Table 7 . . . . Equations for Boiling Heat Transfer*

Description	Reference	Equation	
I. Free Convection Boiling, or boiling without bubbles for low Δt and $N_{Gr}N_{Pr} < 10^9$. (All properties based on liquid state).			
a. Vertical Submerged Surface (characteristic length = height)	14	$N_{Nu} = 0.61(N_{Gr}N_{Pr})^{1/4}$	(1)
b. Horizontal Submerged Surface	14	$N_{Nu} = 0.16(N_{Gr}N_{Pr})^{1/3}$	(2)
c. Simplified Equation for Refrigerant 12 (horizontal tube) ($1 < \Delta t < 4$ F, $t \approx 65$ F)	22	$h = 37\Delta t^{1/3}$	(3)
d. Simplified Equation for Refrigerant 22 (horizontal tube) ($1 < \Delta t < 4$ F, $t \approx 65$ F)	22	$h = 47\Delta t^{1/3}$	(4)
e. Simplified Equation for Water (horizontal plate) ($0.1 < \Delta t < 3$ F, $P = 1$ atm.)	12	$h = 150\Delta t^{1/3}$	(5)
II. Nucleate Boiling, or boiling with bubbles.			
a. Initial Bubble Diameter	23	$D_{b_1} = \frac{4\sigma_l T(\rho_l - \rho_v)}{\Delta t \rho_l \rho_v h_{fg}}$	(6)
b. Maximum Bubble Diameter; θ is the angle of contact measured within the liquid	23	$D_{b_2} = c\theta\sqrt{\frac{2\sigma_l}{(\rho_l - \rho_v)g}}$	(7)
c. General Correlation according to Rohsenow	24	$\frac{hD_{b_2}}{k_l} = c_1\left[\frac{q/A\,D_{b_2}}{\mu_l h_{fg}}\right]^{2/3}(N_{Pr_l})^{-0.7}$	(8)
d. General Correlation according to Kutateladze	25	$\frac{hD_{b_1}}{k_l} = c_2\left[\frac{q/A\,D_{b_1}\rho_l}{\mu_l h_{fg}\rho_v}\right]^{0.7}(N_{Pr_l})^{0.35}\left[\frac{P}{\sqrt{\sigma_l g(\rho_l - \rho_v)}}\right]^{0.7}$	(9)
e. General Correlation according to Forster and Zuber; ΔP is difference in pressure at saturation corresponding to Δt	26	$\frac{hD_{b_1}}{k_l} = c_3\left[\frac{D_{b_1}\sqrt{\rho_l\Delta P}}{\mu_l}\right]^{0.5}(N_{Pr_l})^{0.333}\left[\frac{\Delta t c_l \rho_l}{\rho_v h_{fg}}\right]^{0.25}$	(10)
f. Simplified Equation for Refrigerant 12 (horizontal tube) ($5 < \Delta t < 30$ F, $t \approx 65$ F)	22	$h = 16\Delta t^{1.6}$	(11)
g. Simplified Equation for Refrigerant 22 (horizontal tube) ($5 < \Delta t < 20$ F, $t \approx 65$ F)	22	$h = 6.1\Delta t^{2.3}$	(12)
h. Simplified Equation for Water (horizontal plate) (13 F $< \Delta t < 30$ F, $P = 1$ atm.)	14	$h = 0.17\Delta t^3$	(13)
III. Forced Convection with Boiling (Based on data for Refrigerant 12 and 22 inside horizontal tubes).	44	$N_{Nu} = c(N_{Re}^2 K_f)^n$	(14)
a. For exit vapor fractions below 85% $10^9 < N_{Re}^2K_f < 2 \times 10^{11}$	46	$\frac{h_{avg}d}{k_l} = 0.0009\left[\left(\frac{Gd}{\mu_l}\right)^2\left(\frac{J\Delta x h_{fg}}{L}\right)\right]^{0.5}$	(15)
$2 \times 10^{11} < N_{Re}^2K_f < 1.5 \times 10^{12}$	46	$\frac{h_{avg}d}{k_l} = 0.0225\left[\left(\frac{Gd}{\mu_l}\right)^2\left(\frac{J\Delta x h_{fg}}{L}\right)\right]^{0.375}$	(16)
b. For exit superheat up to 11 F and inlet vapor fraction below 50%	46	$\frac{h_{avg}d}{k_l} = 0.0032\left[\left(\frac{Gd}{\mu_l}\right)^2\left(\frac{J\Delta x h_{fg}}{L}\right)\right]^{0.4}$	(17)

* Equations in this table are approximate, at best, since coefficients may be influenced by many factors not specified here. Original references should be consulted before extrapolations to other conditions are attempted.

due to surface tension, it detaches and rises through the liquid. The diameter at the moment of detachment is given by Equation 7, Table 7. These diameters are used as characteristic lengths in many of the equations which have been proposed for correlating experimental data for nucleate boiling.[23]

No equation has been found which provides a reasonably accurate correlation of the existing data in all cases. Most of the difficulty originates from the dependence of the heat transfer rate on the bubble population, which in turn depends upon the detailed physical characteristics of the surface. Three of the more commonly used correlating equations, developed by Rohsenow,[24] Kutateladze,[25] and Forster and Zuber,[26] appear as Equations 8, 9, and 10 in Table 7. Simplified equations for Refrigerants 12 and 22, based on the experiments of a number of investigators[22,27,28,29,30] appear as Equations 11 and 12. Equation 13 is a simplified equation for water at atmospheric pressure.

Flooded Evaporators

The use of the equations in Table 7 for predicting heat transfer rates in flooded evaporators gives approximate results, at best. One of the reasons for this is that vapor entering

the evaporator, combined with vapor generated within the evaporator, may produce significant forced convection effects superimposed on those due to nucleation. Nonuniform distribution of the two-phase, vapor-liquid flow within the tube bundle of shell-and-tube evaporators, or within the tubes of vertical-tube flooded evaporators, is also an important factor.

The effect of vapor generated by the bottom rows of a tube bundle on the heat transfer coefficient for the upper rows was shown by Myers and Katz.[31] Improvement in coefficients for the upper tube rows was greatest at low Δt where nucleation effects are less pronounced. Other data for flooded tube bundles[32,33,34] are summarized by Hofmann.[35]

Curves typical of the performance of vertical tube natural circulation evaporators, based on data for water,[36] are shown in Fig. 8. Low coefficients are obtained at low liquid levels due to insufficient liquid coverage of the heating surface. The decrease in coefficient at high levels is due to an adverse effect of hydrostatic head on the temperature difference and circulation rate. Similar effects have been noted in horizontal shell-and-tube evaporators.[36]

Boiling with Forced Convection

When boiling occurs inside tubes, forced convection effects may exert considerable influence on the heat transfer rate. In general, higher coefficients are obtained, although they are accompanied by a drop in pressure which decreases the net temperature difference available for heat transfer. As evaporation takes place along the tube, various two-phase flow patterns may be encountered depending upon the fraction of vapor present, the flow rate, and other variables. A comprehensive review of heat transfer in two-phase flow is given by Collier.[37]

The variation in local heat transfer coefficient for forced convection evaporation inside a horizontal tube is shown in Fig. 9. In these tests, based on Anderson's data for Refrigerant 22,[38] the outlet vapor fraction was varied while the change in vapor fraction was fixed at $\Delta x = 0.2$. At low loads, the heat transfer coefficient varies very little with exit vapor fraction up to about $x_2 = 0.8$. At higher loads, however, the coefficient increases with increases in vapor fraction due to the influence of higher vapor velocities and better surface wetting. The coefficient continues to increase up to a leaving vapor fraction of about 90 percent, at which point it decreases sharply. It is believed that the rapid drop-off in coefficient is

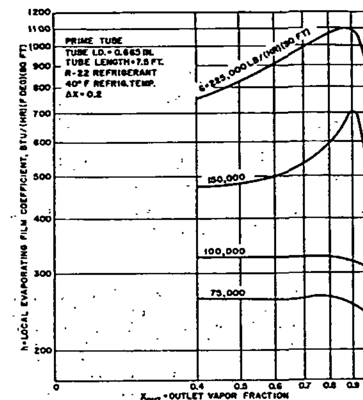


Fig. 9 . . . . Variation of Boiling Heat Transfer Coefficient at Different Qualities

due to insufficient liquid for wetting the tube walls. At 100 percent evaporation, the coefficient approaches values for single-phase gas convection. Tests by Witzig[39] and Seigel[40] indicate a characteristic similar to that shown in Fig. 9.

Data for forced convection evaporation of refrigerants have been reported by Witzig,[39] Ashley,[41] Davis,[42] Pierre,[43,44] Johnston and Chaddock,[45] Altman, Norris and Staub,[46] and Worsøe-Schmidt.[47] Ashley's tests were conducted with Refrigerant 12 inside a 0.575 in. I.D. tube at a refrigerant temperature of 40 F. Fig. 10 shows his results, together with an estimation of the performance of other tube diameters, obtained by assuming that the heat transfer coefficient increases as the mass velocity raised to the 0.8 power. These curves are meant only to indicate the trend, since the values are unconfirmed by tests. The effect of evaporating temperature on average heat transfer coefficients is shown in Fig. 11 based on the data of Witzig with Refrigerant 12.[39] Similar results are reported by Davis.[42]

Bo Pierre[43,44] measured average coefficients with Refriger-

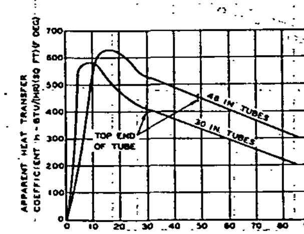
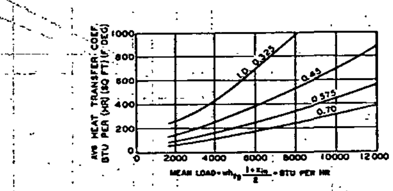


Fig. 8 . . . . Boiling Heat Transfer Coefficient for a Flooded Evaporator



* At evaporating temperature of 40 F.

Fig. 10 . . . . Boiling Heat Transfer Coefficients for Refrigerant 12 Inside Horizontal Tubes*