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Interfacial Phenomena in Falling Film Evaporation of Natural Seawater

The fluid dynamics and heat transfer of boiling seawater in falling film evaporators have been investigated. Large interfacial disturbances have been observed, caused by surfactants in seawater. Although these disturbances enhance heat transfer, they increase entrainment and the tendency for scale formation in fluted tubes.

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SCOPE

Distillation of seawater in multiple effect falling film type of evaporators is an established technique to produce fresh water from seawater. In such evaporators, steam generated in one effect condenses on the outside of vertical tubes in the next effect, causing seawater inside the tubes to boil. The seawater runs down the inside tube wall in an annular type of flow. Because of the small temperature difference between the condensing steam and the boiling seawater, the boiling mechanism is generally one of evaporation at the liquid-vapor interface.

Substantial differences in heat transfer for natural seawater, sodium chloride solutions, and city water have been observed by other workers, but no conclusive explanations have as yet been given. These differences have sometimes been associated with the tendency of natural seawater to foam.

By using techniques developed specifically for this work, it was possible to measure inside heat transfer coefficients for localized areas, the waviness of the falling film, and the liquid entrained in the vapor phase. An approximate description of the morphology of the two-phase mixture inside the tube could thereby be obtained. This information provides insight into the heat transfer and fluid dynamic characteristics of falling film evaporation of natural seawater.

A new technology is emerging which uses fluted evaporator tubes instead of the usual smooth tubes. With respect to the inside of the tubes, the heat transfer and fluid dynamic characteristics have been previously investigated by others using mainly city water or sodium chloride solutions. This information may not be applicable for natural seawater, as shown in this paper.

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CONCLUSIONS AND SIGNIFICANCE

In falling film evaporation, the presence in natural seawater of small amounts of surfactants appears to cause rather large interfacial disturbances resulting in increased waviness of the falling film compared to that for city water. The resulting improved heat transfer can be further enhanced by an inlet device which induces flow disturbances at the tube inlet. One such device is the Vortex Level Control and Flow Distributor designed by Bromley and Read (1970).

In the case of fluted tubes, heat transfer is further improved by thin film evaporation at the ridges. The increased thinning of the film at the ridges for natural seawater is in contrast to the observations for sodium chloride solutions reported by Unterberg and Edwards (1965) and by Jansen and Owzarski (1971). Because of the tendency for overevaporation at the tube ridges, the scaling tendency for fluted tubes used to evaporate seawater is higher than for smooth tubes.

PREVIOUS WORK

The occurrence of interfacial instabilities in falling film evaporators has been observed by Alexander and Hoffman (1971), Hewitt and Taylor (1970), and others. These interfacial disturbances strongly affect heat transfer, as explained by Frisk and Davis (1972). Entrainment generation too depends strongly on the waviness of the falling liquid film, as shown by Hewitt and Taylor (1970) and Wallis (1969).

Hewitt and Taylor (1970) describe how under adiabatic conditions and without mass transfer, Kelvin-Helmholtz instabilities can originate and grow. The stability of falling liquid films, under adiabatic conditions and without mass transfer, has been studied by Anshus and Goren (1966).

With mass and/or heat transfer, King (1971) explains how surface tension gradients can originate at the liquid-vapor interface and how these gradients can either dampen or enhance certain instabilities.

Unterberg and Edwards (1965) compared the stability of falling evaporating films of sodium chloride solutions and distilled water. While running down the outside of a smooth tube, sodium chloride solutions appeared more stable.

In cases of liquid films running down corrugated surfaces with evaporation at the liquid-vapor interface, Jansen and Owzarski (1971) observed that a sodium chloride solution replenishes the ridges whereas distilled water does not.

Kays and Chia (1971), when evaporating falling films of freshwater and salt solutions in fluted tubes, observed considerably higher heat transfer coefficients for 3.5% sodium chloride solutions than for freshwater. The heat transfer coefficients for natural seawater were even higher.

Alexander et al. (1970) encountered unexpected calcium sulfate scale problems while evaporating seawater in fluted tubes. Hodgson et al. (1973) found that for falling film evaporation of natural seawater in fluted tubes, the maximum temperature for scale free operation decreases with increasing heat flux.

EQUIPMENT

The test facility was part of the Bodega Marine Laboratory located at Bodega Bay, California.

A single effect downflow evaporator was used for the major portion of the experimental work. A schematic diagram of the evaporator system is given in Figure 1 (Table 1). A more detailed description is given by Van der Mast (1975). This evaporator consisted of a simple smooth copper tube, 1.37 m long and 0.0381 m O.D. The tube was divided into three equal sections, and cups were installed to collect the condensate from each section. The water enters the tube through a Vortex Level Control and Flow Distributor (nozzle) designed by Bromley and Read (1970). These nozzles have a converging inlet section and a diverging discharge section. Tangential inlet slots generate a vortex. This puts the liquid on the tube wall and generates an annular type of flow. Nozzles of two different throat diameters (4.06 and 7.62 mm) were used in the single effect evaporator.

A cone shaped extension was attached to the outlet of the evaporator tube. The cone was at an angle of 10 deg. with respect to the tube axis. Inside the cone a tube was installed concentric with the evaporator tube. This tube could be moved down from the outlet of the evaporator tube over about 0.08 m. The movable tube and the evaporator tube had the same inside diameter. A cup was also installed at the bottom of the cone separator to collect all liquid running down the outside of the movable tube.

A five effect Multiple Effect Flash Evaporator, designed by Bromley, Read, and Diamond (1969), was also used in this work. It had four downflow stages. This evaporator resembled very closely some of the more conceptual designs made earlier by Bromley and Read (1970). Both smooth and spirally corrugated copper tubes were used. More detailed information is provided by Van der Mast (1975).

PROCEDURES

In both evaporator systems, fresh once-through seawater from the Pacific Ocean was used. Because of the location of the Marine Laboratory, the ocean was assumed to be relatively unpolluted.

The seawater intake was in a rocky zone, at a depth of about 2 m. below the water surface. This area is continuously pounded with large incoming waves. The surrounding intertidal zone is covered with an abundance of plant and animal growth. The seawater feed to the evaporators was screened, filtered in a sand filter, acidified with sulfuric acid to a *p*H of 4.5, decarbonated in an atmospheric spray column, and degassed in a packed vacuum column.

For some runs, Bodega Bay city water was used. This water is generated from local wells. Because of its high alkalinity (2.8×10^3 meq/m^3, this water was pretreated in the same way as seawater.

The feed to the evaporator tubes was at or near its boiling point. As the liquid passes through the nozzle throat, it flashes and a two-phase annular flow is generated.

Condensing steam at the outside of the tubes causes the liquid inside to boil. Most runs were made with good dropwise condensation on the outside of the tubes. This minimizes the outside heat transfer resistance. Based upon extensive work on dropwise condensation by Wilkins (1972), the outside heat transfer coefficient can also be estimated quite accurately. This allows accurate measurement of the inside heat transfer coefficient.

In the single effect evaporator, the cone shaped extension at the outlet of the tube and the movable tube were used to study the fluid dynamics of the system. If the movable tube is lowered sufficiently, surface tension forces keep the liquid film at the wall of the cone, while inertia forces drive the entrained droplets into the movable tube. This allows the measurement of the total entrainment at the outlet of the

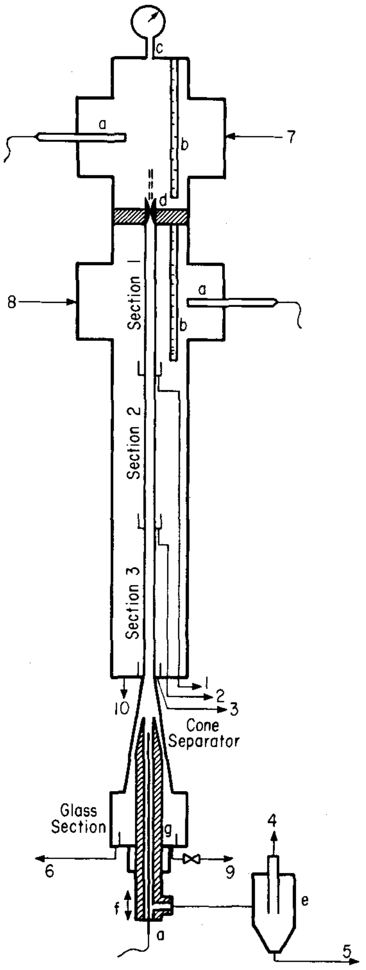

Fig. 1. Single stage downflow evaporator.

TABLE 1. LEGEND TO FIGURE 1

Flows

1. Condensate from cup 1
2. Condensate from cup 2
3. Condensate from cup 3 .
4. Product steam
5. Liquid entering movable tube
6. Brine out
7. Pretreated feed (natural seawater or city water)
8. Dry saturated steam to chest
9. Drainage from cup in cone separator
10. Vent

Instrumentation

a. Hewlett Packard 2850 series probes for Hewlett Packard 2801A quartz thermometer
b. Brooklyn mercury thermometers—2/100°K accuracy
c. Heise Gauge—172 N/m^2 accuracy
d. Vortex Level Control and Flow Distributor
e. Cyclone separator
f. Movable tube
g. Cup at bottom of cone separator

tube. When the tube is moved upwards, liquid bridging will eventually occur between the cone wall and the movable tube, as evidenced by an increase in liquid entering the movable tube and by the increased rate of fill-up of the cup, located at the bottom of the cone separator. The liquid entering the tube will then consist of entrained droplets as well as tops of waves. Results for a typical run are shown in Figure 2. From these data, it is possible to determine approximately the true entrainment at the outlet of the tube. It also allows the approximate determination of the maximum liquid film thickness and the liquid mass flux through a given cross-sectional area of the outlet of the tube, as shown in Figure 3.

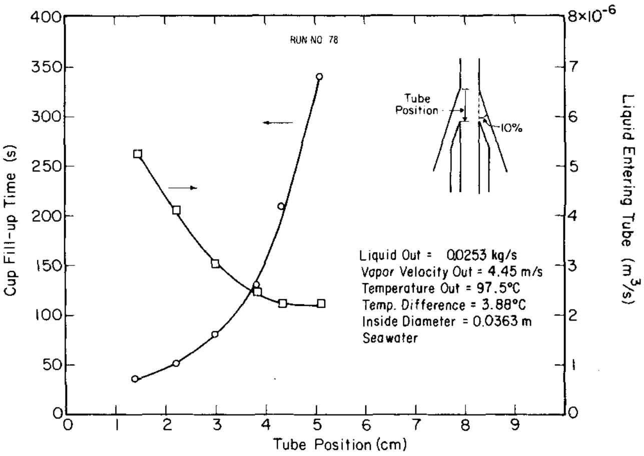

Fig. 2. Cup fill-up time and liquid entering tube vs. true position.

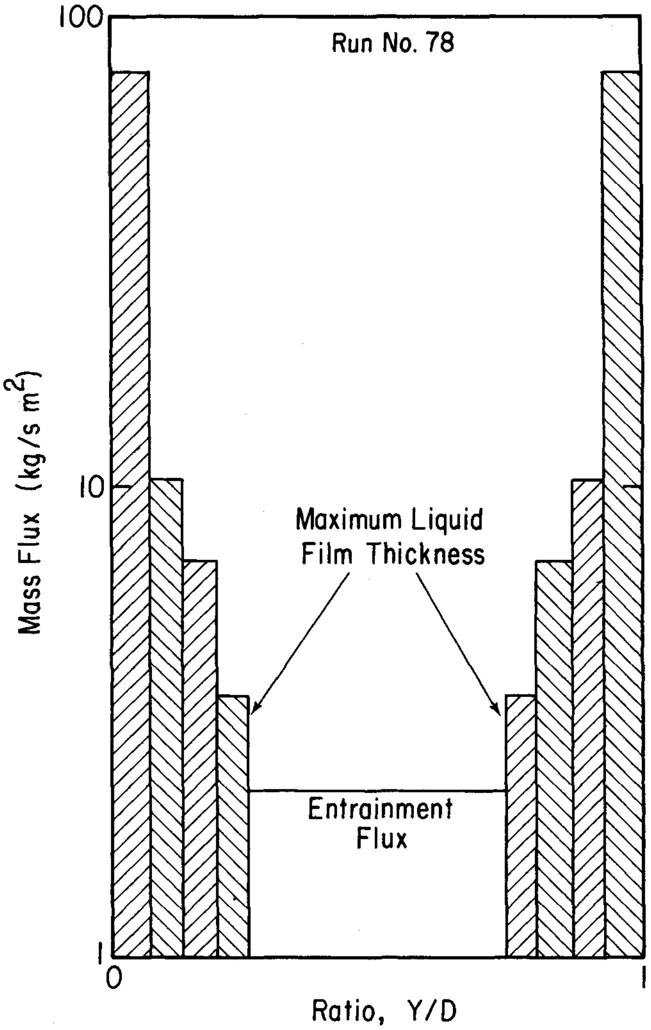

Fig. 3. Total liquid mass flux (liquid film and entrainment) at the outlet of the tube vs. distance from the wall.

Detailed descriptions of other experimental procedures are given by Van der Mast (1975).

The range of experimentation was within the range of interest in the distillation of seawater:

Brine temperature	110° to 60°C
Heat fluxes	25,000 to 157,000 J/m^{2}s
Liquid film flow	0.105 to 0.505 kg/s m
Vapor velocity at the outlet of the tube	3.04 to 36.4 m/s

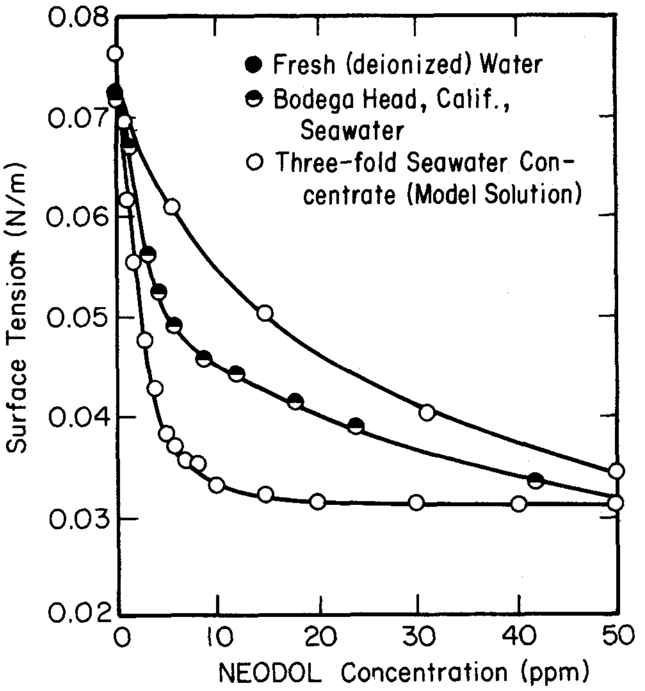

Fig. 4. Surface tension vs. bulk concentration of Neodol in solutions of various salinities.

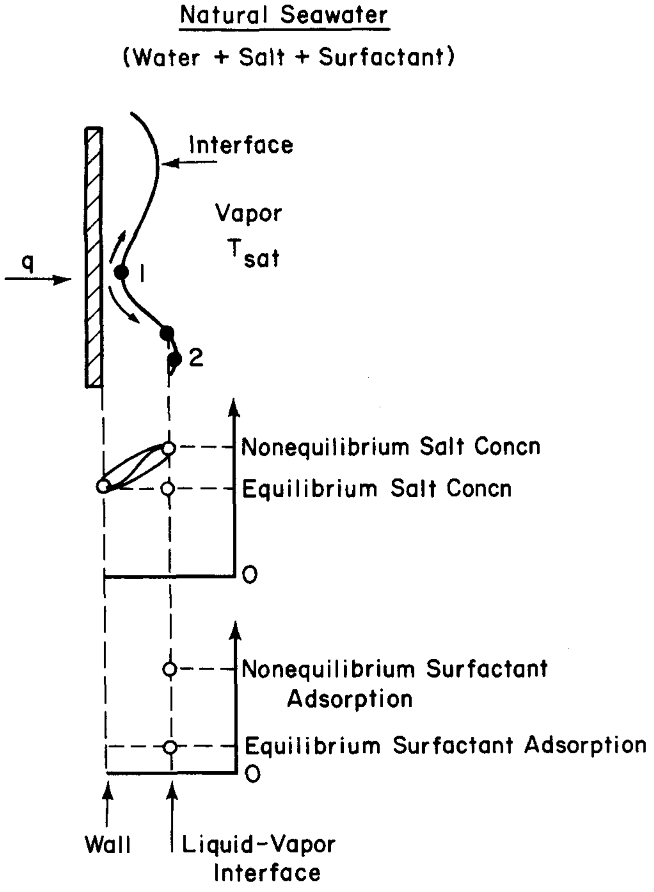

Fig. 5. Concentration profile of salt and excess surfactant adsorption generated by surface evaporation.

THEORY

It has been shown by Anshus and Goren (1966) that falling films of a pure liquid with a free surface are hydrodynamically unstable, even at small Reynolds numbers.

In concurrent flow of a pure liquid and a gas, and without heat or mass transfer, interfacial disturbances are enhanced by Kelvin-Helmholtz types of instabilities, as explained by Hewitt and Taylor (1970). The surface tension of the liquid works as a restraining force.

Unterberg and Edwards (1965) describe how in case of surface evaporation of a falling film of a sodium chloride solution running down the outside of a smooth tube, there are less interfacial disturbances than with city water. This is explained by the fact that in case of salt solutions, the salt concentration near the liquid-vapor interface is higher in areas where the film thickness is smaller because of a higher rate of evaporation in these areas. Higher salinity means higher surface tension. As the interface strives to a condition of minimum surface energy, liquid will flow from the thick areas to the thin areas, thereby causing damping.

Jansen and Owzarski (1971) observed the same phenomena for salt solutions running down corrugated surfaces. In this case, thin film areas are mechanically provided. The liquid, therefore, will flow out of the valleys and onto the ridges providing good wetting characteristics and providing enhanced heat transfer because of thin film evaporation at the ridges and because of the mixing cells set up in the valleys.

Natural seawater is generally thought of as a simple salt solution. The simplest form of synthetic seawater is a 3.5% sodium chloride solution. More sophisticated simulations of natural seawater use a combination of salts, similar to the composition given by Sverdrup et al. (1959).

Revak (1973) has shown that besides certain salts, natural seawater also contains surface active species. He experimentally determined the concentrations of many of these surfactants in Bodega Bay seawater, obtained from the same source as the seawater used in this work. Fatty acids were believed to be the main surface active species. As reported by Horne (1969), the concentration of these organic molecules generally decreases with increasing depth of intake and with increasing distance from shore. The concentrations are also a direct function of the marine fertility of the area.

Even though the total surfactant concentration may be as small as 0.5 p.p.m. or less, Valdes-Krieg et al. (1975) have shown that the surface tension of salt solutions may decrease rapidly with addition of certain surfactants, such as the anionic surfactant Neodol,[*] as shown in Figure 4. The Gibbs equation for adsorption of surfactant at the interface

$$\Gamma_{\text{ads}} = -\frac{C}{RT}\cdot\frac{d\sigma}{dC}$$

where Γ_{ads} is the molar excess of surfactant adsorbed at the liquid-vapor interface, indicates that for a given bulk concentration of surfactant, the larger $d\sigma/dC$ the more surfactant will move towards the interface and be adsorbed there.[†] This equation is only valid below a critical surfactant concentration where micelles start forming. From Figure 4 it follows that for a given bulk concentration of surfactant below the critical one, salt solutions will have more surfactant adsorbed at the surface than has deionized water. This may cause the surface tension of salt solutions to be smaller than for distilled water, even at low surfactant concentrations. It is also of interest to note that at room temperature, the surface tension of natural Bodega Bay seawater is smaller than for deionized water,

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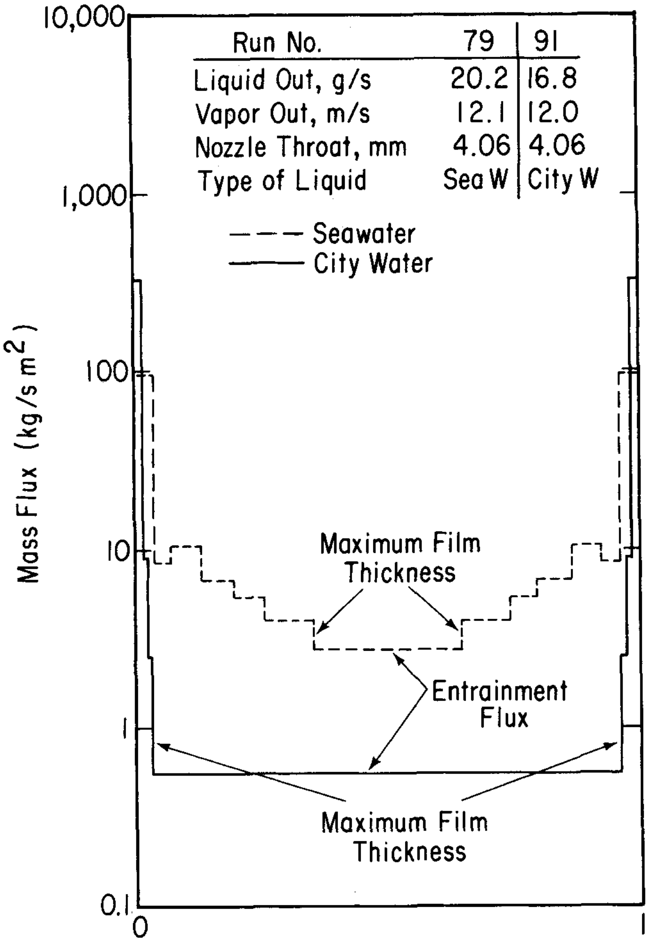
[*] Neodol 25-3A (Shell Chemical Company) is an ammonium salt of a sulfated primary alcohol containing three ethylene oxide groups. Average molecular weight is 436. It has twelve to fifteen alkyl groups. Commercially available as 60 wt% of ethanol-water solution.

[†] Strictly, the equation is valid only for a binary system of surfactant and solvent; however, experimental evidence of measured surface tensions in seawater systems indicates that it is a good approximation in this multicomponent system (see Figure 4).



Run No.	79	91
Liquid Out, g/s	20.2	16.8
Vapor Out, m/s	12.1	12.0
Nozzle Throat, mm	4.06	4.06
Type of Liquid	Sea W	City W

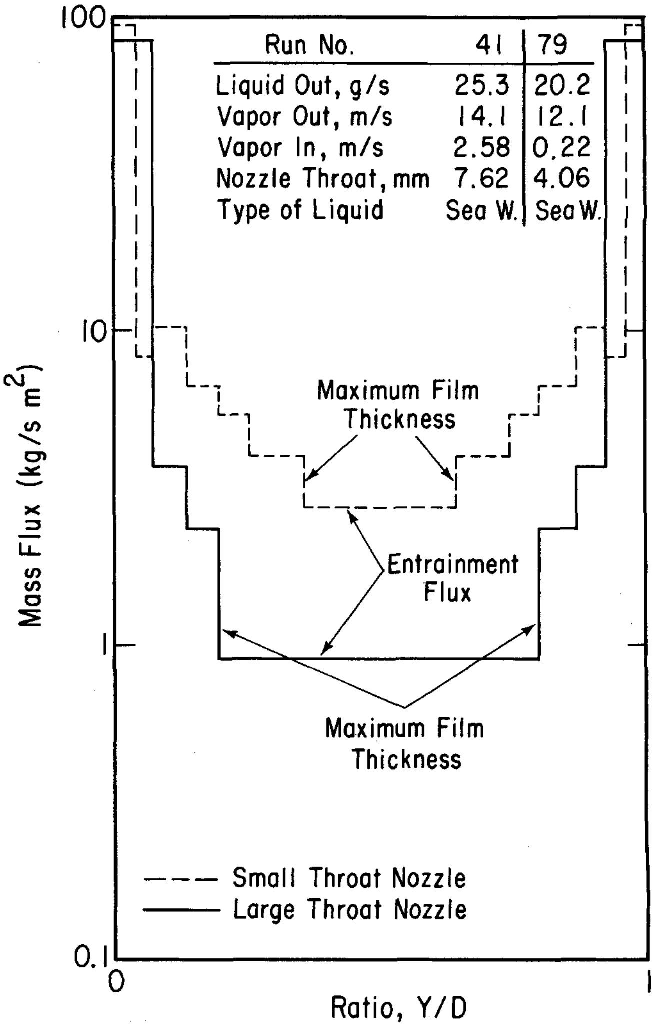
Fig. 6. Total liquid mass flux at the outlet of the tube for city water and seawater.

as shown in Figure 4.

Natural seawater should therefore be considered as a water-salt-surfactant solution. Up to this point, the effect of surfactants in seawater under equilibrium conditions only has been considered. In falling film evaporators, having evaporation at the liquid-vapor interface, non-equilibrium phenomena should also be taken into account.

Because of surface evaporation at any point on the interface, the salt concentration near the interface is higher than the bulk concentration, and the amount of surfactant adsorbed at the interface is larger than at equilibrium, as shown in Figure 5. Because of the concentration gradient, salt ions will diffuse into the bulk of the liquid. The shape of the concentration profile depends upon the flow conditions. Surfactant molecules also move towards the bulk of the liquid. First, however, the surfactant has to desorb from the interface. This additional step and the larger size of the surfactant molecules will result in the surfactant molecules diffusing more slowly than the salt ions. This causes the increase in surfactant at the surface to be larger than the corresponding increase in salinity. The non-equilibrium surface tension is lower than the equilibrium surface tension at any point at the interface. Because of this weakening of the interface, Kelvin-Helmholtz types of instabilities will be larger. This effect is largest in the shallow areas, where the heat flux is highest. Surface tension gradients are set up between neighboring areas, the shallow areas having the lower surface tension. This would further enhance the instabilities.

According to this theory, natural seawater would enhance instabilities in contrast with salt solutions of the same ionic strength which dampen instabilities.



Run No.	41	79
Liquid Out, g/s	25.3	20.2
Vapor Out, m/s	14.1	12.1
Vapor In, m/s	2.58	0.22
Nozzle Throat, mm	7.62	4.06
Type of Liquid	Sea W.	Sea W.

Fig. 7. Total liquid mass flux at the outlet of the tube for different nozzles at the inlet of the tube.

EXPERIMENTAL RESULTS AND DISCUSSION

It has been shown by Van der Mast (1975) that under the conditions obtained in this work, the boiling mechanism is one of evaporation at the liquid-vapor interface.

Figure 6 gives a comparison for the total liquid mass flux (liquid film and entrainment) at the outlet of the single effect tube for city water and natural seawater for about the same operating conditions. As can be seen, there is a drastic difference in maximum film thickness, mass flux caused by the liquid film and entrainment. This is in agreement with the theory developed in this work.

Figure 7 gives a comparison for the total liquid mass flux (liquid film and entrainment) at the outlet of the tube, with different nozzles at the inlet of the tube. The main difference between the two nozzles is the different diameter of the nozzle throat. In case of a small diameter nozzle throat, only an insignificant amount of steam can enter the nozzle, so that while it passes through the throat, flashing will cause a sudden drastic change in specific volume of the liquid-vapor mixture. The instabilities generated at the inlet of the tube will therefore be larger in case of a nozzle having a smaller throat diameter. These instabilities grow as they move down the tube, also causing larger instabilities at the outlet of the tube.

Similar observations were made with respect to the heat transfer characteristics. Heat transfer coefficients are higher with natural seawater than with city water and higher with a small throat nozzle than with a larger throat nozzle.

To check whether the natural surfactants in seawater are responsible for this behavior, a synthetic surfactant could be added so as to bring the surfactant concentration in the feed close to the micellar concentration, at which point $d\sigma/dC$ disappears, and both city water and seawater have about the same surface tension. Tests were made with Neodol addition to the feed. A foamy layer was formed adjacent to the liquid film at the wall. This obscured the interpretation of the results. It is of interest to note, however, that after Neodol addition all differences between city water and seawater disappeared, as well as the differences between small throat and large throat nozzles. It is also of interest to note that the maximum film thickness and entrainment in case of the small throat nozzle and with seawater feed was actually decreased upon Neodol addition, whereas the opposite was true for the large throat nozzle.

Some runs were also made in the five effect Multiple Effect Flash Evaporator with spirally corrugated copper tubes. High heat transfer coefficients were generally observed. At a low flow rate, scale formation was observed in the low temperature effect. About 0.6m down, calcium sulfate scale started to develop on the ridges only. This scale grew thicker going further down the tube. The valleys, however, stayed scale free. Remarkably, also the smooth section at the outlet of the tube was scale free. These observations seem to indicate unmistakably that corrugated tubes, in falling film evaporators, have a stronger tendency to scale-up than do smooth tubes. And although it does not necessarily confirm the arguments developed in this work, it does at least bring into question the intensity of the healing[*] characteristics often attributed to seawater. This tendency of corrugated tubes to scale-up in falling film evaporators would be expected to be larger for straight fluted tubes than for spirally corrugated ones, where gravity has a tendency to replenish the thin liquid films on the ridges.

Alexander et al. (1970), when evaporating natural seawater in fluted tubes in downflow at temperature differences of about 11°C and liquid film Reynolds numbers $4\gamma/\mu$ of over 1 800, also report calcium sulfate scale problems, even at salinities around 4% by weight. Hodgson et al. (1973) found that for falling film evaporation of natural seawater in fluted tubes, the maximum temperature for scale free operation (calcium sulfate scale) decreased with increasing heat flux. This behavior cannot be easily explained if seawater is assumed to have strong healing characteristics. Thus, the observation is in complete agreement with the theory developed here.

Kays and Chia (1971) observed higher heat transfer coefficients for natural seawater than for sodium chloride solutions in fluted tube, falling film evaporators. They speculate that this might be caused by the foaming of natural seawater. Seawater was never observed to foam in our work. Instead, the high coefficients might be explained by thin film evaporation of natural seawater at the ridges.

ACKNOWLEDGMENT

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NOTATION

C = molar bulk concentration of surfactant
D = inside tube diameter
q = heat flux through the tube wall
R = universal gas constant
T = temperature
y = distance from the wall
γ = liquid film flow
Γ = molar surface excess of surfactant at the liquid-vapor interface
σ = surface tension of the liquid
μ = liquid viscosity

Subscripts

ads = surfactant adsorbed at the interface
sat = saturation temperature
1 = location 1 at the liquid-vapor interface
2 = location 2 at the liquid-vapor interface

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[*] By healing is meant the tendency for the liquid to spread into a more or less uniform thickness.