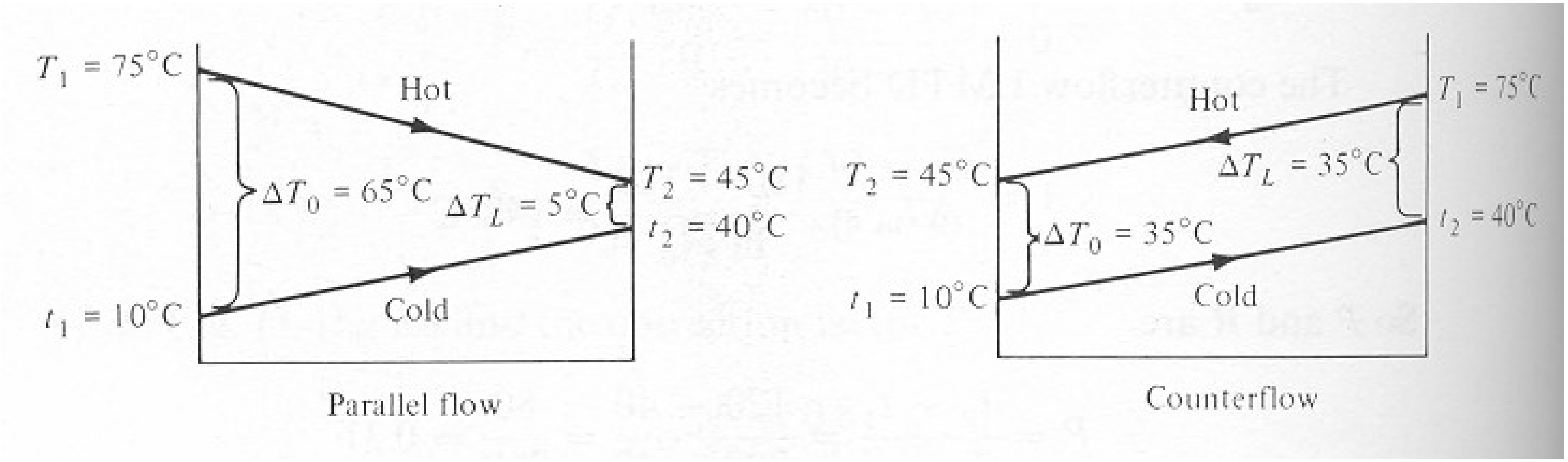
Heat Exchangers

Flow Patterns

- Parallel Flow
- Counter Current Flow
- Shell and Tube with baffles
- Cross Flow

Temperature Profiles



ΔT = Approach Temperature

Heat Exchanger Temperature Profiles

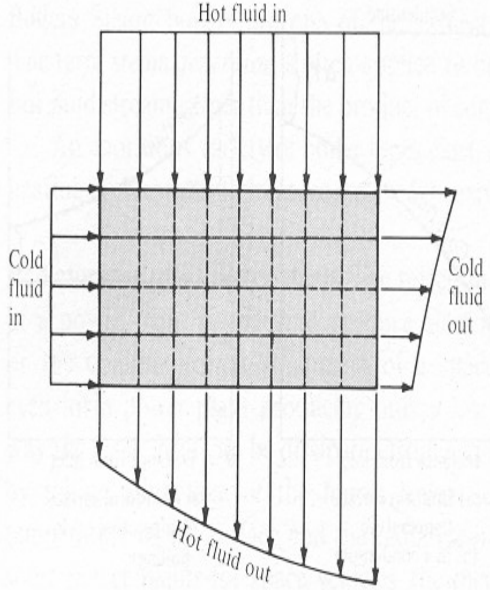
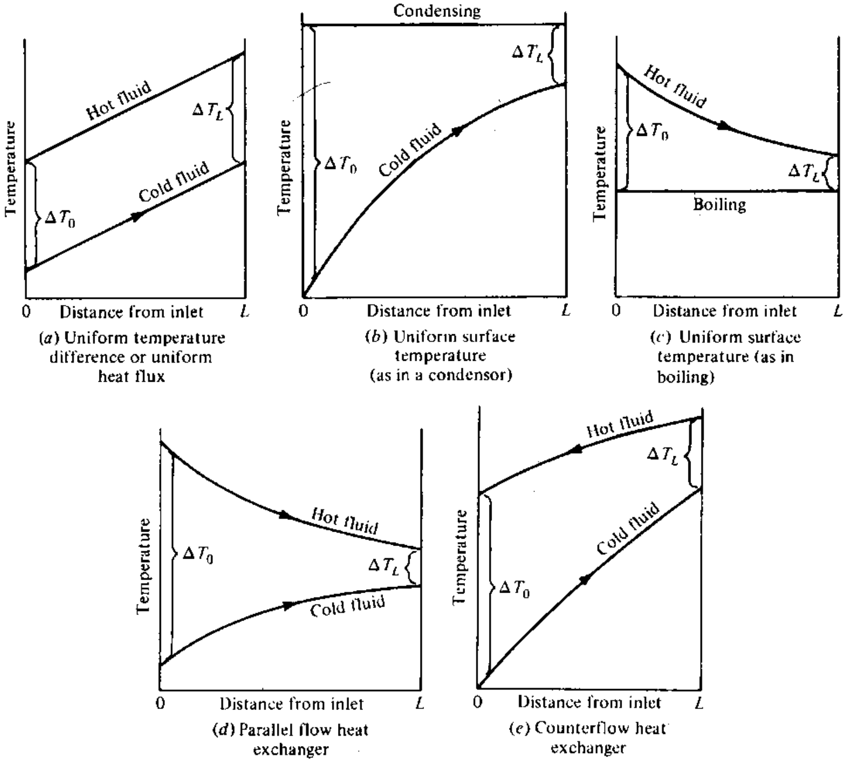


Figure 11-14 Temperature distribution in a cross-flow heat exchanger. Both fluids are unmixed.



(*a*) Uniform temperature difference or uniform heat flux

(*b*) Uniform surface temperature (as in a condensor)

(*c*) Uniform surface temperature (as in boiling)

(*d*) Parallel flow heat exchanger

(*e*) Counterflow heat exchanger

Figure 11-12 Axial temperature distribution in typical single-pass heat transfer matrices.

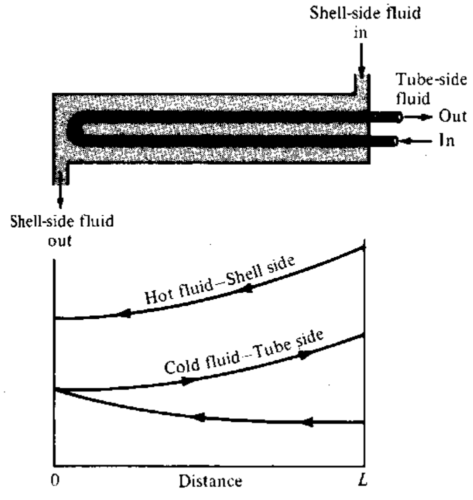


Figure 11-13 Axial temperature distribution in a one shell pass, two tube pass heat exchanger.

Flow Structure

$Q = U\,A\,F\,\Delta T_{\text{lm-counter}}$

$$F = \frac{\sqrt{R^2+1}\,\ln\left[\frac{(1-S)}{1-RS}\right]}{(R-1)\ln\left[\frac{2-S\left(R+1-\sqrt{R^2+1}\right)}{2-S\left(R+1+\sqrt{R^2+1}\right)}\right]}$$

$$R = \frac{T_{hot\,in} - T_{hot\,out}}{T_{cold\,out} - T_{cold\,in}} \qquad S = \frac{T_{cold\,out} - T_{cold\,in}}{T_{hot\,in} - T_{cold\,in}}$$

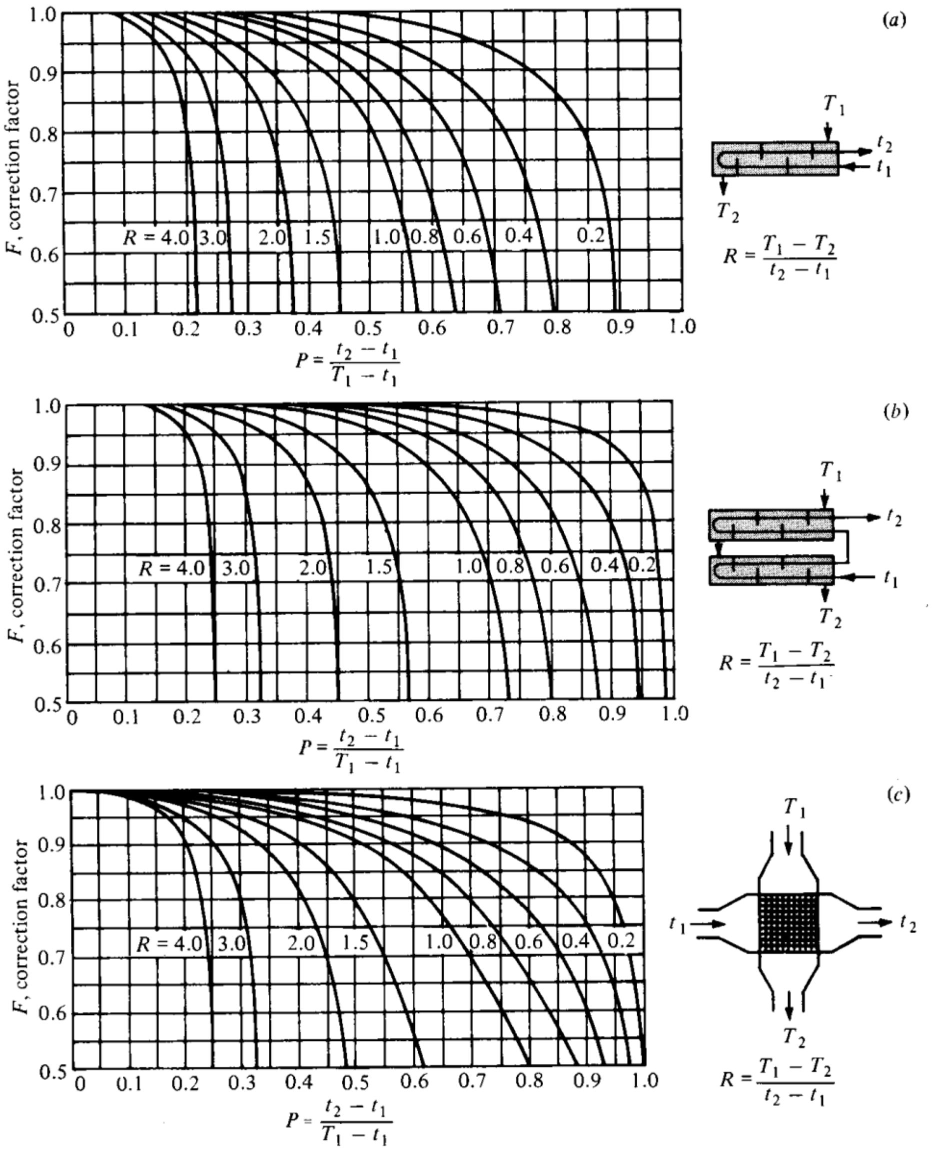
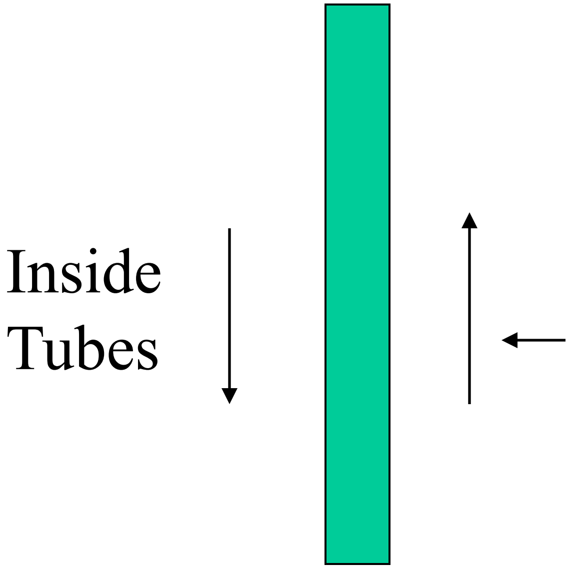


Figure 11-16 Correction factor F for computing $\Delta T_{\text{corrected}}$ for multipass and cross-flow exchangers. (*a*) One shell pass and two tube pass or multiple of two tube pass; (*b*) two shell pass and four tube pass or multiple of four tube pass; (*c*) single-pass, cross-flow, both fluids unmixed. (*From Bowman, Mueller, and Nagle* [45].)

Overall Heat Transfer Coefficient

- Series of Resistances
- Basis
  - Inside
  - Outside


Inside Tubes

$$U_o = \left[R_{f,i} \frac{A_o}{A_i} + \left(D_o / D_i \right)(1/h_i) + \left[1/\left(2k_w \right) \right] D_o \ln(D_o/D_i) + \left(1/h_o \right) + R_{f,o} \right]^{-1}$$

R_f=fouling factors, inside and outside

See table 18.5 for range of U values for different cases.

Heat Transfer inside a tube

$$Nu = \frac{hD}{k_f} = 0.027\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

$$L/D > 60, \text{ smooth tube}$$

$$0.7 < \mathrm{Pr} = \frac{C_p\mu}{k_f} < 16{,}700$$

$$\mathrm{Re} > 10{,}000 \quad \text{Turbulent}$$

Also other correlations valid over wider ranges

Heat Transfer outside of Tube

$$Nu = \frac{hD}{k_f} = (0.4\,\mathrm{Re}^{0.5} + 0.06\,\mathrm{Re}^{2/3})\,\mathrm{Pr}^{0.4}\left(\frac{\mu_b}{\mu_w}\right)^{0.25}$$

$$0.25 < \frac{\mu_b}{\mu_w} < 5.2$$

$$0.67 < \mathrm{Pr} = \frac{C_p \mu}{k_f} < 300$$

$$40 < \mathrm{Re} < 100{,}000$$

Also other correlations valid over wider ranges

Thermal Conductivity

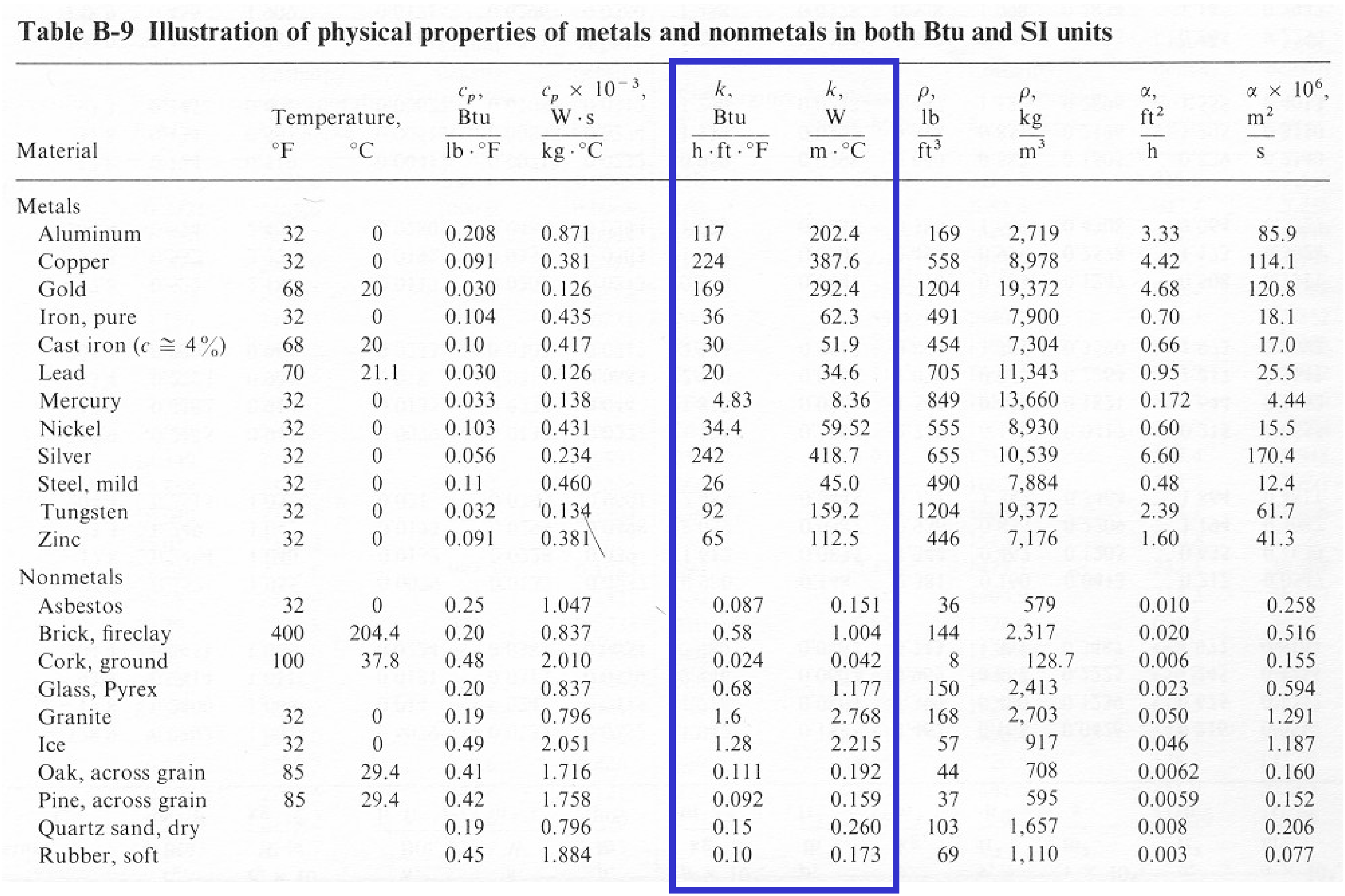


Table B-9 Illustration of physical properties of metals and nonmetals in both Btu and SI units

Material	Temperature, °F	°C	c_p, $\frac{\text{Btu}}{\text{lb}\cdot°\text{F}}$	$c_p \times 10^{-3}$, $\frac{\text{W}\cdot\text{s}}{\text{kg}\cdot°\text{C}}$	k, $\frac{\text{Btu}}{\text{h}\cdot\text{ft}\cdot°\text{F}}$	k, $\frac{\text{W}}{\text{m}\cdot°\text{C}}$	ρ, $\frac{\text{lb}}{\text{ft}^3}$	ρ, $\frac{\text{kg}}{\text{m}^3}$	α, $\frac{\text{ft}^2}{\text{h}}$	$\alpha \times 10^6$, $\frac{\text{m}^2}{\text{s}}$
Metals										
Aluminum	32	0	0.208	0.871	117	202.4	169	2,719	3.33	85.9
Copper	32	0	0.091	0.381	224	387.6	558	8,978	4.42	114.1
Gold	68	20	0.030	0.126	169	292.4	1204	19,372	4.68	120.8
Iron, pure	32	0	0.104	0.435	36	62.3	491	7,900	0.70	18.1
Cast iron ($c \cong 4\%$)	68	20	0.10	0.417	30	51.9	454	7,304	0.66	17.0
Lead	70	21.1	0.030	0.126	20	34.6	705	11,343	0.95	25.5
Mercury	32	0	0.033	0.138	4.83	8.36	849	13,660	0.172	4.44
Nickel	32	0	0.103	0.431	34.4	59.52	555	8,930	0.60	15.5
Silver	32	0	0.056	0.234	242	418.7	655	10,539	6.60	170.4
Steel, mild	32	0	0.11	0.460	26	45.0	490	7,884	0.48	12.4
Tungsten	32	0	0.032	0.134	92	159.2	1204	19,372	2.39	61.7
Zinc	32	0	0.091	0.381	65	112.5	446	7,176	1.60	41.3
Nonmetals										
Asbestos	32	0	0.25	1.047	0.087	0.151	36	579	0.010	0.258
Brick, fireclay	400	204.4	0.20	0.837	0.58	1.004	144	2,317	0.020	0.516
Cork, ground	100	37.8	0.48	2.010	0.024	0.042	8	128.7	0.006	0.155
Glass, Pyrex			0.20	0.837	0.68	1.177	150	2,413	0.023	0.594
Granite	32	0	0.19	0.796	1.6	2.768	168	2,703	0.050	1.291
Ice	32	0	0.49	2.051	1.28	2.215	57	917	0.046	1.187
Oak, across grain	85	29.4	0.41	1.716	0.111	0.192	44	708	0.0062	0.160
Pine, across grain	85	29.4	0.42	1.758	0.092	0.159	37	595	0.0059	0.152
Quartz sand, dry			0.19	0.796	0.15	0.260	103	1,657	0.008	0.206
Rubber, soft			0.45	1.884	0.10	0.173	69	1,110	0.003	0.077

What Temperature Approach

- Heuristic 26.
  - Near-optimal minimum temperature approaches in heat exchangers depend on the temperature level as follows:
    - 10°F or less for temperatures below ambient,
    - 20°F for temperatures at or above ambient up to 300°F,
    - 50°F for high temperatures,
    - 250 to 350°F in a furnace for flue gas temperature above inlet process fluid temperature.

Where are the Heat Exchangers?
What is happening in each

Octane Reaction
$2C_2H_4 + C_4H_{10} \rightarrow C_8H_{18}$
P= 20 psia, T=93C,
X=98% Conversion

	T_{BP}
C_2H_4	−103.7 °C
C_4H_{10}	+0.5 °C
C_8H_{18}	+125.52 °C

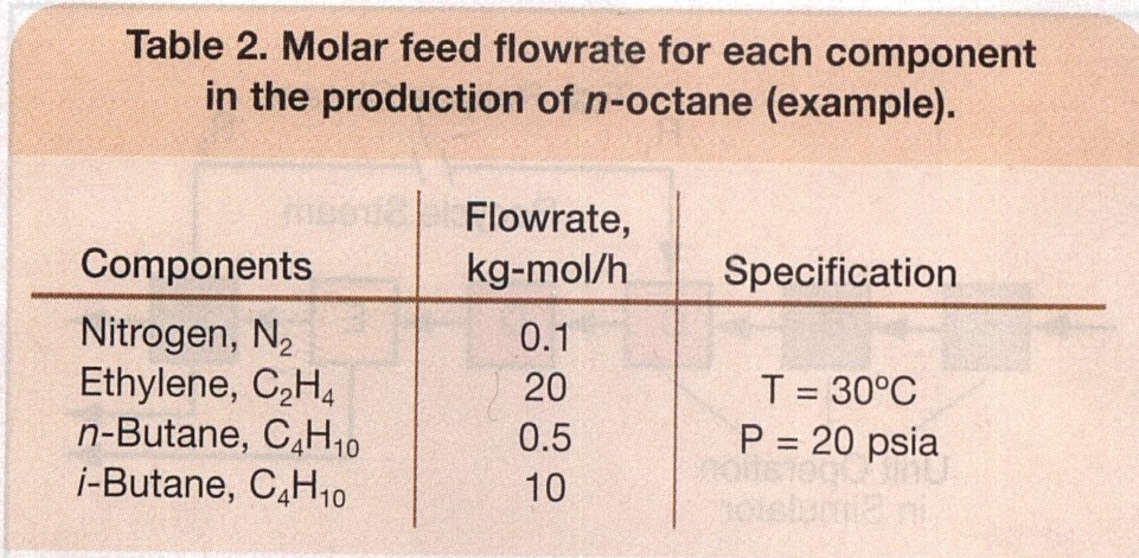
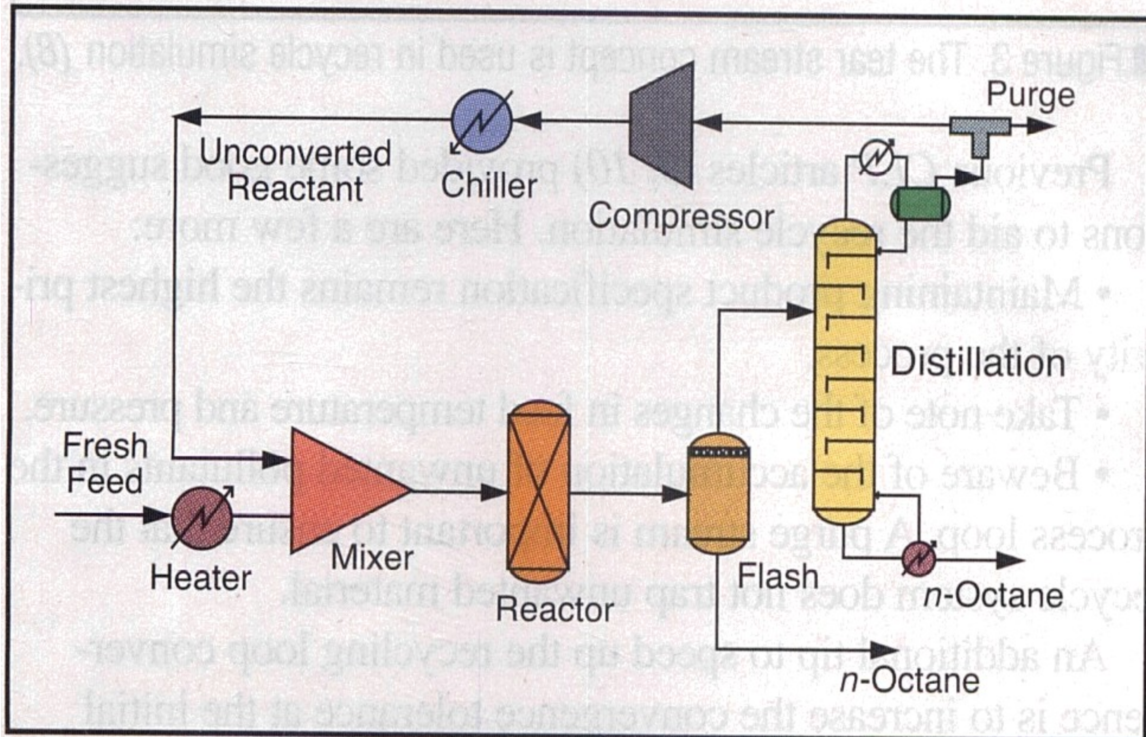


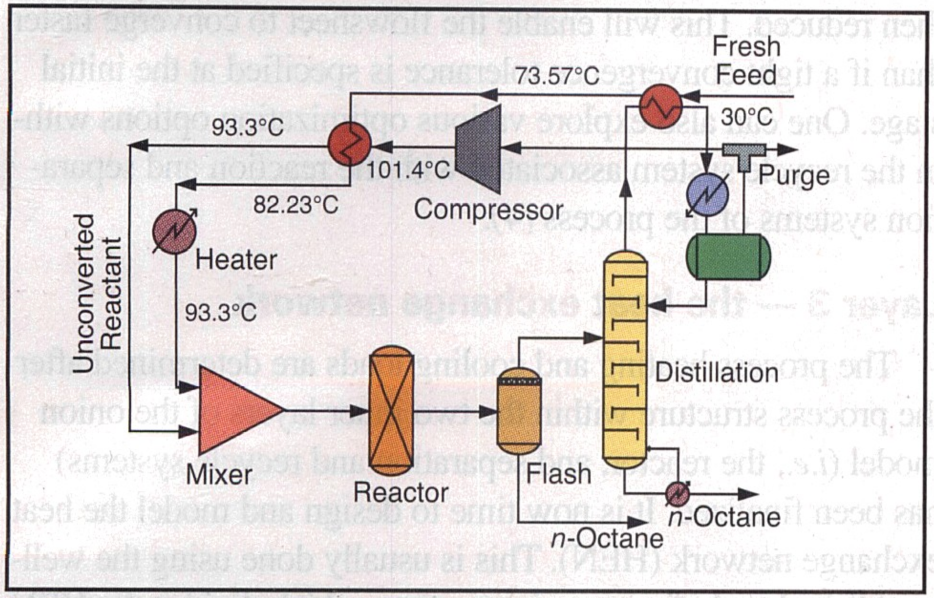
Table 2. Molar feed flowrate for each component in the production of *n*-octane (example).

Components	Flowrate, kg-mol/h	Specification
Nitrogen, N_2	0.1	
Ethylene, C_2H_4	20	T = 30°C
n-Butane, C_4H_{10}	0.5	P = 20 psia
i-Butane, C_4H_{10}	10	

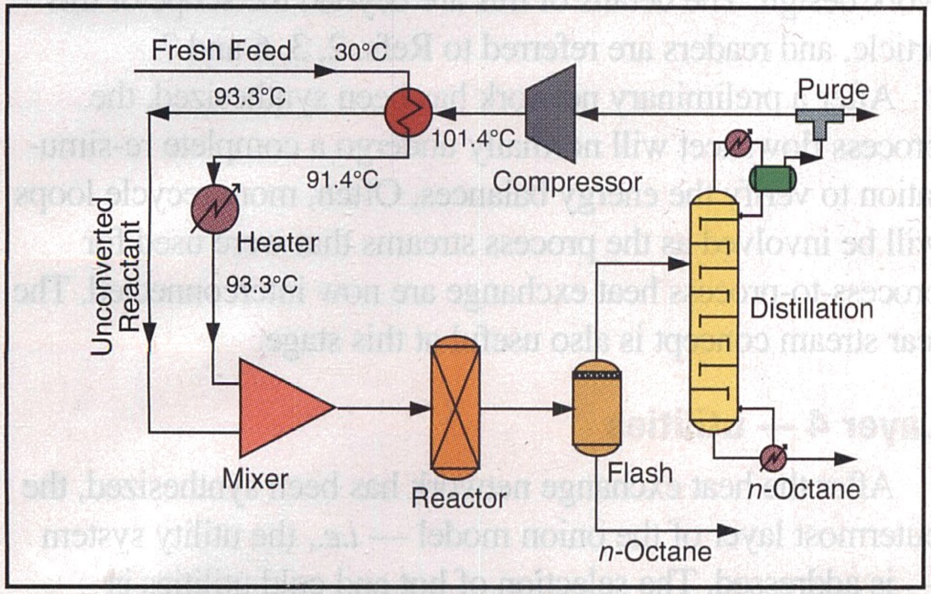


■ Figure 4. The preliminary flowsheet for the production of *n*-octane after completion of onion model layers 1 and 2.

Where are the Heat Exchangers?



■ Figure 5. The complete flowsheet with a heat-integrated distillation column.



■ Figure 6. The complete flowsheet with a stand-alone distillation column.

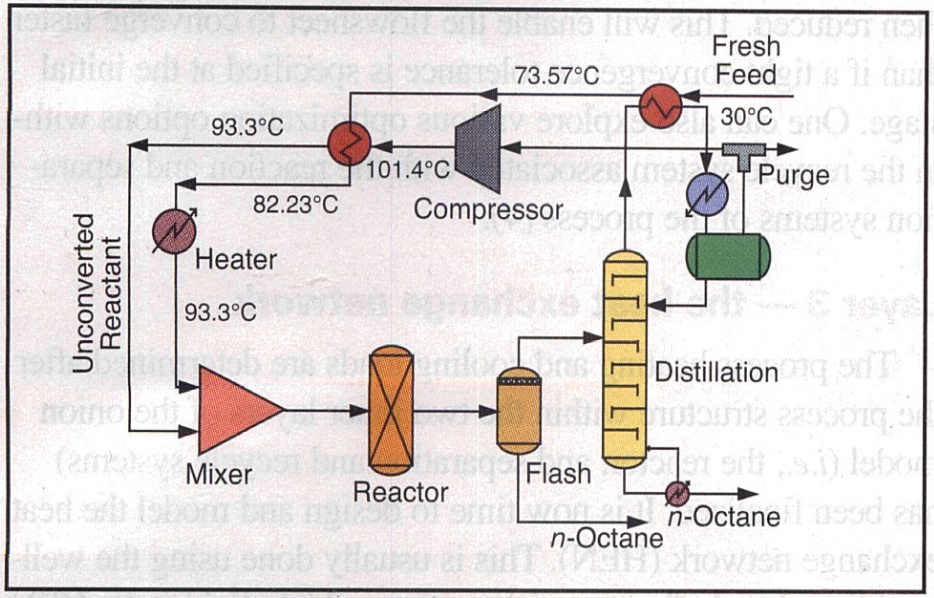
Heat Transfer With Phase Change

- Tricky Problems
  - Examples
    - Reboiler on Distillation Unit
    - Condenser on Distillation Unit
    - Flash Units
    - Boilers

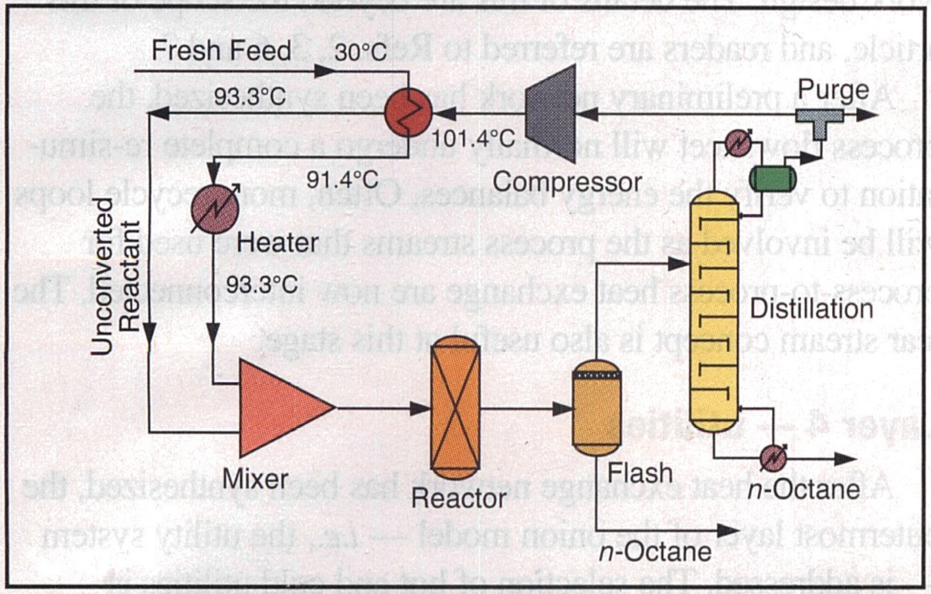
A Word About Steam

- Simulator Assumptions
  - Inlet – Saturated Vapor
      - Pressure
      - 100% Vapor
  - Outlet – Saturated Liquid
    - Liquid Only Leaves via steam trap
      - Pressure = P_{in}- ΔP (1.5 psi, Heuristic-31)
      - 100% Liquid

Where are the Tricky Heat Exchangers?



■ Figure 5. The complete flowsheet with a heat-integrated distillation column.



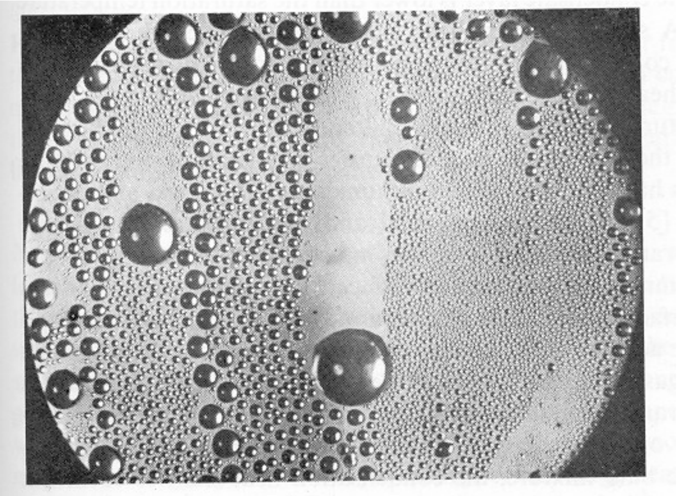
■ Figure 6. The complete flowsheet with a stand-alone distillation column.

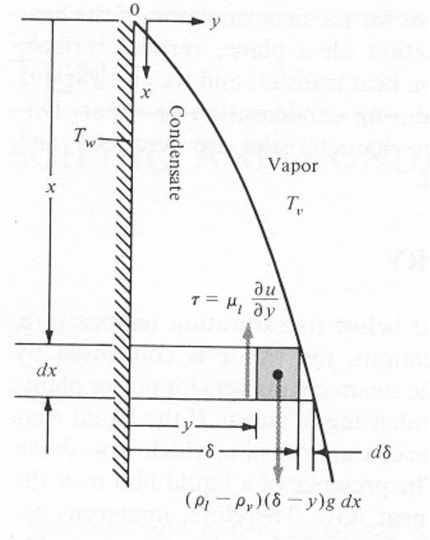
Condensation Heat Transfer

Assume Film Condensation

- Drop Wise Condensation
  - Special Case
    - Very High Heat Transfer
    - 5 to 10 x Film Condensation
- Film Condensation
  - Laminar

$$Nu_x = \frac{h_x x}{k_l} = \left[\frac{g\rho_l(\rho_l - \rho_v)\Delta H_{vap} k_l^3}{4\mu_l(T_v - T_w)x} \right]^{1/4}$$





Laminar to Turbulent Condensate Flow

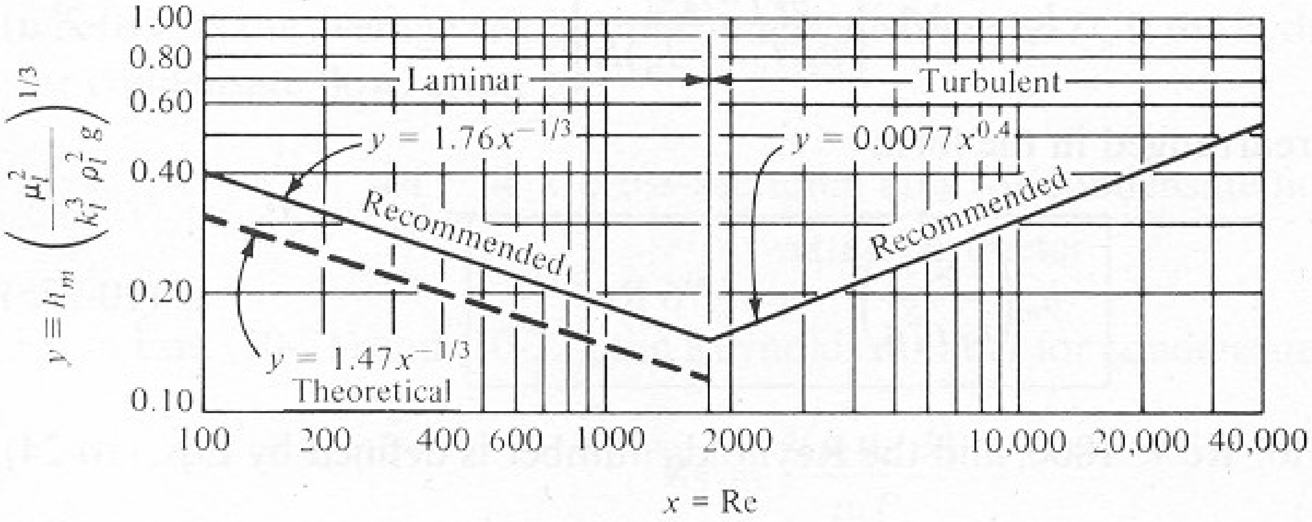


Figure 10-4 Average heat transfer coefficient for filmwise condensation on a vertical surface for laminar and turbulent flow regions.

Boiling Heat Transfer Coefficient

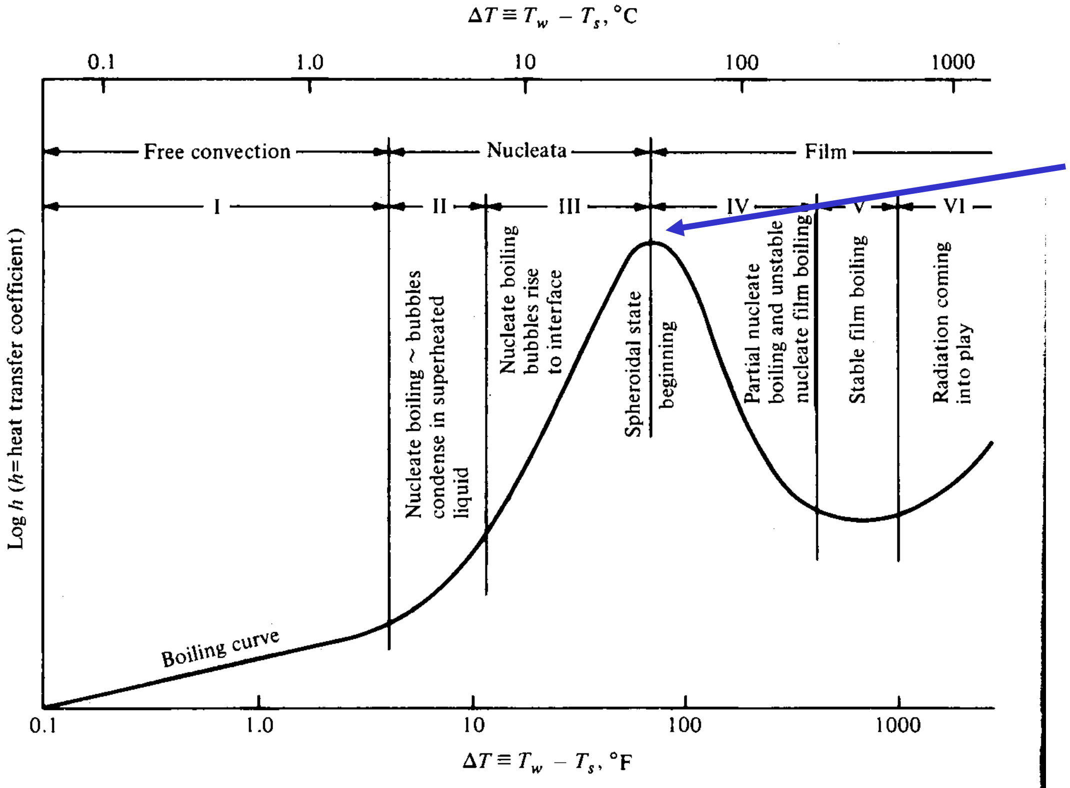


Figure 10-6 Principal boiling regimes in pool boiling of water at atmospheric pressure and saturation temperature T_s from an electrically heated platinum wire. (*From Farber and Scorah* [62].)

Highest Heat Transfer Coef. But hard to control HX operating here

Various correlations depending upon boiling mechanism

Heuristic 28

- Boil a pure liquid or close-boiling liquid mixture in a separate heat exchanger, using a maximum overall temperature driving force of 45 F to ensure nucleate boiling and avoid undesirable (low h) film boiling.

Effective Flow Conditions with Boiling in Thermo siphon

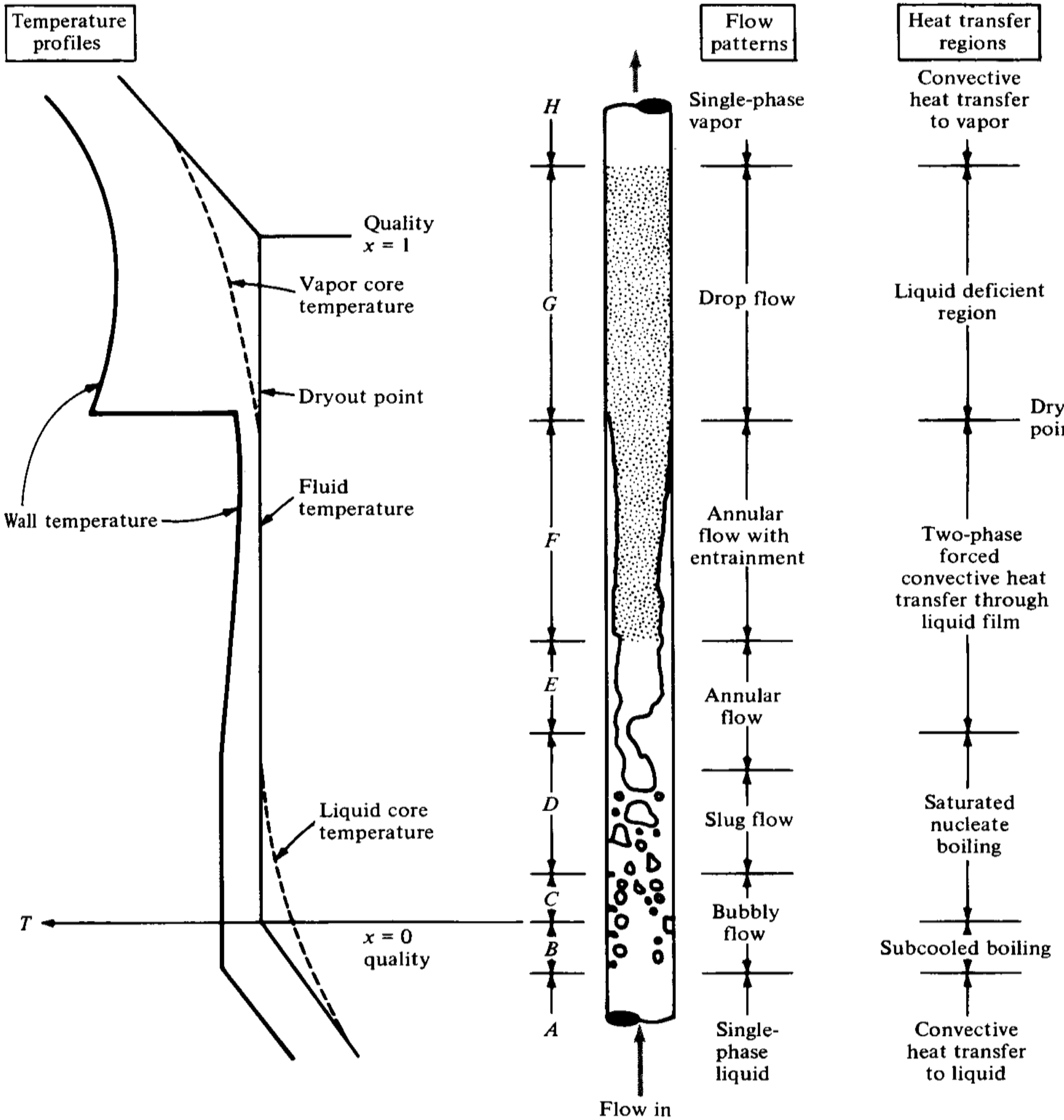


Figure 10-10 Various flow and heat transfer regimes in forced convection inside a vertical tube subjected to uniform heat flux.

Kettle (Re)Boiler Design

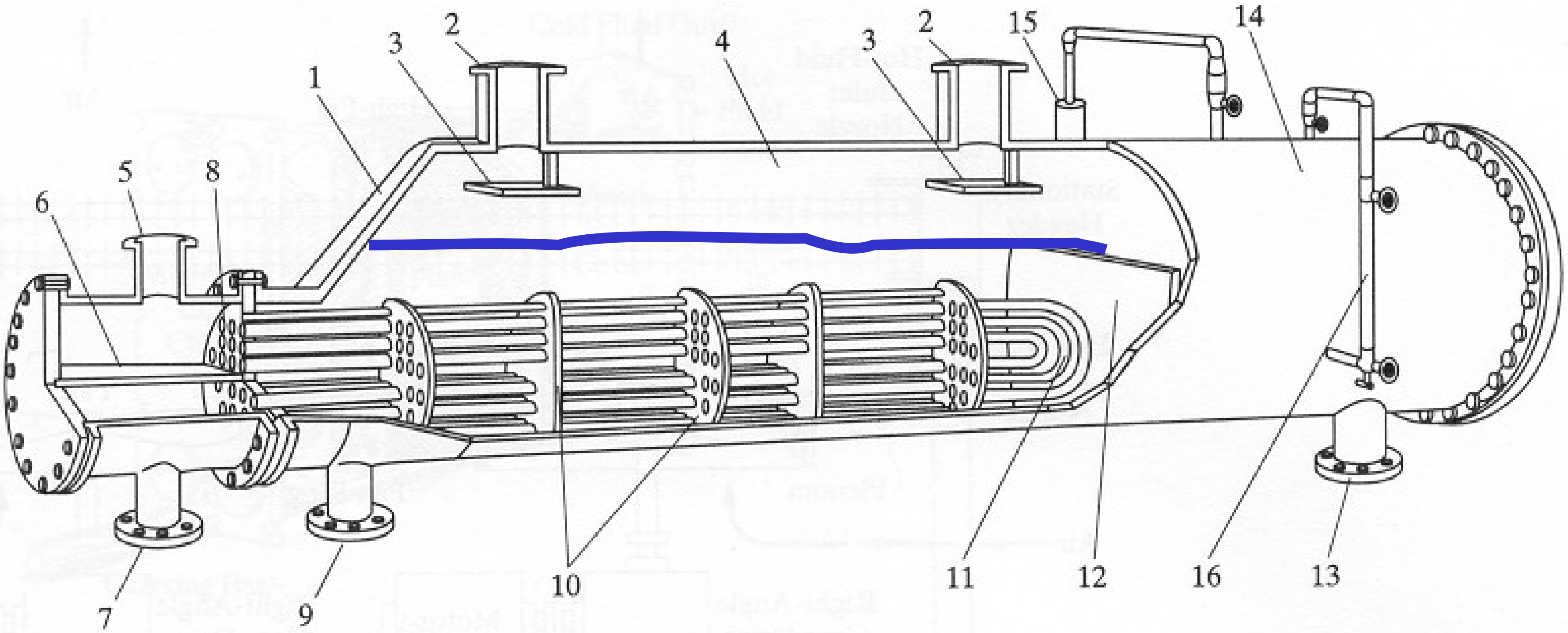


Figure 13.10 Kettle reboiler: (1) shell; (2) shell outlet nozzles (vapor); (3) entrainment baffles; (4) vapor-disengaging space; (5) channel inlet nozzle; (6) channel partition; (7) channel outlet nozzle; (8) tube sheet; (9) shell inlet nozzle; (10) tube support plates; (11) U-tube returns; (12) weir; (13) shell outlet nozzle (liquid); (14) liquid holdup (surge) section; (15) top of level—instrument housing (external displacer); (16) liquid level gauge.

Aspen - Zone Analysis
ProMax – Heat Release Increments

- Heuristic 29.
  - When cooling and condensing a stream in a heat exchanger, a zone analysis, described in Section 18.1, should be made to make sure that the temperature difference between the hot stream and the cold stream is equal to or greater than the minimum approach temperature at all locations in the heat exchanger. The zone analysis is performed by dividing the heat exchanger into a number of segments and applying an energy balance to each segment to determine corresponding stream inlet and outlet temperatures for the segment, taking into account any phase change. A process simulation program conveniently accomplishes the zone analysis.

Pressure Drop & Flow Rate

- Laminar vs. Turbulent
  - Heuristic 31.
    - Estimate heat-exchanger pressure drops as follows:
      - 1.5 psi for boiling and condensing,
      - 3 psi for a gas,
      - 5 psi for a low-viscosity liquid,
      - 7-9 psi for a high-viscosity liquid,
      - 20 psi for a process fluid passing through a furnace.

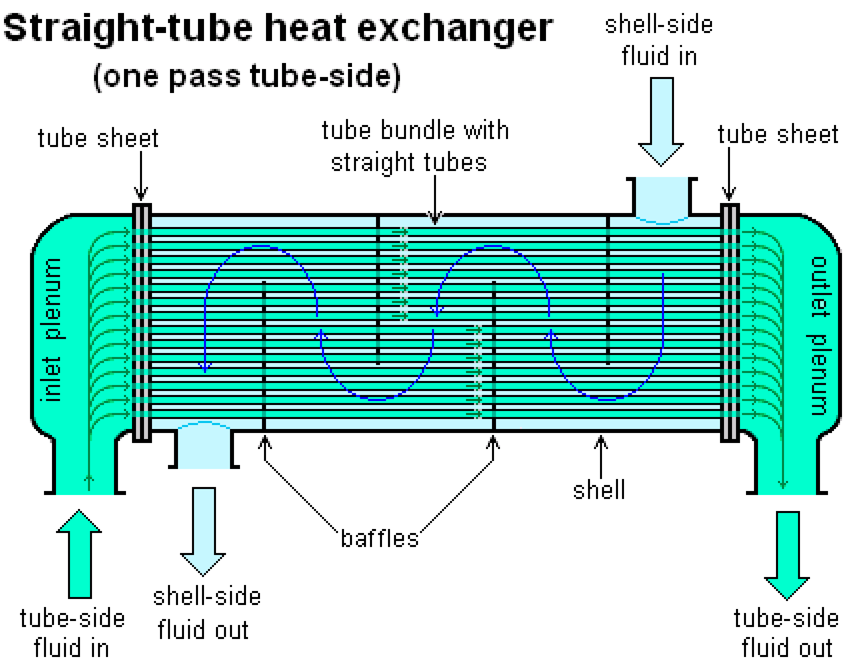
Controlling ΔP in Simulator

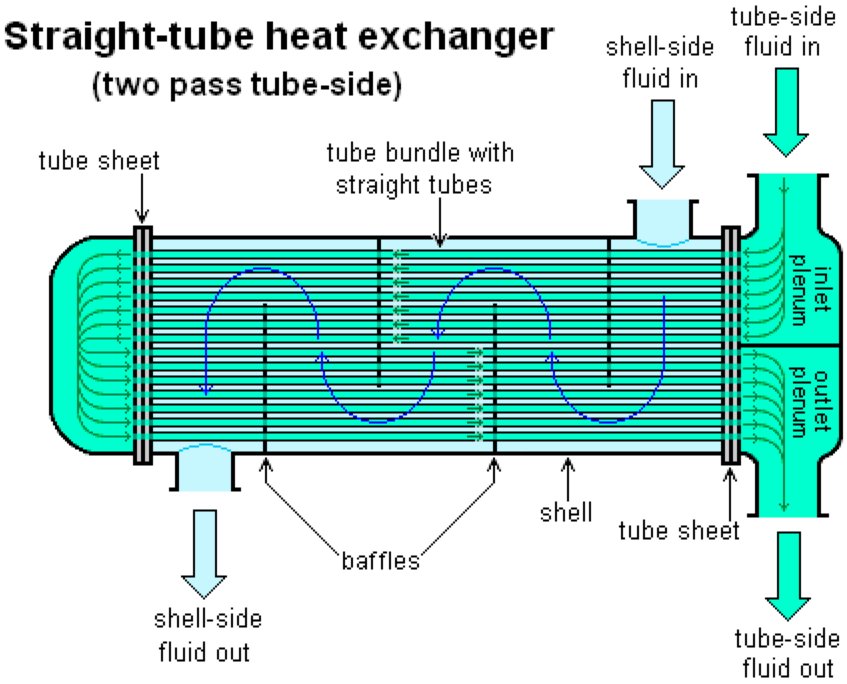
- Shell side
  - Nozzle diameter
    - Inlet and Outlet
  - Number of Baffles
  - Tubes
    - Number, diameter, pitch, No. passes
- Tube side
  - Nozzle diameter
    - Inlet and Outlet
  - Tubes
    - Number, diameter, pitch, No. passes

Note interactions!

Shell Heads, Shell Type

- See ProMax Help/index “Shell, types”



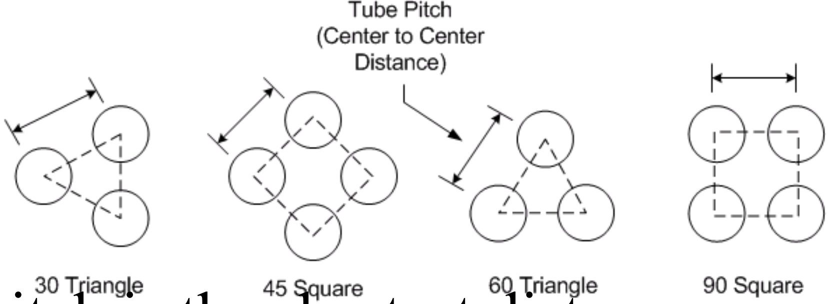


HX Cost

- Size Factor HX Area
- $C_{Base(6\text{-}2000)}$=exp[11.0545-0.9228*ln(A)+0.09861*ln(A)^{2}]
- Purchase Price
  - $C_{P\text{-}fob} = F_{\mathbf{P}}(P) * F_{\mathbf{M}aterial}(A) * F_{\mathbf{L}}(L) * C_{Base} * (CPI/394)$
  - $C_{BM} = F_{BM} * C_{P\text{-}fob}$
  - $C_{BM} = 3.17 * C_{P\text{-}fob}$
- Cost depends on HX Area
- Pumping Cost
  - Work = Q*ΔP

Controlling A in Simulator

- $A = N_{tubes} \pi D_{tubes} L_{tubes}$
- Shell
  - Shell Diameter and pitch determines N_{tubes}
- Tubes
  - D_{tubes}
  - L_{tubes}
  - Tube pitch-The transverse pitch is the shortest distance from the center lines of two adjacent tubes.
  - Tube pitch ratio 1.25 to 1.5 typically



Controlling U in a Simulator

- For a given heat duty and geometry - U determines the HX area
- Steps
  - Identify the controlling heat transfer resistance
  - h_o-Manipulate the shell side Reynolds number
    - Shell diameter
    - Tube pitch
    - Number of baffles
  - h_i-Manipulate the tube side Reynolds number
    - Tube diameter
    - Number of tubes (shell diameter and tube pitch)
    - Number of passes
  - If odd things happen check to see that you have the same controlling heat transfer resistance

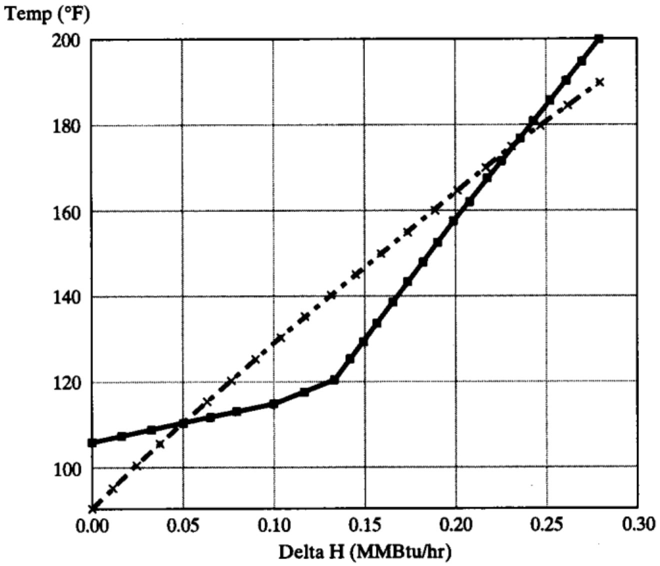
Note interactions!

Other Issues

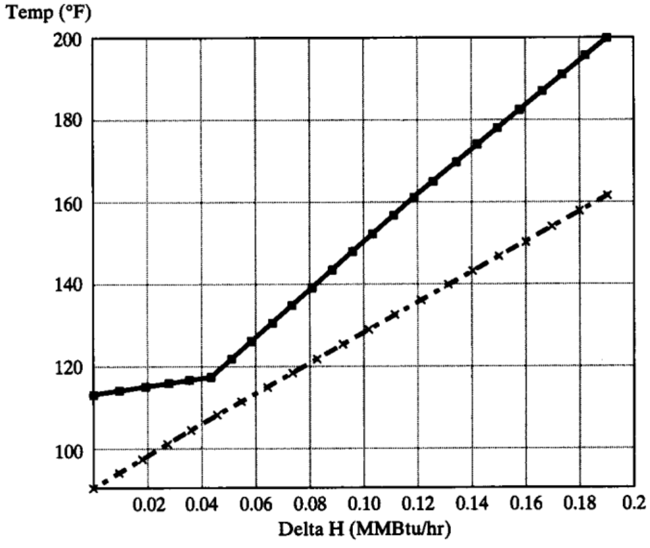
- Materials of Construction
  - Strength at temperature, life time, heat conduction, fouling
- Design layout
  - Tube pitch, baffles, tube and shell diameters

Heat Exchanger Problems

- Temperatures Cross Each Other
  - Non-functioning Exchanger
  - To solve increase approach ΔT
- Condensation/Evaporation
  - Heat transfer with multiple heat transfer coefficients in a single apparatus
    - Various regimes of boiling
    - Various regimes of condensation



(a)



(b)

Zone Analysis