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AN EXPERIMENTAL STUDY OF FLASH EVAPORATION FROM LIQUID POOLS

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SUMMARY

The objective of this study is, based on experiments, to improve the understanding of flash evaporation from pools, and to develop empirical correlations of the total quantity of vapor released and the rate of vapor generation (both in non-dimensional form) as a function of the primary nondimensional parameters which govern the process: the Jakob number (Ja_p), Prandtl number (Pr), a dimensionless hydrostatic head ($\Delta p/H$), and the salt concentration (C). The work was done in the range of parameters characteristic to desalination plants and to open-cycle ocean-thermal energy conversion. Experiments were performed with fresh water and with saline water (3.5% NaCl concentration), for initial temperatures from 25°C - 80°C, flash-down temperature differences from 0.5°C - 10°C, and pool depths of 6.5" (165 mm), 12" (305 mm) and 18" (457 mm). The prediction of flashed mass as a function of the nondimensional parameters is accurate to within 7.5% . A new time scale $\tau = (\sigma/\Delta p)^2/\alpha_l$ (where σ = surface tension, α_l = thermal diffusivity of the liquid, and Δp = pressure difference between the liquid and the vapor space) was employed. The expressions for the rate of flashed steam using this time scale show a scatter of ± 68%. The asymptotic value of the flashed mass increases with Jakob number, increases slightly with pool depth, and decreases with increasing liquid Prandtl number. The comparisons show very good agreement with the experimental values, but underpredict the data obtained from other experiments.

SYMBOLS

A	free surface area of the liquid
a_{1-4}	correlation powers, eq. (7)
C	concentration of NaCl in the solution
C_1	correlation coefficient, eq. (7)
C_2	correlation coefficient, eq. (9)
c_p	specific heat
H	depth of the pool
h_{fg}	latent heat of vaporization
Ja	Jakob number ($= c_p\Delta T/h_{fg}$)
k	thermal conductivity
m	amount of vapor released
m_∞	asymptotic value of vapor released, after a long time

$\bar{m}$	$= m/m_v$
m_v	total mass of vapor : eq. (5)
$\dot{m}$	rate of flashing
$\dot{m}_0$	initial rate of flashing
Pr	Prandtl number of the liquid ($= c_p\mu/k$)
P_2	parameter in the least-squares curve fit
Δp	flash-down pressure difference
t	time
T_0	initial temperature of pool
T_e	final equilibrium temperature
ΔT	overall superheat
τ	bubble time scale
μ	viscosity
ρ	density

Subscripts

0	initial
e	equilibrium
l	liquid
P	pressure, eq. (4)
sat	saturation
T	thermal, eq. (3)
v	vapor

INTRODUCTION

Flash evaporation is widely used in distillation processes, such as in water desalination, and in energy conversion and storage processes for steam production. For example, the open-cycle ocean-thermal energy conversion (OTEC) process (first developed by Claude, ref. 1) employs flash evaporation of the warmer surface layer of the ocean to generate steam for driving a turbine; "steam accumulators" have been used for many years in Rankine power plants to store heat in pressurized water when demand is below the boiler capacity, and then to generate steam by flash evaporation for power production when demand rises above boiler capacity (ref. 2). Knowledge of the flash evaporation rates, and their economical maximization, is necessary in the design and application of all of these processes.

Flash evaporation is initiated by exposing the liquid to a pressure lower than that corresponding to saturation at the existing conditions. This causes at least some of the liquid to violently undergo a transition to the vapor phase in the presence of vigorous ebullition. As described by many researchers (refs. 3-12), this is a complex process, difficult to both analyze and measure. The small temperature differences associated with water desalination and with OTEC, make precise measurements even harder. It is no surprise therefore that knowledge of the process is still quite inadequate, and that process design is based for the most part on empirical correlations with limited ranges of validity and large scatter (cf. recent review by Lior, ref. 12).

Miyatake et al. (ref. 6) conducted experiments, somewhat similar to the ones described in this paper, to investigate the behavior of a pool of liquid in a tank subjected to a suddden reduction in the pressure of the vapor space. They found two exponential time decay processes - the initial with a higher slope indicating vigorous ebullition, and the second with relatively quiescent evaporation. They proposed dimensional-parameter correlations to predict the flashed steam rate and the nonequilibrium fraction. Nakamura et al. (ref. 7) studied the dynamic behavior of flashing in vessels which are subjected to reduction in pressure in the steam vent line. They found that the narrowest diameter of the steam vent line, the initial water depth, and the initial pressure, influenced the process. In particular, the time constant of the pressure reduction was found to be directly proportional to the initial water level and inversely proportional to the 1.8^{th} power of the nozzle throat diameter. Some of the other studies on flashing flow in multistage flash evaporators (refs. 8-10) have been aimed at the design optimization of such units. Sugeta and Toyama (ref. 8) found experimentally that the nonequilibrium temperature difference (which represents the degree of incompleteness of the evaporation) increased with flow rate of the flashing liquid. They proposed a chamber having a trapezoidal bottom to reduce this temperature difference. Lior and Nishiyama (ref. 9) studied the effect of noncondensables on the flash evaporation process. The heat transfer characteristics and the approach to equilibrium were found to improve with an increase of the concentration of the noncondensable in the liquid, because the noncondensables enhance bubble nucleation. They also proposed a correlation to quantify this effect. Miyatake et al. (ref. 10) studied the effect of flashing from superheated jets of water sprayed into a low pressure chamber. An empirical equation for the prediction of temperature of the jet with residence time was presented.

Peterson et al (ref. 13) examined the case of a postulated pipe break in a nuclear reactor cooling system which could result in flashing flow. The rate of pressure reduction imposed in the experimental setup was of the order found in such situations, and they found that the flashed steam rate was about 20 times that due to evaporation alone. Correlations which predict these values for the range of parameters investigated were also given. Clegg and Papadakis (ref. 14) studied the evaporation rates of Freon-11 from storage tanks which hold the liquid under low gauge pressures. The depressurization rates were taken to be linear, and correlations for the boiling as well as the evaporation regimes were obtained by experiments. Based on an analogy to the surface evaporative processes, a heat transfer coefficient and Nusselt number were proposed and expressed as a function of the superheat. It was found that beyond a supersaturation pressure (Δp) of 5.5 kPa, a transition from the evaporative regime to the boiling regime took place, resulting in increased fluxes. The results were also used to predict the behavior of LNG tanks.

One of the applications of flash evaporation under investigation at the University of Pennsylvania is that of steam generation from a stratified thermal storage tank which is part of a hybrid Rankine power cycle (ref. 15). In this cycle, solar energy or other low level energy sources are used to heat water in a storage tank, and by opening a valve which connects the tank to the vapor space of the condenser, flash evaporation is initiated, thus producing steam which is then superheated using conventional fuel before entering the turbine. The advantages of higher system efficiency, better thermal source-sink matching, and the elimination of a boiler in the conventional sense depend upon the proper design and operation of the flash evaporator. Experiments have been conducted on this system (with flash-tank volume of about 20 m^3), and preliminary design experience has been gained (ref. 16). One of the aims of this study is to develop expressions for flashing rates that can be used in that system.

All the studies mentioned above develop expressions for flashing that are valid only in limited ranges of the parameters, and cannot usually be extended to cover related applications. This study is aimed at the prediction of flash evaporative fluxes primarily for the range of parameters of relevance in the desalination industry and for open-cycle OTEC development, but it has wider applicability than some of the earlier studies because non-dimensional parameters are employed in the correlation. The empirical correlation is also intended to reveal some of the subtler aspects of the theory which can be used in the formulation of theoretical models of the flash evaporation process.

THE EXPERIMENTAL FACILITY

The experimental facility for pool flashing is shown in Fig. 1. It consists of a Pyrex cylinder of 6" (152 mm) internal diameter and 24" (610 mm) height which serves as the evaporation chamber. This evaporator is enclosed concentrically in a 12" (305 mm) diameter acrylic cylinder, and the space between the two cylinders is evacuated to reduce heat losses. The top of the evaporator is connected to a 5 ft^3 (0.1416 m^3) sealed tank by means of a 2" (51 mm) copper tube. A quarter-turn 2" (51 mm) ball valve is used in this line to produce the necessary pressure drop in the evaporator vapor space. The reduction in pressure

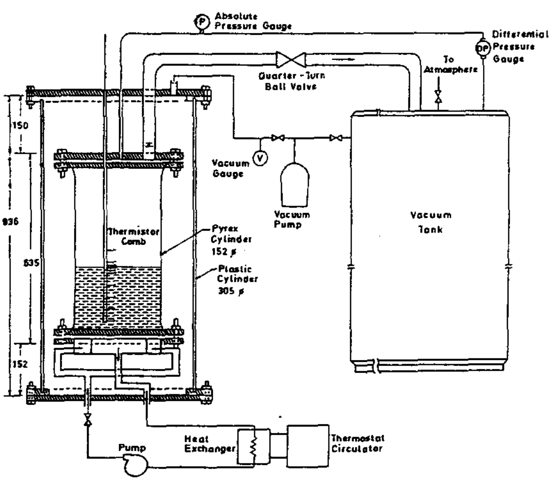

Fig. 1 Schematic of the Pool Flashing Apparatus

necessary to cause flashing is obtained by pre-evacuating the tank to the desired pressure, below the saturation pressure corresponding to the initial temperature of the liquid. The initial liquid temperature is brought to the desired value by circulating the liquid to be flashed through a heat exchanger, which is heated by oil coming from a temperature-regulated circulator. The pyrex evaporator and the surrounding cylinder are transparent, enabling good visual observation of the process.

The variables in this process which need precise measurement include transient temperature and pressure distributions. The temperatures were measured using a specially designed "thermistor comb". It consists of a vertical probe on which 44 unevenly spaced miniature thermocouples are mounted. The thermistors are 0.02" (0.508 mm) in diameter, and the entire assembly can be moved up and down, and rotated about its axis by 360^{0} (Fig. 1). The probe is positioned such that the temperature profiles in the vapor space as well as the liquid can be measured. Closer spacing is provided at the free surface of the liquid where the gradients are expected to be largest.

Absolute pressure in the vapor space of the flash tank, as well as the differential pressure between the vapor space and the vacuum tank, were measured. A parallel connection of electronic pressure transmitters and mercury manometers was used. Liquid level was measured using a cathetometer, and the salinity of the liquid was measured using a conductivity monitor.

The experiment was started by filling the evaporator to the required depth. The liquid was deaerated thoroughly by opening the ball valve and exposing the liquid to a lower pressure for a few trial runs. The liquid temperature was maintained constant by pumping it through the heat exchanger. The ball valve was then closed, and the vacuum tank depressurized to the desired flash-down pressure by operating the vacuum pump. The actual run was started by quick opening of the ball valve and consequent exposure of the liquid to the lower pressure.

All the measurements were recorded using a computer-aided Data Acquisition System (DAS). The DAS consists of a Hewlett Packard (HP) 9845 desktop computer which controls an HP 3456 digital voltmeter and an HP 3497 digital scanner. The 24 channels used for measurement were monitored at the rate of 2.1 seconds per scan.

DATA ANALYSIS

The range of parameters cosidered in this study are: fresh water and saline water with 3.5% NaCl concentration, initial temperatures (T_0) from 25°C - 80°C, flash-down temperature difference (ΔT) from 0.5°C - 10°C, and pool depths (H) of 6.5" (165 mm), 12" (305 mm) and 18" (457 mm).

The temperature, pressure and other data for each run was used in carrying out a liquid-to-vapor heat balance to obtain the flashed mass and other related quantities. An error analysis indicated that the experimental rms error in the mass of vapor released ranged from 2.4 to 4.2%. Saturation conditions were assumed at the bubble interface. Once the curve of flashed mass versus time for each run was obtained, a least-squares curve fit (using eqn. 1 below) was employed to get the parameters corresponding to that particular run.

The experimental data for the mass of flashed steam as a function of time was found to be correlated very well by

$$m = m_\infty(1 - \exp(-P_2 t)). \tag{1}$$

Hence, the mass flow rate due to flashing can be expressed by

$$\dot{m} = m_\infty P_2 \exp(-P_2 t) = \dot{m}_0 \exp(-P_2 t) \tag{2}$$

A dimensional analysis of the variables in the system was performed to identify the non-dimensional parameters that could be used to get a universal correlation. The following numbers were found to be representative of the nature of the process:

1) $Ja = c_p \Delta T/h_{fg}$, the Jakob number, which represents the driving force for evaporation (superheat)

2) $Pr = c_p \mu/k$, the Prandtl number, which relates to the heat transfer through the liquid to the evaporating interfaces

3) $\Delta p/H$, a term which relates the diving force for evaporation (in terms of pressures) to the ebullition-supression hydrostatic head (depth of liquid) H

4) 1+C, to express the effect of NaCl concentration.

The definition of Ja used above was modified in two ways. First, the ratio of liquid to vapor densities was included to get

$$Ja_T = \rho_l c_p \Delta T/\rho_v h_{fg}, \tag{3}$$

since the pressure reduction Δp is the primary driving force in flashing unlike the boiling situation where the superheat ΔT produced by wall heating is the important parameter. Using Clapeyron's equation to relate Δp and ΔT, the modified definition, Ja_p, is given as

$$Ja_p = c_p T_0 \Delta p(\rho_l/\rho_v^2 - 1/\rho_v)/h_{fg}^2 \quad (4)$$

The ranges of variables used in this study correspond to the following ranges of these non-dimensional parameters:

$$12 < Ja_p < 197$$
$$2.706 < Pr < 5.941$$
$$0.1116 < \Delta p/H < 2.615$$
$$1 < 1+C < 1.035$$

m_∞ was scaled by m_v, the maximal amount of vapor that can be liberated (i.e., for attainment of stable equilibrium),

$$m_v = Ja(A)(H)(\rho_l) \quad (5)$$

The time t was scaled by a time characteristic to bubble growth limited by heat transfer, τ where:

$$\tau = (\sigma/\Delta p^2)/\alpha_l, \quad (6)$$

in lieu of a better scale. We note that this scaling is probably reasonable for the very early time when the vigor of the flashing process is such that a bubble time scale governs the rate of flashing. Beyond this time, the rate of pressure reduction in the vapor space could be a significant factor controlling the process, and this time scale may not be satisfactory.

The coefficients m_∞ and P_2 from the least-squares correlation of each experimental run were used as the data points in a multiple linear regression (MLR) fit to generate a single predictive correlation. The scaled m_∞ was taken to be a function of the four non-dimensional parameters defined above:

$$m_\infty/m_v = C_1(Ja_p)^{a_1}(Pr)^{a_2}(\Delta p/H)^{a_3}(1+C)^{a_4}, \quad (7)$$

or,

$$\ln(m_\infty/m_v) = \ln(C_1) + a_1 \ln(Ja_p) + a_2 \ln(Pr) + a_3 \ln(\Delta p/H) + a_4 \ln(1+C) \quad (8)$$

The constants C_1, a_1, a_2, a_3 and a_4 were obtained by the regression analysis. A similar predictive pattern was tried for the inverse time scale P_2, but there was much more scatter in the prediction. After a few trials using various combinations of the variables, the final expression using MLR for P_2 was

$$P_2 = C_2(Ja_p)^{b_1}(\Delta p/H)^{b_2}/\tau \quad (9)$$

or,

$$\ln(P_2) = \ln(C_2) + b_1 \ln(Ja_p) + b_2 \ln(\Delta p/H) - \ln(\tau) \quad (10)$$

RESULTS AND DISCUSSION

The final form of the correlation and the numerical values of the constants are $m = m_\infty\{1 - \exp(-P_2 t)\}$,

where
$$m_\infty = m_v(C_1)(Ja_p)^{a_1}(Pr)^{a_2}(\Delta p/H)^{a_3}(1+C)^{a_4},$$
$$P_2 = (C_2)(Ja_p)^{b_1}(\Delta p/H)^{b_2}/\tau \cdot 1000,$$

with
$$C_1 = 0.8867$$
$$C_2 = 0.27$$
$$a_1 = 0.05 \quad (11)$$
$$a_2 = -0.05$$
$$a_3 = -0.05$$
$$a_4 = 0.06$$
$$b_1 = 0.133,$$
and
$$b_2 = -1.6.$$

The curve-fit for the mass of flashed steam as a function of time for a sample run (run # 15) is shown in Fig. 2. It can be seen that the exponential fit is quite good. Such a correlation was obtained for all of the other runs, with an overall standard error of roughly 1.8 %.

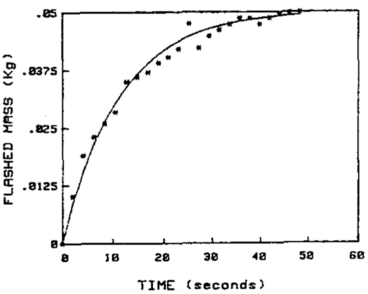

Fig. 2 Curve-fit of experimental data for Run #15 (T_0 = 63.5°C, ΔT = 5.77°C, H = 12" (305mm))

The results of MLR on the parameter m_∞ are shown next in Fig. 3. The residuals resulting from the linear regression were found to be quite small (with an overall standard error of the estimate of 7.5% which was considered satisfactory). As a measure of the goodness of the fit, a plot of calculated m_∞ versus experimentally observed m_∞ is shown in Fig. 4. The closer the points are to the 45° line, the better the fit is. It can be seen that the prediction is quite accurate.

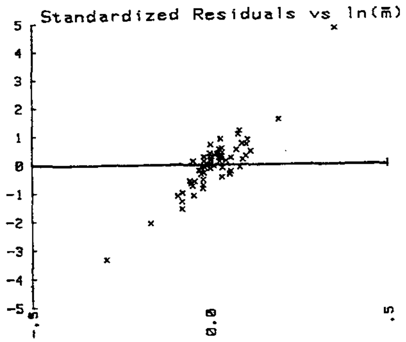

Fig. 3 Linear regression on $\bar{m}$

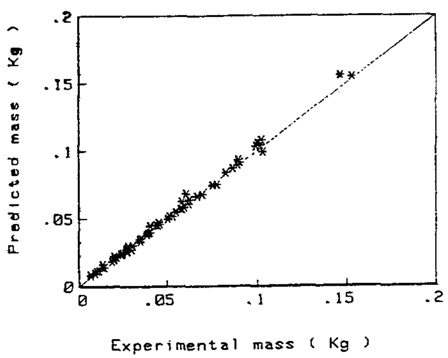

Fig. 4 Comparison of correlation with experiment

Next, the results of the regression analysis on the exponent P_2 are shown in Fig. 5. The large scatter in the prediction, which amounts to about ±60% (±1.8 standard residuals) was attributed to the inadequacy of the measurements to determine the fast transients which occur during the initial second of the

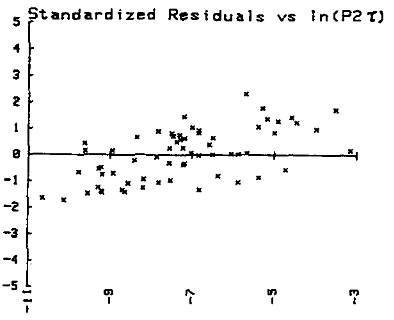

Fig. 5 Linear regression on $P_2\tau$

process, and possibly to other phenomena, not taken into consideration by the definition of the nondimensional parameters used here, such as, for example, the **rate** of pressure reduction which may be an important factor in the early stages of the process. We also tried other forms of correlation such as nonlinear regression and the use of other time scales with limited success. Within a period of 30 seconds from the start, the above-described scatter in the value of P_2 amounts to a scatter of ±68% in the flash evaporation rate m. It is noteworthy that no correlations for this purpose seem to exist at this time which have smaller scatter.

The available data in the literature on pool flashing is either in the form of rate expressions (which must be integrated over time to compare with the total flashed mass data in our experiment), or they were obtained for parameters outside the range of this study. The data obtained by Miyatake et al. (ref. 6) was used for comparison with the expressions found in our study. In their experiments, the flashed mass flux was expressed as a function of the equilibrium temperature at the end of flashing and the overall superheat. The range of non-dimensional numbers corresponding to their variables was found to be within our range of parameters, and hence a comparison could be made. The results are shown in Fig. 6. The observed differences may be attributed to the more accurate technique (by maybe an order of magnitude, because of the use of thermistors instead of thermocouples) used in the measurement of temperature in the

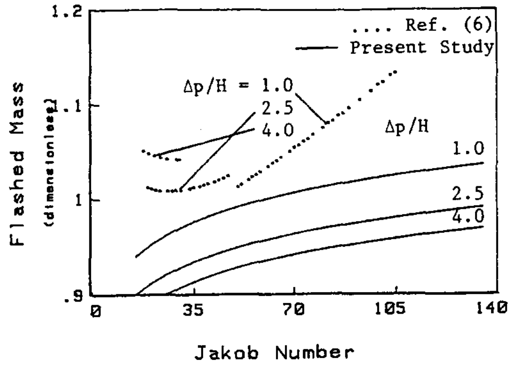

Fig. 6 Comparison with correlations of Ref. (6)

study reported in this paper. Furthermore, the trends observed in this study (Fig. 6) appear to be physically more plausible than those observed in ref. 6, esspecially in the low Ja region.

CONCLUSIONS

In summary, this study resulted in a general expression for the evaluation of flashed mass in a pool flash evaporator. The experiments were carried out in the range of operation of desalination and OTEC plants, but the conclusions reached may possibly be valid for other applications because of the non-dimensional nature of the correlation.

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