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Formulas for Calculating the Approach to Equilibrium in Open Channel Flash Evaporators for Saline Water

NOAM LIOR

Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, PA 19104 (U.S.A.)

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SUMMARY

The evaporator used in multistage flash desalination plants, and considered for open cycle ocean-thermal energy conversion (OTEC) plants is the open-channel type, in which an essentially-horizontal stream of seawater is passed through an open channel in which it is exposed to a pressure lower than the saturation pressure which corresponds to its temperature. This paper reviews the equations used at present to determine the nonequilibrium allowance Δ' which indicates how far from equilibrium the seawater stream is as it leaves the evaporator.

Flash evaporation in open channels is used in most of the water desalination plants, and the existing equations for Δ' have been developed for that application. The equations are typically empirical correlations, each developed for one type of geometry and range of parameters. The equations are compared graphically, plotted side-by-side to express Δ' as a function of the major parameters: stage saturation temperature, stage flash-down, flashing seawater flow rate, stage length, and flashing seawater depth.

It was found for water desalination applications that there exists a large spread between the non-equilibrium fraction values calculated by the different equations, of about one order of magnitude. The situation is even worse for OTEC conditions. Consequently, it was concluded that no general method exists for the adequately accurate prediction of Δ', i.e. of the approach to equilibrium of flashing free stream channel flows.

SYMBOLS

A and B	— constants from the relation $P = Ae^{BT}$ (Eqs. 16, 17), calculated for a 5% NaCl solution

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*The units used in the equations are shown in their SI; British forms.

A_x — cross-sectional area of brine flow in the stage at location x along it, ft.^{2}
BPE — boiling point elevation, °C; °F
c_p — heat capacity
C — salt concentration, ppm
G — flow rate, ft.^{3}/s
h — liquid depth, m; in.
H — level of flashing liquid, m; in.
k — evaporation coefficient, Eq. (16)
K — flashing coefficient, Eq. (17), $K = 16\, n\pi$
J_a — $C_p \rho \Delta T/\rho_v \lambda$, nondimensional
L — stage length, m; ft.
M — (T_{Bi}) — (outlet temperature of condenser coolant) or (T_{Bo}) — (inlet temperature of condenser coolant), °C; °F
n — number of bubbles (liquid—vapor interfaces in the liquid)
P — pressure
P_{vo} — vapor pressure at mean exit liquid temperature, mm Hg
ΔP — actual pressure drop across the stage, i.e., (vapor pressure of incoming liquid) — (stage saturation pressure)
ΔP_B — stage pressure drop. Values are taken from the respective values of saturation pressure as equivalent to ΔT_B for the given temperature
ΔP_{vf} — vapor pressure difference between the vapor pressure of the liquid at T_{Bi} and that of the liquid at T_{Bo}, mm Hg
T_B — mean liquid temperature, °C,; °F
T_{Bi} — mean liquid temperature at stage inlet, °C; °F
T_{Bo} — mean liquid temperature at stage outlet, °C; °F
T_{Boa} — T_{Bo} (absolute temperature), K; °R
ΔT_B — stage flashdown defined by $(T_{Bi} - T_{Bo})$, °C; °F
ΔT_s — superheat defined by $(T_{Bi} - T_{vm})$, °C; °F
ΔT — $\Delta T_B + \Delta'$, °C; °F
T_v — stage saturation vapor temperature, °C; °F
T_{vm} — mean vapor space temperature, °C; °F
V_g — vapor specific volume (at T_v unless otherwise specified), m^3/kg; ft.^{3}/1b
w — liquid flow rate per unit stage width, kg/h m; 1b/h ft.
W — flow rate of flashing seawater, kg/h m width
λ — heat of vaporization, J/kg; Btu/lb
Δ' — nonequilibrium allowance, Eq. (2), °C, °F
Δ'_x — Δ' at location x, °C; °F
Δ'_{10} — Δ' for a 10-ft. stage, °C; °F
ρ — density of brine, kg/m^3; 1b/ft.^{3}
ρ_v — vapor density, kg/m^3; 1b/ft.^{3}

INTRODUCTION

The open-channel flash evaporator is used widely in the multi-stage flash distillation process for water desalination [1—3] and has been proposed for use as the steam generator in the open cycle ocean—thermal energy conversion (OTEC) process [4,5]. The configuration of such an evaporator is very simple: a free-surface stream flows through a horizontal (or slightly inclined) channel, and releases vapor along the way.

The process of flash evaporation occurs when a liquid is exposed to a pressure lower than the saturation pressure which corresponds to its temperature. In contrast to other evaporation processes for which heat is supplied to the liquid from outside, sensible heat stored in the liquid as superheat is converted during the flash evaporation process into latent heat of evaporation. If left alone (i.e., insulated and with no further reduction in the pressure), the system will approach an equilibrium state as the average temperature of the liquid approaches some asymptotic value. The temperature difference between this equilibrium state and the average temperature of the liquid is the minimal superheat required to overcome the various effects which inhibit flashing.

The first of these effects is the Boiling Point Elevation (BPE). At a given pressure, it is the increase in the boiling temperature due to the salts dissolved in the water.

A second effect is the resistance to vapor bubble production which results from the work needed to separate the water and to form the curved interface by overcoming the surface tension and the surrounding hydrostatic pressure. This can be explained by the balance of forces on the bubble

$$P_2 = P_1 + \frac{2\sigma}{r} \tag{1}$$

where P_2 is the pressure inside the bubble and P_1 in the surrounding liquid, σ is the surface tension, and r the bubble radius. For equilibrium, i.e., just to keep the bubble from collapsing, P_2 has to be larger than P_1 by the amount contributed by the surface tension. The vapor in the bubble is saturated at T_2 which is the temperature at the interface. Since P_1 is smaller than P_2, the liquid close to the interface must be superheated. Furthermore, a temperature gradient must be established in the liquid for heat to flow to the bubble—liquid interface, if vapor production is to occur.

The third retarding effect results from the hydrostatic pressure. As the pressure increases with depth, so does the saturation temperature. The available liquid superheat decreases correspondingly, and it may vanish in some cases. A flashing penetration depth is thus established, below which no flashing occurs.

Another possible effect is the contamination of the liquid by materials which may retard evaporation, such as various organic substances [6]. It is hard to prevent the intrusion of small amounts of such materials, which originate either in an imperfectly cleaned evaporator, or from the feedwater. Even small quantities, which tend to migrate to evaporating interfaces, may have severe effects on inhibiting evaporation rates. It should also be noted that in some cases, surface-active impurities may induce foaming and thus enhance evaporation by improving the heat transfer rates through the liquid [7,3].

A major portion of the work related to flash evaporation has been done for multistage flash evaporators used in water desalination. A typical stage is shown in Fig. 1.

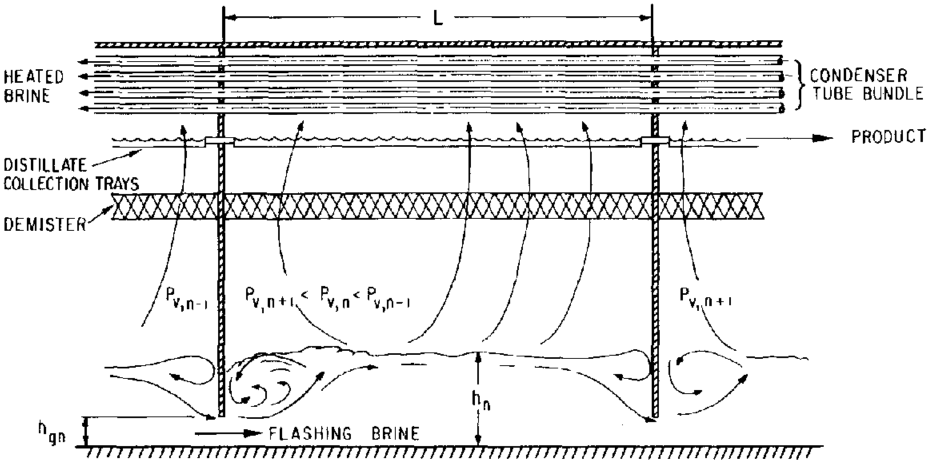


Fig. 1. The *n*th stage of a multistage flash evaporator.

The liquid flows through the inlet orifice into a region where the pressure is lower than its saturation pressure. Flashing is initiated, and the liquid cools down as it evaporates and flows towards the exit. Since it usually cools increasingly as the free surface is approached, a temperature gradient is created. The temperature at the surface is the stage saturation temperature plus the BPE, and it increases towards the bottom due to the effects mentioned above. Thus, the liquid leaving the stage has an average temperature higher than would be expected. (Ideally, we would expect the liquid to be in equilibrium with the vapor at the stage saturation temperature plus the BPE). For a given vapor temperature T_v, the difference between the mean liquid temperature, T_B, and the superheated vapor temperature (that is: T_v + BPE) is called Δ': the nonequilibrium allowance.

$$\Delta' \equiv T_B - T_v - \text{BPE} \tag{2}$$

Some investigators include BPE in Δ' and define this as $\Delta' t$

$$\Delta' t \equiv T_B - T_v \tag{3}$$

In the rest of the paper, the symbol Δ' will refer to the conditions at stage exit. In general, Δ' varies with stage length and can be defined at any position (Fig. 2). The decrease of Δ' would obviously result in the driving potential being used to a fuller extent, and thus more vapor will be produced for a given stage length.

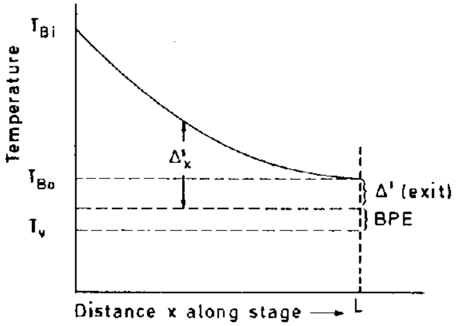


Fig. 2. A qualitative description of the nonequilibrium allowance Δ'_x as a function of location x along stage.

The experimental data obtained from the research performed so far indicate that the major parameters affecting Δ' are:

(a) Liquid level (stream depth). Increasing level will cause an increase in Δ' because of the hydrostatic suppression of bubble nucleation and flashing.

(b) Flow rate and stage length combination determine the residence time of the liquid in the stage. Since flash evaporation is a rate process, Δ' decreases as the residence time increases. Therefore, letting the liquid flash for a longer time (for a longer stage or smaller flow rate) will result in a smaller Δ'.

(c) Temperature. It was found that Δ' decreases as the temperature of the flashing liquid increases. This is mainly because the saturation pressure-versus-temperature slope of water increases strongly with temperature. Consequently, smaller temperature differences are needed at the higher temperature levels to generate bubbles (see Eq. 1) for any given hydrostatic head (stream depth).

(d) Stage flashdown temperature drop ΔT_B: Δ' decreases with increasing ΔT_B, where

$$\Delta T_B = T_{Bi} - T_{Bo} \tag{4}$$

This temperature difference is the driving force for the evaporation process, affecting both bubble nucleation and evaporation rates, and its increase obviously reduces the Δ'.

(e) Flow pattern. Flashing can be enhanced and thereby Δ' decreased by directing the incoming flow towards the free surface where the hydrostatic suppression effect is diminished, or by increasing turbulent mixing in the stream whereby heat is transferred more rapidly to the evaporating interfaces.

Other factors such as stage geometry, stage-to-stage liquid transfer aperture size and shape, and chemical treatment also affect Δ'.

To be able to design a flash evaporator, it is necessary to know the quantitative relationship between the Δ' and the process parameters and stage geometry. No satisfactory analytical results exist for that purpose, principally due to the complexity of the heat transfer and fluid mechanics in the process [3,8,9]. Consequently, several groups have developed empiricaly correlations from their own experiments, usually in an attempt to satisfy their own design needs. The use of different experimental facilities and sometimes different definitions and terminology make the general use and comparison of these correlations somewhat difficult.

This paper describes twelve different equations for Δ' and compares their dependence on the major parameters: liquid saturation temperature, flash-down temperature difference, water flow rate, stage length and stream depth. The comparison is performed for two water temperature ranges: 20—140°C (centered around a vapor temperature of 70.44°C, 175°F) for water desalination applications, and 20—50°C (centered around a vapor temperature of 30°C) for OTEC evaporator applications.

NONEQUILIBRIUM ALLOWANCE CORRELATIONS

The correlations are listed according to their authors:

American Machine & Foundry Co.

AMF Eq. no. 1 [10]

Their first equation is based on experiments conducted in a two stage plant. Information about the stage geometry was not provided in the reference. The first stage was the test stage but it is not known whether the second (downstream) stage was flashing too.

In SI units

$$\Delta' = 2.19 \exp\left[2.76h + (0.032w)(10^{-5}) - 0.0641T_{\mathrm{vm}}\right] \tag{5}$$

In British units

$$\Delta' = 12.3 \exp\left[0.07h + (0.476w)(10^{-6}) - 0.0356T_{\mathrm{vm}}\right] \tag{5a}$$

With all other parameters remaining constants, Δ' was found to be invariant for $1.1°\mathrm{C} < \Delta T_{\mathrm{B}} < 3°\mathrm{C}$.

AMF Eq. no. 2 [10]

A second equation developed by AMF [10] was based on the 3-stage unit which was a modification of the 2-stage unit mentioned above. An additional stage was added with the middle stage being the test stage. This arrangement resulted in a more realistic simulation of the *n*th stage in a multistage flash evaporation plant where the stage is preceded and followed by active stages. In addition, adjustable louvers were installed to prevent impingement on the demistors by the splashing brine, and thereby stage capacity and distillate purity were increased.

The stages were contained in a steel cylinder with 1.22 m diameter, and the brine flow was confined between two vertical plexiglas walls 0.305 m apart. The first stage was 1.42 m long, the second (test stage) 3.45 m, and the third 1.83 m. Full-width (0.305 m) rectangular orifices were used with adjustable vertical opening from 0 to 0.51 m. Each stage had its own condenser while the condenser coolant flowed in series from the third to the first stage. For more complete details, refer to Fig. 3.

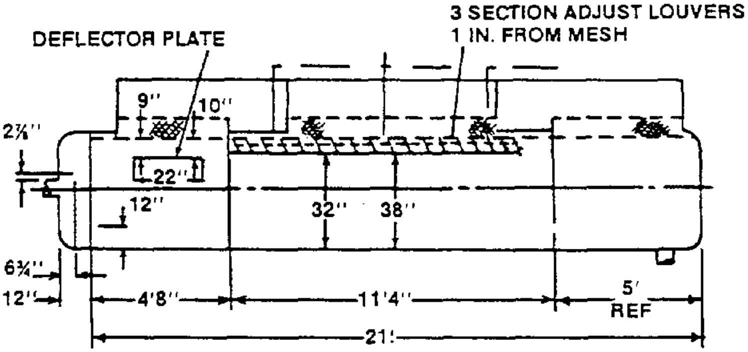


Fig. 3. Experimental 3-stage flash evaporator used for deriving AMF eqs. Nos. 2 and 3.

In SI units

$$\Delta' = 0.156 h^{0.86} V_g^{0.71} (w \times 10^{-5})^{0.455} \Delta T_B^{-0.5} \tag{6}$$

In British units

$$\Delta' = 0.00267 h^{0.86} V_g^{0.71} (w \times 10^{-5})^{0.455} \Delta T_B^{-0.5} \tag{6a}$$

where V_g is the specific volume of saturated vapor corresponding to the mean exit brine temperature (ref. 10, p. 17).

When compared by the Catalytic Co. [11], AMF eq. 2 was found to be closer to measured Δ' than AMF eq. 1.

AMF Eq. no. 3 [12]

AMF eq. 2 was modified to include an additional parameter M which is defined as follows

$$M \equiv (T_{Bi}) - (\text{outlet temperature of condenser coolant}) \tag{7}$$

or

$$M \equiv (T_{\mathrm{Bo}}) - (\text{inlet temperature of condenser coolant}) \qquad (7a)$$

In SI units

$$\Delta' = h^{0.86} V_{\mathrm{g}}{}^{0.71} M^{0.19} (w \times 10^{-5})^{0.17} / 6.1488\, \Delta T_{\mathrm{B}}^{0.5} \qquad (8)$$

In British units

$$\Delta' = h^{0.86} V_{\mathrm{g}}{}^{0.71} M^{0.19} (w \times 10^{-5})^{0.17} / 449\, \Delta T_{\mathrm{B}}^{0.5} \qquad (8a)$$

It was found by AMF that their eq. 3 reduced the difference between the measured and calculated Δ' to half as compared to that obtained by using their eq. 2 [12]. When used with data from tests where an evaporation enhancer had been incorporated, their eq. 3 gave results only slightly higher than those obtained by measurement, while their eq. 2 gave much higher values of Δ'.

The brine used in the AMF experiments was concentrated sea water, deaerated and acidified, with concentration maintained at about 1.5—2 times that of normal sea water.

Oak Ridge National Laboratory/AMF [13]

Based on AMF eq. 1 and some more data from a few commercial plants (unspecified) the following equation was obtained by the Oak Ridge National Laboratory (ORNL)

In SI units

$$\Delta'_{10} = (0.9784)^{T_{\mathrm{vm}}} (15.7378)^{h} (1.3777)^{w \times 10^{-6}} \qquad (9)$$

In British units

$$\begin{aligned} \Delta'_{10} &= (0.4235)(5.878)^{(246 - T_{\mathrm{vm}})/146} (1.522)^{(h-12)/6} (1.176)^{(w \times 10^{-6} - 0.66)/0.34} \\ &= 2.65(0.988)^{T_{\mathrm{vm}}} (1.073)^{h} (1.6109)^{w \times 10^{-6}} \qquad (9a) \end{aligned}$$

Equation (9) was further modified by ORNL to account for stage length. It was assumed that half of the stage temperature drop occurred at the interstage orifice and that the temperature decayed exponentially to the end of the stage.

In SI units

$$\Delta' = [\Delta'_{10} / (\tfrac{1}{2}\Delta T_{\mathrm{B}} + \Delta'_{10})]^{0.3281L} (\tfrac{1}{2}\Delta T_{\mathrm{B}} + \Delta'_{10}) \qquad (10)$$

In British units

$$\Delta' = [\Delta'_{10} / (\tfrac{1}{2}\Delta T_{\mathrm{B}} + \Delta'_{10})]^{L/10} (\tfrac{1}{2}\Delta T_{\mathrm{B}} + \Delta'_{10}) \qquad (10a)$$

While Eq. (9) is applicable only for a 10 ft. long stage, Eq. (10) can be used for different stage lengths.

Baldwin—Lima—Hamilton Corp. (BLH)

BLH Eq. No. 1 [14]

The test stage has a rectangular cross section; $L = 4.57$ m, width = 0.53 m, stage height = 2.06 m and demister height = 1.55 m.

The condensers are of a shell and tube type, separated from the stage. Four ducts, 18 in. diameter each, carry the vapor from the top of the stage (above the demisters) to the condensers. The same coolant flows through all condensers starting at the third.

The orifices have an opening adjustable up to 0.56 m high (ref. 14, p. 10), rectangular in shape.

The whole unit includes 3 stages with the middle one serving as a test stage. No baffles were used. The flashdown ΔT_B was calculated in three ways:

(a) $\Delta T_B = T_{Bi} - T_{Bo}$

(b) From measured product flow

$$\Delta T_B = \frac{(\text{product flow})(\lambda)}{(w)(c_p)} \tag{11}$$

(c) From the condenser loop cooling water temperature rise

$$\Delta T_B = \frac{(\text{condenser loop flow})(\Delta T\ (\text{coolant}))(c_p\ (\text{coolant}))}{(w)(c_p\ (\text{brine}))} \tag{12}$$

BLH found that the best ΔT_B was the average of the three above. The following equation was obtained

In SI units

$$\Delta' = \Delta T_B (2.88\ \Delta P_B{}^{-0.22}\ V_g{}^{-0.05} - 1) \tag{13}$$

In British units

$$\Delta' = \Delta T_B (1.39 \Delta P_B{}^{-0.22}\ V_g{}^{-0.05} - 1) \tag{13a}$$

BLH Eq. No. 2 [12]

In SI units

$$\Delta' = 0.857 h^{0.344}\ V_g{}^{0.284} (w \times 10^{-5})^{0.182}\ \Delta P_B{}^{-0.348} \tag{14}$$

In British units

$$\Delta' = 0.054 h^{0.344}\ V_g{}^{0.284} (w \times 10^{-5})^{0.182}\ \Delta P_B{}^{-0.348} \tag{14a}$$

Burns and Roe construction (B & R) [15]

Based on the data obtained from stages 4 and 5 of the 8-stage MSF module at the San Diego test facility, without enhancers. The equation is referred to as the 'baseline relation'.

The test stages had a curve bottom with a radius of 3.66 m, with the sides formed by two vertical walls 3.15 m apart. The stage's length L was 3.45 m. Brine depth, h, was measured at the exit centerline. Other variables such as temperatures, flow rates, etc. were averaged over the cross section.

The B & R equation

In SI units

$$\Delta' = (7867.17)\,h^{1.1}\,\Delta T_B^{-0.25}\,(w \times 10^{-3})^{0.5}\,(1.8T_v + 32)^{-2.5} \qquad (15)$$

In British units

$$\Delta' = (352)\,h^{1.1}\,\Delta T_B^{-0.25}\,(w \times 10^{-3})^{0.5}\,T_v^{-2.5} \qquad (15a)$$

B & R found the equation to fit all the data for stages 4 and 5 without enhancers, with a standard deviation in Δ' of 0.22°C (ref. 15, p. 31).

Aqua-Chem [16]

The Aqua-Chem equation is an analytical derivation based on the stage configuration shown in Fig. 4.

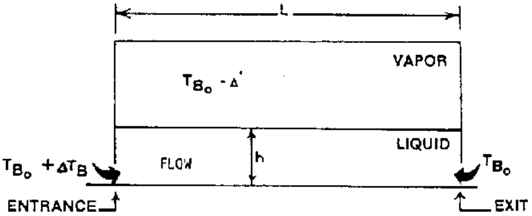


Fig. 4. Schematic description of the stage used in the derivation.

In SI units

$$\Delta' = \frac{1}{1.8}\left\{1.8T_{Bo} + 32 - \frac{1.8}{B}\ln\left[\exp[B(1.8T_{Bo} + 32)/1.8] - \frac{z}{(\exp ky) - 1}\right]\right\} \qquad (16a)$$

where

$$y = (0.85)\,\lambda\,T_{Boa}\,\Delta P_{vF}\,c_p^{-1} P_{vo}^{-2/3}[L/(h \times \Delta T_B \times w \times 10^{-5})]^{1/2} \qquad (16b)$$

and

$$z = \exp[B(T_{Bo} + \Delta T_B)] - \exp BT_{Bo} \qquad (16c)$$

For SI units

$T \leqslant 49°\text{C}, P = 6.3228 \exp 0.0531T, B = 0.0531$

$T > 49°\text{C}, P = 8.3158 \exp 0.04725T, B = 0.04725$

For British units

$T \leqslant 120°\mathrm{F}, P = 2.46 \exp 0.0295T, B = 0.0295$

$T > 120°\mathrm{F}, P = 3.59 \exp 0.02625T, B = 0.02625$

$T_{\mathrm{Boa}} \equiv T_{\mathrm{Bo}}$ absolute

k = Evaporation coefficient; $k = 2.00 \times 10^{-5}$ without enhancer, 2.675×10^{-5} in the case of a submerged jet and 3.35×10^{-5} for a weir. Values of k for other types of enhancers were not given.

Catalytic Construction Company [17]

The equation was derived from a heat transfer model. Catalytic equation:

$$\Delta' = (\Delta P/BP) - (G^{3/2}/K)^{1/2}\,\Delta T_{\mathrm{B}}/J_{\mathrm{a}}(LA_x)^{1/4} \quad (17)$$

Fujii et al., Kyushu University [18]

Fujii has obtained two empirical relations for Δ'. One based on data from runs with a baffle and another without a baffle (empty stage). The apparatus used for the experiments was a three-stage unit with the test stage being the middle one. The stages were each 1.0 m long and 0.10 m wide. The orifices were rectangular 0.1 m wide and 0.15 m high. See Fig. 5 for more details.

Fujii Eq. no. 1 (without baffle)

In SI units

$$\Delta' = 1.13\Delta T_{\mathrm{s}} \exp[(-2/V_{\mathrm{g}}) + (0.65h \times w \times 10^{-5} - 0.5)\Delta T_{\mathrm{B}}] \quad (18)$$

In British units

$$\Delta' = (1.1304)\Delta T_{\mathrm{s}} \exp[(-32.05/V_{\mathrm{g}}) + (0.0136h \times w \times 10^{-5} - 0.278)\Delta T_{\mathrm{B}}] \quad (18a)$$

Fujii Eq. no. 2 (with baffle)

In SI units

$$\Delta' = 1.31\Delta T_{\mathrm{s}} \exp[(-5.07/V_{\mathrm{g}}) + (0.74h - 0.96)\Delta T_{\mathrm{B}}] \quad (19)$$

In British units

$$\Delta' = 0.404\Delta T_{\mathrm{s}} \exp[-81.216/V_{\mathrm{g}} + (0.0104h - 0.533)\Delta T_{\mathrm{B}}] \quad (19a)$$

Miyatake et al., Kyushu University [19]

The equation was developed to correlate data from flash evaporation experiments in a pool of pure water, and is included here just to compare flash evaporation pools and streams. T_{v} (equilibrium temperature is the term used in ref. 19 for T_{v}) was determined as the saturation temperature corresponding to the vapor pressure in the vessel which was measured 20 s

TABLE I

SUMMARY OF PARAMETERS AND EXPERIMENTAL SYSTEM VARIABLES USED TO DETERMINE Δ' BY THE DIFFERENT EQUATIONS

		AMF			ORNL	BLH	
		no.1	no. 2	no. 3		no. 1	no. 2
Cross sectional shape of stage		Rectangular with curved bottom	Rectangular with curved bottom	Rectangular with curved bottom	Rectangular with curved bottom	Rectangular	
Stage length	m ft.	4.27 14	3.44 11.3	3.44 11.3	variable	4.57 15	4.57 15
Stage width	m ft.		0.305 1	0.305 1		0.305 1	
Demisters height	m ft.		10.4 3.17	10.4 3.17		1.55 5.1	
Enhancer presence		No	No	No	No	No	No
T_{Bi}	°C °F			26.7–57.8 80–136[a]		37.2–82.8 99–181	
ΔT_B	°C °F	1.11–3.06 2–5.5	1.11–3.89 2–7	1.11–3.89 2–7	1.11–3.06 2–5.5	0.97–3.78 1.75–6.8	
T_v	°C °F	37.8–62.8 100–145	24–60 75–140	24–60 75–140	37.8–62.8 100–145		
ΔT_s	°C °F						
$T_{\text{coolant out}}$	°C °F			28.9–61.7 52–111[a]			
W kg/h m × 10^5 lbm/h ft. × 10^5		7.44–14.88 5–10	3.72–14.88 2.5–10	3.72–14.88 2.5–10	7.44–14.88 5–10	6.7–16.2 4.5–10.9	
h	m in.	0.3–0.56 12–22	0.25–0.61 10–24	0.25–0.61 10–24	0.3–0.56 12–22	0.3–0.7 12–27.5	
v_g m^3/kg ft.^{3}/lbm			9.4–32.3 151–518	9.4–32.3 151–518			
Definition of Δ'		$T_{Bo}-T_{vm}$	$T_{Bo}-T_{vm}$	$T_{Bo}-T_{vm}$	$T_{Bo}-T_{vm}$	T_B-T_v–BPE	T_B-T_v–BPE
Plant location		Millstone Point, CT	Millstone Point, CT	Millstone Point, CT	Millstone Point, CT	Wrightsville Beach, NC	Wrightsville Beach, NC
Type of flashing liquid		Seawater	Seawater	Seawater	Seawater	Seawater	Seawater

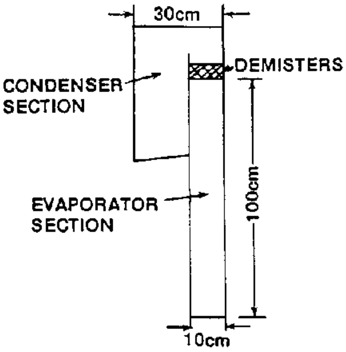
Table I (continued)

		Burns & Roe	Aqua-Chem[b]	Catalytic Eq.[b]	Fujii		Miyatake[c]
					no. 1	no. 2	
Cross sectional shape of stage		Rectangular with curved bottom	Rectangular	Rectangular	Rectangular	Rectangular	Circular
Stage length	m	3.45			1	1	
	ft.	11.3			3.281	3.281	
Stage width	m	3.15			0.1	0.1	0.08
	ft.	10.33			0.328	0.328	0.262
Demisters height	m				1	1	0.4
	ft.				3.281	3.281	1.31
Enhancer presence		No	No	No	No	Yes	No
T_{Bi}	°C				31.1–72.2	30–71	
	°F				88–162	86–160	
ΔT_B	°C	1.11–5.8			0.77–2.86	0.96–4.12	3–5
	°F	2–10.5			1.39–5.15	1.73–7.42	5.4–9
T_v	°C	27.8–54.4					40–80
	°F	82–130					104–176
ΔT_s	°C				2.55–5.61	1.48–4.78	
	°F				4.6–10.1	2.67–8.6	
$T_{\text{coolant out}}$	°C						
	°F						
W kg/h m × 10^5		9.7–15.3			0.34–0.83	0.34–0.8	0
lbm/h ft. × 10^5		6.5–10.3			0.23–0.56	0.23–0.54	0
h	m	0.43–0.71			0.376–0.72	0.376–0.72	0.2–0.22
	in.	17–28			14.8–28.5	14.8–28.3	0.66–0.72
v_g m^3/kg					5.34–41.4	5.24–40.9	
ft.^{3}/lbm					85.6–663	84–655	
Definition of Δ'		$T_{Bo}-T_{vm}$	$T_{Bo}-T_{vm}$	$T_{Bo}-T_{vm}$	$T_{Bo}-T_{vm}$	$T_{Bo}-T_{vm}$	T_B-T_v
Plant location		San Diego, CA					
Type of flashing liquid		Seawater	5% NaCl solution		Fresh water	Fresh water	Pure water

[a] These values were found in ref. 12. They may not cover the whole range since there is a discrepancy. T_v has an upper limit of 140°F, while T_{Bi} has a maximum of 136°F, which is impossible.

[b] Formula derived for no particular range.

[c] Dimensions of the flash chamber are given as equivalents to parameters defined for stage in a MSF Plant.



CONSTRUCTION OF BAFFLE PLATE

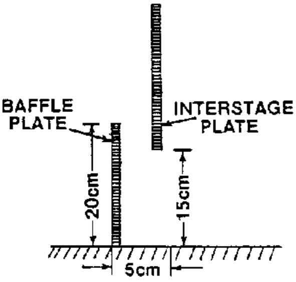


Fig. 5. Cross sectional view of stage.

after flashing had been initiated. At the same time ΔT_B was determined as $\Delta T_B \equiv T_{Bi} - T_v$ where T_{Bi} is the mean liquid pool temperature at time = 0 (initial water temperature). The flash chamber was made of a glass cylinder 8 cm diameter and 40 cm high, connected to a vacuum tank. The experiments were carried out at equilibrium temperatures of $T_v = 40$, 60 and 80°C and $\Delta T_B = 3$ and 5°C. The water depth ranged from 19.6 to 22.5 cm.

Miyatake equations

$$\Delta' = \frac{33\,\Delta T_B^{0.55}}{T_v}, \quad T_v \text{ and } \Delta T_B \text{ in } {}^\circ\mathrm{C} \tag{20}$$

$$\Delta' = \frac{43\,\Delta T_B^{0.55}}{T_v - 32}, \quad T_v \text{ and } \Delta T_B \text{ in } {}^\circ\mathrm{F} \tag{20a}$$

The parameters and experimental system variables used to determine Δ' by the different equations are summarized in Table I.

APPLICABILITY FOR OTEC FLASH EVAPORATORS

A major conclusion from the previous section relative to the application of existing equations for Δ' to proposed open cycle OTEC flash evaporators is summarized in Table II. Major differences are found between the flashing parameters planned for the open cycle OTEC system and between those which were used for the development of the available flashing correlations for seawater. Hence, the Δ' values calculated for the OTEC conditions would necessarily be by *extrapolations* of these correlations. Extrapolation of empirical correlations is typically unacceptable, and, particularly in the case of a complex thermohydrodynamic process such as flash evaporation, it could lead to significant errors. It is noteworthy that while flows and geometries could possibly be scaled from smaller models (although no proven method for scaling of flash evaporators has been demonstrated yet anyway), the flashing temperature level cannot be 'scaled'. Hence, the fact that practically all the correlations are for temperatures above those used in OTEC, poses a severe problem.

TABLE II

COMPARISON OF MAJOR PLANNED OTEC FLASHING PARAMETERS (cf. ref. 4) WITH THOSE IN AVAILABLE CORRELATIONS

Parameter	Typical values	
	OTEC	State-of-the-art correlations
Flashing temperature, °C	23—27	AMF no. 2 and AMF no. 3 $>$ 24 Burns & Roe $>$ 27.8 Others $>$ 30
Flashdown, °C	1—5	0.7—5.8
Stage width, m	∞, radial flow in annulus	0.1—3.15, rectangular
Stage length, m	18	1—4.57
Flashing seawater mass flow rate, kg/h m	5.22×10^6	$(0.34 \times 10^5 - 1.53 \times 10^6)$
Flow depth, m	0.2	0.25—0.72

Due to the fact that some quantitative conclusions relating to equilibration in flash evaporators of OTEC systems were required in spite of the paucity of pertinent data, all the existing correlations were plotted side by side to express the ratio $\Delta'/\Delta T_B$ (the nonequilibrium fraction) as a function of the major parameters: stage saturation temperature T_v, stage flashdown ΔT_B (or DTB), flashing seawater flow rate w, stage length L, and flashing seawater depth H.

In view of the large number of correlations, the wide range of data and the need to determine various temperature, pressure and concentration dependent fluid properties for the evaluation of Δ', a computer program was developed which incorporates the Δ' correlations, fluid property equations, and a plotting subroutine. The program thus computes the nonequilibrium fraction $(\Delta'/\Delta T_B)$ in any range of variables, and plots it as a function of any desired parameters, eliminating unreasonable values such as $(\Delta'/\Delta T_B) < 0$ and $(\Delta'/\Delta T_B) > 1$. Most of the equations blow up in such or other ways when extrapolated outside their original range. The results are shown in Figs. 6—10. The letters A—O describing the curves stand for the following correlations defined in the previous section:

A: AMF No. 1
B: AMF No. 2
C: BLH No. 1
D: BLH No. 2
E: Burns & Roe
F: Fujii No. 1 (without baffle)
G: Miyatake (pool flashing)
H*: ORNL (general)
H: ORNL for $L = 1$ m
I: ORNL for $L = 3.45$ m
J: ORNL for $L = 4.27$ m
K: ORNL for $L = 4.57$ m
L*: Aqua-Chem (general)
L: Aqua-Chem for $L = 1$ m
M: Aqua-Chem for $L = 3.45$ m
N: Aqua-Chem for $L = 4.27$ m
O: Aqua-Chem for $L = 4.57$ m

The four different stage lengths in curves H—O were chosen to correspond to the various stage lengths used in the experiments from which the other correlations were derived.

In the figures
DTB $\equiv \Delta T_B$ = stage flashdown, °C
T_v = stage saturation temperature, °C
W = flow rate of flashing seawater, kg/h m
H = level of flashing liquid, m

The curves were drawn around the baseline values of $T_v = 30$°C, DTB = 1.5°C, $W = 1.5 \times 10^6$ kg/h m, $H = 0.3$ m. The dashed part of some of the curves is for ranges outside those for which the equations were developed.

Inspection of the graphs produces the following major conclusions:

(a) There exists a large spread between the nonequilibrium fraction values calculated by the different correlations, of up to about one order of magnitude. This makes it practically impossible to make acceptable predictions of nonequilibrium.

(b) All the correlations show a very large nonequilibrium fraction, above about 0.8, in the stage saturation temperature range and flashdown range relevant to OTEC systems.

(c) Since the proposed OTEC stage length is 4—5 times longer than the baseline values used in the correlations, Fig. 9, which was plotted for the only two correlations which are a function of stage length (ORNL: H*, and Aqua-Chem: L*), indicates that the nonequilibrium fraction values may decrease markedly below the high values indicated in (b) above. Unfortunately

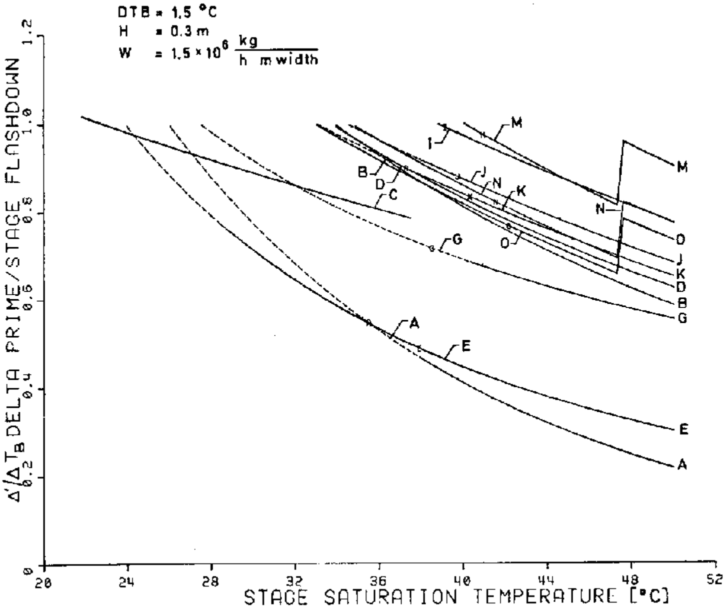


Fig. 6. $\Delta'/\Delta T_B$ versus stage saturation temperature. (——) Within applicable range; (- - -) outside applicable range.

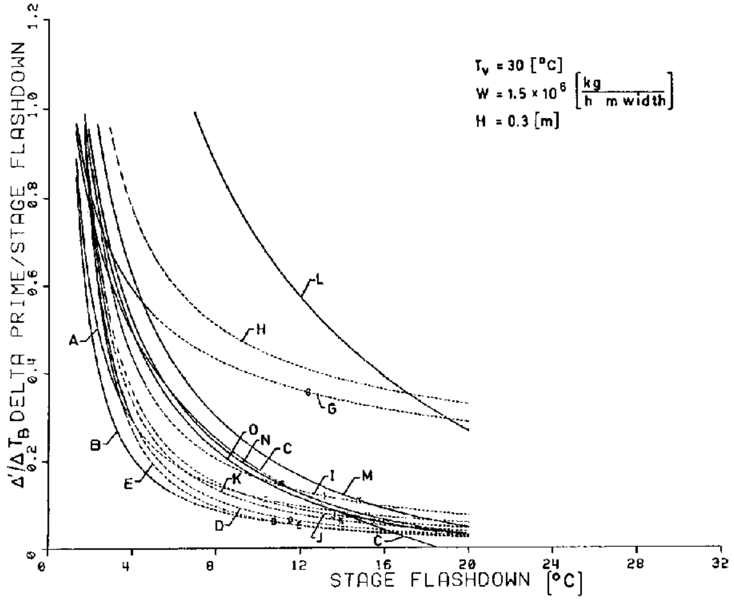


Fig. 7. $\Delta'/\Delta T_B$ as a function of stage flashdown temperature difference. (——) Within applicable range; (- - -) outside applicable range.

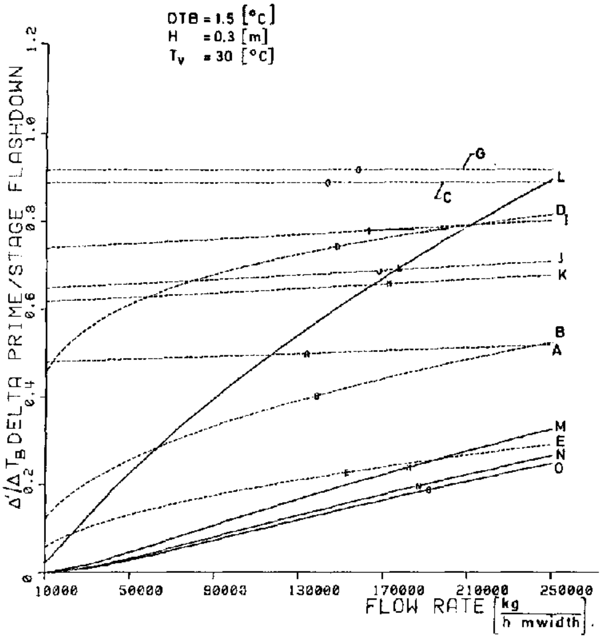


Fig. 8. $\Delta'/\Delta T_B$ as a function of the flashing seawater's mass flow rate. (——) Within applicable range; (- - -) outside applicable range.

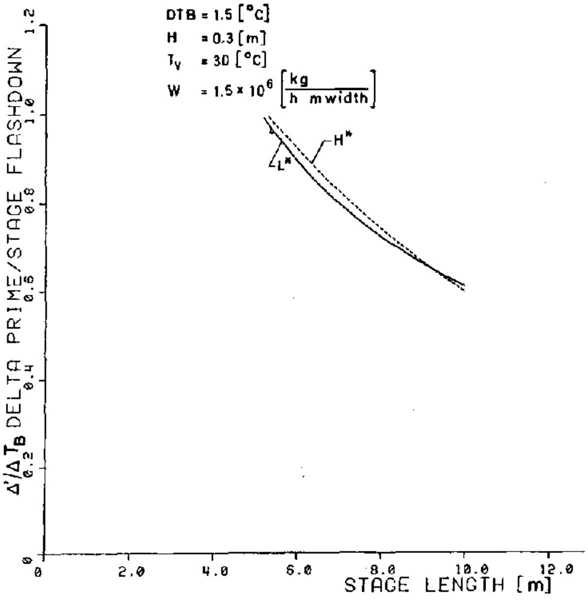


Fig. 9. $\Delta'/\Delta T_B$ as a function of flashing stage length. (——) Within applicable range; (- - -) outside applicable range.

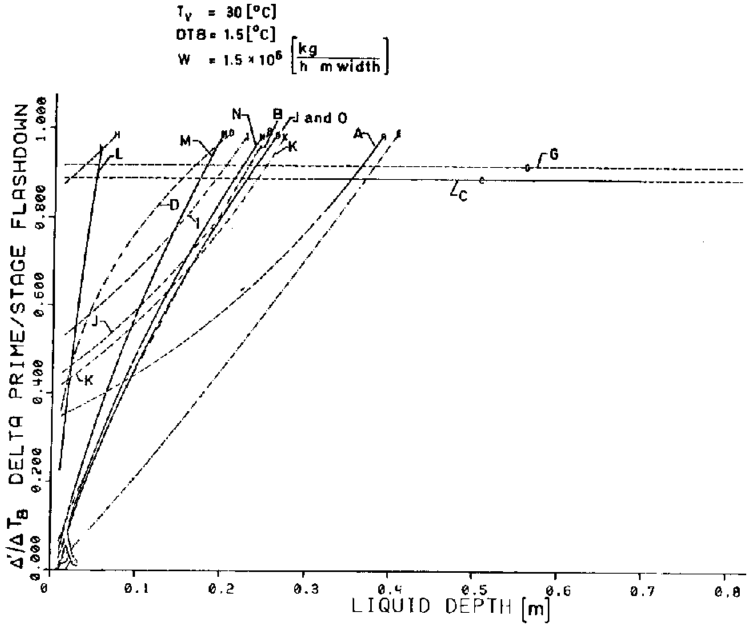


Fig. 10. $\Delta'/\Delta T_B$ as a function of the flashing seawater's depth. (——) Within applicable range; (- - -) outside applicable range.

correlations H* and L* were developed for T_v values larger than those encountered in the OTEC system, and thus could not be used with certainty for a quantitative evaluation.

(d) The trends of all the correlations are similar: the nonequilibrium fraction is reduced by increasing T_v, DTB, and L, and by decreasing W and H. This suggests the design recommendation to implement long stages with shallow flashing liquid flowing at a low flow rate if a better approach to equilibrium is desired, assuming T_v and DTB are basically fixed.

(e) All the existing empirical correlations are valid only outside the range relevant to OTEC due to one or more significant parameters, and are hence inapplicable for the calculation of nonequilibrium in OTEC systems. The major problems arise from the fact that they were developed for stage saturation temperatures above that used in OTEC, that either stage length was not included in them as a variable or that they were developed for stages much shorter than those encountered in OTEC, and that they were developed for significantly lower mass flow rates.

Westinghouse in their proposed open-cycle OTEC plant design [4,5] chose for the open-channel flash evaporator conditions described in the first column of Table II. The major differences between these values and the ones used in this paper for Figs. 6—10 are that a much higher flow rate and stage length (18 versus 3.45 m), and somewhat lower stream depth were required for the plant design. This brings the parameters of interest even further from the values for which the formulas were originally developed, and their applicability is thus even more in question.

The sensitivity of the non-equilibrium fraction, centered around the parameters of this case ($T = 23.5°\text{C}$, $\Delta T_B = 3.33°\text{C}$, $W = 5.22 \times 10^6$ kg/h m, $H = 0.2$ m, $L = 18$ m, $C = 35\,000$ ppm), is shown in Figs. 11—15. The longer stage and the shallower stream are used to keep the non-equilibrium fraction from rising to unacceptable values due to the strongly increased flow rate, and actually reduce it in this design below the values obtained for the configuration described by Figs. 6—10. The large spread amongst the predictions, observed in Figs. 6—10, also characterizes this case.

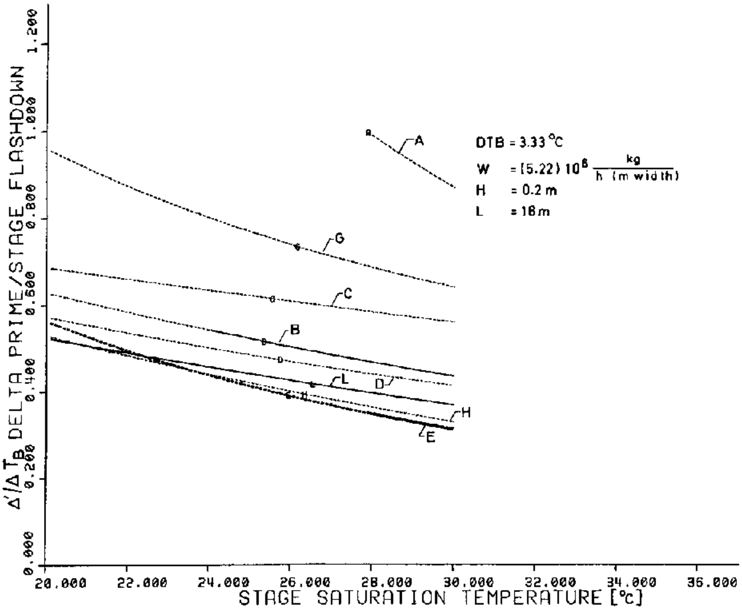


Fig. 11. $\Delta'/\Delta T_B$ as a function of the stage saturation temperature. (——) Within applicable range; (- - -) outside applicable range.

APPLICABILITY FOR WATER DESALINATION MSF EVAPORATORS

A graphical parametric study of the nonequilibrium fraction $\Delta'/\Delta T_B$ was performed similarly for the parameter range pertinent to MSF evaporators used in water desalination. The mid-range baseline values for the study were: $T_v = 175°\text{F}$ (79.44°C), $H = 1.5$ ft, (0.467 m), $\Delta T_B = 5°\text{F}$ (2.78°C), $L = 11.3$ ft. (3.45 m), $W = 750\,000$ 1bm/h ft. (1.1116×10^6 kg/h m) and $C = 44\,000$ ppm. The calculations of $\Delta'/\Delta T_B$ were also performed for salt concentration $C = 34\,000$ ppm.

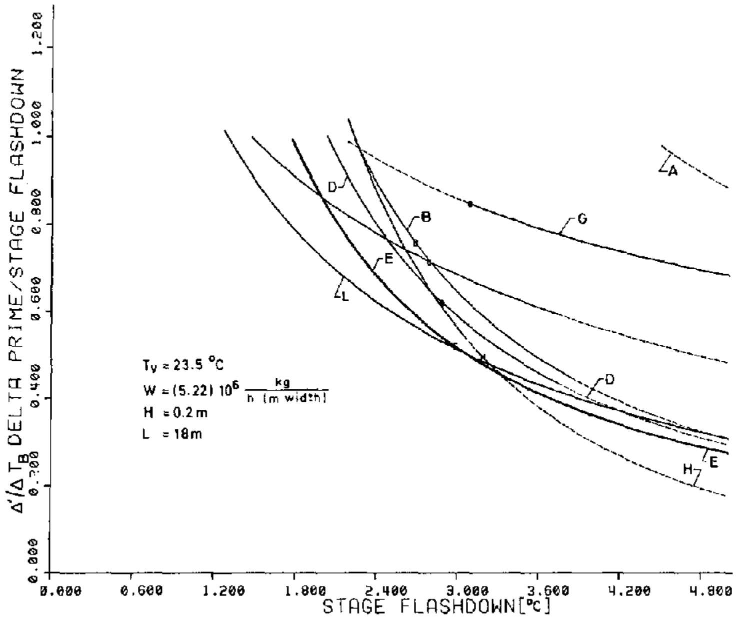


Fig. 12. $\Delta'/\Delta T_B$ as a function of stage flashdown temperature difference. (——) Within applicable range; (- - -) outside applicable range.

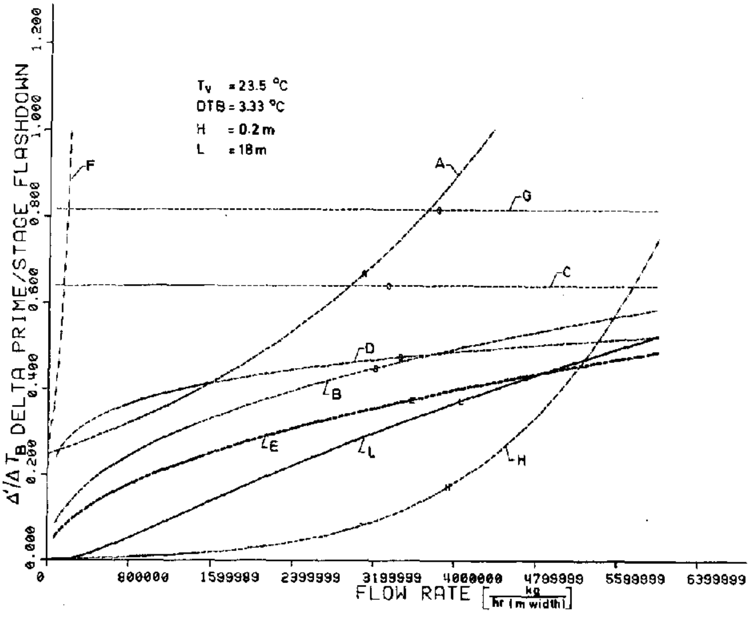


Fig. 13. $\Delta'/\Delta T_B$ as a function of flashing seawater's mass flow rate. (——) Within applicable range; (- - -) outside applicable range.

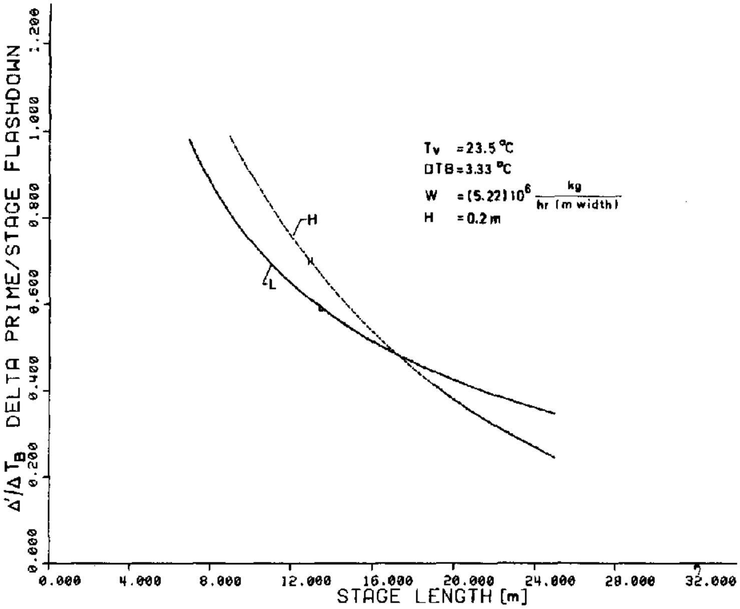


Fig. 14. $\Delta'/\Delta T_B$ as a function of flashing stage length. (——) Within applicable range; (- - -) outside applicable range.

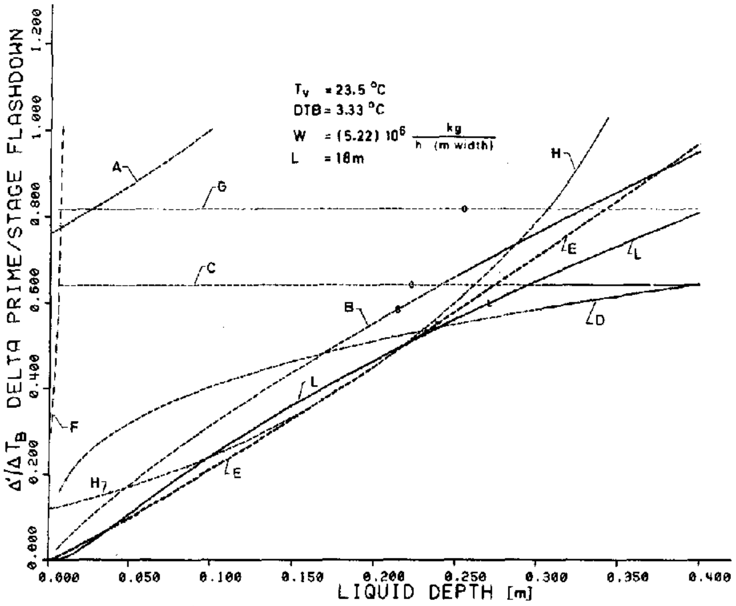


Fig. 15. $\Delta'/\Delta T_B$ as a function of flashing brine depth. (——) Within applicable range; (- - -) outside applicable range.

Each parameter was varied through its pertinent range while holding the rest at the baseline values. The plots are displayed in Figs. 16—20. The effect of changing the seawater concentration from 44 000 to 34 000 ppm was negligible for all correlations except that recommended by Aqua-Chem, which predicted Δ' values up to 10% higher for the lower concentration.

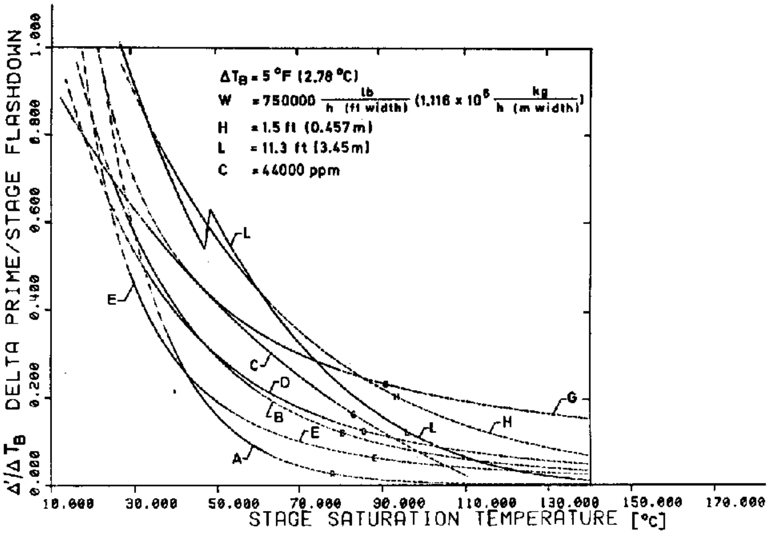


Fig. 16. $\Delta'/\Delta T_B$ as a function of the stage saturation temperature. (——) Within applicable range; (- - -) outside applicable range.

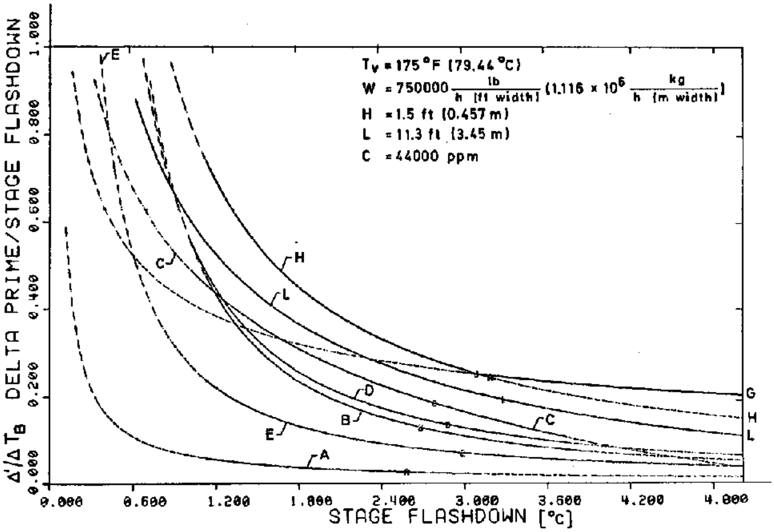


Fig. 17. $\Delta'/\Delta T_B$ as a function of stage flashdown temperature difference. (——) Within applicable range; (- - -) outside applicable range.

The most impressive conclusion from the examination of these figures is the large spread, of approximately one order of magnitude between the Δ' values predicted by the different correlations. This points to the magnitude of uncertainty in designing MSF evaporators based on the present state of the art.

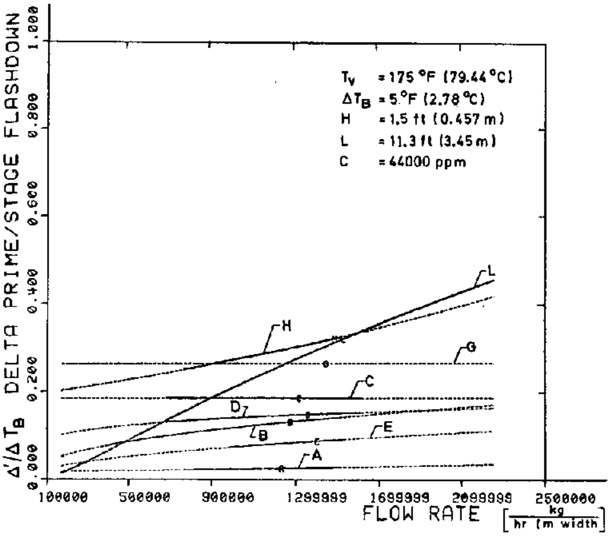


Fig. 18. $\Delta'/\Delta T_B$ as a function of the flashing seawater's mass flow rate. (——) Within applicable range; (- - -) outside applicable range.

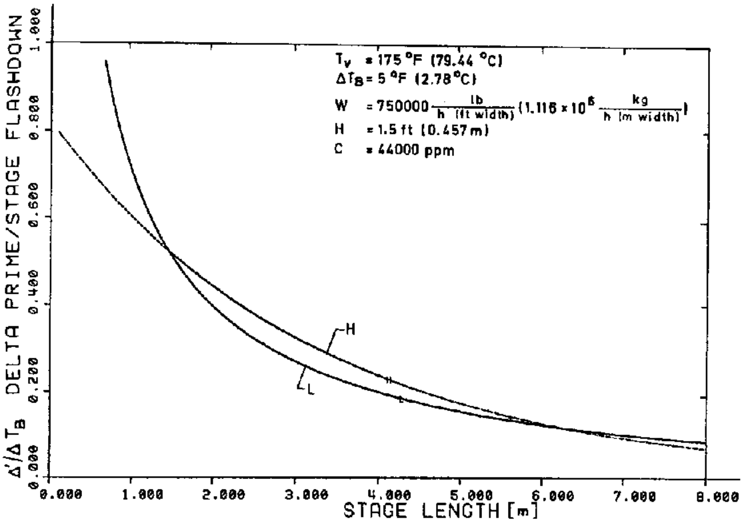


Fig. 19. $\Delta'/\Delta T_B$ as a function of flashing stage length. (——) Within applicable range; (- - -) outside applicable range.

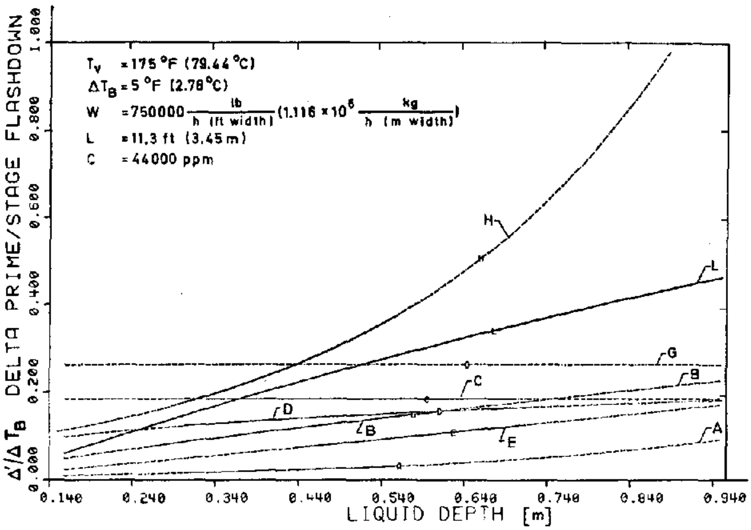


Fig. 20. $\Delta'/\Delta T_B$ as a function of flashing brine depth. (——) Within applicable range; (- - -) outside applicable range.

DISCUSSION AND CONCLUSIONS

The comparison of the twelve different equations available for predicting nonequilibrium allowance (Δ') in open channel flash evaporators indicates that the results have a spread of approximately one order of magnitude. When the correlations are used to predict Δ' outside the range of experimental values in which they were developed, the spread becomes even worse and physically-erroneous results are often obtained.

Since all of the equations were obtained for conditions applicable to water desalination plants, the calculation of Δ' in OTEC applications must be performed by using these equations in their extrapolated region. This region is at lower overall temperatures, and higher ΔT_B, flow rate, and length, than those for which the correlations were developed. The large spread of the data, accompanied by the uncertainty inherent in extrapolating empirical correlations, indicates that these equations cannot be used to predict Δ' in OTEC applications. No other design or theoretical method for that purpose is known either.

The order-of-magnitude spread of Δ' results for desalination MSF plant conditions does not instill confidence in the ability to generally predict Δ' even for that application. At best, the individual correlations may represent Δ' for the specific test apparatus and conditions in which they were empirically developed.

The large discrepancies amongst the correlations arise probably due to both experimental error and inadequate correlation technique. The measurement error comes from the fact that the very small temperature differences, of say 0.5—2°C, and the vapor temperature, need to be measured accurately. Furthermore, the velocity distribution at the inlet and outlet of the evaporator needs usually to be known for the determination of T_{Bi} and T_{Bo}. The low-velocity (around 1 m/s) typically two-phase flow makes this very difficult to measure with adequate accuracy.

It is noteworthy that all the correlations are dimensional. They do not use characteristic nondimensional numbers (such as Reynolds, Prandtl, Jakob, Froude) which are needed for a good correlation, and thus also ignore most of the property varitions which influence the process, such as those in viscosity, thermal conductivity, specific and latent heat, and surface tension.

The inevitable conclusion for improvement in the ability to predict the approach to equilibrium in open channel flash evaporators, is that both better measurements and correlations are needed, in the entire range of parameters of interest.

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