5.10. Example of Design Problems for Trufin in Boiling Heat Transfer

5.10.1. Design Example - Kettle Reboiler

Size a kettle reboiler to transfer 43.3(10^6) Btu/hr to vaporize a hydrocarbon mixture at 170 psia using steam available at 395°F. The critical pressure of this liquid is 434 psia and it has a boiling range of 60°F. The boiling temperature is 330°F.

Design the reboiler using 3/4-in. OD tubes on 1.125-in square pitch. We will estimate the latent heat as 144 Btu/lb_m and liquid density as 41 lb_m/ft^3.

Step 1. Calculate or estimate heating medium, tube wall, and fouling coefficients.

For this example (and in order to compare to a test unit) the steam coefficient is 2000 and the tube wall is 4800. This reboiler was claimed to be clean; hence,

$$R_o = \frac{1}{h_o} + \frac{1}{h_w} + R_f$$

$$R_o = 1/2000 + 1/4800 = 0.000708$$

Step 2. Calculate the mixture correction factor, F_m from eq. 5.38.

$$F_m = \exp(-\,00.015 \times 60) = 0.41$$

Step 3. Calculate B and R_oB and find q. From eqns. 5.8a, 5.10 and 5.62.

$$A^* = 0.00658(434)^{.69} = 0.435$$

$$F(P)_2 = 1.8\left(\frac{170}{434}\right)^{.17} = 1.535$$

$$B = [(0.435)(1.535)]^{3.33} = 0.26$$

Correcting B for the mixture, use fig. 5.29 at BR of 60°F,

$$B = 0.26 \times 0.41 = 0.1066$$

hence

$$R_oB = 0.\,1066 \times 0.000708 = 7.5(10^{-5})$$

At ΔT=65 Figure 5.33 gives q/B=280,000 hence

$$q = 0.1066 \times 280{,}000 = 29{,}848 \text{ Btu/hr ft}^2$$

Step 4. Calculate single tube maximum q_1, eq. 5.5

q_{1max} = 803(434)(170/434)$^{.35}$ (1 – 170/434)$^{.9}$ = 160,488 Btu/hr ft^2

Step 5. Preliminary estimate of bundle size

For a bundle

$q_b = q_{1max}\,\Phi_b$

where

$\Phi_b = 2.2(\pi D_B L/A_s)$.

If we approximate

$\Phi = 2.2\Psi$

by letting Ψ be (for square pitch)

$$\frac{\pi D_B L}{A_s} = \frac{\pi D_B L}{\frac{\pi D_B^2 L}{4} \times \frac{\pi d_o}{p_t^2}} = \frac{4 p_t^2}{\pi D_B d_o}$$

Now let

$$\Phi_b = 2.2\left(\frac{4 p_t^2}{\pi D_B d_o}\right) = \frac{q_b}{q_{1\max}}$$

$$\therefore \quad D_B = \frac{(2.2)(4) P_t^2 q_{1\max}}{q_b \pi d_o} = \frac{(2.2)(4)(1.125/12)^2 (160.488)}{(29{,}848)(\pi)(0.75/12)} = 2.118 \ ft$$

As the above approximation ignores the additional effect of circulation on the boiling coefficient, D_B = 2 ft.

Step 6. Calculate bundle maximum flux, eqn, 5.23

For U-tube on this pitch a total of 180 U-tubes or 360 ends will form a 2 foot diameter.

For one foot of bundle length

$$\Psi = \frac{\pi D_B L}{A_s} = \frac{\pi(2)(1)}{(360)\pi\ (.75/12)} = 0.0889$$

$\Phi_b = 2.2\Psi = (2.2)(0.0889) = .1956$

maximum bundle flux

$q = \Phi_b q_{1max}$

$q = 0.1956 \times 160{,}488 = 31{,}392$ Btu/hr ft^2

Step 7 Calculate the bundle heat transfer

For a 2 ft bundle assume q = 28,600 Btu/hr ft^2 and calculate heat transfer coefficients based on this flux and the values obtained in steps 3 and 5.

From eqn. 5.8 calculate h_{nbl}

$h_{nbl} = (0.435)(1.535)(28{,}600)^{0.7} = 878.3$ Btu/hr ft^2°F

Step 8. Calculate natural convection coefficient, eqn 5.7

We have insufficient information to calculate this coefficient but we will assume it is 40 Btu/hr ft^2°F.

Step 9. Calculate bundle coefficient, eqn. 5.22

$h_b = 878.3 \times 0.41 \times 1.5 + 40 = 580.1$ Btu/hr ft^2°F

$U = 1/(115\ 80.1 + 0.000708) = 411.2$ Btu/hr ft^2°F

$q=U\Delta T$

$q = 411.2 \times 65 = 26{,}730$ Btu/hr ft^2°F

The measured coefficient for this reboiler (72) was 440 Btu/hr ft^2°F or 7% higher.

Step 10. Check bundle design.

Step 9 heat flux (26,730) is less than the maximum allowed bundle flux of step 6 (31,392) hence OK. Since Φ_b in step 6 is greater than 0. 1 no vapor lanes or larger pitches are required; therefore, bundle is OK.

Step 11. Size the bundle.

$$\text{Required length} = \frac{43\times10^6}{26{,}730\times360\times.1963} = 22.8 \text{ ft}$$

This length checks with the test unit length of 23 ft.

Step 12. Check for entrainment.

Number of vapor nozzles per eqn. 5.64

$$N_n = \frac{23}{5\times2} = 2.3 \text{ round up to } 3$$

Vapor per nozzle

$$W_n = \frac{43{,}300{,}000}{144 \times 3} = 100{,}231 \ lb_m/hr$$

Entrainment limit, eq. 5.63

$$VL = 2290 \ X \ 1.725 \left[\frac{5}{41 - 1.725}\right]^{.5} = 1409 \ lb_m/hr \ ft^3$$

(Note dynes/cm = [lb_f/ft] / 6.86 x 10^{-5})

Therefore the vapor volume/nozzle = 100,231/1409 = 71.1 ft^3. If the shell is 25 ft long then the cross section area for vapor above the liquid level is 71.1/8.33 = 8.537 ft^2. The shell diameter is then determined from tables of segmental areas; however, for first approximation assume a liquid level at the center line then

$$D_s = (2 \ x \ 8.537 \ x \ 4/\pi)^{0.5} = 4.66 \ ft$$

This is a large shell compared to the bundle diameter; therefore, consider the use of entrainment separation devices.

5.10.2. In-Tube Thermosyphon - Example Problem

Size a vertical thermosyphon vaporizer to transfer 1,483,000 Btu/hr to an organic liquid with the following properties: boiling point @ 17 psia = 185.5°F, $c_{p\ell}$ = 0.45, latent heat= 154.8 Btu/lb, μ_ℓ = 0.96 lb/ft. hr, μ_v = 0.0208 lb/ft. hr, k = 0.086 Btu/hr ft. °F, and densities lb/ft^3 liquid = 44.8, vapor = 0. 18 1, $\underline{P}_c$ = 593.9 psia. Heating medium is steam at 217.4°F. Use 1-in. 12 BWG carbon steel tubes 8 ft. long. For this problem assumes no other fouling is present. This example is based on a test by Johnson (73). Boiling point elevation for 8 ft static head is 9°F. The heat source is steam condensing on the outside of the tubes with a coefficient of 1000.

Step 1.

Calculate R_o

$$R_w = \frac{(0.109/12)(1)}{(30)(.891)} = 0.00035$$

$$R_o = \frac{1}{1000} + 0.00034 = 0.00135$$

Step 2

Calculate the maximum limiting flux using eqn. 5.37

$$q_{max} = 16066 \left[\frac{(.782/12)^2}{8}\right]^{.35} (593.9)^{.61} \left(\frac{17}{593.9}\right)^{.25} (1 - .0286) = 22{,}548 \ Btu/hr \ ft^2$$

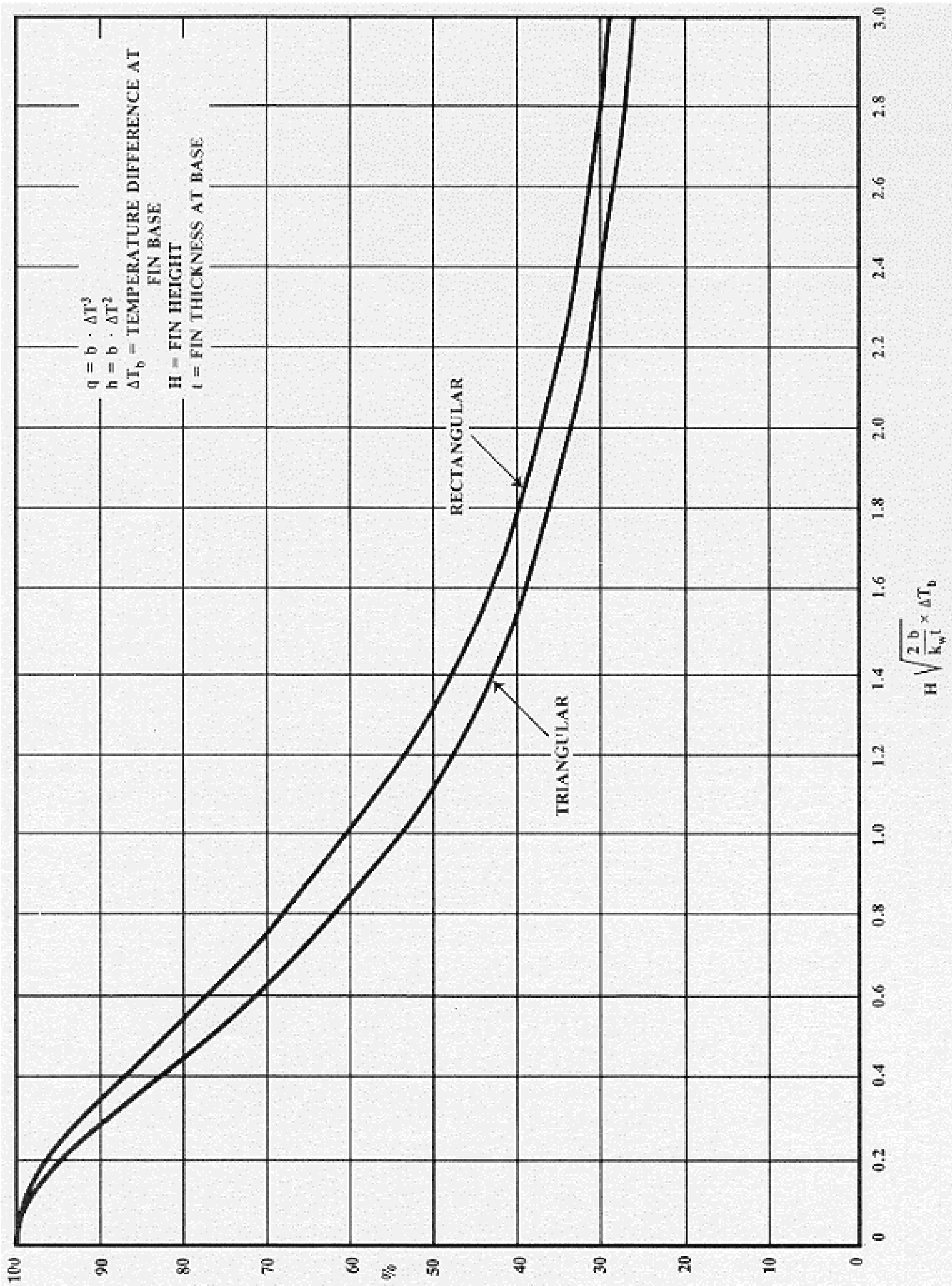

Fig. 5.37 Fin Efficiency for Boiling on Fins

This is a high flux and would require a 22548 x.00135 = 30.4 temperature drop across the steam tube wall. As only 217.4 – 185.5 = 31.9°F is available it is obvious the operation is well below the maximum.

Step 3. Determining a boiling flux

Calculate a nucleate boiling flux using Figure 5.33

Here

$$B = [0.00658(593.9)^{.69}(1.8)(17 / 593.9)^{.17}]^{3.33} = 0.1214 \tag{5.62}$$

hence

$$R_oB = 0.00135 \times 0.1214 = 0.00016$$

For ΔT = 31.9° from the figure we should calculate

$$q = 44{,}000 \times 0.1214 = 5342 \text{ Btu/hr ft}^2$$

This flux represents only the nucleate boiling coefficient and this is a lower limit. To include a two-phase convective effect assume a 50% increase in the boiling side. Hence, from the above flux and ΔT get U (167.4), subtract the R_o (.00135) resistances to get the boiling coefficient (216.4) increase the nucleate coefficient by the assumed ratio (= 324.6), then recalculate the new overall coefficient (225.7) and heat flux (7200).

Step 4. Determining the recirculation rate.

Vapor per tube = 8 x 0.2618 x 7200 / 154.8 = 97.4 lb/hr

Now one has to assume the fraction vaporized. We will short cut this trial and error by assuming the experimental value of 9%. Therefore, the feed rate/tube = 97.4/.09 = 1082 lb/hr.

Step 5. Calculate basic values needed to check pressure drop, circulation rate, and preheat zone.

$$G_t = 1082 / (\pi \times (.782)^2 / [4 \times 1441) = 324{,}404 \text{ lb/ft}^2 \text{ hr}$$

$$V = 324{,}404 / (3600 \times 44.8) = 2.01 \text{ ft/sec}$$

$$Re = .782 \times 324{,}404 / (12 \times .96) = 22{,}021$$

From friction factor charts f = 0.0075

Hence in the liquid zone the head loss per foot of tube is by eqn. 5.51

$$\Delta H = (4 \times .0075 \times 12 / .782) \times 2.01^2 / 64.4 = 0.029 \text{ ft/ft}$$

Using an average vaporization of 9/2 = 4.5% we can calculate X_{tt}, (eqn. 5.29)

$$X_{tt} = \left(\frac{1-.045}{0.045}\right)\left(\frac{0.181}{44.8}\right)^{0.57}\left(\frac{0.96}{0.0208}\right)^{0.11} = 1.398$$

Next get $\Phi^2_{\ell tt}$ (eqn. 5.55)

$$\Phi^2_{\ell tt} = 1 + 20 / 1.398 + (1 / 1.398)^2 = 15.82$$

The two-phase AH based on average liquid content of 0.955 is

$$\Delta H = 15.82 \times .029\ (0.955)^2 = 0.42 \text{ ft/ft}$$

The two-phase density due to slip is (eqn. 5.48 and 5.49)

$$R_v = 1 - 1/\sqrt{15.82} = 0.749$$

$$\rho_{tp} = (.749 \times .181) + [(1 - .749) \times 44.8] = 11.38 \text{ lb/ft}^3$$

The boiling zone static head loss is

$$\Delta H = 11.38/44.8 = 0.254 \text{ ft/ft}$$

Using eqn. 5.50 for $P\Delta_m$

$$G_t = 324{,}404/3600 = 90.11 \text{ lb/ft}^2 \text{ sec}$$

$$\Delta P_m = \frac{(90.11)^2}{32.2}\left(\frac{(1-.09)^2}{44.8\times .251}+\frac{(.09)^2}{.181\times .749}\right) = 33.64 \text{ lb/ft}^2 = 0.751 \text{ ft}$$

Heat transfer in preheat zone; eqn. 5.25

$$h = 0.023(22021)^{.8}\left(\frac{.45\times .96}{.086}\right)^{1/3}\left(\frac{.086\times 12\times .782}{.782}\right) = 121.1 \text{ Btu/hr ft}^2\ {}^\circ\text{F on outside area}$$

Therefore

$$U = 1 / (1 / 121.1 + .00135) = 104.1 \text{ Btu/hr ft}^2\ {}^\circ\text{F}$$

Using a $\Delta T = 31^\circ F$ the temperature rise in preheat zone is

$$\frac{104.1\times .2618\times 31}{1012\times .45} = 1.86\ {}^\circ\text{F/ft}$$

Step 6. Estimating preheat and boiling lengths.

Assume preheat zone = 3 ft

Friction loss in preheat zone = 3 x .029 = 0.087 ft

Effective submergence at this point = total head (8) – friction loss (.087) – preheat zone (3) = 4.91 ft liquid

which is equivalent to a boiling point elevation of

(4.91/8) x 9 = 5.53 °F

Length required for this temperature rise is 5.53/1.74 = 3.18 ft. Close enough.

Check on circulation and pressure drops

Available head = 8 ft liquid neglecting liquid line losses

Overall momentum loss =	.751 ft
Friction losses	
boiling zone 5 x .42	2.100
preheat zone	.087
Static heads	
boiling zone 5 x .254	1.270
preheat zone	3.000
	7.21ft

Considering there is some losses in the liquid recirculating line the above agreement is close enough.

Step 7. Calculate heat transfer in boiling zone

From eqn. 5.8

$$h_{nbl} = 0.00658(593.9)^{.69}(7200)^{.7}[1.8(17 / 593.9)^{.17}$$
$$= 266.2 \times .782 / 1 = 208.\ 1 \text{ Btu/hr ft}^2 \text{ °F on OD area}$$

From eqn. 5.28

$$F_{ch} = 2.35\left(\frac{1}{1.398} + 0.213\right)^{0.73} = 2.226$$

Determines from eqn. 5.31

$$Re_{tp} = 22{,}021 \times 2.226^{1.25} = 59{,}874$$

$$s = 1 / \{1 + [2.53(10^{-6}) \times (59{,}874)^{1.17}]\} = 0.504$$

From eqn. 5.27

$$h_{cb} = 121.1 \times 2.226 = 269.6 \text{ Btu/hr ft}^2 \text{ °F on an outside area basis}$$

From eqn. 5.26

h_b = (.504)(208.1) + 268.6 = 374.5

Adding the steam and wall resistance to obtain U for the boiling section

U = 1 / [(1 / 374.5) + 0.00135] = 249

Step 8. Calculate average coefficient for tube and area

An average coefficient for the preheat and boiling zone is

U_{av} = (3 x 104.1 + 5 x 249.0)/8 = 194.5 Btu/hr ft^2 °F

Required area = 1,483,000/194.5 x 31.9 = 239 ft^2 vs. 201 ft^2 in the test vaporizer.

Thus, this simplified calculation came within 19% of predicting the test results which is acceptable. In design case after calculating the required area (239 ft^2) a safety factor should be added to allow for the error spread in all the involved equations. Also fouling should be considered and should be included in the term R_o term. We did not include fouling in this example since we were trying to compare the calculation method with data obtained in a clean vaporizer.

5.10.3. Boiling Outside Trufin Tubes - Example Problem

To illustrate the value of and methods of calculation for Trufin tubes in boiling, a comparison of the performance of a plain surface and finned surface tube will be made. The plain tube is 0.75 and o.d., 18 B.W.G. wall and 90/10 Cu-Ni. The Trufin is Wolverine Cat. No. 65-265049-53. This tube has a surface area of 0.640 ft^2/ft with an A_o/A_i ratio of 4.61, a fin height of 0.057 and width of 0.012 inches. There are 26 fins per inch. The tubes are heated with steam having a coefficient of 2000. A pure hydrocarbon having a critical pressure of 489 psia will be boiled at 100 psia with an overall temperature difference of 10'F. The bundle factor, F_b, is 1.5 and the surface factor, F_s, for this temperature is 1.0 for the plain tube and 1.5 for the Trufin tube.

Evaluation of the Plain Tube Performance

1. Calculate R_o.
   where R_o = wall resistance + tube-side resistance

$$R_{wall} = \frac{(.049/12)(.75)}{29(.652)} = .000162$$

h_{wall} = 6174

$$R_o = \frac{1}{6174} + \frac{.75}{2000(.652)} = .00074$$

2. Calculate the single tube boiling coefficient using eq. 5.32

h_{nbl} = (5.43)(10^{-8})(489)$^{2.3}$[1.8(100 / 489)$^{0.17}$]$^{3.33}$ $\Delta T^{2.3}$ = 0.24 $\Delta T^{2.3}$

assuming the maximum possible ΔT of 10°F

$$h_{nbl} = (0.24)(10)^{2.3} = 47.9$$

3. Calculate the bundle boiling coefficient, overall U, and the heat flux then check the assumed ΔT. Assume a natural convection coefficient, h_{nv} = 40, and using the bundle factor of 1.5 in eq. 5.22.

$$h_b = (47.9)(1.5) + 40 = 111.\ 8$$

$$U_0 = 1 / (1 / 111.8 + .00074) = 103.2$$

the available boiling ΔT is then

$$\Delta T_b = 10 - (10)(.00074)(103.2) = 9.2°F$$

This is not close enough to the assumed value of 10 so repeat steps 2 and 3.

2’ Assume ΔTb = 9.2

$$h_{nbl} = (0.24)(9.2)^{2.33} = 42.25$$

3' $h_b = (42.25)(1.5) + 40 = 103.4$

$$U_0 = 1 / [(1 / 103.4) + .00074] = 96$$

4. Calculate available boiling ΔT.

$$\Delta T_b = 10 - (10)(.00074)(96) = 9.29°F$$

$$q = U\Delta T = (96)(10) = 960 \text{ Btu/hr ft}^2 \text{ (outside area)}$$

Evaluation of the Trufin Tube Performance

1. Calculate R_o
   The inside area basis will be used

$$R_{wall} = \frac{(.049/12)(.53)}{(29)(.579)} = 0.00013$$

R_o (wall + steam resistance) = 0.00013 + 1/2000 = 0.00063

2. Calculate the boiling coefficient using eq. 5.32 with a surface factor of 1.5

$$h_{nbl} = (1.5)(0.24)\ \Delta T^{2.33} = 0.36\ \Delta T^{2.33}$$

assume a boiling ΔT of 8°F

$$h_{nbl} = (0.36)(8)^{2.33} = 45.8$$

using eq. 5.22 with F_b = 1.5 and h_c =30

h_b = (45.8)(1.5) + 30 = 98.7

3. Adjust for fin efficiency.
   Figure 5.37 is used. This was derived for the case boiling liquids on fins where $h = b\Delta T^2$.

   using the assumed ΔT of 8 and h_b = 98.7

   $b = 98.7 / (8)^2 = 1.542$

   the abscissa for fig 5.37 is then

$$\frac{.057}{12}\sqrt{\frac{(2)(1.542)}{(29)(0.018/12)}} \times 8 = .320$$

   an efficiency of 87% is read and

   h_b = (98.7)(.87) = 85.9 on an outside area basis

   On an inside area basis;

   h_b (85.9)(4.61) = 396

   U = 1/ (1/396 + .00063) = 317

   q = UΔT = (317)(10) = 3170 Btu/hr ft^2 (inside basis)

   Check assumed value of boiling ΔT of 8°F.

   ΔT (wall + steam) = (0.00063)(3170) = 2.0

   $\Delta T_{boiling}$ = 10 – 2 = 8°F

   This checks with assumed value. If not then, repeat steps 2 and 3 with a new value.

Comparison of Performance

Since the area per foot of the two tubes are different, comparison will be made on a per foot of length basis.

1. For plain tube

   q/foot = (960)(.1963) = 188.5 Btu/hr-foot length

2. For Trufin

   q/foot =(3170)(.640/4.61) = 440.1 Btu/hr-foot length

   Therefore the performance ratio of Trufin to plain is: 440.1 / 188.5 = 2.3

Table 5.1

Simple dimensional equation for nucleate pooling boiling heat transfer (after Borishanski)

Liquid	Pressure range atm.	A^* from exp	A^* Eqn 5.9	Critical pressure atm.	No. in Fig 5.18
Water	1 – 70	1.61	1.66	216.9	1
Water	1 – 196	1.58	1.66	216.9	2
Water	0.09 – 1	2.28	1.66	216.9	3
Water	1 – 72.5	1.76	1.66	216.9	4
Water	1 – 170	1.75	1.66	216.9	5
Water	1 – 5.25	2.26	1.66	216.9	6
Pentane	1 – 28.6	.429	.449	32.8	7
Heptane (80%)	0.45 – 14.8	.464	.381	25.9	8
n-heptane	0.45 – 14.8	.642	.381	25.9	9
Benzene	1 – 44.4	.417	.588	48.1	11
Benzene	0.9 – 20.7	.520	.583	48.1	--
Diphenyl	0.9 – 8	.441	.425	30.4	--
Methanol	0.08 – 1.39	(.272)	.815	78.0	13
Ethanol	1 – 20.7	.720	.701	62.6	10
Ethanol	1 – 59	1.019	.701	62.6	12
Butanol	0.17 – 1.38	(.173)	.547	43.8	14
R11	1 – 3	.768 [.681]	.539	42.9	--
R12	1 – 4.9	.956	.516	40.3	15
R12	6 – 40.5	1.37 [1.01]	.516	40.3	--
R13	2.8 – 10.5	.705	.496	37.9	--
R13B1	17 – 39	1.744 [.976]	.508	39.1	--
R22	0.4 – 2.15	[.941]	.586	48.4	--
R113	1 – 3	.488	.453	33.4	--
R115	8 – 31	1.49 [.934]	.425	30.6	--
RC318	3.6 – 27	1.23 [.984]	.394	27.3	--
Methylene chloride	1 – 4.5	(.752)	.677	59.6	--
Ammonia	1 – 8	1.54	1.039	110.8	--
Methane	1 – 42	1.06	.563	45.6	--

Values shown in round brackets ( ) are uncertain.

Values shown in brackets [ ] relate to the use of Equations 5.11 for F(P).

NOMENCLATURE

A^*	Constant defined in equation 5.9.	dimensionless
A_s	Surface area.	ft^2
B	Constant defined in equation 5.62.	dimensionless
BR	Boiling range, dew point-bubble point.	°F
c_p	Specific heat, $c_{p\ell}$ for liquid and c_{pv}, for vapor	Btu/lb_m °F
d	Tube diameter, d_o for outside and d_i for inside.	ft.
D_p	Diameter of tube bundle.	ft.
D_s	Shell diameter.	ft.
F_b	Tube bundle correction factor.	dimensionless
F_{cb}	Chen Factor.	dimensionless
F_m	Mixture correction factor.	dimensionless
f	Friction factor.	dimensionless
G	Mass velocity.	lb_m/ft^2 hr
G_t	Mass velocity based on total flow.	lb_m/ft^2 hr
G_{tmax}	Total mass velocity based on minimum cross flow area.	lb_m/ft^2 hr
G_{mm}	Mass velocity at beginning of mist flow.	lb_m/ft^2 hr
g	Gravitational constant.	ft/hr^2
g_c	Conversion constant.	lb_m ft/lb_f hr^2
H	Height.	ft
H_ℓ	Height of liquid zone.	ft
ΔH	Head loss per foot of tube.	ft/ft
h	Film heat transfer coefficient; h_b = boiling, h_c = convective, h_f film, h_ℓ = liquid, h_r = radiation, h_{cb} = convective boiling, h_{ft} = film total, h_{nb} = nucleate boiling, h_{nbl} = single tube nucleate boiling.	Btu/hr ft^2 °F

K	Constant in equation 5.23.	dimensionless
k	Thermal conductivity.	Btu/hr ft^2 °F
L	Length.	ft
L_c	Minimum unstable wave length.	ft
m	Exponent.	dimensionless
N	Number of tube rows.	dimensionless
N_n	Number of vapor nozzles.	dimensionless
Nu	Nusselt number.	dimensionless
P	Pressure.	lb_f/ft^2
$\underline{P}_c$	Critical pressure.	lb_f/in^2
P_r	Reduced pressure = P/P_C.	dimensionless
Pr	Prandtl number.	dimensionless
P_{sat}	Saturation pressure at plane interface.	lb_f/ft^2
p_t	Transverse tube pitch.	ft
ΔP	Pressure drop; ΔP_T = total, ΔP_s =static, ΔP_m = momcntum, ΔP_f = friction.	lb_f/ft^2
q	Heat flux; q_{max} = maximum, q_{mf} = minimum film, q_{nc} = natural convection, q_{cr} = critical.	Btu/hr ft^2
Re	Reynolds number.	dimensionless
R_ℓ, R_v	Volume fraction of liquid, vapor.	dimensionless
R_o	Sum of thermal resistances other than the boiling resistance.	hr ft^2 °F/Btu
r_c	Radius of bubble.	ft
s	Chen suppression factor.	
T	Temperature; T_s = steam, T_w = wall, T_{sat} = saturation.	°F
ΔT	Temperature difference; ΔT_b = tube wall-saturation, ΔT_c = critical, ΔT_O = tube wall-bulk liquid, ΔT_{min} = difference at minimum film boiling coefficient.	°F
V	Velocity.	ft/hr

V_∞	Velocity approaching tube.	ft/hr
VL	Vapor load.	$lb_m/hr\ ft^3$
X_{tt}	Martinelli parameter, equation 5.29.	
x	Weight fraction of vapor.	
y	Mole fraction low boiling component in liquid.	

GREEK

β	Coefficient of thermal expansion.	1/°R
Γ	Flow rate per unit length.	$lb_m/hr\ ft$
λ	Latent heat; λ_e, λ' = effective latent heats see eqn. 5.17, 5.19.	Btu/lb_m
μ	Dynamic viscosity; μ_ℓ = liquid, μ_v = vapor	lb./ft hr
ρ	Density; ρ_ℓ = liquid, ρ_v = vapor, ρ_b = bulk average, ρ_{tp} = two-phase.	
σ	Surface tension.	lb_f/ft
v	Specific volume change liquid-vapor.	ft^3/lb_m
Φ_b	Bundle maximum flux correction factor.	dimensionless
$\Phi^2_{\ell tt}, \Phi^2_{vtt}$	Martinelli two phase factors.	dimensionless

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