HEAT TRANSFER

Mechanisms of Heat Transfer:

(1) Conduction

$$\frac{dQ}{dt} = -k\,A\frac{dT}{dx}$$

where Q is the amount of heat, Btu, transferred in time *t*, h

k is the thermal conductivity, Btu/[h ft^2 (^{o}F/ft)]

A is the area of heat transfer normal to heat flow, ft^2

T is the temperature, ^{o}F

x is the thickness of the conduction path, ft.

(2) Convection

$$\frac{dQ}{dt} = h\,A\,\Delta T$$

h is the heat transfer coefficient, Btu/[h ft^2 ^{o}F].

HEAT TRANSFER

Mechanisms of Heat Transfer:

(3) Radiation

$$\frac{dQ}{dt} = \sigma \varepsilon A T^4$$

where

σ is the Stefan-Boltzmann constant = 0.1713 10^{-8} Btu/(h ft^2 $^oR^4$)

ε is the emissivity of surface

A is the exposed area for heat transfer, ft^2

T is absolute temperature, ^{o}R.

Overall Heat Transfer Coefficient

Definition of the overall heat transfer coefficient, *U*

$$q = U\, A \Delta T_{tot}$$

U [=] Btu/(h ft^2 ^{o}F)

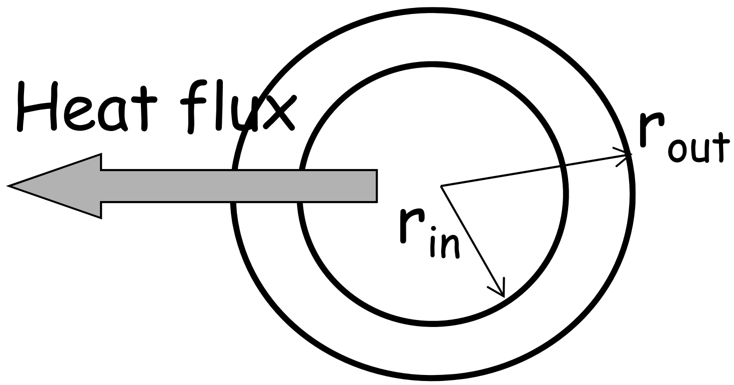
ΔT_{tot} is the total temperature difference (overall driving force for the process).

Important:

The overall heat transfer coefficient, *U*, is an approximate value.

It is defined in combination with the area *A* (e.g. inside/outside area of a pipe).

Overall Heat Transfer Coefficient



General correlation:

Intensity=Potential/Resistance

Rate = Driving Force/Resistance

Applies for electricity, flow, flux etc.

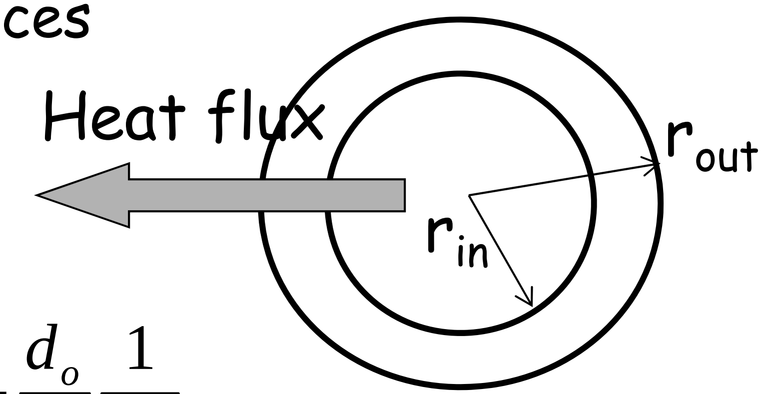
Heat transport: $q = U\,A\Delta T_{tot}$

Overall resistance, $R=1/UA$

Overall Heat Transfer Coefficient

Resistances in series:
Overall resistance = Sum of resistances

In our case:



$$\frac{1}{U_o} = \frac{1}{h_o} + \frac{1}{h_{od}} + \frac{d_o \ln(d_o/d_i)}{2k_w} + \frac{d_o}{d_i}\frac{1}{h_i} + \frac{d_o}{d_i}\frac{1}{h_{id}}$$

U_o: overall heat transfer coefficient based on the outside area
h_o, h_i: outside/inside film heat transfer coefficient
d_o, d_i: outside/inside pipe diameter
k_w: wall thermal conductivity
h_{od}, h_{id}: outside/inside fouling heat transfer coefficient

Heat Transfer Equipment

Usual terminology:

- Exchanger: heat exchange between two process streams.
- Heater or Cooler: a process stream is heated/cooled by a utility stream.
- Vaporiser: a process stream is completely vaporised.
- Reboiler: vaporiser associated with a distillation column.
- Evaporator: used to concentrate a solution.
- Fired heater: heating is done by combustion.

Heat Transfer Equipment

- Double-pipe exchanger, used for cooling or heating.
- Shell and tube heat exchangers
- Plate-fin exchangers.
- Spiral heat exchangers.
- Air cooled: coolers and condensers.
- Fired heaters.

Heat Transfer Equipment

Tube and shell heat exchanger:

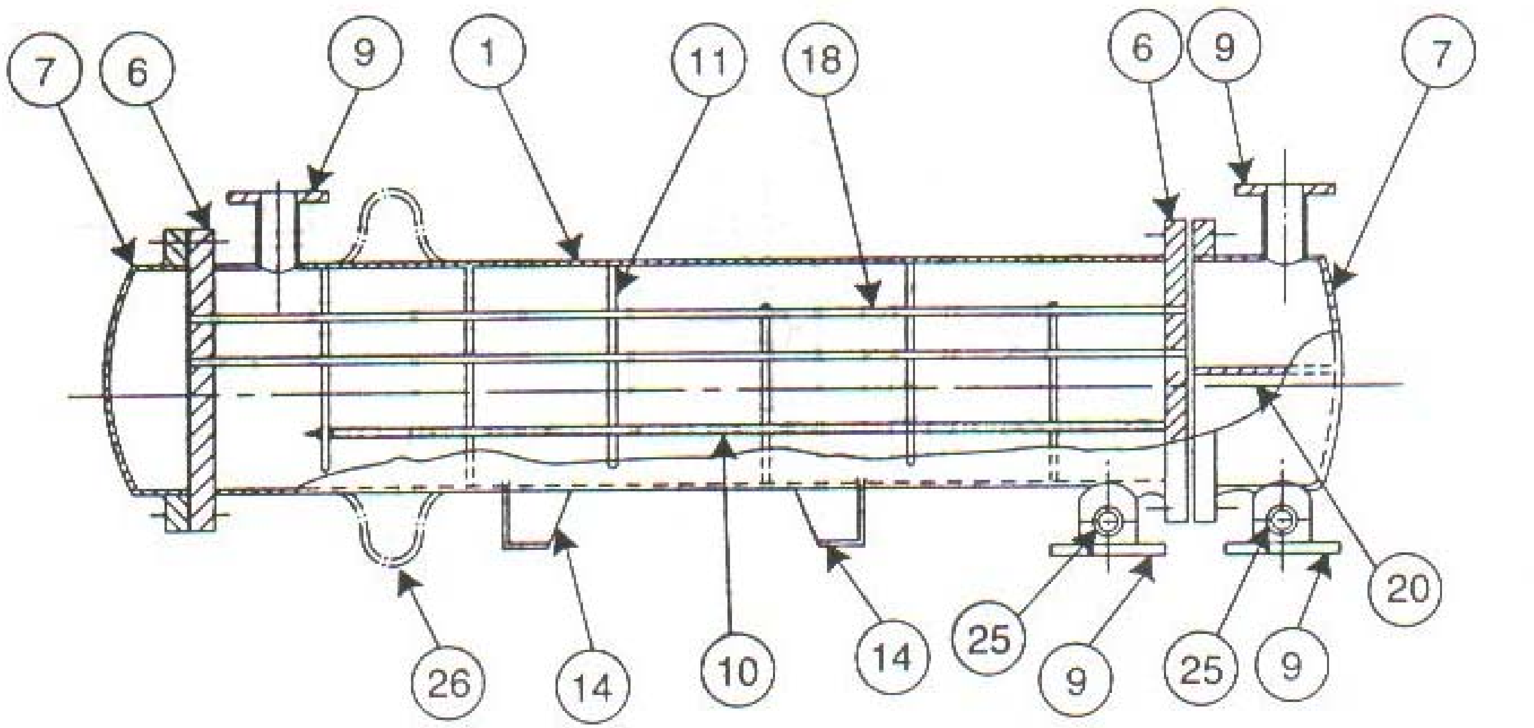


Figure 12.3. Fixed-tube plate (based on figures from BS 3274: 1960)

Tube and shell heat exchanger:

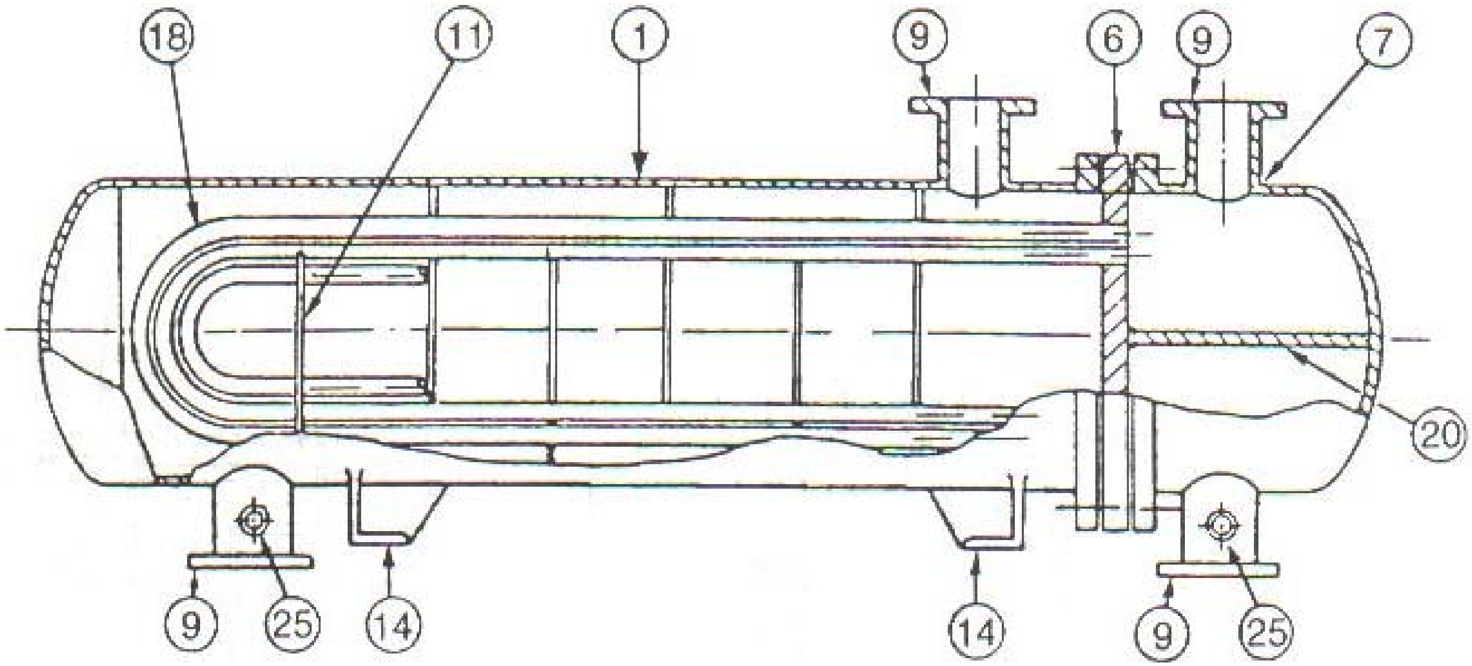
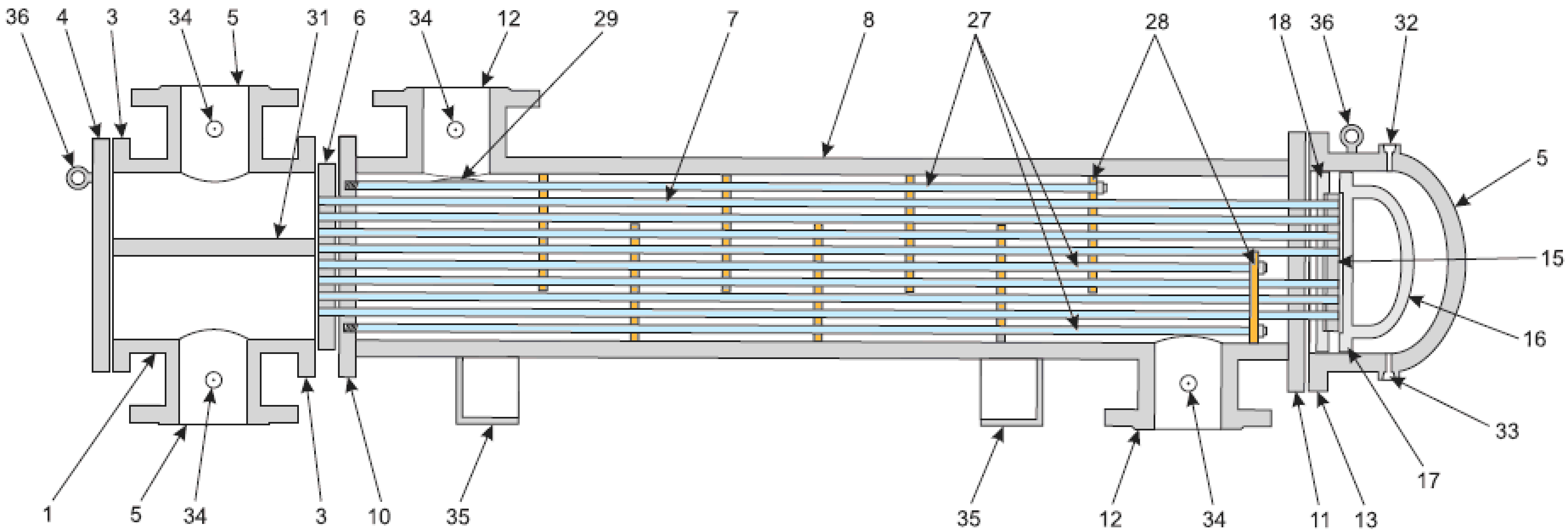


Figure 12.4. U-tube (based on figures from BS 3274: 1960)

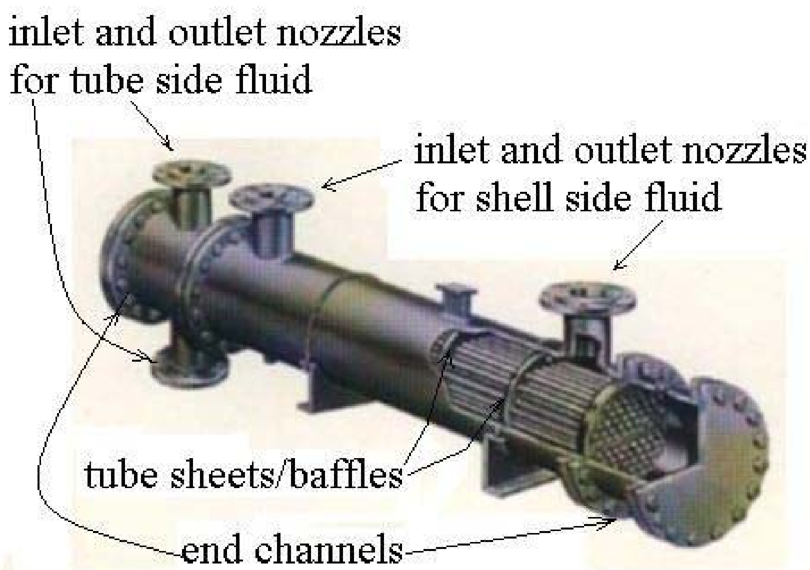
Heat Transfer Equipment

Tube and shell heat exchanger:

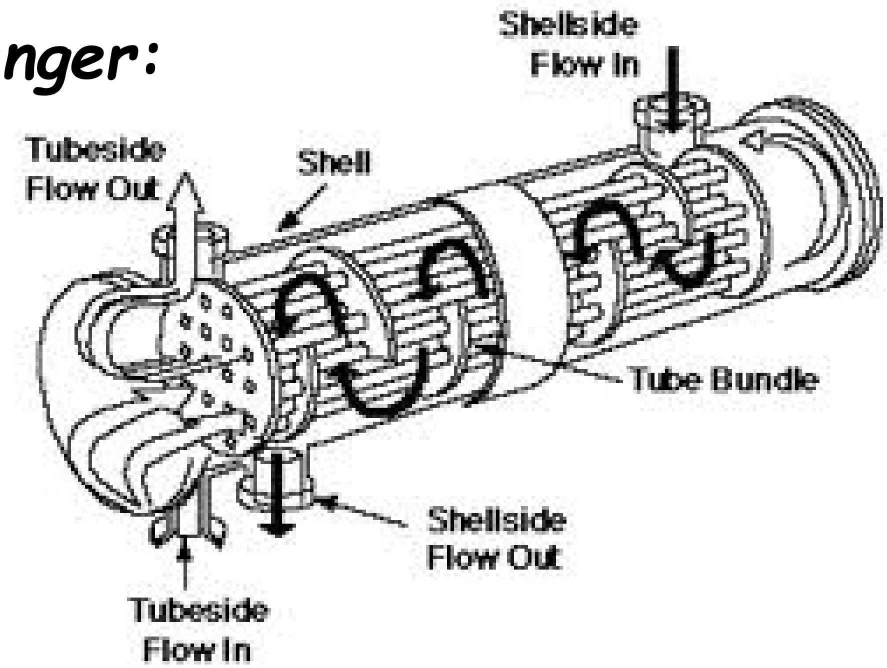


Heat Transfer Equipment

Tube and shell heat exchanger:

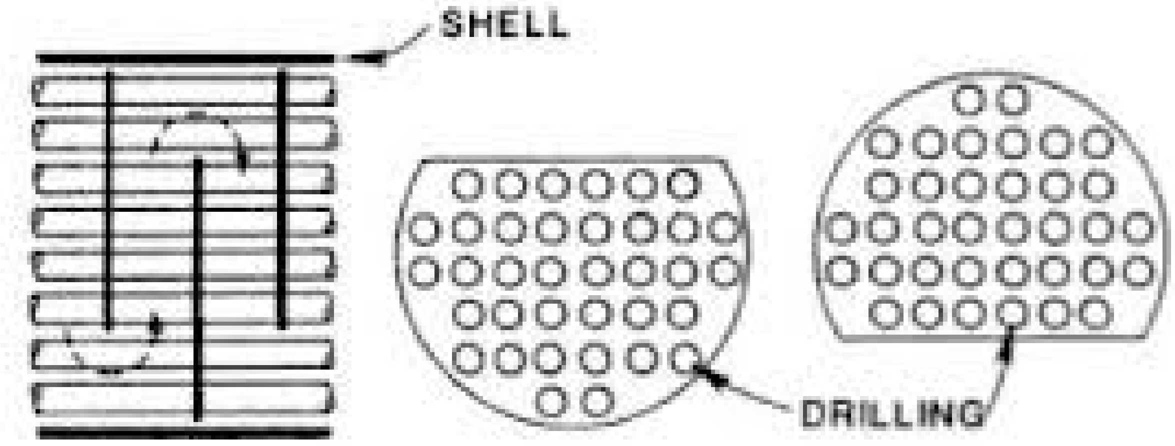


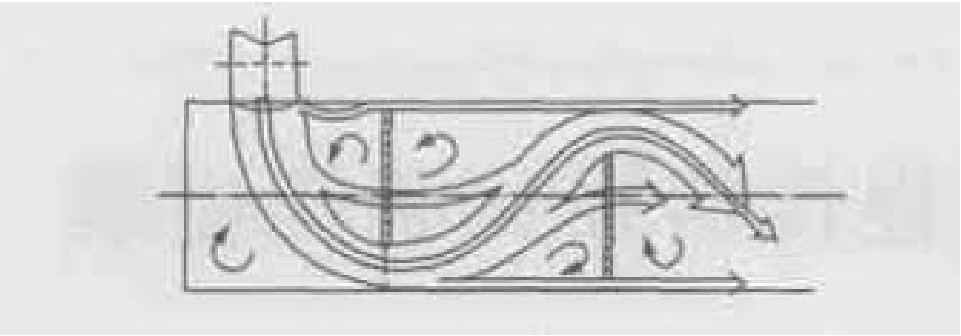
Straight Tube, Two Pass
Shell and Tube Heat Exchanger



Heat Transfer Equipment

Tube and shell heat exchanger: Baffles





Heat Transfer Equipment

Tube and shell heat exchanger: Tube Pitch

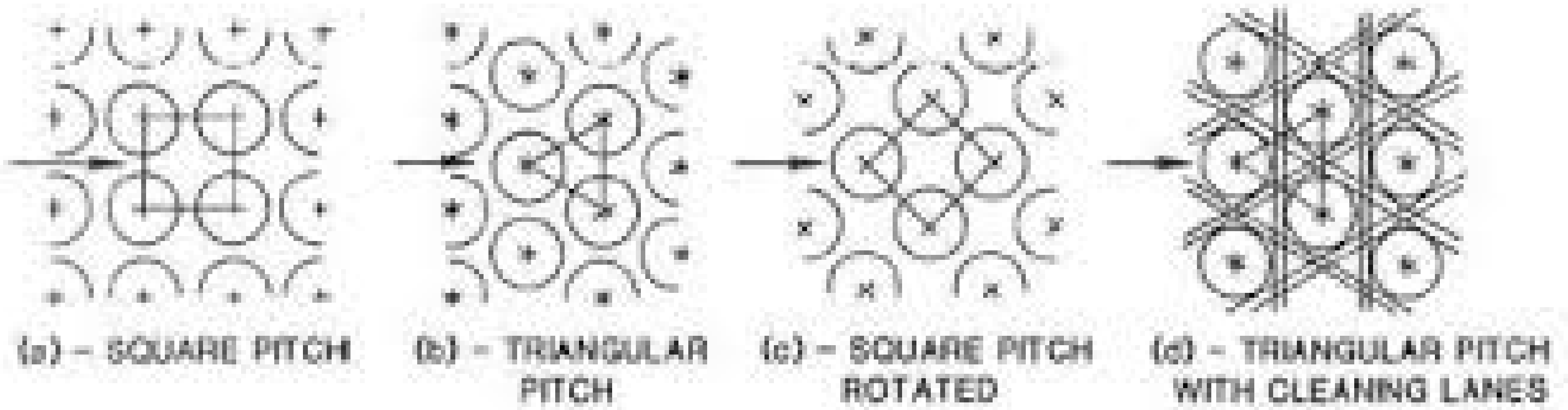


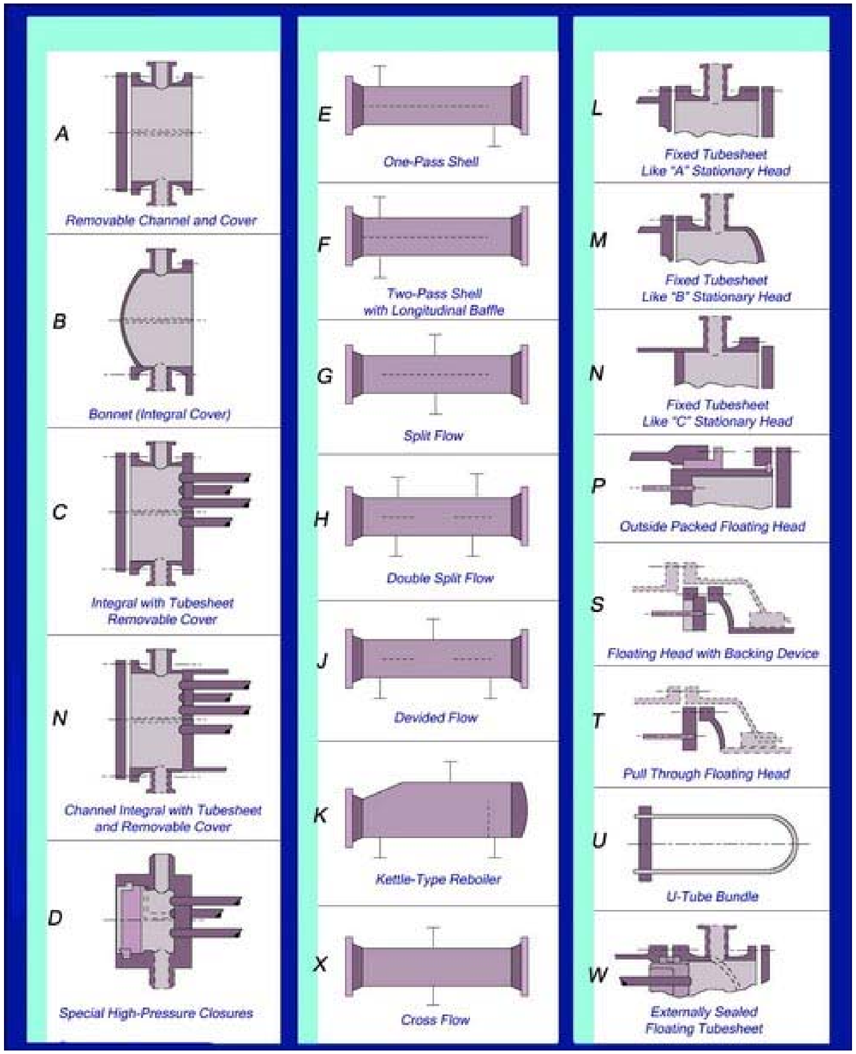
Figure 3-5. Common tube layouts for shell-and-tube heat exchangers.

Heat Transfer Equipment

Trains

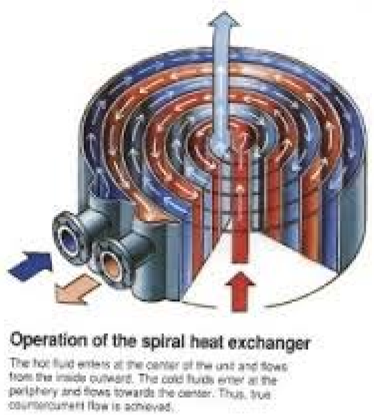
Heat Transfer Equipment

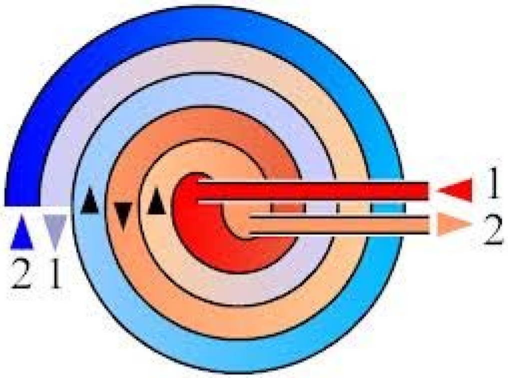
TEMA
Tubular Exchanger Manufacturers Association



Heat Transfer Equipment

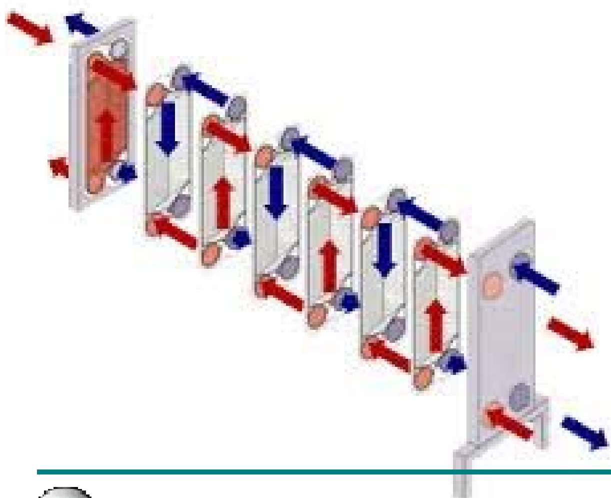
Spiral Exchangers





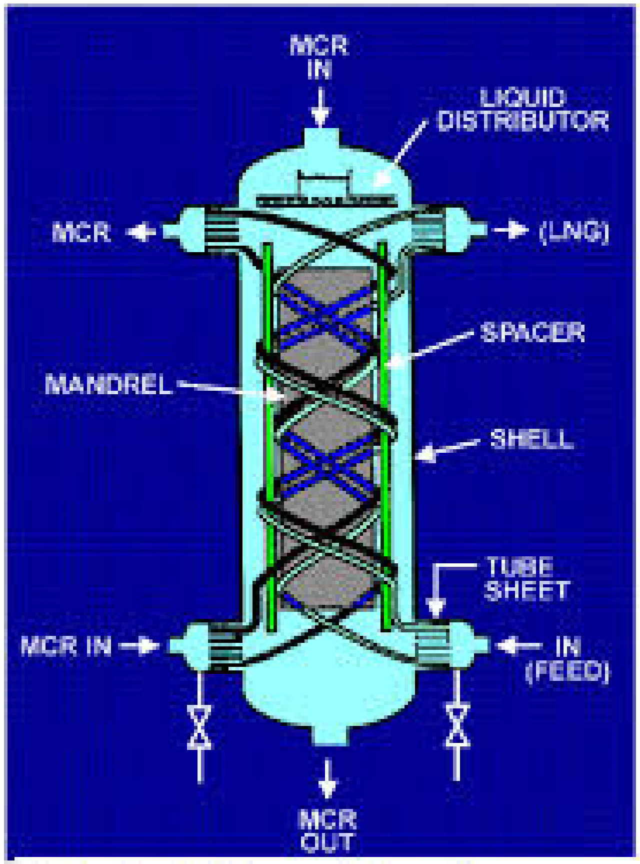
Heat Transfer Equipment

Plate Exchangers



Heat Transfer Equipment

Spiral Wound Exchangers



Spiral Wound Exchanger

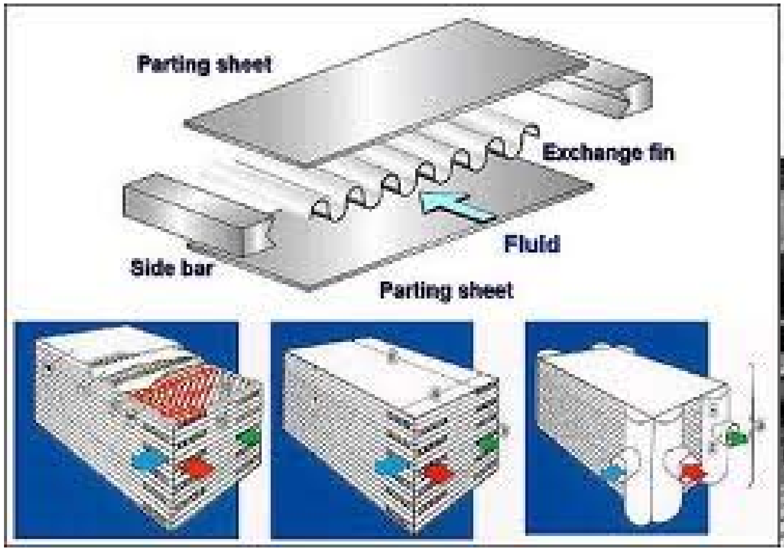
Heat Transfer Equipment

Air Coolers

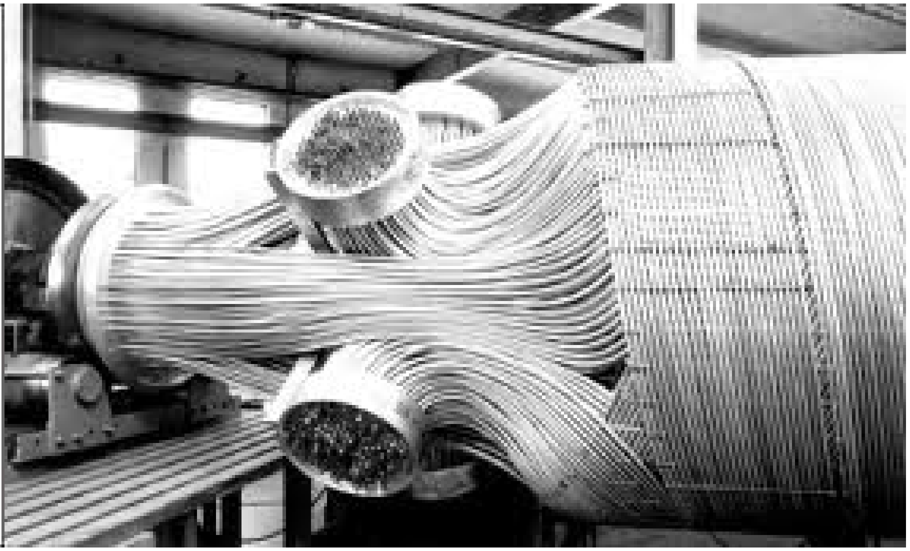
Heat Transfer Equipment

LNG Exchangers

Plate



"Special Shell and Tube"

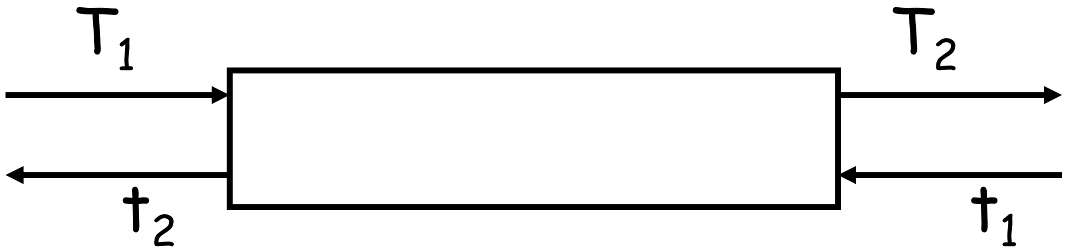


Heat Exchangers - Typical Old Fashion design

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties (ρ, μ, k).
3) Decide on the type of exchanger.
4) Select a trial value for U.
5) Calculate the mean temperature difference, ΔT_m
6) Calculate area required.
7) Decide on the exchanger layout.
8) Calculate individual coefficients.
9) Calculate U. If significant difference from step (4), substitute in (4) and repeat.
10) Calculate the pressure drop. If it is not satisfactory, back to (7) or (4) or (3).
11) Optimise: repeat (4) to (10) to determine cheapest solution (usually smaller area).

Heat Exchangers

(4) Use first order approximations for *U*, such as table 14-5 pg. 663 in PT&W.



Now we have:

$$q = U\,A\Delta T_{tot}$$

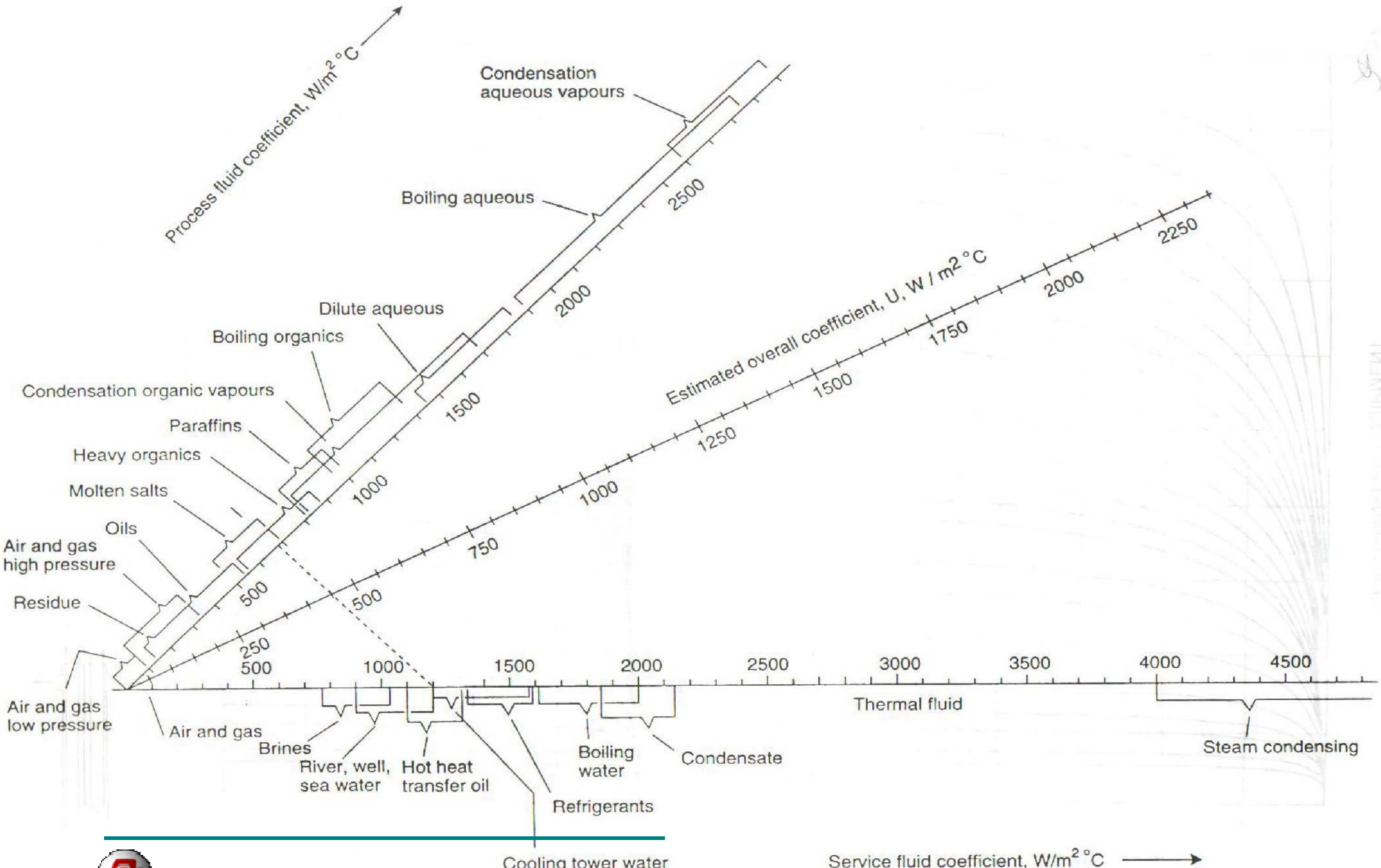
at every location in the exchanger. In differential form:

$$dq = (U)_{loc}\,(\Delta T_{tot})_{loc}\,dA$$

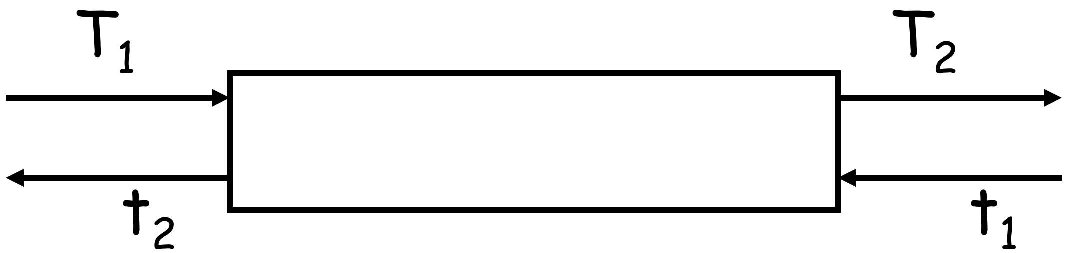
and in a simplified integral/overall form (used in step 6) :

$$q = U\,A\Delta T_m$$

Overall Heat Transfer Coefficient



Heat Exchangers



(5) Mean temperature difference for counter-current flow:

$$\Delta T_m = \Delta T_{lm} = \frac{(T_1 - t_2) - (T_2 - t_1)}{\ln \frac{(T_1 - t_2)}{(T_2 - t_1)}}$$

In reality, combination of co-current, countercurrent and cross flow.

What do we do? Use a correction factor, F_t, (see figs 14-4 and 14-5 in PT&W)

$$\Delta T_m = F_t \Delta T_{lm}$$

Parameters:

$$R = \frac{(T_1 - T_2)}{(t_2 - t_1)}, \qquad S = \frac{(t_2 - t_1)}{(T_1 - t_1)}$$

Heat Transfer Equipment

Correction factor:

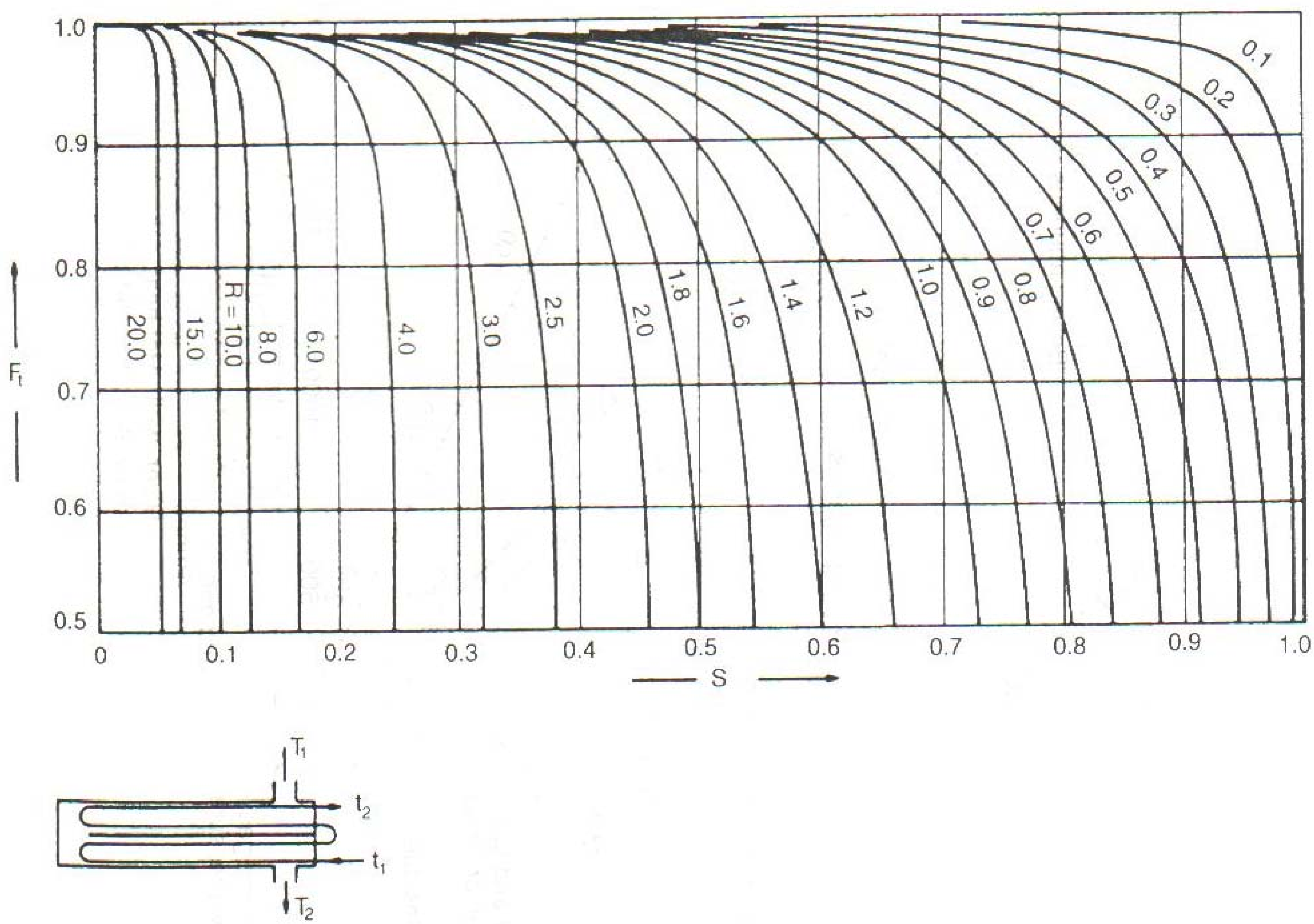


Figure 12.20. Temperature correction factor: two shell passes; four or multiples of four tube passes

Heat Transfer Equipment

Correction factor:

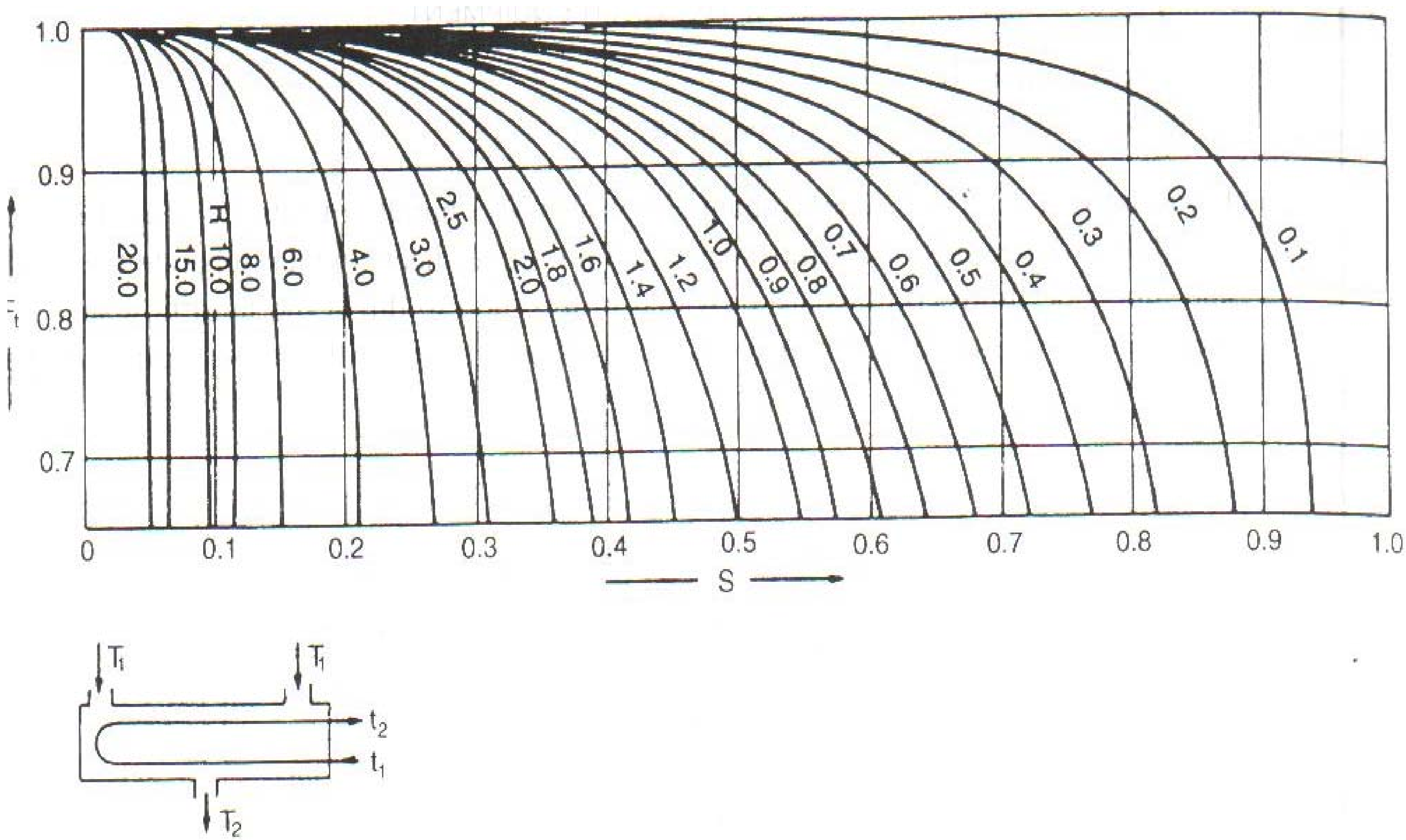


Figure 12.21. Temperature correction factor: divided-flow shell; two or more even-tube passes

Heat Transfer Equipment

Correction factor:

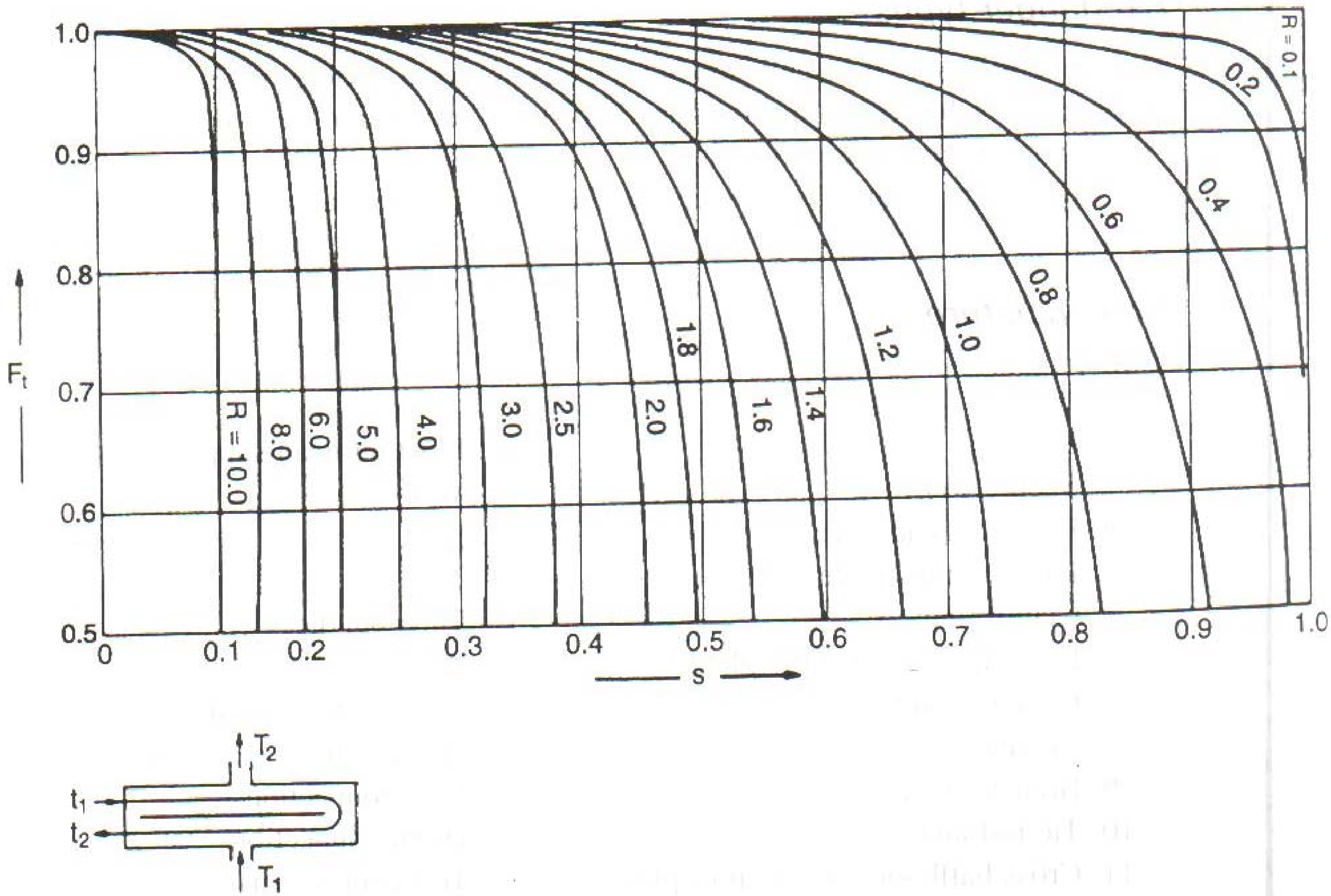


Figure 12.22. Temperature correction factor, split flow shell, 2 tube pass

Heat Transfer Equipment

Correction factor:

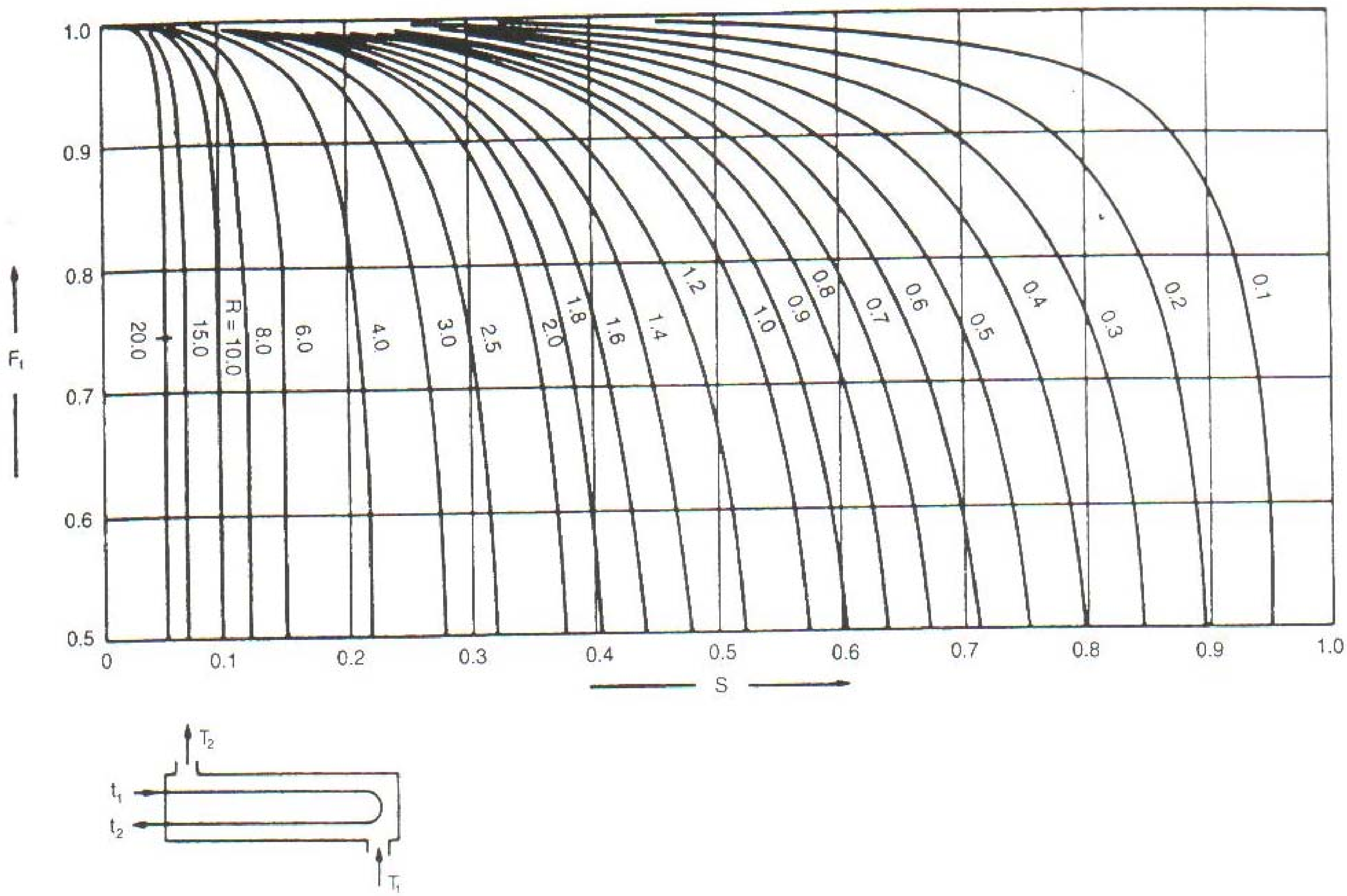


Figure 12.19. Temperature correction factor: one shell pass; two or more even tube 'passes

Heat Exchangers - Typical design

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties (ρ, μ, k).
3) Decide on the type of exchanger.
4) Select a trial value for U.
5) Calculate the mean temperature difference, ΔT_m
6) Calculate area required.
7) Decide on the exchanger layout.
8) Calculate individual coefficients.
9) Calculate U. If significant difference from step (4), substitute in (4) and repeat.
10) Calculate the pressure drop. If it is not satisfactory, back to (7) or (4) or (3).
11) Optimise: repeat (4) to (10) to determine cheapest solution (usually smaller area).

Shell and Tube Heat Exchangers

Most commonly used heat exchangers.

Advantages:

- Large surface area in a small volume.
- Good mechanical layout.
- Uses well established fabrication methods.
- Can be constructed from a wide variety of materials.
- Easily cleaned and maintained.
- Well established design procedures.

Shell and Tube Heat Exchangers

Tube size:

Length is standard, commonly 8, 12 or 16 ft.
Diameter: most common 3/4 or 1 in OD

Tube pitch and clearance:

Pitch is the shortest center-to-center distance between adjacent tubes. Commonly 1.25 to 1.5 time the tube diameter.

Clearance is the distance between tubes. It should be larger than 25% of the tube diameter.

Triangular or square arrangement of tubes are quite common.

Baffles:

Baffles are usually spaced between 20% and 100% of the ID of the shell.

Shell and Tube Heat Exchangers

Fluid location:

Corrosive fluids flow inside the tubes.

Fluid with higher fouling tendency inside the tubes.

High pressure fluid inside the tubes (if everything else the same).

Hot fluid inside the tubes.

Typical velocities:

Liquids: 1-2 m/s in tubes, max 4 m/s to reduce fouling.
0.3 to 1 m/s in shell

Vapors: 50-70 m/s (vacuum), 10-30 m/s (1 bar),
5-10 m/s (high P)

Shell and Tube Heat Exchangers

Shell:

Up to 24 in nominal size, use standard pipes.

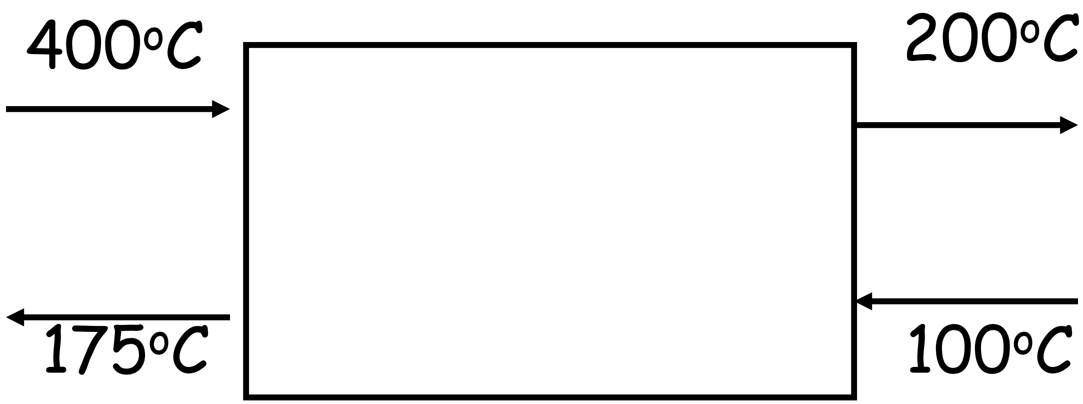
Passes:

Most usual pass is one (type E according to TEMA standards).

Split flow arrangement (types G and J) are used for pressure drop reduction, when the pressure drop is the controlling factor in the design.

Heat Exchangers: The T-Q Diagram

• A T-Q diagram is a visual representation of the energy balance equation for each stream.



Single phase streams with constant C_p and no pressure effect on enthalpy:

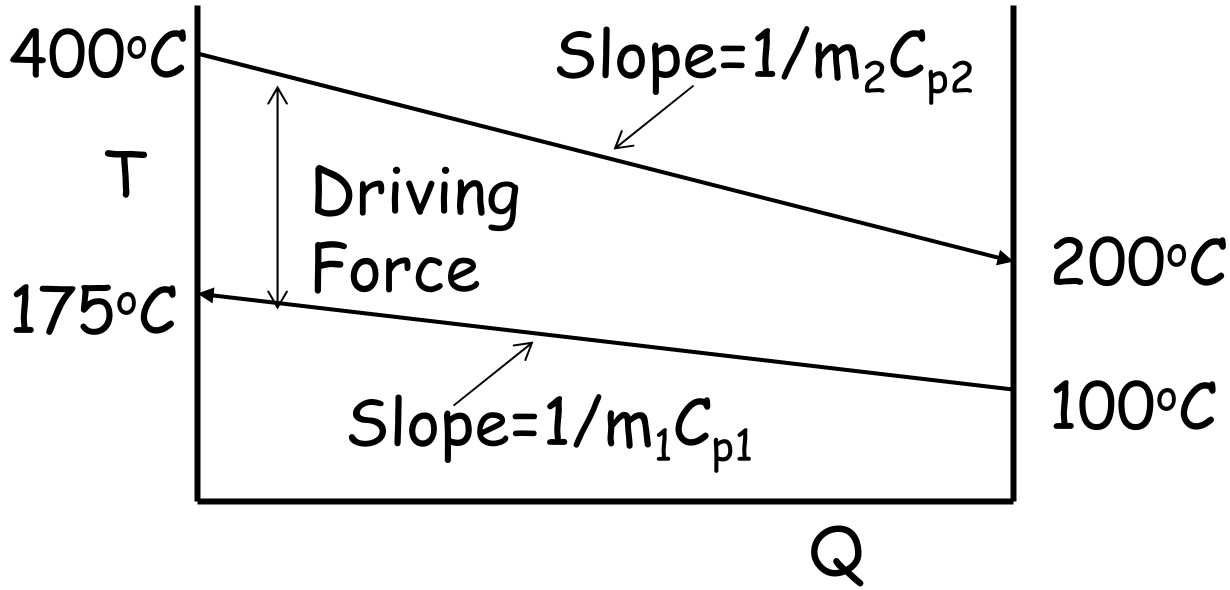
$$q = \dot{m} C_p \Delta T$$

Pure components undergoing phase change:

$$q = \dot{m} \lambda$$

Heat Exchangers: The T-Q Diagram

For the previous example:



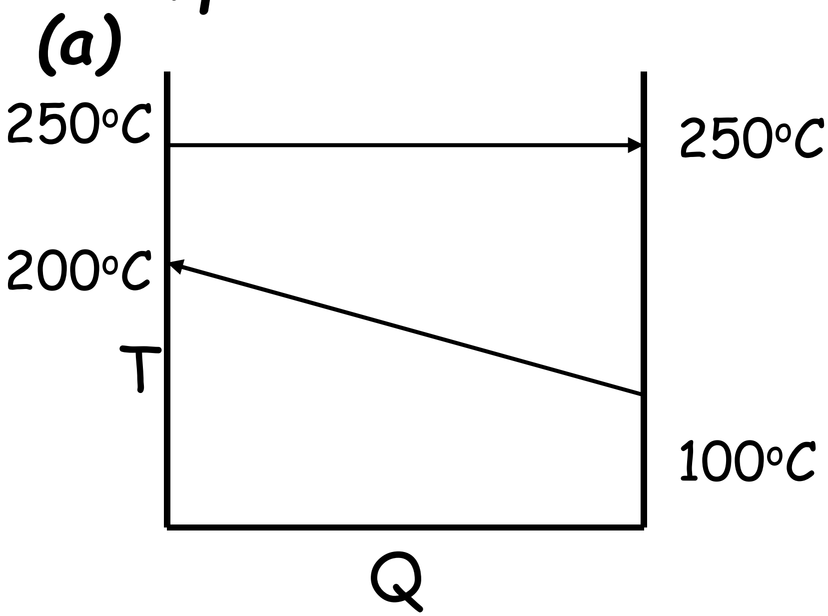
The T-Q diagram reveals two important truths regarding heat transfer:

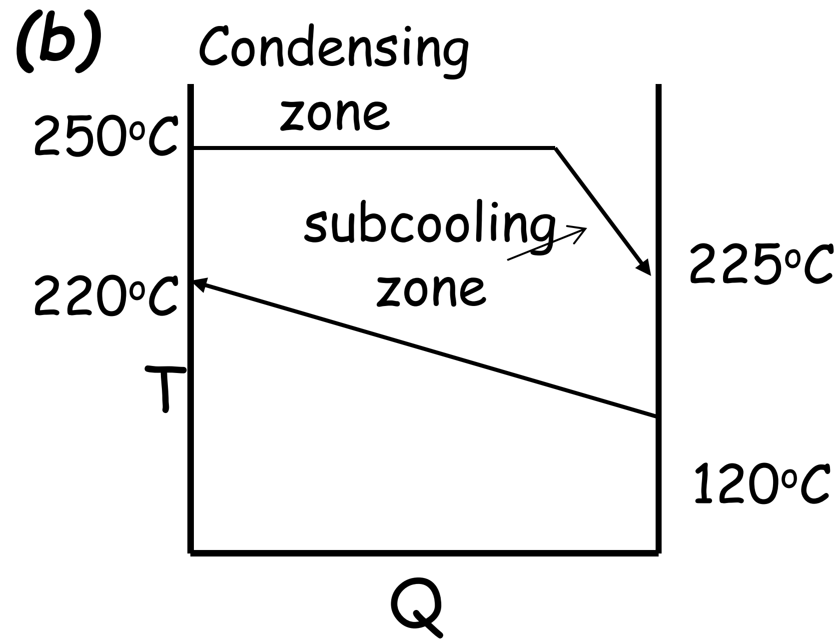
(1) T-lines for counter-current flows do not cross! It is impossible.

(2) T-lines should not approach each other too closely: As they approach, the area required for heat transfer goes to infinity. The point of closest approach is called ***pinch point.***

Heat Exchangers: The T-Q Diagram

Examples:





(a) A single-phase stream is heated from 100 to 200°C by condensing saturated steam to saturated liquid at 250°C in a countercurrent heat exchanger.

(b) A single-phase stream is heated from 120 to 220°C by condensation of saturated steam at 250°C and by subcooling the liquid to 225°C in a countercurrent heat exchanger.

Shell and Tube Heat Exchangers - Design

- Tube side: Configuration (pitch, number of tubes, dimensions).
  Heat transfer coefficient.
  Pressure drop.

- Shell side: Configuration (dimensions, baffles).
  Heat transfer coefficient.
  Pressure drop.

Cost influenced by:

- Heat transfer area
- Tube diameter and length
- Pressure
- Material of construction
- Baffle type
- Special features, such as U bends, floating heads, fins etc.

Tube Side

1) Define duty: heat transfer rate, flows, temperatures.
2) Collect required physical properties (ρ, μ, k).
3) Select a value for U.
4) Calculate the mean temperature difference, ΔT_m. Use the correction factor, F_t.
6) Calculate area required.
7) Decide on the exchanger layout. Select one of the standard tube lengths and tube diameters. Calculate the number of tubes needed from the area estimated in (6). Decide on pitch.

Calculate bundle diameter from the following:

$$N_t = K_1 \left(\frac{D_b}{d_o} \right)^{n_1} \qquad D_b = d_o \left(\frac{N_t}{K_1} \right)^{1/n_1}$$

Tube Side

N_t is the number of tubes
D_b is the bundle diameter
d_o is the tube outside diameter

$$D_b = d_o \left(\frac{N_t}{K_1} \right)^{1/n_1}$$

Constants:

Triangular pitch, p_t =1.25d_o					
No. passes	1	2	4	6	8
K_1	0.319	0.249	0.175	0.0743	0.0365
n_1	2.142	2.207	2.285	2.499	2.675
Square pitch, p_t =1.25d_o					
No. passes	1	2	4	6	8
K_1	0.215	0.156	0.158	0.0402	0.0331
n_1	2.207	2.291	2.263	2.617	2.643

Heat Transfer Equipment

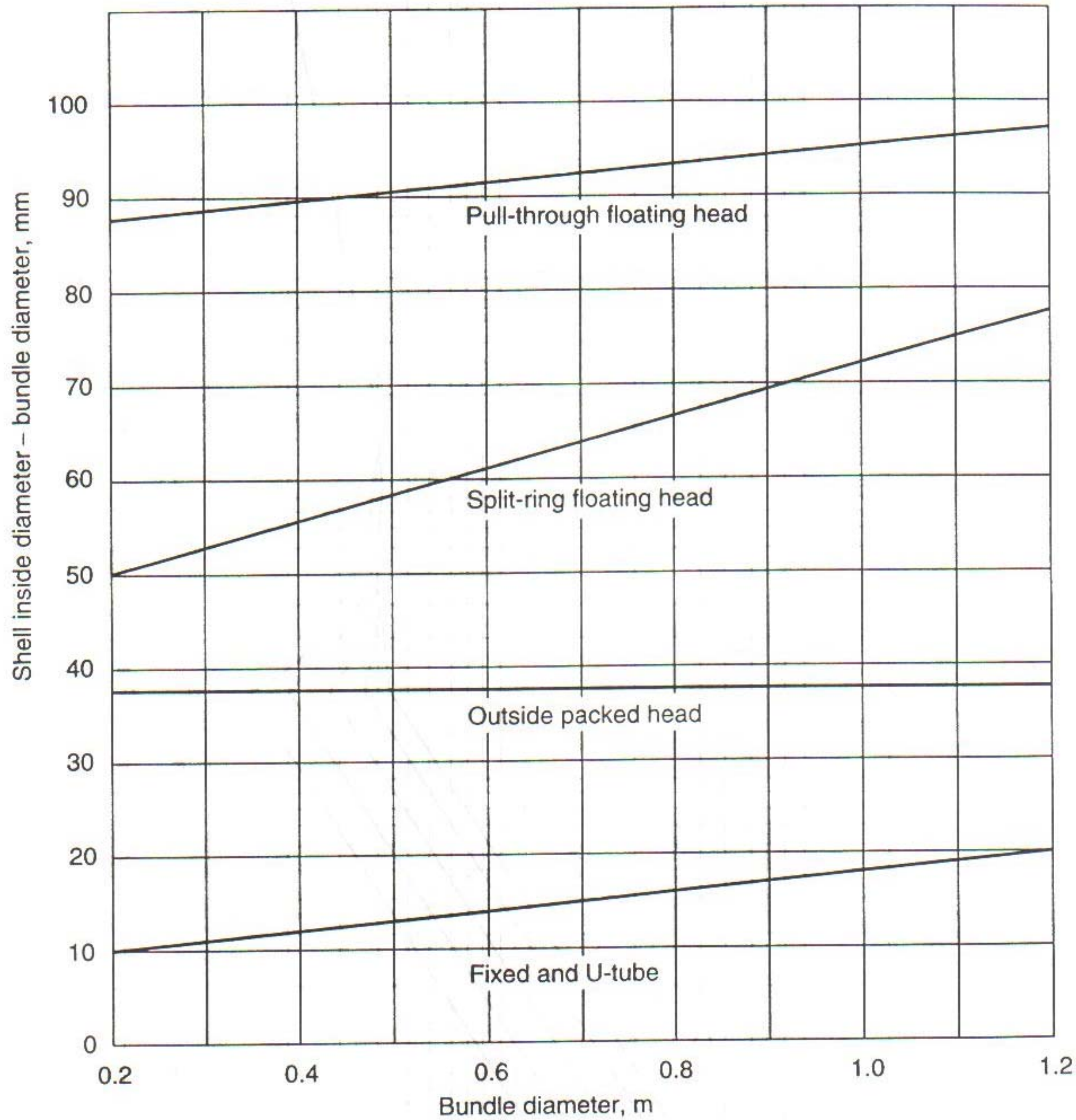


Figure 12.10. Shell-bundle clearance

Tube Side

From the bundle diameter calculate shell diameter!

8) Calculate heat transfer coefficient.
For turbulent flow inside the tubes (Sieder & Tate):

$$Nu = C\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

Nu is the Nusselt number, $Nu = h_i\, d_e / k_f$
Re is the Reynolds number, $Re = \rho\, u_t\, d_e / m$
Pr is the Prandtl number, $Pr = C_p\, \mu / k_f$
u_t is the fluid velocity inside the tube,
k_f is the fluid conductivity
d_e is the equivalent (hydraulic) diameter
d_e = 4 x (cross section area available to flow)/(heated perimeter)
C= 0.021 for gases, 0.023 for non-viscous and 0.027 for viscous liquids

Tube Side

Use of the heat transfer factor, j_h, for transition and laminar flow:

$$Nu = j_h \,\mathrm{Re}\,\mathrm{Pr}^{0.33}\left(\frac{\mu}{\mu_w}\right)^{0.14}$$

See figure 14-9 in page 658 of PT&W.

Also, see table 14-3, pg. 661 in PT&W.

9) Calculate pressure drop.
Use the friction factor, as for pipe flows, in the Fanning equation.

Heat Transfer Factor

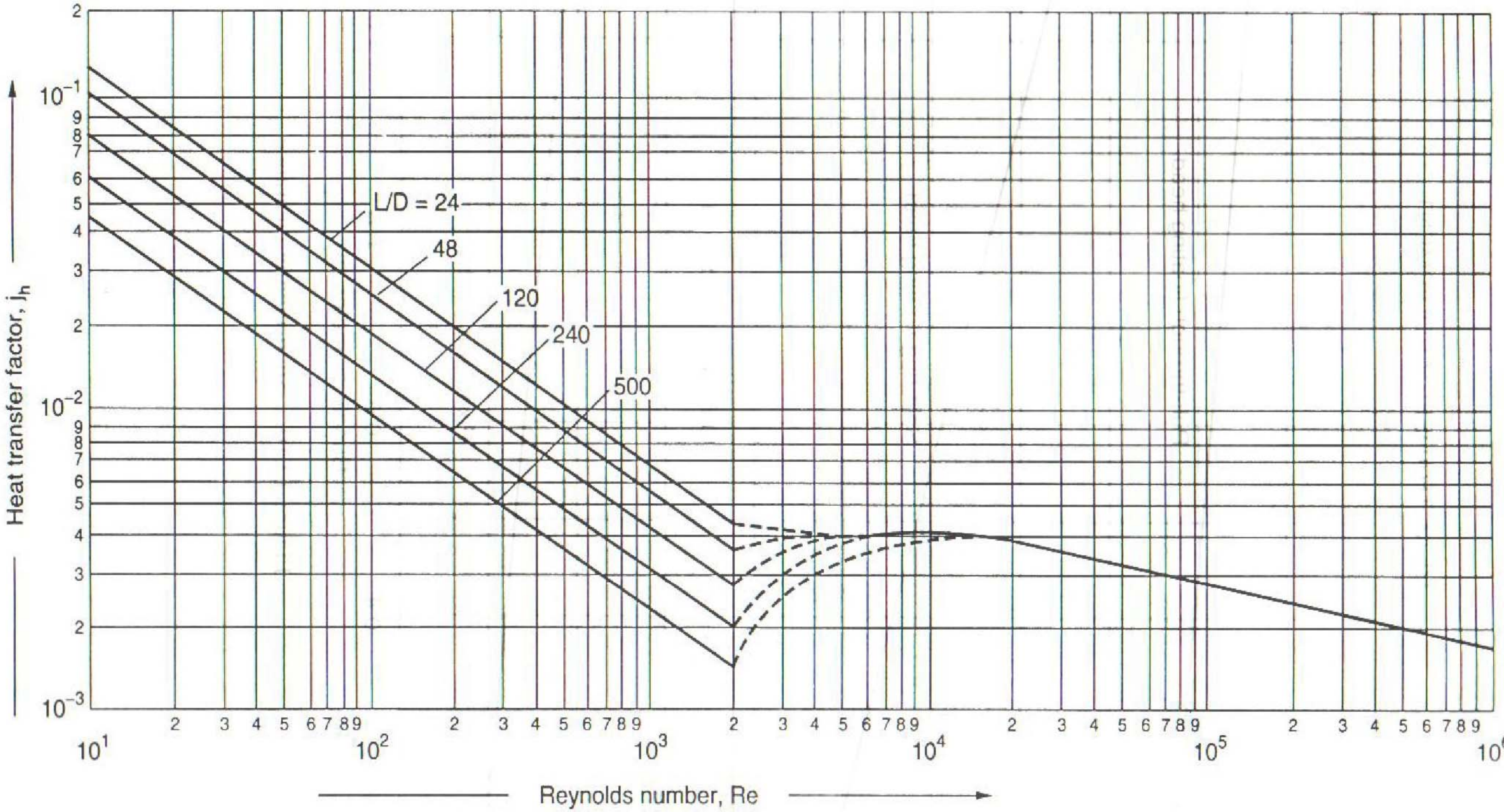


Figure 12.23. Tube-side heat-transfer factor

Tube Side

9) Calculate pressure drop.

$$\Delta P_i = \frac{B_i 2 f_i G^2 L n_p}{g_c \rho_i d_i \phi_i}$$

f_i is the friction factor for isothermal flow at the mean temperature

n_p is the number of tube passes

g_c is the unit conversion factor

ϕ_i is a correction factor for non-isothermal flow

$$\phi_i = 1.1\left(\mu_i / \mu_w\right)^{0.25} \qquad \text{for Re} < 2100$$

$$\phi_i = 1.02\left(\mu_i / \mu_w\right)^{0.14} \qquad \text{for Re} > 2100$$

B_i is a correction factor for friction due to contraction, expansion and reversal of flow direction

G is the mass velocity inside the tube

Shell Side

From the bundle diameter we have the shell diameter (step 7)!

10) Calculate shell side heat transfer coefficient.
For turbulent flow outside the tubes:

$$Nu = \frac{a_o}{F_s} \mathrm{Re}^{0.6} \mathrm{Pr}^{0.33}$$

Nu is the Nusselt number, $Nu = h_o\, d_o / k_f$
Re is the shell side Reynolds number, $Re = G_s\, d_o / \mu$
Pr is the shell side Prandtl number, $Pr = C_p\, \mu / k_f$
a_o = 0.33 if the tubes are staggered and 0.26 if they are in line
F_s is a safety factor to account for bypassing (usually 1.6)
G_s is the mass velocity across tubes, based on the minimum free area between baffles.

Also see: Kern, "*Process heat transfer*", McGraw Hill, 1950

Shell Side

11) Calculate pressure drop.

$$\Delta P_o = \frac{B_o 2 f_o G_s^{\,2} N_r}{g_c \rho_o}$$

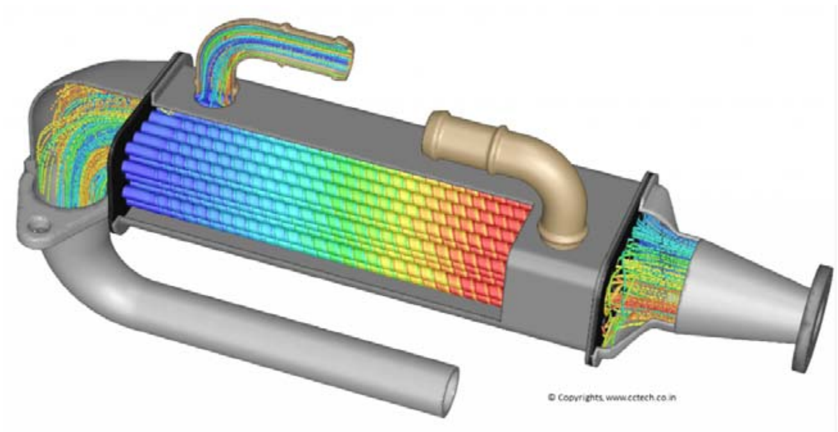
f_o is the friction factor for the shell side (see p. 665 PT&W)

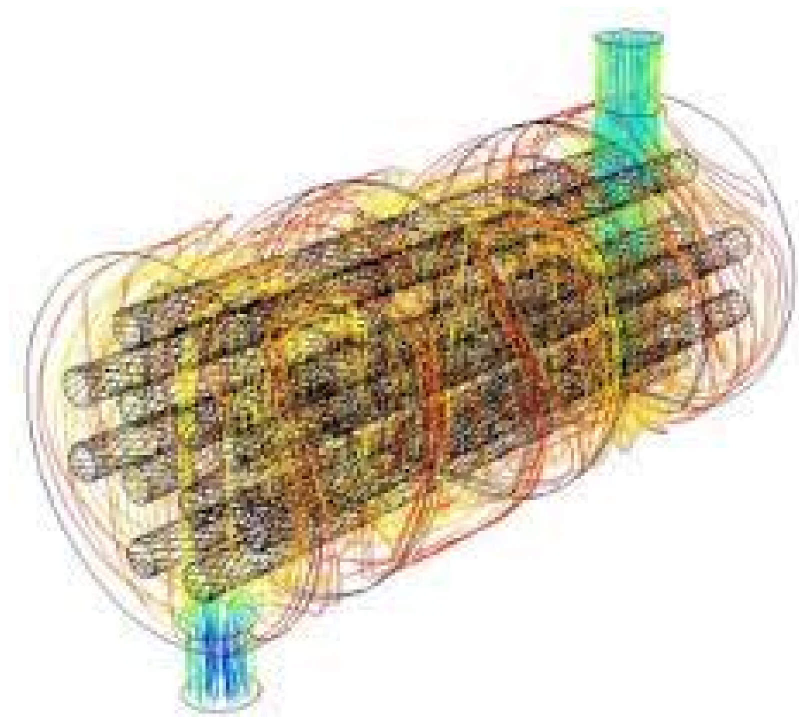
$$f_o = b_o \left(\frac{d_o G_s}{\mu} \right)^{-0.15}$$

N_r is the number of rows of tubes
B_o is a correction factor for friction due to reversal of flow direction. It can be equal to the number of tube crossings (e.g., one when there are no baffles).
See example 14-3 in PT&W (pg. 666)
12) **Now we can recalculate *U* and make a decision.**

Heat Transfer Equipment

Tube and shell heat exchanger: Modern Simulation (COMSOL, FLUENT) using finite elements





Heat Transfer Equipment

Tube and shell heat exchanger:

Commercially the designs are done by companies

- ***HTRI (Heat Transfer Research Institute; http://www.htri.net/index.php) and other programs.***

- ***Manufacturers***