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THE EFFECT OF GAS BUBBLES ON FLASH EVAPORATION

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ABSTRACT

The effect on evaporation rates of air content in flashing water was investigated experimentally in a scaled-down open-channel flash evaporator. The water was at 97°C-98°C, the flash-down temperature differences were up to about 2°C, and air content was up to 6.32 ppm. The ratio $(\Delta T_s/R_c)$, of the local liquid superheat to the equilibrium radius of bubbles was proposed as the correlating parameter for the flash-evaporation heat transfer Stanton Number, and a correlation was developed. The presence of air in the water was found to have an important influence on the process: both the Stanton Number and the approach to equilibrium of the flashing water were seen to improve with air concentration.

SYMBOLS

A_e	Area of liquid free surface
C_p	Specific heat
D	Depth of stream in stage
D_{sg}	Gate opening
G	Mass flow rate of liquid
h	Heat transfer coefficient
H	Henry's Law constant
P	Pressure
R	Bubble radius
R_c	Radius of bubble in equilibrium ("critical radius")
St	Stanton Number
t	time
U	Average liquid velocity in channel

Greek

α	Thermal diffusivity
ΔT_s	Liquid superheat, T_L-T_v
λ	Latent heat of evaporation
ρ	Density
σ	Surface tension

Subscripts

d	Due to fluid-dynamic effects
g	Gas
i	In inlet stage
L	Liquid
m	Maximal
sg	At sluice gate
v	Vapor
x	Distance along channel

INTRODUCTION

The principal objective of this study is the investigation of the effect of noncondensable gas present in water, on flash evaporation of free-surface water streams. Experiments were conducted for that purpose, and the data were

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correlated and analyzed.

As discussed and shown in several previous studies on flash evaporation of free-surface streams (cf. [1,2]), the vapor is released due to both surface evaporation and boiling. The latter process is particularly important, being associated with the nucleation, growth, and violent motion of many bubbles, which account for the major part of the generated vapor due to their large vapor-liquid interfacial area, and the effective turbulent convection of heat from the liquid to these interfaces. Various impurities serve as sites for bubble nucleation. These sites may consist of vapor or gas bubbles trapped in surface-crevices or present in the bulk liquid, and of solid particles suspended in the liquid. The effect of such impurities on lowering the superheat needed for bubble nucleation becomes evident upon examination of Gibbs' equation (1) which describes the equilibrium conditions for a spherical bubble:

$$P_v - P_L = \frac{2\sigma}{R_c} \tag{1}$$

The superheat ($P_v - P_L$) can be reduced by:

a) Increasing the radius R, by the initiation of the nucleus on an existing gas bubble or solid impurity, b) Increasing the pressure inside the bubble nucleus by the presence of a noncondensable gas (adding P_g to P_v), c) Decreasing the pressure P_L of the liquid surrounding the nucleus, such as in cavitation, and d) Decreasing the surface tension σ, by the addition of surfactants for instance.

The pressure reduction in c) above may occur due to the dynamic action of the streaming liquid as in cavitation [3]. The reduced pressure can be either steady or fluctuating. The negative portion of the fluctuation could lead to gas release, and nucleus formation.

Of particular interest to multistage-flash evaporation are the cavitation conditions for flow under sluice gates. Information on this subject is rather scant and pertains only to large hydraulic structures (cf. [4-6]). Nevertheless, it is clearly shown that cavitation occurs in such structures at regions of irregularity of the stream boundary, such as gate and guide edges and the downstream hydraulic jump (cf. [7-9]).

Although suspended solid particles are typically discounted as the source of cavitation in clear liquids (as indicated above), they may well have an influence in the flashing of seawater, which contains silt, algae, and plankton [10]. In the experiments conducted here, however, the stream to be flashed was recirculated through a 5 μ filter, thus essentially eliminating the influence of solid particles.

When the size of a bubble nucleus exceeds the critical value given by eqn (1), the bubble will grow. A few milliseconds after the growth has begun, the inertia and the surface tension forces could be neglected and the growth is governed by the rate at which heat can be supplied from the superheated liquid to the bubble interface. The asymptotic solution at this stage can be approximated by [11]:

$$R = \rho_L \frac{c_{pL}(\pi\alpha_L)^{\frac{1}{2}}}{\lambda\rho_g} \Delta T_s \sqrt{t} \tag{2}$$

The liquid superheat ΔT_s is obviously the primary driving force for bubble growth.

THE PROPOSED MODEL

In an attempt to determine a good way to correlate the evaporative heat flux to the most influential process parameters, the discussion above leads to the tentative conclusion that this flux will increase with the number of bubble nuclei which can be destabilized to grow, with the liquid's superheat ΔT_s which is the driving potential for bubble growth, and with the rate of supply of sensible heat for the evaporation process.

The potential of bubble nucleation is somehow related to the critical radius of the bubbles in the liquid: the larger this radius needs to be to prevent bubble collapse, the less is the probability that conditiions would be present for bubble nucleation. The Gibbs quation, rewritten to include the effects of gas (P_g) and of flow-induced pressure fluctuation ($\pm\Delta P_d$) is

$$R_c = \frac{2\sigma}{(P_v - P_L) + P_g + \Delta P_d} \tag{3}$$

Assuming that the partial pressure of the gas in the nucleus attains its equilibrium value, and for small gas concentrations, Henry's Law can be applied to calculate P_g from the gas concentration in the liquid, (cf. [12]):

$$P_g = Hc_g \tag{4}$$

where H is Henry's Law constant (here approximately 0.07 atm/ppm).

The relation of the dynamic pressure component ΔP_d to the liquid velocity is quite complex, since it depends on many variables, including geometry, turbulence, and upstream flow conditions. As a first attempt to characterize this value, the observations made by Arndt and Daily [13], and others [7-9], that cavitation occurs when the mean static wall pressure exceeds the critical pressure by at least 5% of the free-stream dynamic pressure, would be used:

$$\Delta P_d = (0.05)\tfrac{1}{2}\rho U^2 \tag{5}$$

Substituting eqns (4) and (5) into (3) gives

$$R_c = \frac{2\sigma}{(P_v - P_L) + Hc_g + 0.025\rho U^2} \tag{6}$$

As seen from eqn (3), the minimal radius needed to maintain a stable bubble can be lowered as the liquid superheat $(P_v - P_L)$ increases, as the concentration of the gas in the bubble increases, and as the stream velocity increases.

At this first attempt for correlation, it would be assumed that the flash evaporation rate is inversely proportional to R_c. Consequently, the general functional relationship of the flash evaporation heat transfer coefficient h can be expressed as

$$h = h(\rho c_p U, \Delta T_s, R_c^{-1}) \tag{7}$$

which leads to the proposal of a correlation

$$\frac{h}{\rho c_p U} = St = f(\Delta T_s / R_c) \tag{8}$$

where the Stanton Number St is a function of the parameter $\Delta T_s/R_c$.

In the open-channel horizontal flash evaporator studied here, h between streamwise positions x_1 and x_2 can be determined by using the LMTD:

$$h_{x_{1,2}} = [G\ c_p\ \ln(\Delta T_{sx_1}/\Delta T_{sx_2})\ ]\ /\ A_e \tag{9}$$

The wall-jet results of Myers et al. [14] were adapted for the determination of the local average channel velocity U to be used in eqn (6), and for the determination of T_{x_1} and T_{x_2} in eqn (9), from the experimental results.

THE EXPERIMENT

A scaled-down, well-controlled flash evaporator, described in detail in [15], was used in the experiments. The evaporator consists of an evaporating stage, 113 cm long, with an overhead full-length condenser and of a nonflashing flow-straightening inlet stage, 73 cm long (Fig. 1). The stages have a rectangular cross-section, 7.8 cm wide.

A multi-probe differential temperature measuring system (the "thermistor comb"), has been developed and utilized for the determination of temperature profiles along a line vertical to the stage floor, in both the liquid and vapor regions, to an accuracy of ±0.02°C and better. It can be moved and positioned at any location along the stage.

For typical experiments, the system was carefully dearated prior to taking data, and was vented during the experiments (by a vacuum pump) to eliminate noncondensables. In the experiments where the influence of air on flashing is being investigated, air was injected into the stream at the heater inlet.

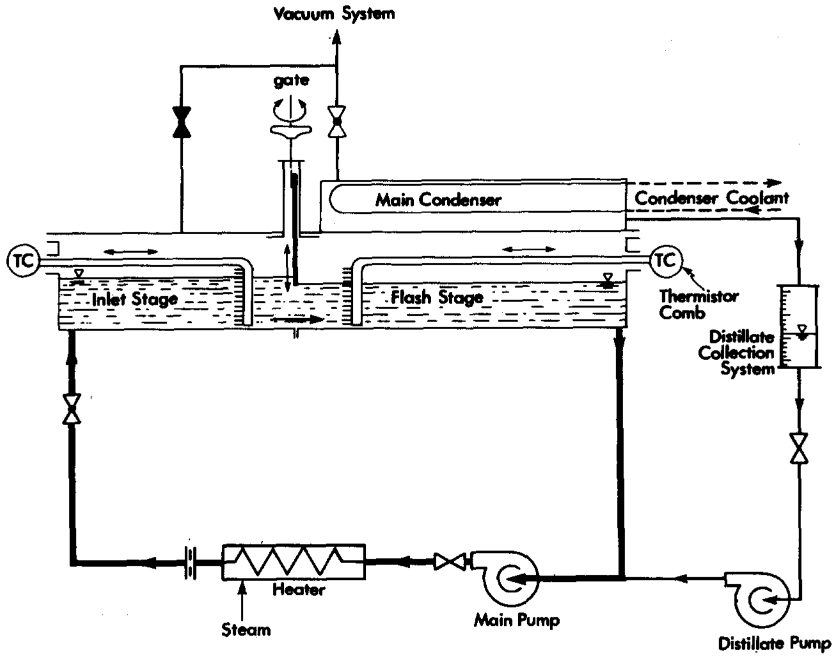

Fig. 1. Simplified Flow Diagram of the Experimental System

The long path from the heater to the flash evaporator, and the passage through the flow-control valve, allow the air to form many small bubbles by the time it arrives to the evaporator. The concentration of air in liquid was determined by a system built for that purpose, which resembles the Van Slyke apparatus (cf. [16]), and which has an error smaller than 0.3 ppm. The water samples were withdrawn at the exit from the flash evaporator stage.

RESULTS AND DISCUSSION

The results are shown in Table 1, and the temperature profiles along the channel are shown in Fig. 2. It was found that the major influence on R_c (eqn 6), for a given σ , is of the air concentration. Calculations were made to examine the effect of 0.5 ppm air, and are shown in Table 1 for runs 8, 9, and 10, to compare them to the dearated case. It can be seen that an air concentration of 0.5 ppm has an effect approximatly equivalent to that of 1°C superheat, and is, in the other runs, the dominant term in determining R_c. The calculated effect of the velocity-driven pressure fluctuations was found to be very small, of the order of 1% of the total pressure inside the bubble, and could have probably been neglected in the calculation of R_c. It is noteworthy though that this effect was calculated for the average velocities in the channel. The actual local velocities may be higher than the average by one-to-

TABLE 1: Experimental Results

Run #	T_v, °C	P_v, Bar	G, kg/s	$\bar{D}_i$, mm	D_{sg}, mm	$\bar{D}$, mm	c_g, ppm	x, mm	U_x, m/s	ΔT_s, °C	R_c, μ	$(\Delta T_s/R_c)$, °C/mm	St x 10^2	h, kW/m^2C
1	97.5	0.936	1.27	30	6.0	93	5.95	12	2.49	1.23	2.53	332.0	3.5	223.0
								300	1.16	0.48	2.69	161.0	1.7	70.9
								500	0.94	0.39	2.71	130.0	0.8	25.0
								1040	0.67	0.32	2.73			
2	98.3	0.956	1.27	30	7.0	96	6.32	12	2.16	1.04	2.43	310.5	3.1	178.4
								300	1.06	0.49	2.54	166.6	2.8	105.2
								500	0.86	0.36	2.57	114.5	2.0	56.6
								1040	0.62	0.23	2.59			
3	97.4	0.923	1.28	35	6.6	94	5.41	12	2.30	0.89	2.84	227.7	2.4	133.1
								400	0.98	0.42	2.97	117.4	1.4	43.6
								1040	0.64	0.28	3.00			
4	97.2	0.928	1.27	32	4.5	107	6.30	12	3.24	1.54	2.34	443.6	3.0	231.4
								300	1.37	0.58	2.53	196.7	2.2	110.2
								500	1.10	0.42	2.56	140.0	1.2	42.5
								1040	0.78	0.30	2.59			
5	96.8	0.917	1.27	40	9.5	100	1.86	400	0.79	0.51	7.86	55.2	1.4	34.2
								1040	0.52	0.37	8.14			
6	97.0	0.910	1.27	30	9.0	100	3.78	400	0.81	0.52	4.12	117.2	0.6	15.4
								1040	0.54	0.45	4.16			
7	97.1	0.914	1.28	38	9.0	100	2.70	400	0.82	0.53	5.61	79.3	1.5	38.6
								1040	0.54	0.37	5.77			
8	97.5	0.942	1.26	32	9.5	100	0.00*	12	1.60	2.04	15.70			
							(0.50)*				(10.67)	79.7	5.4	267.8
								200	1.00	0.97	33.10	(124.7)		
											(16.60)	20.7	2.3	72.2
								620	0.65	0.62	51.80	(44.5)		
											(20.31)	10.5	1.0	22.3
								1040	0.52	0.54	59.60	(27.9)		
											(21.40)			

TABLE 1 (cont)

Run #	T_v, °C	P_v, Bar	G, kg/s	$\bar{D}_i$, mm	D_{sg}, mm	$\bar{D}$, mm	c_g, ppm	x, mm	U_x, m/s	ΔT_s, °C	R_c, μ	$(\Delta T_s/R_c)$, °C/mm	St x 10^2	h, kW/m^2C
9	96.9	0.918	1.26	30	7.6	120	0.00*	12	1.98	2.44	13.09			
							(0.50)*				(9.40)	101.5	4.7	241.8
								350	0.94	0.73	43.87	(149.0)		
											(18.96)	11.6	3.2	104.2
								650	0.72	0.46	69.65	(29.4)		
											(22.57)	5.9	0.8	21.6
								1010	0.59	0.41	78.29	(18.9)		
											(23.41)			
10	97.2	0.910	1.85	40	15.0	120	0.00*	12	1.52	1.04	30.59			
							(0.50)*				(15.97)	22.6	3.2	141.0
								400	0.86	0.60	53.36	(47.2)		
											(20.54)	9.1	2.6	80.9
								700	0.70	0.47	68.22	(25.1)		
											(22.40)	5.94	1.8	47.2
								1040	0.59	0.40	80.24	(19.0)		
											(23.58)			

*Assumed values

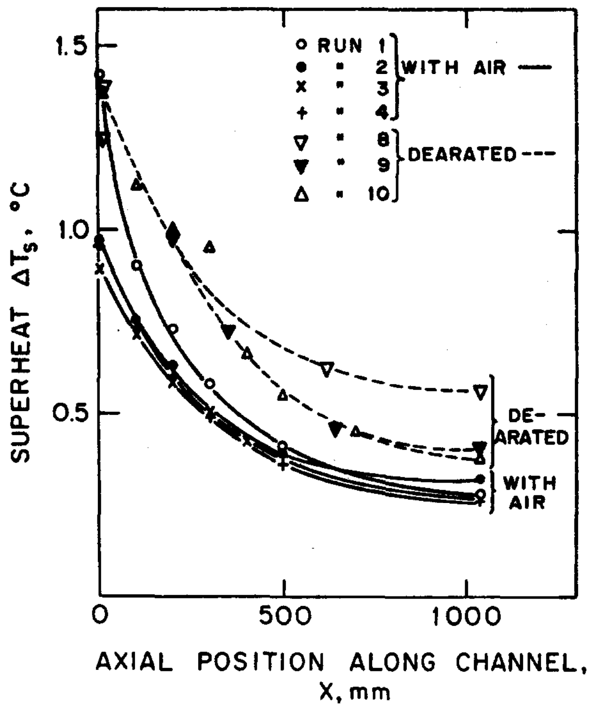

Fig. 2. Variation of the Liquid Superheat ΔT_s Along the Flash Evaporator Stage

two orders of magnitude, particularly right next to the gate, where they could have a major contribution to bubble nucleation.

Figure 2 shows that the aerated water approaches equilibrium at the exit from the stage significantly closer than dearated water, a 33% improvement approximately. It also shows the large rates of evaporation at the inlet to the stage, and their exponential decay with distance along the channel. This is also evident in the values of the evaporation heat transfer coefficient h (Table 1).

Figure 3 shows the experimental data plotted as suggested by eqn (8). It became obvious that the data for aerated water and those for dearated water (assuming zero air concentration for the latter) clustered separately. A least-squares regression analysis provided the following relationship for the dearated water:

$$St = (5.81)10^{-3} (\Delta T_s/R_c)^{0.49} \tag{10}$$

and for water containing air

$$St = (8.14)10^{-4} (\Delta T_s/R_c)^{0.61} \tag{11}$$

where $(\Delta T_s/R_c)$ is in °C/mm.

It was observed experimentally that water thought to be dearated, actually contained some air, typically about 1.5 ppm. Recalculation of the values of $(\Delta T_s/R_c)$ for that concentration brought the results much closer to those predicted by eqn (11), as shown in Figure 4.

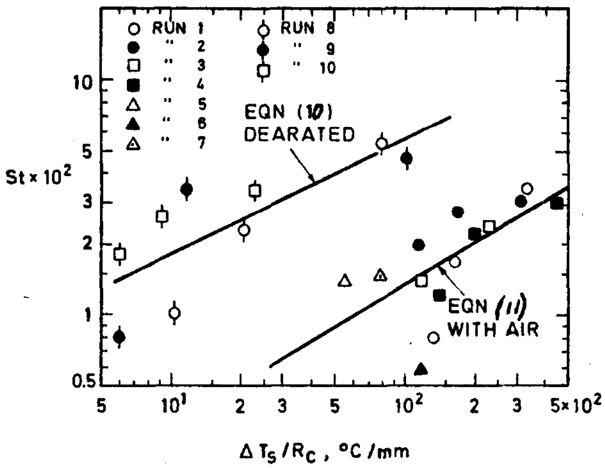

Fig. 3. Correlation of the Stanton Number with $(\Delta T_s/R_c)$.

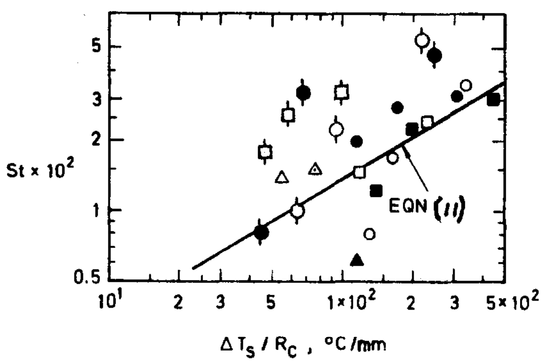

Fig. 4. Correlation of the Stanton Number with $(\Delta T_s/R_c)$. The water used in Runs No. 8, 9, and 10 is assumed to contain 1.5 ppm air (the symbols for the experimental points are the same as those described in Fig. 3).

The scatter of the data is rather large and it is obvious that additional parameters influence the process. For example, St here is determined as an average for a relatively large area, whereas the ebullition processes are strongly localized and vary exponentially with distance. This points to the need to obtain local measurements both of the thermal and fluid-mechanics aspects of the problem. At the same time, Figs. 3 and 4 indicate an obvious trend of increasing St with the parameter ($\Delta T_s/R_c$), which increases primarily with ΔT_s and gas concentration.

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