experimental apparatus and conducted preliminary experimental investigation and theoretical analysis on the foam layer expansion behavior during the static flash evaporation process of NaCl solutions under various initial parameters. The experiments covered superheat values ranging from 2.9-30 K, initial liquid film thicknesses of 0.1 m and 0.2 m, and initial solution mass fractions of 0.2-0.25. Experimental results demonstrate that foam layer expansion initiates earlier and proceeds more rapidly at larger superheat or smaller initial liquid film thickness, whereas solution concentration exhibits negligible influence on foam layer expansion behavior. Furthermore, based on bubble growth theory and mass and energy balance, this paper established and derived a calculation model for foam layer expansion behavior, enabling the prediction of foam layer height variation with time, which shows good agreement with experimental results.

Full Text

Experimental Study on the Expansion Law of the Foam Layer During Static Flash Evaporation of Aqueous Sodium Chloride Solutions

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Abstract: This paper presents a static flash evaporation experimental setup and conducts preliminary experimental studies and theoretical analysis on the foam layer expansion law during the static flash process of NaCl solution under

different initial parameters. In the experiments, the superheat ranged from 2.9 to 30 K, the initial liquid film thicknesses were 0.1 m and 0.2 m, and the initial mass fractions ranged from 0.2 to 0.25. Experimental results showed that: under larger superheat or smaller initial liquid film thickness, foam layer expansion began earlier and proceeded faster; while solution concentration had almost no influence on the foam layer expansion law. Furthermore, based on bubble growth theory and mass-energy balance, this paper derived a calculation model for foam layer expansion law, which calculates the variation of foam layer height with time and shows good agreement with experimental results.

Keywords: Static flash evaporation; Foam-like boiling; Law of foam layer expansion; NaCl solution

0 Introduction

Flash evaporation refers to the phenomenon where a superheated liquid, when exposed to a space with pressure below its saturation pressure, undergoes sudden evaporation and its temperature drops rapidly. Due to its high separation efficiency and heat transfer capacity, flash evaporation finds wide applications in seawater desalination, waste heat recovery in thermal power plants, concentration and separation technologies in salt chemical industry, drying technologies, and other fields.

Miyatake[1] conducted experimental studies on static flash evaporation, proposing that superheat is the driving force of flash evaporation and introducing two concepts: Non-Equilibrium Temperature Difference (NETD) and Non-Equilibrium Fraction (NEF). Gopalakrishna[2] theoretically investigated bubble growth patterns under different pressure drop rates, finding that bubble growth rate increases with increasing pressure drop rate. Bi Qincheng et al.[3] experimentally studied the flash evaporation process of NaCl solution droplets, discovering that increasing droplet concentration or flash chamber pressure could weaken droplet flash evaporation intensity. Tewari et al.[4] experimentally investigated nucleate boiling characteristics of NaCl solutions under atmospheric and sub-atmospheric pressures, finding that the boiling heat transfer coefficient increases with surface roughness and decreases with increasing concentration.

The evolution of the foam layer is an important phenomenon in static flash evaporation, affecting boiling heat transfer and vapor entrainment, yet it has been rarely studied in the past. Moreover, the droplet entrainment model previously established by our research group is not applicable to foam-like boiling under high superheat. To address these deficiencies, this paper presents experimental studies on NaCl solutions with initial superheat of 2.9~30 K, initial liquid film thickness of 0.1 m and 0.2 m, and initial mass fraction of 0.2, 0.23, and 0.25. Visual investigations were performed on foam layer expansion during static flash evaporation to observe its evolution process. Comparative studies

were conducted on the effects of superheat, initial liquid film thickness, and initial solution concentration on foam layer expansion laws. Furthermore, based on classical bubble growth theory and energy-mass balance during flash evaporation, a calculation model for foam layer expansion was derived.

Funding: This work was supported by the National Natural Science Foundation of China (NO.51306148/51125027) and the Fundamental Research Funds for the Central Universities.

1.1 Experimental Apparatus and Procedure

The static flash evaporation experimental system is shown in [Figure 1: see original paper]. A solenoid valve divides the system into high-pressure and low-pressure sides. The main components on the high-pressure side are the heater and flash chamber, while the low-pressure side primarily consists of a vacuum chamber, vacuum pump, and auxiliary condensation loop. A high-speed camera is additionally installed to record foam layer height variations during the flash process. The flash chamber, the core component of the system, has dimensions of 0.2 m (length) × 0.2 m (width) × 0.61 m (height), and is equipped with a level gauge for reading liquid level and foam layer height.

The pressure inside the flash chamber is measured by a piezoresistive pressure sensor with 0.75% accuracy installed at the top. The temperature inside the flash chamber is measured by 15 T-type thermocouples with 0.2 K accuracy, arranged vertically on an adiabatic support at the axial position. The high-speed camera is a Phantom V611 model.

1-Heater; 2-Flash chamber; 3-Vacuum chamber; 4-Cooling water tank; 5-Condenser; 6-Vacuum pump; 7-Solenoid valve; 8-Thermometer; 9-Pressure gauge; 10-Regulating valve; 11-Pressure sensor; 12-Exhaust valve; 13-Water injection valve; 14-Drain valve; 15-Cooling water pump; 16-Vacuum valve; 17-Thermocouple; 18-Level gauge; 19-High-speed camera

Fig.1 Static flash evaporation experimental system

During experiments, the prepared NaCl solution was injected into the heater and heated to slightly above the set temperature, then transferred into the flash chamber to reach the designated liquid level. The vacuum pump was activated to adjust the vacuum chamber pressure to the set value. Upon opening the solenoid valve, flash evaporation occurred. The pressure in the flash chamber, gas-liquid temperatures, and temperature and pressure values in the vacuum chamber were recorded, while the high-speed camera was activated to capture visual data at a sampling rate of 1000 fps. After flash evaporation concluded, the equilibrium liquid level height was recorded.

1.2 Uncertainty Analysis

[Figure 2: see original paper] shows the method for determining the upper and lower edge heights of the foam layer. As illustrated, during foam layer expansion, the heights of its upper and lower edges can be read from visual images captured by the high-speed camera. The foam layer height is defined as the difference between the upper and lower edge heights, i.e.:

$$H_{foam} = H_u - H_d$$

where H_{foam} is the foam layer height, H_u is the upper edge height of the foam layer, and H_d is the lower edge height of the foam layer.

This paper employs the method proposed by Moffat for uncertainty analysis of experimental results. presents the uncertainty analysis results for all experimental parameters.

Table 1 Uncertainty analysis of experimental parameters

Parameter	Absolute Uncertainty
ΔT	5.0$×10^{-4}$ K
H_0	5.0$×10^{-4}$ m
H_{foam}	1.0$×10^{-3}$ m

2 Experimental Results and Analysis

2.1 Influence of Superheat on Foam Layer Expansion

The initial superheat in our experiments ranged between 2.9 K and 30 K. A comparison of foam layer height variation with time under different superheat conditions is shown in [Figure 3: see original paper].

The results indicate that greater superheat leads to earlier onset of foam layer expansion and faster height growth, suggesting more intense flash evaporation. This phenomenon occurs because under larger superheat, more liquid phase transforms into vapor phase within the same time period, generating more bubbles and resulting in faster foam layer expansion.

Fig.3 Influence of superheat on foam layer expansion

2.2 Influence of Initial Liquid Film Thickness on Foam Layer Expansion

The initial liquid film thicknesses used in our experiments were 0.1 m and 0.2 m. A comparison of foam layer height variation with time under different initial film thicknesses is shown in [Figure 4: see original paper].

The results demonstrate that larger initial liquid film thickness leads to later onset of foam layer expansion and slower height growth, indicating that flash evaporation proceeds more slowly. This phenomenon arises because as the liquid film thickness increases, the hydrostatic pressure generated by the film becomes non-negligible. The increased hydrostatic pressure reduces the effective superheat, thereby decreasing the driving force for flash evaporation and slowing down the process. This conclusion is consistent with the finding from the previous section that superheat is the driving force for flash evaporation.

Fig.4 Influence of initial water film height on the expansion of foam layer

2.3 Influence of Initial Solution Concentration on Foam Layer Expansion

Mass fraction was selected as the measure of NaCl solution concentration. The initial mass fractions used in our experiments were 0.20, 0.23, and 0.25. A comparison of foam layer height variation with time under different initial concentrations is shown in [Figure 5: see original paper].

The results indicate that foam layer expansion patterns show no significant difference under various initial mass fractions, suggesting that initial solution concentration has almost no effect on foam layer expansion. This occurs because the solute content in NaCl solution primarily affects the bubble nucleation stage, whereas during the subsequent foam-like boiling stage, foam layer expansion mainly depends on bubble generation and rupture rather than the number of nucleation sites. Therefore, solution concentration has minimal influence on foam layer expansion.

Fig.5 Influence of initial water film concentration on the expansion of foam layer

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3.1 Foam Layer Expansion Mechanism

As shown in [Figure 6: see original paper], two opposing effects influence foam layer expansion during flash evaporation: First, at the lower edge of the foam layer, liquid continuously transforms into vapor, with newly generated bubbles attaching to the foam layer bottom, causing the lower edge height H_d to rise by H^+_{foam}, defined as the lower edge increment. Second, at the upper edge of the foam layer, the pressure in the upper space of the flash chamber continuously decreases, increasing the pressure difference between the interior and exterior of bubbles exposed to the vapor space, ultimately causing upper-edge bubbles to rupture and the upper edge height H_u to decrease by H^-_{foam}, defined as the upper edge increment.

Combining with the concept of Non-Equilibrium Fraction (NEF) previously introduced by Miyatake, further derivation yields:

$$H^+ = b \cdot \mathrm{NEF}$$

where b is a proportional coefficient defined as the foam layer expansion coefficient.

The H^- term can be derived through mass and energy balance. During flash evaporation, bubbles at the top of the foam layer continuously rupture, with high-temperature steam continuously escaping. This not only causes the foam layer height to decrease by H^-_{foam}, but also leads to macroscopic temperature reduction in the foam layer. Therefore, the foam layer height decrease can be inferred from the macroscopic temperature drop.

Fig.6 Mechanism of foam layer expansion

3.2 Calculation Model Derivation

In the governing equations, the H^+_{foam} term can be determined based on the bubble radius growth rate formula for isothermal processes obtained previously by Bankoff et al.[5]. In the above equation, the Non-Equilibrium Fraction (NEF) can be directly obtained using the previously fitted correlation for NEF variation with time from our research group[6]. The physical property parameters involved in coefficient B can all be found in NaCl solution property tables, while b is obtained through back-calculation from experimental values and linear fitting with respect to superheat, initial liquid film thickness, and initial solution concentration yields the complete model.

Comparison of Results

[Figure 7: see original paper] compares the calculated and experimental results of foam layer height under different initial conditions, while [Figure 8: see original paper] plots the maximum relative error between model calculations and experimental results. The good agreement demonstrates that the model not only describes the time evolution of foam layer height but also accurately reflects the variation patterns of foam layer expansion with superheat, initial liquid film thickness, and initial solution concentration.

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4 Conclusions

Static flash evaporation experiments were conducted on NaCl solutions with initial liquid film superheat of 2.9~30 K, initial liquid film thickness of 0.1 m and 0.2 m, and initial mass fraction of 0.2, 0.23, and 0.25. Preliminary experimental

and theoretical investigations were performed on foam layer expansion laws, leading to the following conclusions:

1. Under larger superheat, foam layer expansion begins earlier and proceeds faster.
2. Under larger liquid film thickness, foam layer expansion begins later and proceeds slower.
3. Initial solution mass fraction has almost no influence on foam layer expansion laws.
4. Based on classical bubble growth theory and mass-energy balance during flash evaporation, this paper derived a calculation model for foam layer expansion law, enabling prediction of foam layer expansion height variation with time, which shows good agreement with experimental results.

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Note: Figure translations are in progress. See original paper for figures.