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Some experiments on flash evaporation enhancement by electrolytically generated bubbles

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Abstract

Experiments were conducted in a scaled-down stage of a multi-stage flash evaporator at about 100°C to examine the effects of electrolytically generated hydrogen bubbles on flash evaporation. The bubble generator was placed just downstream of the hydraulic jump, in the tranquil single-phase flow region. It was found that these hydrogen bubbles (<0.5 ppb in the solution) have indeed promoted ebullition in flash stage regions where the superheat was otherwise too low for flash evaporation, and have thus reduced the non-equilibrium temperature difference by up to 15%. The energy investment for such bubble generation is negligible.

Keywords: Flash evaporation; Bubbles; Bubble-nucleation; Multi-stage flash evaporation; Electrolysis

1. Introduction

It is well known by now that vapor is released in flash evaporation by both bubble and surface evaporation mechanisms, with the former more prominent wherever the pressure (or the equivalent temperature) difference driving force (i.e., superheat) are sufficient for bubble nucleation or even just for their rapid growth if nuclei are available [1,2]. A simplified but useful way to begin to understand the bubble nucleation and

growth mechanism is the examination of the conditions at which a spherical bubble can be at equilibrium in a liquid at pressure P_l and temperature T_l containing vapor at pressure P_v and dissolved gas at concentration c_g and partial pressure P_g . These conditions are expressed in the steady state by the Laplace equation which shows that the minimal radius (called the critical radius, R_{cr}) at which a bubble will remain in equilibrium in the liquid is

$$R_{cr}(c_g, T_l) = \frac{2\sigma}{P_g + P_v - P_l}, \quad (1)$$

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where σ is the liquid-(gas and vapor) interface surface tension. To nucleate and grow, and thus release vapor from the liquid, the bubble must have at least the radius R_{cr} . Since these radii are orders of magnitude larger than intermolecular distances in the liquid, it is clear that a significant disturbance of the liquid or the liquid/gas solution must be present for nucleating a bubble. This is supported by the general observation that bubbles indeed do not form even for superheats of 60°C if extreme measures are taken to maintain the liquid very quiescent, pure, devoid of any pre-existing bubbles or solid particles, and contained in a meticulously clean vessel which has no surface cavities that could serve as bubble nucleation sites [3]. Obviously, the smaller is R_{cr} , the more likely it is for a bubble to nucleate or start its growth.

Eq. (1) thus shows that the likelihood of bubble nucleation and growth increases with increasing partial pressure of the dissolved gas (which increases with c_g), increasing vapor pressure (which increases with T), and decreasing σ (which decreases with increasing T) and P_t . The fact that the flash evaporation rates increase when the local liquid pressure is decreased was also confirmed in the experimentally validated model by Miyatake et al. [4]. For a given temperature and concentration, bubble nucleation may be facilitated (although no conclusive experimental evidence for that is available yet) if solid particles are present in the liquid to serve as loci for bubble nucleation. More importantly, the need for bubble nucleation in the bubble-flash-evaporation process is diminished significantly altogether, and the evaporation rates are concomitantly increased significantly, if the liquid already contains some small bubbles. The very existence of these bubbles indicates that they have radii of at least R_{cr} , and they would thus serve as nuclei for vapor formed from the liquid due to the available superheat, without the need to supply the pressure/temperature perturbations which are large enough to form the vapor void of radius R_{cr} in a single phase liquid. In MSF stages the liquid contains such bubbles because they are carried

downstream from a variety of bubble generation sources, such as those in which the pressure is reduced abruptly (e.g., pumps, abrupt flow passage changes, deaerators, previous flash stages) resulting in air ingestion, in decrease of the gas-dissolving capacity of the liquid, and in vapor bubble formation.

A very rough evaluation of the potential effect of the infusion of bubble nuclei into a flash stage can be made as follows. At the temperature level of 100°C and other conditions pertinent to the experiment described in this paper, and assuming an air bubble of 0.1 mm radius, the bubble rise velocity calculated from [5] is of the order of 200 mm/s. The water stream has a similar horizontal velocity, about 160 mm/s in the below-described experiments. With a stream depth of 100 mm, the bubble rise time is thus about 0.5 s and the horizontal travel about 80 mm. Using [6–8], one can estimate that for a superheat of 1°C the bubble will grow by evaporation to a diameter of about 1.5 mm by the time it departs from the free surface, having accumulated during its growth a mass of about $0.91(10)^{-8}$ kg vapor. In comparison, the overall amount of vapor produced in a flash evaporator for a water temperature drop of 1°C and flow rate of $(1.27)10^{-3}$ m³/s is $2.3(10)^{-3}$ kg/s. This production can thus be accomplished in its entirety by the injection of $2(10)^{-7}$ kg/s of air, i.e., an air concentration of only about 16 ppm wt in the water, if all of the injected bubbles indeed serve as nuclei for evaporation. Since surface evaporation and entrained vapor bubbles also play an important role in flash evaporation, this calculated amount of air may be a rather conservative estimate.

Exploitation of the opportunity to increase the rate of bubble generation, or just to increase the rate of evaporation into existing bubbles in flash evaporation, by increasing the noncondensable gas pressure P_g or simply by generating noncondensable gas bubbles in the flashing liquid, is simple and intriguing. For example, we have studied the effect of air concentration in flashing water on evaporation rates and approach to equilibrium [1]. The experiments were conducted in

a scaled-down stage typical of MSF evaporators, and the air was introduced by aspiration and mixing into the water upstream of the flashing stage. We found that increasing the inlet concentration of the air to about 6 ppm (from the original value, without air aspiration, of about 1.5 ppm) has increased evaporation rates and thus reduced the nonequilibrium temperature difference by about 33%.

Gas for bubble formation can also be released by chemical or electrochemical reactions in the liquid. For example, a patented system for foam induction [9] is composed of hydrogen peroxide and then silver oxide deposited on alumina and introduced into surfactant-containing water. Oxygen is evolved from the reaction and serves to form the foam bubbles. Incidentally, this reaction is exothermic, and the temperature increase of the foam also helps promote foaming. To promote vapor bubble nucleation in flash evaporation, Drake [10] has proposed (but did not test) that hydrogen bubbles be generated electrolytically in the flashing and predicted that this can be accomplished at negligible energy (0.00065 kWh/1000 gal water produced) and gas (below ppb wt levels) inputs. Miyatake et al. [11] have shown that electrolytic bubble generation in spray-flash jet nozzles produced a significant improvement in the jet breakup and approach to thermal equilibrium. They also noted that the amount of noncondensables added by the electrolysis (29 ppm of the gas-vapor mixture) would have negligible effect on condensation heat transfer.

2. The experiments

Exploratory experiments were conducted in the well-instrumented scaled-down stage typical of MSF evaporators described in [1,2,12] and schematically depicted in Fig. 1, to examine the effect of electrolytically generated hydrogen bubbles on flash evaporation rates in the downstream region of the stage where the bubble formation and growth have already diminished and the flow has become quiescent. This region, identified in Fig. 2, is just past the submerged

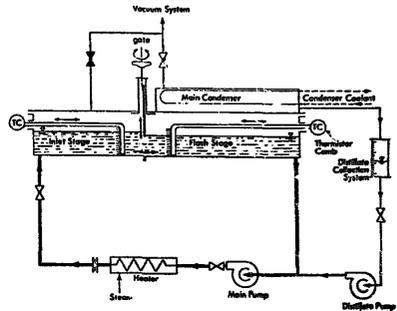


Fig. 1. Simplified flow diagram of the experimental system.

hydraulic jump at the downstream face of the gate. Since the jump region has already exhibited strong bubbling action with the existing bubble nuclei and nucleation and growth mechanisms, it was of some interest here to explore the potential of artificial bubble generation (here by electrolysis) on increasing the evaporation rates and improving the approach to equilibrium in stage regions where the driving force for evaporation (here the local superheat $\Delta T_{s,x} \equiv T_i - T_{l,x}$, where T_i is the water temperature at the stage inlet and $T_{l,x}$ is the water temperature at distance x from the stage inlet) has diminished to values notably smaller than the originally available one, $\Delta T_s = T_i - T_o$, where T_o is the water temperature at the stage outlet. Since most of the intense, bubble-accompanied flashing has taken place upstream of the bubble generator location, it was also easy to observe the histories of the electrolytically generated bubbles. All water temperatures in the stage are taken to be vertically averaged.

The stages of the experimental apparatus have a rectangular cross section 7.8 cm wide. The flash stage is 113 cm long. "Thermistor combs" which contain closely-spaced 0.25 mm diameter thermistors placed in a line vertical to the stage floor and which can measure temperatures with

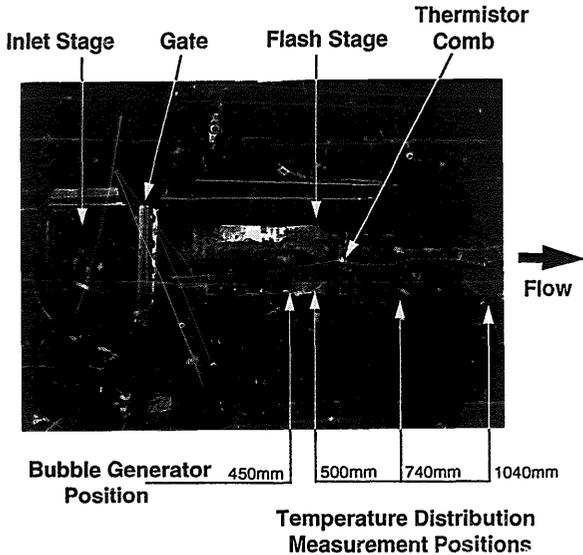


Fig. 2. Photograph of typical flash evaporation in the stage (the bubble generator was not installed in the experiment in which this picture was taken).

an accuracy of $\pm 0.02^\circ\text{C}$ and better were used to measure the temperature distributions in the water and vapor in the stages. One, having 36 thermistors, was positioned in the inlet stage and one, having 68 thermistors, in the flash stage, and they both were traversable along the flow direction. More details about this experimental apparatus can be found in [12].

An electrolytic hydrogen bubble maker was manufactured based on [13] and placed in the flashing stream at a distance of 450 mm downstream of the gate upstream face. It has a DC circuit in which the anode is a 0.0025 in. Nichrome wire and the cathode are the wall of the stage. Passage of current through the circuit causes electrical dissociation of the water and production of hydrogen bubbles at the wire (anode). At a current of 0.1 A (the voltage was

about 20 V), the hydrogen production rate is $0.695(10)^{-3}$ l/min. The Nichrome wire was kinked at intervals of about 3 mm because the sharp corners of the kinks consistently produce bubbles. The bubble maker was screwed into the stage floor (Fig. 3), centered between the side walls.

Noncondensable gas content in the water prior to the introduction of the electrolytically generated gases was measured from water samples taken at the stage exit by a system built for that purpose, which resembles the Van Slyke apparatus [14]. It was determined by calibration that its accuracy was about 0.07 ppm wt of gas.

The water-filled experimental system was deaerated prior to each experiment by means of a vacuum pump connected to both stages (Fig. 1). The remaining content of noncondensables (pri-

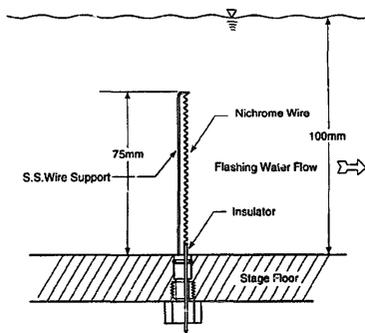


Fig. 3. Electrolytic bubble generator.

marily air) in the water was measured to be typically 2.6 ppm. The vacuum pump was also used to continuously vent the noncondensables during the experiments at a rate that kept the stage vapor-space pressure constant, meaning that the rates of noncondensables venting and evolution were equal.

To properly evaluate the effect of bubble generation on flashing, a flashing experiment with deaerated water *without* electrolysis was conducted once just before (Run 1) and once just after (Run 3) the experiment in which bubbles were generated electrolytically (Run 2H). All three experiments had the same conditions: water mass flow rate of the flashing water: 1.26 kg/s; water level 100 mm, gate opening 9.7 mm; and the inlet temperatures as described in Table 1. In the experiment with electrolytic hydrogen bubble

generation, the hydrogen generation rate was $1.885(10)^{-10}$ kg/s. Since this would at most generate a hydrogen concentration of 0.1 ppb wt in the water, it was negligible compared with the concentration of other noncondensables and no need was seen to actually measure it.

3. Results

The hydrogen bubbles evolving from the bubble generator had a diameter range of 0.1–0.25 mm, less than half the size of the air bubbles which evolved from supersaturated water in the experiments described in [1]. They have grown rapidly and departed from the free surface at various distances downstream from the bubble generator. The temperature distributions were measured at three locations along the stage: 500 mm (i.e., 50 mm downstream of the bubble generator), 740 mm, and 1040 mm. They are shown in Fig. 4. It is obvious that the measurement of the very small and inherently fluctuating temperature differences, complicated to some extent by process control instabilities which are at least of the order of the magnitude of these differences, is not easy, and thus the results cannot be precise. Nevertheless, examination of this figure and Table 1 show that the addition of hydrogen bubbles has consistently improved the approach to equilibrium, reducing the local non-equilibrium temperature difference $\Delta' = \bar{T}_w - T_v$ by up to 15% (\bar{T}_w is the vertically averaged temperature of the flashing water at a location along the stage, and T_v is the vapor temperature in the stage).

Table 1
Experimental conditions and results

Run No.	Inlet temperature, T_p , °C	Interstage superheat, ΔT_{sp} , °C	Δ' , °C		
			@ 500 mm	@ 740 mm	@ 1040 mm
1	99.16	1.75	0.48	0.46	0.42
2H	99.19	1.75	0.47	0.39	0.38
3	99.29	1.79	0.48	0.44	0.43

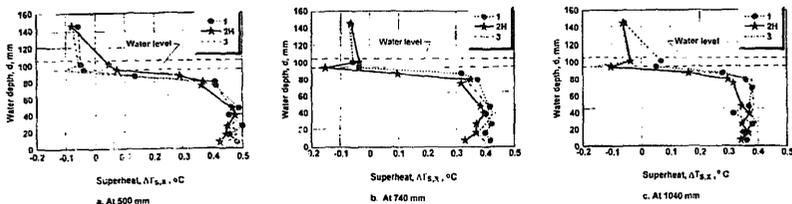


Fig. 4. Temperature distributions in the stage $\Delta T_{s,x} \equiv T_{w,x} - T_v$, where subscript x refers to a location x along the stage. Hydrogen bubbles were released into the water in Run 2H; Runs 1 and 2, without gas addition, were made for comparison.

Fig. 4a also shows that the temperature near the water surface at the location closest to the bubble generator is slightly elevated when bubbles are generated. It is likely a consequence of bubbles departing from the surface and thus spraying the thermistors at that position with superheated water.

4. Conclusions

We have shown that electrolytically generated hydrogen bubbles have indeed promoted ebullition in flash stage regions where the superheat was otherwise too low for flash evaporation, and thus have increased evaporation rates, resulting in a reduction of up to 15% in the nonequilibrium temperature difference. This was accomplished with the addition of less than 0.5 ppb wt of hydrogen.

Flash evaporation enhancement by the addition of gas bubbles is effective and requires negligible energy and gas input. The minute amounts of gas needed are not expected to affect condensation heat transfer coefficients in the condenser/feedwater-heater adversely, and the current venting systems for the stages should be quite adequate in accommodating that small extra load.

Studies of this technique in a wide range of pertinent parameters are recommended.

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