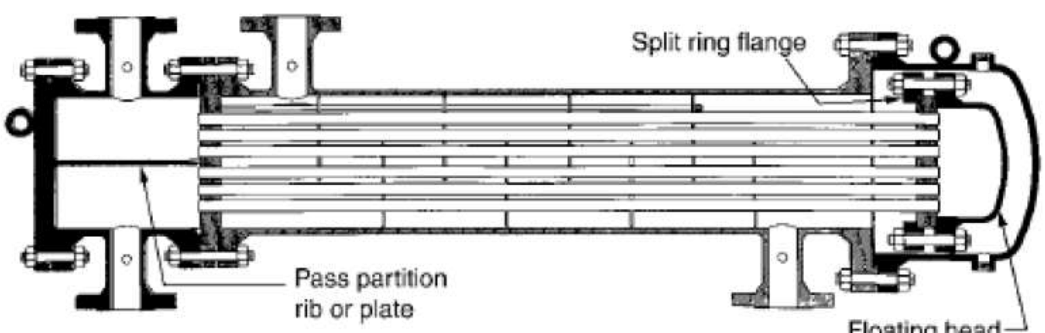
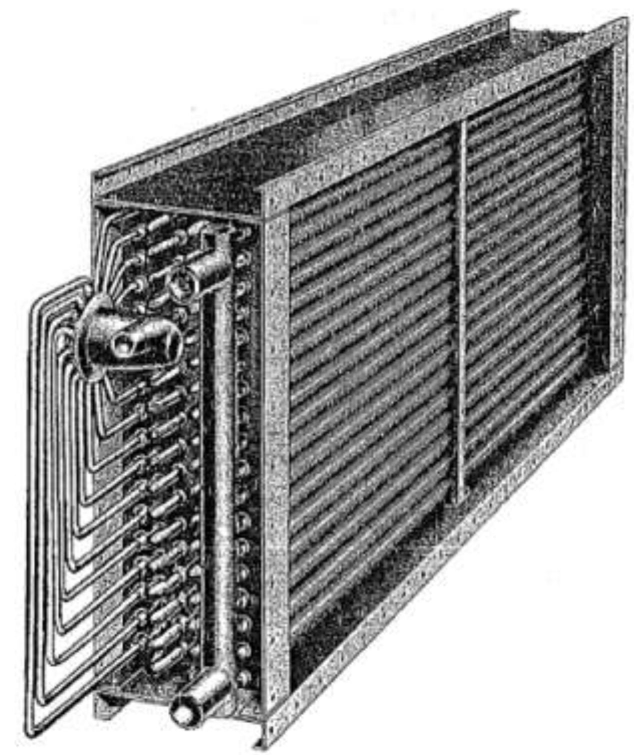
Guide Lines and Practice for Thermal Design of Heat Exchangers

by

Prof. Abdul Rahim Assaad Khaled





Definition of Engineering Design

It is simply finding the appropriate **size** of an engineering system that satisfies predetermined **outputs** fulfilling the user **needs** under specific **constraints** imposed on the user, the designer or both.

ABET EAC Definition of Engineering Design

Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and the engineering sciences are applied to convert resources optimally to meet these stated needs.

Heat Exchanger can be considered as a system or component.

Quality of the Engineering Design

High Quality Design can be the system size that achieves **all** of the costumers and users **needs** satisfying all of imposed **constraints** at minimum cost.

Acceptable Quality Design can be the system size that achieves **direct** users **needs** satisfying all of imposed **constraints** at **available price**.

Design of Heat Exchangers…1

The **size** of heat exchanger includes its dimensions such as length, diameters, height, width, thickness, material type, flow configuration, number of heat exchanging units, fin distribution, ..etc.

Design of Heat Exchangers…2

Outputs of heat exchangers include its heat duty (heat transfer rate), LMTD requirements (Log Mean Temperature Difference)…..

Outputs are the process requirement

Design of Heat Exchangers…3

User **needs** of heat exchanger include types of fluids, quality of fluids (fouled fluids, clean fluids,..etc.)..etc.

Note that user needs are their outputs. The role of engineering designers is to convert the user needs into the heat exchanger outputs

Design of Heat Exchangers…4

Constraints imposed on design of heat exchangers include the following:

- Acoustic noise control during operation
- Flow turbulence control during operation
- Pumping power requirements
- Spatial dimensions requirements
- Availability of materials and standards
- Availability of know and how technology

Acoustic Noise Constraints

United States Department of Labor; 1910.95(b)(2)

TABLE G-16 - PERMISSIBLE NOISE EXPOSURES (1)

Duration per day, hours	Sound level dBA slow response
8	90
6	92
4	95
3	97
2	100
1 1/2	102
1	105
1/2	110
1/4 or less	115

Noise and Vibration Design Guidance (1)

HVAC noise in an accommodation compartment should be a minimum 3 dB below the any specified noise criteria

Noise generation in HVAC system occurs from four basic sources:

- Fans and Blowers
- Flow through Branches
- Flow through Turns
- Flow through Diffusers

http://uhaweb.hartford.edu/BEAUDRY/designguides/NCEDesignGuide_HVAC.pdf

Noise and Vibration Design Guidance (2)

A summary of the general rules are listed below:

1. Air flow velocities should be kept as low as possible. A target should be velocities no higher than 1,000 ft/min., and never exceed 3,000 ft/min.
2. Fan inlet air flow should be straight for at least 3 duct diameters. Turns closer than 3 diameters cause air flow turbulence which increases noise.
3. The fan discharge should be straight for a distance of at least three major duct widths to avoid turbulence. Noise will significantly increase due to turbulence from elbows too close to the discharge (or inlet).
4. Five to ten diameters of straight duct is required for turbulence to die out and flow to equalize. If the air flow does not become smooth before the next fitting or terminal device, the flow noise generated in the next element will increase.
5. Design the HVAC system so that fans operate near peak efficiency. Fans that do not operate near peak efficiency will have higher noise levels than fans operating at peak efficiency.
6. All ventilation fans should be resiliently mounted and all connections to the fan, including ducting and electrical cables, should be flexible and at least as effective as the vibration isolators.

…continued

http://uhaweb.hartford.edu/BEAUDRY/designguides/NCEDesignGuide_HVAC.pdf

Maximum Flow Velocities in Water Systems

The fluid flow velocities in water systems should not exceed certain limits to avoid noise and damaging wear and tear of pipes and fittings. The table below can be used as guidance to maximum velocities:

Application	Maximum Velocity	
	(m/s)	*(ft/s)*
Tap water (low noise)	0.5 - 0.7	1.6 - 2.3
Tap water	1.0 - 2.5	3.3 - 8.2
Cooling water	1.5 - 2.5	4.9 - 8.2
Suction boiler feed water	0.5 - 1.0	1.6 - 3.3
Discharge boiler feed water	1.5 - 2.5	4.9 - 8.2
Condensate	1.0 - 2.0	3.3 - 6.5
Heating circulation	1.0 - 3.0	3.3 - 9.8

http://www.engineeringtoolbox.com/flow-velocity-water-pipes-d_385.html

Water Delivery Flow Velocities

As a rule of thumb the following velocities can be used in design of piping and pumping systems for water:

Pipe Dimension		Water	
inches	*mm*	*m/s*	*ft/s*
1	25	1	3.5
2	50	1.1	3.6
3	75	1.15	3.8
4	100	1.25	4
6	150	1.5	4.7
8	200	1.75	5.5
10	250	2	6.5
12	300	2.65	8.5

http://www.engineeringtoolbox.com/pump-delivery-flow-velocity-water-d_232.html

TEMA, Inc. Standards…. (1)

TEMA, Inc.: Tabular Exchanger Manufacturers Association, Inc.

http://www.tema.org/

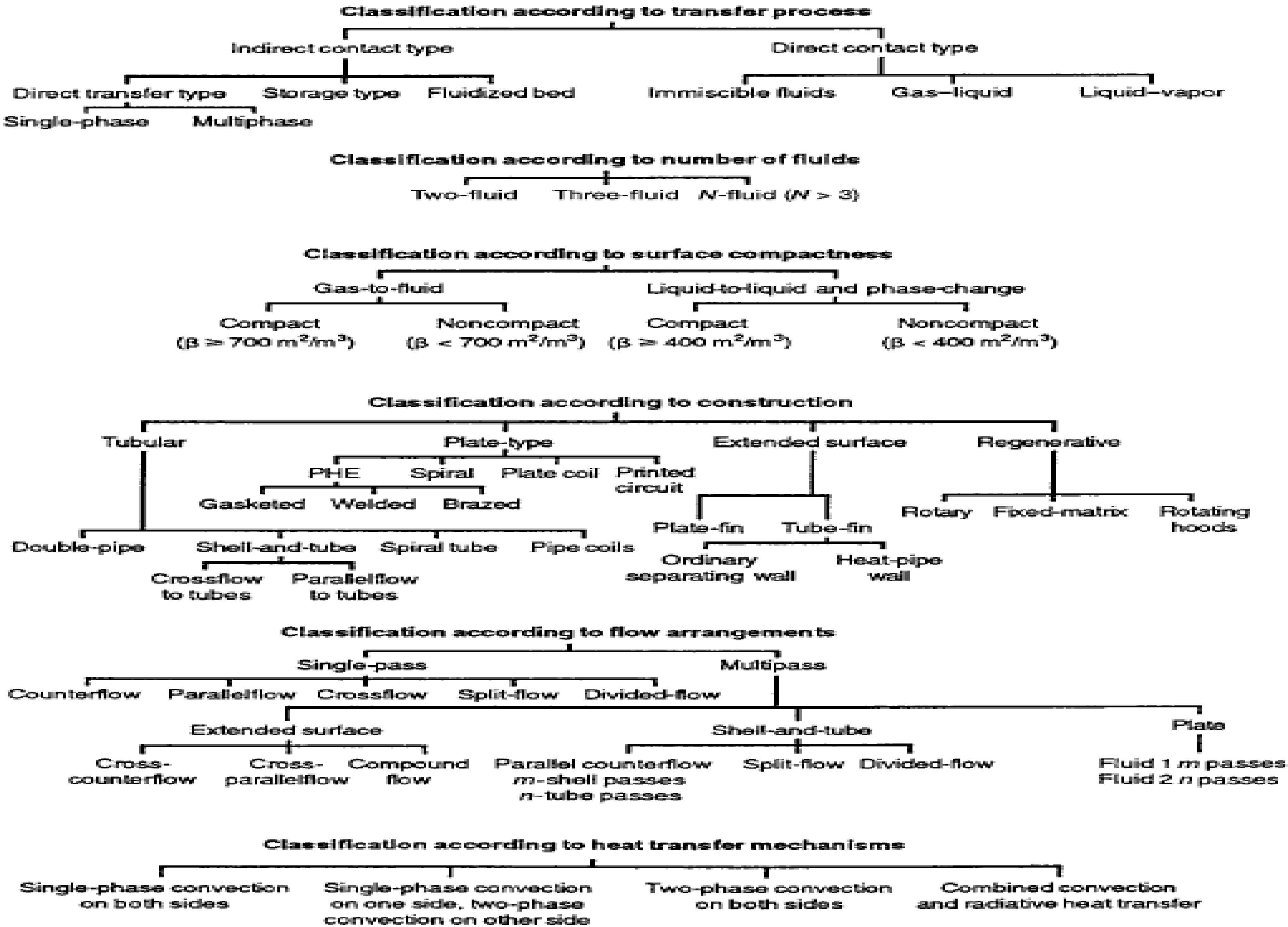
TEMA, Inc. Standards….(2)

TEMA, Inc.: Tabular Exchanger Manufacturers Association, Inc.

http://www.tema.org/

TEMA, Inc. Standards….(3)

http://www.tema.org/



Classification of heat exchangers (Shah, 1981).

Basic Types of Heat Exchangers

- Double-Pipe heat Exchangers
- Shell-and-Tube Heat Exchangers
- Compact Heat Exchangers
- Gasketed-Plate Heat Exchangers

Double-Pipe heat Exchangers

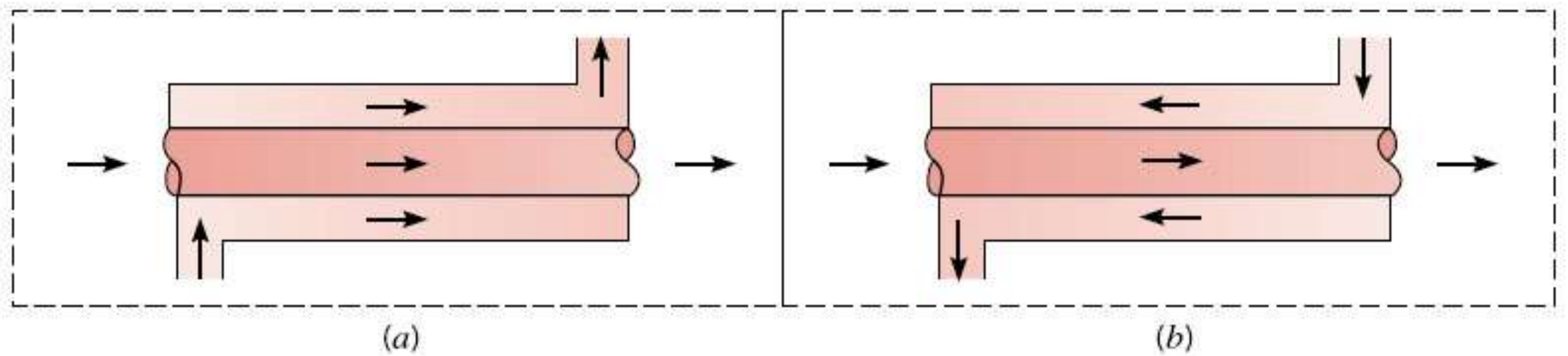


FIGURE 11.1 Concentric tube heat exchangers. (a) Parallel flow. (b) Counterflow.

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Shell-and-Tube Heat Exchangers

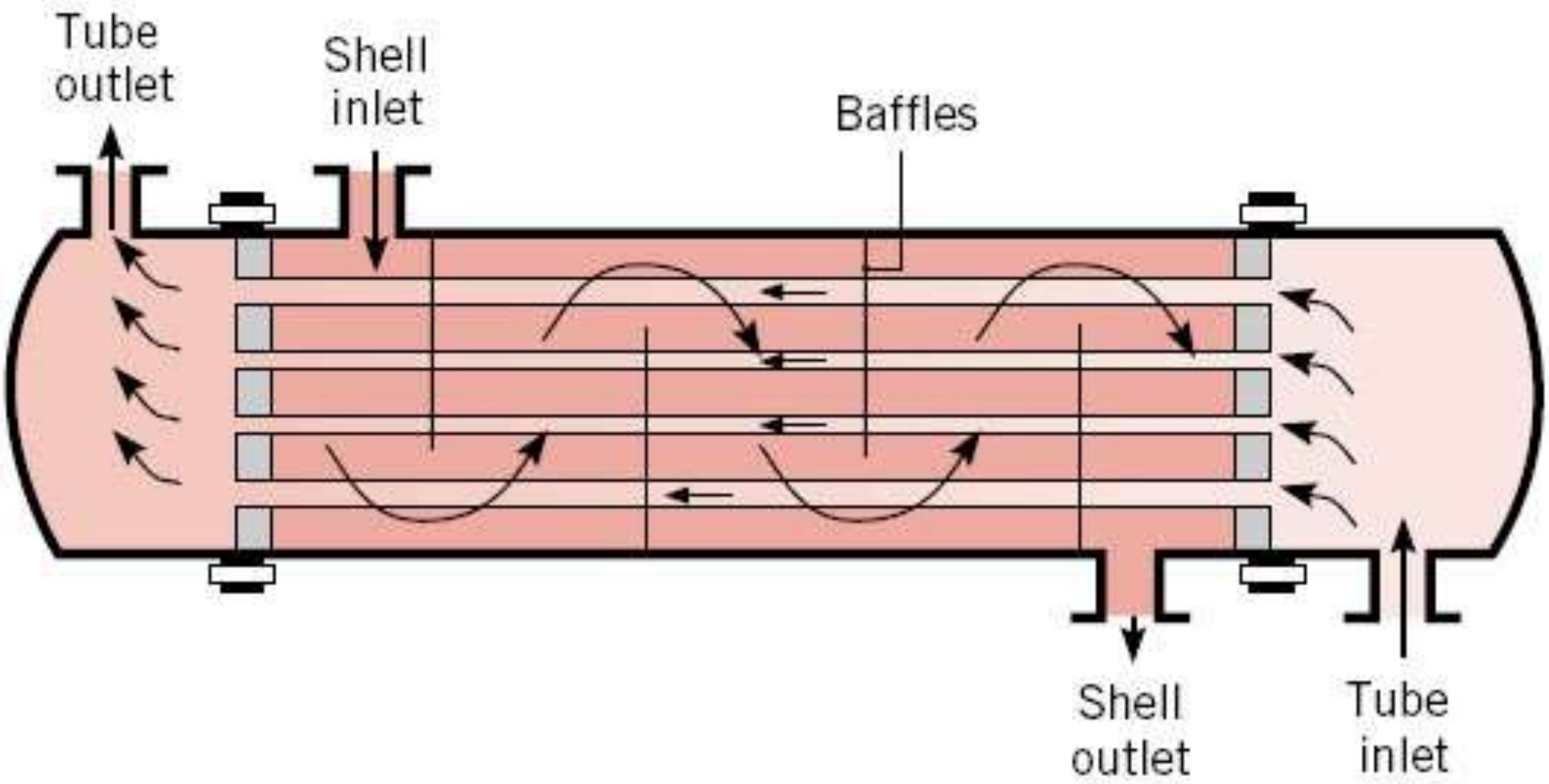

FIGURE 11.3 Shell-and-tube heat exchanger with one shell pass and one tube pass (cross-counterflow mode of operation).

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Compact Heat Exchangers

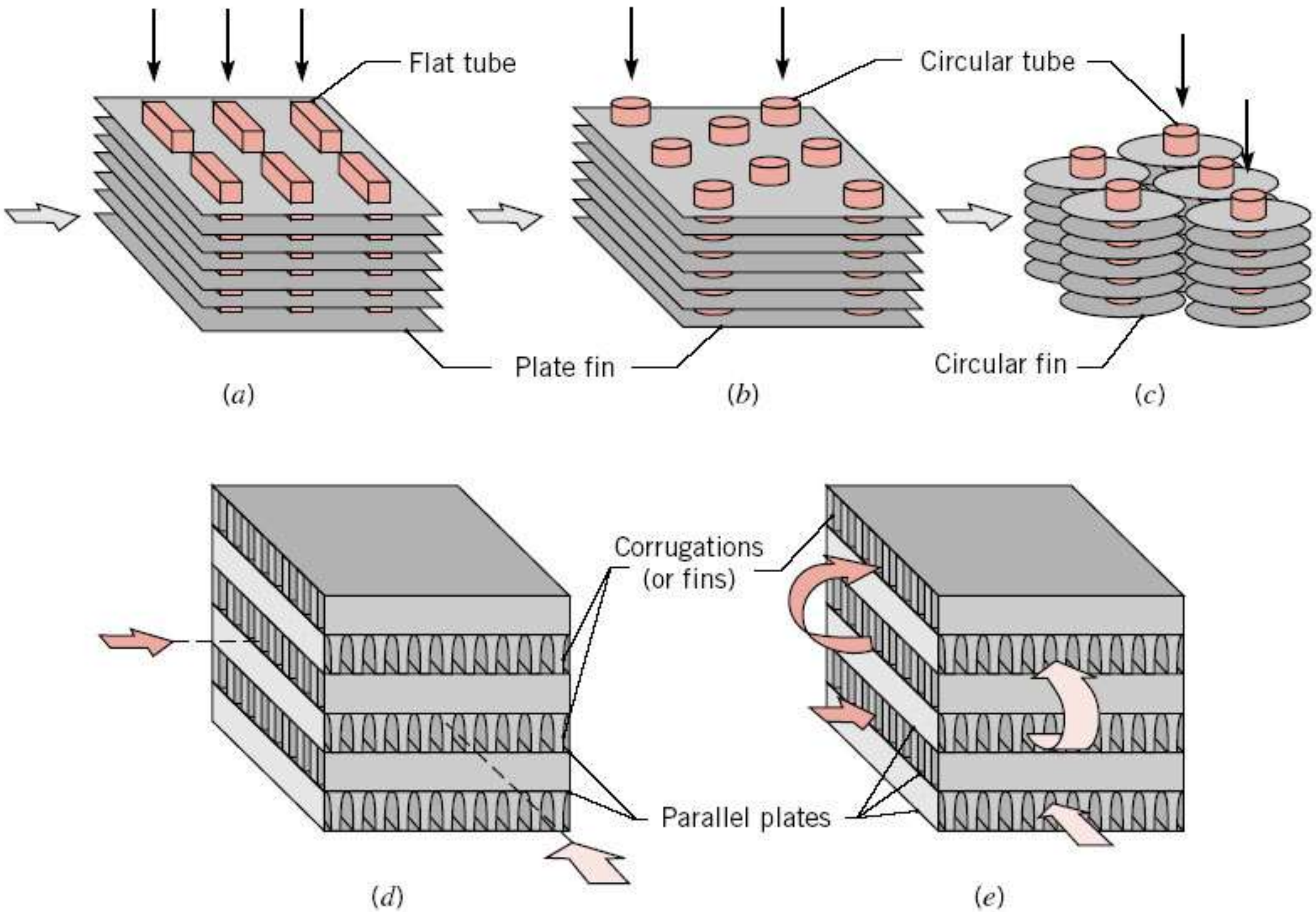

FIGURE 11.5 Compact heat exchanger cores. (*a*) Fin–tube (flat tubes, continuous plate fins). (*b*) Fin–tube (circular tubes, continuous plate fins). (*c*) Fin–tube (circular tubes, circular fins). (*d*) Plate–fin (single pass). (*e*) Plate–fin (multipass).

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Basic Design Methods of Heat Exchangers…..1

LMTD method

$$Q = \dot{m}_h \left(i_{h1} - i_{h2} \right) = \dot{m}_c \left(i_{c2} - i_{c1} \right) = UAF\Delta T_{lm,cf}$$

$$\Delta T_{lm,cf} = \frac{\left(T_{h2} - T_{c1} \right) - \left(T_{h1} - T_{c2} \right)}{ln\left(\dfrac{T_{h2} - T_{c1}}{T_{h1} - T_{c2}} \right)}; \quad F \equiv \frac{\Delta T_{lm}}{\Delta T_{lm,cf}};$$

$$F = \phi\left(P, R,\ flow\ arrangement \right)$$

$$\boxed{\Delta T_{lm,cf} = \frac{\left(T_{h2} - T_{c1} \right) - \left(T_{h1} - T_{c2} \right)}{ln\left(\dfrac{T_{h2} - T_{c1}}{T_{h1} - T_{c2}} \right)}}$$

Basic Design Methods of Heat Exchangers…..2

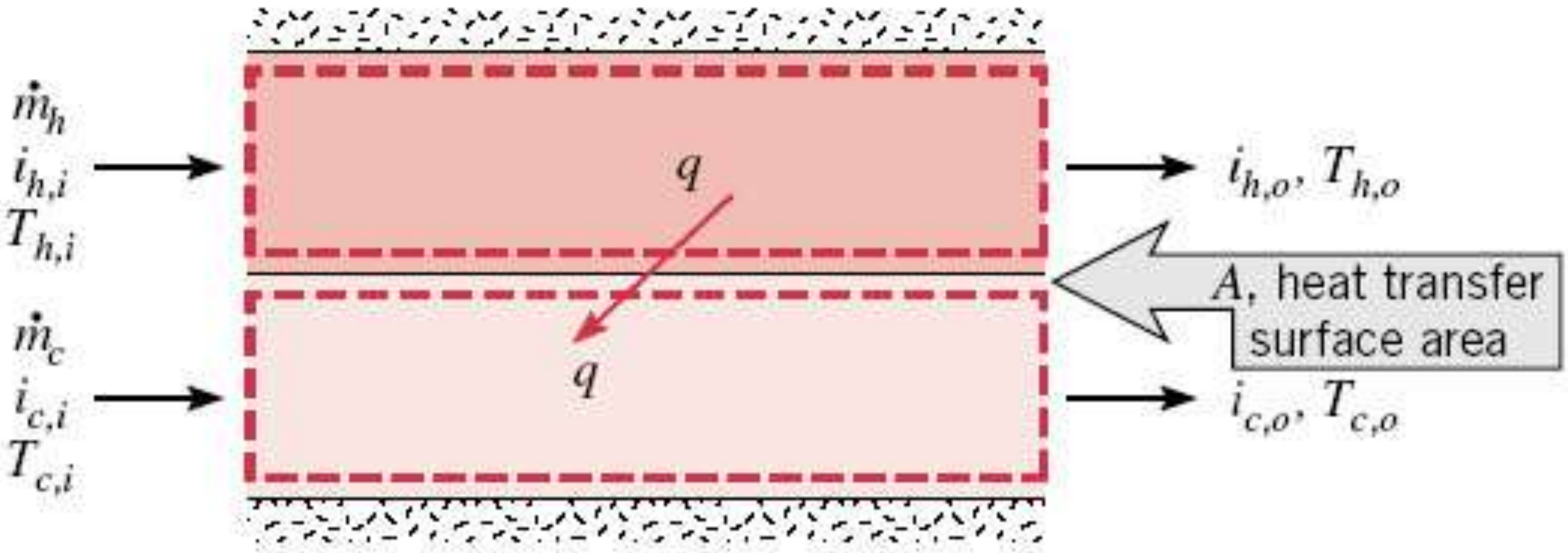

FIGURE 11.6 Overall energy balances for the hot and cold fluids of a two-fluid heat exchanger.

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Basic Design Methods of Heat Exchangers…..3

ε-NTU method

$$C_r = \frac{C_{min}}{C_{max}}; \quad C_{min} = MIN\left[\dot{m}_c c_{pc}; \dot{m}_h c_{ph}\right];$$

$$C_{max} = MAX\left[\dot{m}_c c_{pc}; \dot{m}_h c_{ph}\right]; \quad \varepsilon = \frac{Q}{C_{min}\left(T_{h1} - T_{c1}\right)};$$

$$NTU = \frac{UA}{C_{min}}; \quad \varepsilon = \phi\left(NTU, C_r, \text{ flow arrangement}\right)$$

Table 11.4 Heat Exchanger NTU Relations

Flow Arrangement	Relation	
Concentric tube		
Parallel flow	$\mathrm{NTU} = -\dfrac{\ln[1-\varepsilon(1+C_r)]}{1+C_r}$	(11.28b)
Counterflow	$\mathrm{NTU} = \dfrac{1}{C_r-1}\ln\left(\dfrac{\varepsilon-1}{\varepsilon C_r-1}\right) \quad (C_r<1)$	
	$\mathrm{NTU} = \dfrac{\varepsilon}{1-\varepsilon} \quad (C_r=1)$	(11.29b)
Shell-and-tube		
One shell pass (2, 4, . . . tube passes)	$(\mathrm{NTU})_1 = -(1+C_r^2)^{-1/2}\ln\left(\dfrac{E-1}{E+1}\right)$	(11.30b)
	$E = \dfrac{2/\varepsilon_1-(1+C_r)}{(1+C_r^2)^{1/2}}$	(11.30c)
n Shell passes ($2n$, $4n$, . . . tube passes)	Use Equations 11.30b and 11.30c with $\varepsilon_1 = \dfrac{F-1}{F-C_r} \quad F = \left(\dfrac{\varepsilon C_r-1}{\varepsilon-1}\right)^{1/n} \quad \mathrm{NTU} = n(\mathrm{NTU})_1$	(11.31b, c, d)
Cross-flow (single pass)		
C_{max} (mixed), C_{min} (unmixed)	$\mathrm{NTU} = -\ln\left[1+\left(\dfrac{1}{C_r}\right)\ln(1-\varepsilon C_r)\right]$	(11.33b)
C_{min} (mixed), C_{max} (unmixed)	$\mathrm{NTU} = -\left(\dfrac{1}{C_r}\right)\ln[C_r\ln(1-\varepsilon)+1]$	(11.34b)
All exchangers ($C_r = 0$)	$\mathrm{NTU} = -\ln(1-\varepsilon)$	(11.35b)

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TABLE 11.3 Heat Exchanger Effectiveness Relations [5]

Flow Arrangement	Relation		
Parallel flow	$\varepsilon = \dfrac{1 - \exp[-\mathrm{NTU}(1 + C_r)]}{1 + C_r}$		(11.28a)
Counterflow	$\varepsilon = \dfrac{1 - \exp[-\mathrm{NTU}(1 - C_r)]}{1 - C_r \exp[-\mathrm{NTU}(1 - C_r)]}$	$(C_r < 1)$	
	$\varepsilon = \dfrac{\mathrm{NTU}}{1 + \mathrm{NTU}}$	$(C_r = 1)$	(11.29a)
Shell-and-tube			
One shell pass (2, 4, . . . tube passes)	$\varepsilon_1 = 2\left\{1 + C_r + (1 + C_r^2)^{1/2} \times \dfrac{1 + \exp[-(\mathrm{NTU})_1(1 + C_r^2)^{1/2}]}{1 - \exp[-(\mathrm{NTU})_1(1 + C_r^2)^{1/2}]}\right\}^{-1}$		(11.30a)
n shell passes ($2n$, $4n$, . . . tube passes)	$\varepsilon = \left[\left(\dfrac{1 - \varepsilon_1 C_r}{1 - \varepsilon_1}\right)^n - 1\right]\left[\left(\dfrac{1 - \varepsilon_1 C_r}{1 - \varepsilon_1}\right)^n - C_r\right]^{-1}$		(11.31a)
Cross-flow (single pass)			
Both fluids unmixed	$\varepsilon = 1 - \exp\left[\left(\dfrac{1}{C_r}\right)(\mathrm{NTU})^{0.22}\{\exp[-C_r(\mathrm{NTU})^{0.78}] - 1\}\right]$		(11.32)
C_{max} (mixed), C_{min} (unmixed)	$\varepsilon = \left(\dfrac{1}{C_r}\right)(1 - \exp\{-C_r[1 - \exp(-\mathrm{NTU})]\})$		(11.33a)
C_{min} (mixed), C_{max} (unmixed)	$\varepsilon = 1 - \exp(-C_r^{-1}\{1 - \exp[-C_r(\mathrm{NTU})]\})$		(11.34a)
All exchangers ($C_r = 0$)	$\varepsilon = 1 - \exp(-\mathrm{NTU})$		(11.35a)

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Basic Correlations used in Designing of Heat Exchangers…1

Pressure drop

$$\Delta p = 4 f_a \frac{L}{D} \rho \frac{u_m^2}{2}$$

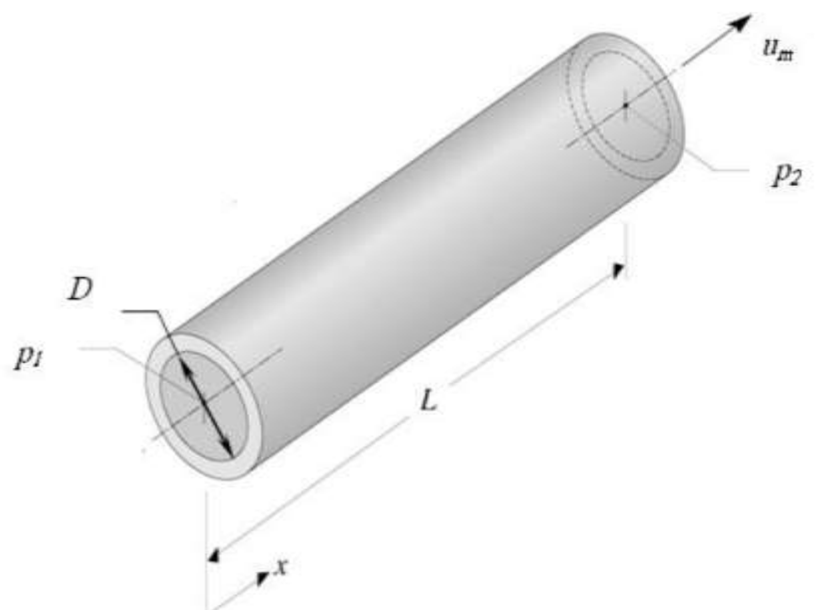
Laminar flow in a circular tube: $f_a = \dfrac{16}{Re_D}$

Turbulent flow in a smooth circular tube:

$$f_a = \left[1.58 \ln(Re_D) - 3.28\right]^{-2}, \quad 3000 \le Re_D \le 5\times10^6$$

Turbulent flow in a roughened circular tube (e: surface roughness):

$$\frac{1}{\sqrt{f_a}} \cong -3.6 \log_{10}\left[\frac{6.9}{Re_D} + \left(\frac{e/D}{3.7}\right)^{1.11}\right]$$



Pumping power requirement

$$\dot{P} = \frac{\dot{m}\Delta p}{\rho \eta_p}$$

η_p : Pump total efficiency

Basic Correlations used in Designing of Heat Exchangers…2

Laminar flow in a circular tube

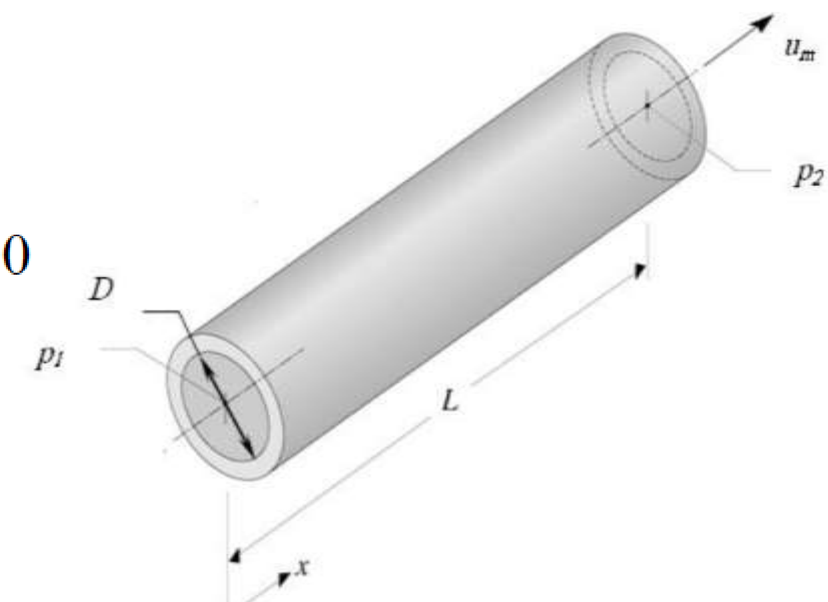
$$Nu_D = 1.86\left(\frac{Re_D\,Pr\,D}{L}\right)^{1/3}\left(\frac{\mu_b}{\mu_s}\right)^{0.14}$$

Turbulent flow in a circular tube

Gnielinski correlation

$$Nu_D = \frac{(f_a/2)(Re_D - 1000)Pr}{1 + 12.7(f_a/2)^{1/2}(Pr^{2/3} - 1)}$$

$$3\times10^3 \le Re_D \le 5\times10^6, \quad 0.5 \le Pr \le 2000$$



Basic Correlations used in Designing of Heat Exchangers…3

$$D_h \equiv \frac{4A_C}{P_w}, \qquad D_e \equiv \frac{4A_C}{P_h}, \qquad Re_{D_h} \equiv \frac{\rho u_m D_h}{\mu}, \qquad Nu_{D_e} \equiv \frac{hD_e}{k}$$

P_w : Wetted perimeter; P_h : Heat transfer perimeter

Developing Laminar flow

$$Nu_{D_{e,o}} = \frac{\bar{h}_o D_{e,o}}{k_o} = 1.86\left(\frac{Re_{D_{h,o}} Pr_o D_{h,o}}{L}\right)^{1/3}\left(\frac{\mu_{b,o}}{\mu_{s,o}}\right)^{0.14}$$

Turbulent fully developed flow

$$Nu_{D_{e,o}} = \frac{(f_{a,o}/2)(Re_{D_{h,o}} - 1000)Pr_o}{1 + 12.7(f_{a,o}/2)^{1/2}(Pr_o^{2/3} - 1)}$$

$$3\times 10^3 \le Re_{D_{h,o}} \le 5\times 10^6, \quad 0.5 \le Pr_o \le 2000$$

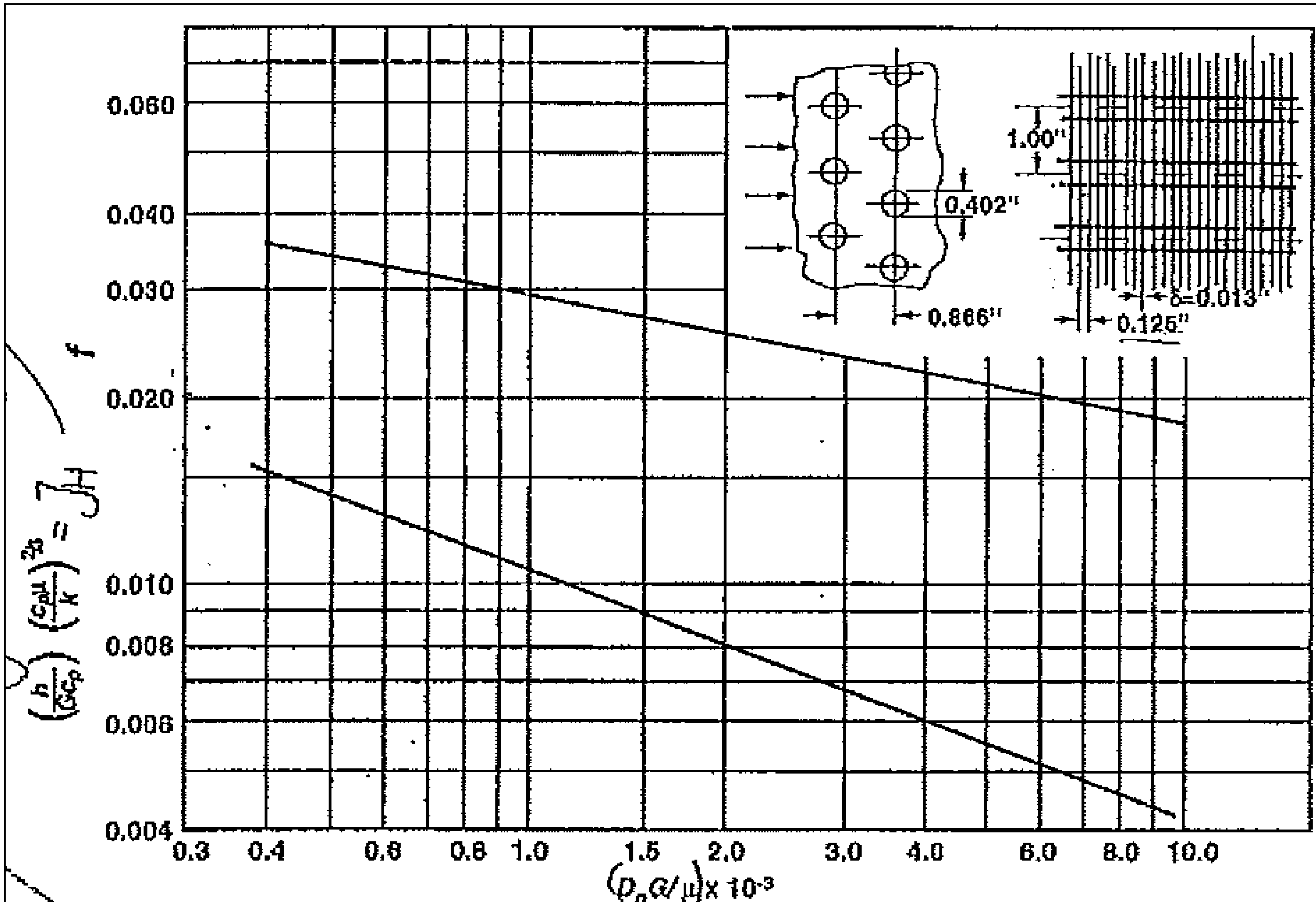
Cross section view of bare tubes inside shell

Basic Correlations used in Designing of Heat Exchangers…4

Excel Correlations

$$j_H = 0.01076049(Re_o x10^{-3})^{-0.41694524}$$

$$f_o = 0.00004356(Re_o x10^{-3})^4 - 0.00084561(Re_o x10^{-3})^3 + 0.00557989(Re_o x10^{-3})^2 - 0.01595749(Re_o x10^{-3}) + 0.04091953$$

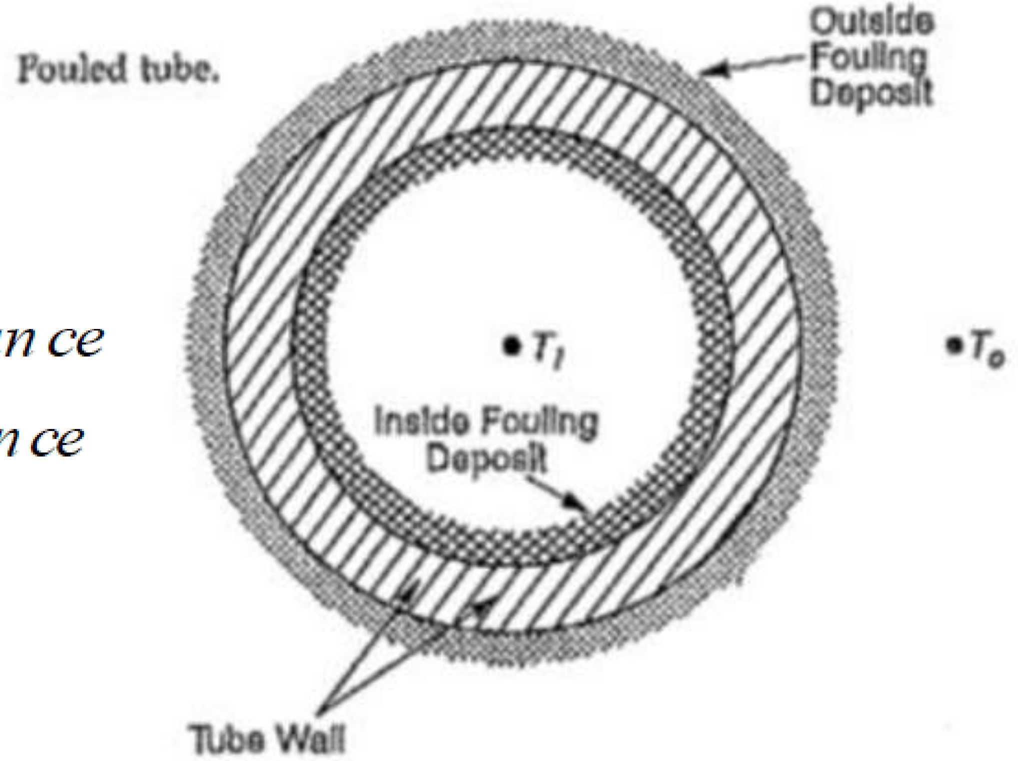


Heat transfer and friction factor for a circular tube continuous fin heat exchanger. Surface 8.0-3/8 T: tube O.D. = 1.02 cm; fin pitch = 3.15/cm; fin thickness = 0.033 cm; fin area/total area = 0.839; air-passage hydraulic diameter = 0.3633 cm; free-flow area/frontal area, σ = 0.534; heat transfer area/total volume = 587 m²/m³. (From Kays, W. M. and London, A. L. [1984], *Compact Heat Exchangers*, 3rd ed., McGraw-Hill, New York. With permission.)

The Overall Heat Transfer Coefficient…1

Bare circular fouled tubes of N_t number of tubes

$$\frac{1}{UA} = \frac{1}{U_o A_o} = \frac{1}{U_i A_i} = \frac{1}{h_o A_o} + \frac{R_{fo}}{A_o} + R_W + \frac{R_{fi}}{A_i} + \frac{1}{h_i A_i}$$



R_{fo} : *outside fouling unit resistance*

R_{fi} : *inside fouling unit resistance*

The Overall Heat Transfer Coefficient…2

Bare circular fouled tubes of N_t number of tubes

$$\frac{1}{U_o} = \frac{1}{h_o} + R_{fo} + \frac{d_o \ln(d_o/d_i)}{2k_{tube}} + \left(\frac{d_o}{d_i}\right) R_{fi} + \left(\frac{d_o}{d_i}\right)\frac{1}{h_i}$$

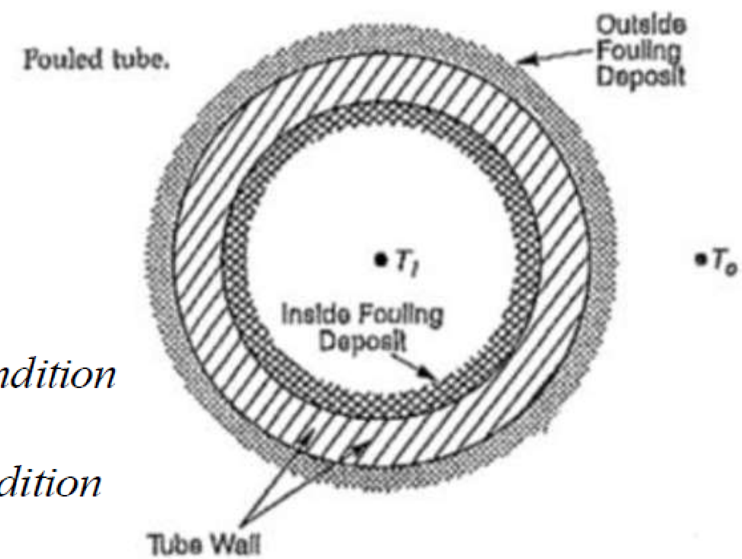
$$\frac{1}{U_i} = \left(\frac{d_i}{d_o}\right)\frac{1}{h_o} + \left(\frac{d_i}{d_o}\right) R_{fo} + \frac{d_i \ln(d_o/d_i)}{2k_{tube}} + R_{fi} + \frac{1}{h_i}$$

$$A_o = \pi d_o N_t L; \qquad A_i = \pi d_i N_t L$$

$$\frac{A_{of}}{A_{oc}} = \frac{U_{oc}}{U_{of}} = 1 + U_{oc} R_{ft} \geq 1.0$$

U_{of} : *Overall heat transfer coefficient based on fouled condition*

U_{oc} : *Overall heat transfer coefficient based on clean condition*



The Overall Heat Transfer Coefficient…3

<u>Finned</u> <u>circular</u> <u>fouled</u> tubes of <u>N_t</u> number of tubes (<u>rectangular fins</u>)

$$\frac{1}{U_o}=\frac{1}{\eta_o h_o}+\frac{R_{fo}}{\eta_o}+\frac{A_o\ln(d_o/d_i)}{2\pi k_{tube}N_t L}+\left(\frac{A_o}{A_i}\right)\frac{R_{fi}}{\eta_i}+\left(\frac{A_o}{A_i}\right)\frac{1}{\eta_i h_i}$$

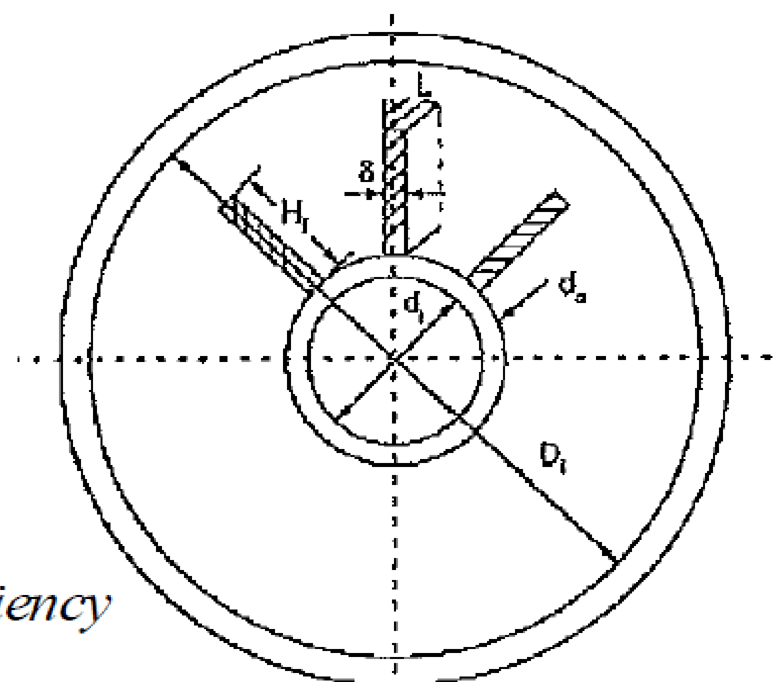
$$A_o=\left(\pi d_o+2H_{fo}N_{fo}\right)N_t L,$$

$$A_{fo}=\left(2H_{fo}+\delta_o\right)N_{fo}N_t L,$$

$$\eta_o=1-\left(1-\eta_{fo}\right)\frac{A_{fo}}{A_o};\quad \eta_i=1-\left(1-\eta_{fi}\right)\frac{A_{fi}}{A_i}$$

(η_o,η_i): $(outer, inner)$ *surface efficiency*

(η_{fo},η_{fi}): $(outer, inner)$ *fin thermal efficiency*

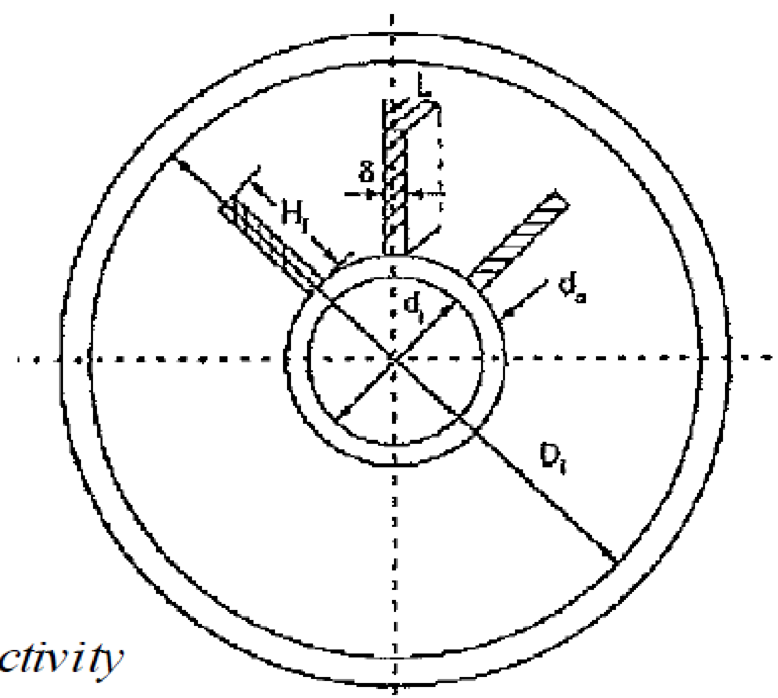


The Overall Heat Transfer Coefficient…4

Finned circular fouled tubes of N_t number of tubes (rectangular fins)

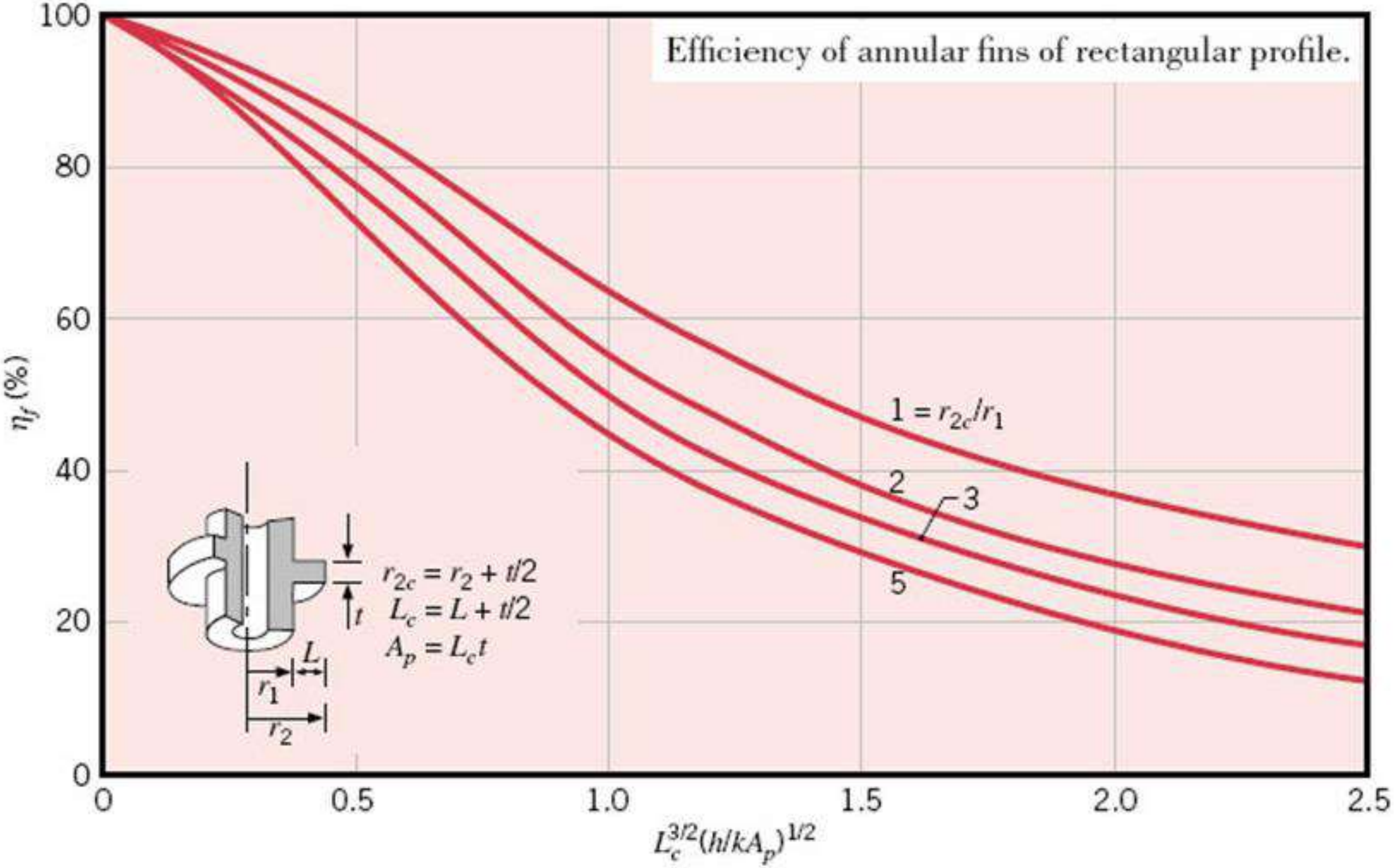
$$\eta_{fo} = \frac{\tanh\left(\left[H_{fo} + \delta_o/2\right]\sqrt{\dfrac{2h_o}{k_{fin,o}\delta_o}}\right)}{\left[H_{fo} + \delta_o/2\right]\sqrt{\dfrac{2h_o}{k_{fin,o}\delta_o}}}$$

$$\eta_{fi} = \frac{\tanh\left(\left[H_{fi} + \delta_i/2\right]\sqrt{\dfrac{2h_i}{k_{fin,i}\delta_i}}\right)}{\left[H_{fi} + \delta_i/2\right]\sqrt{\dfrac{2h_i}{k_{fin,i}\delta_i}}}$$

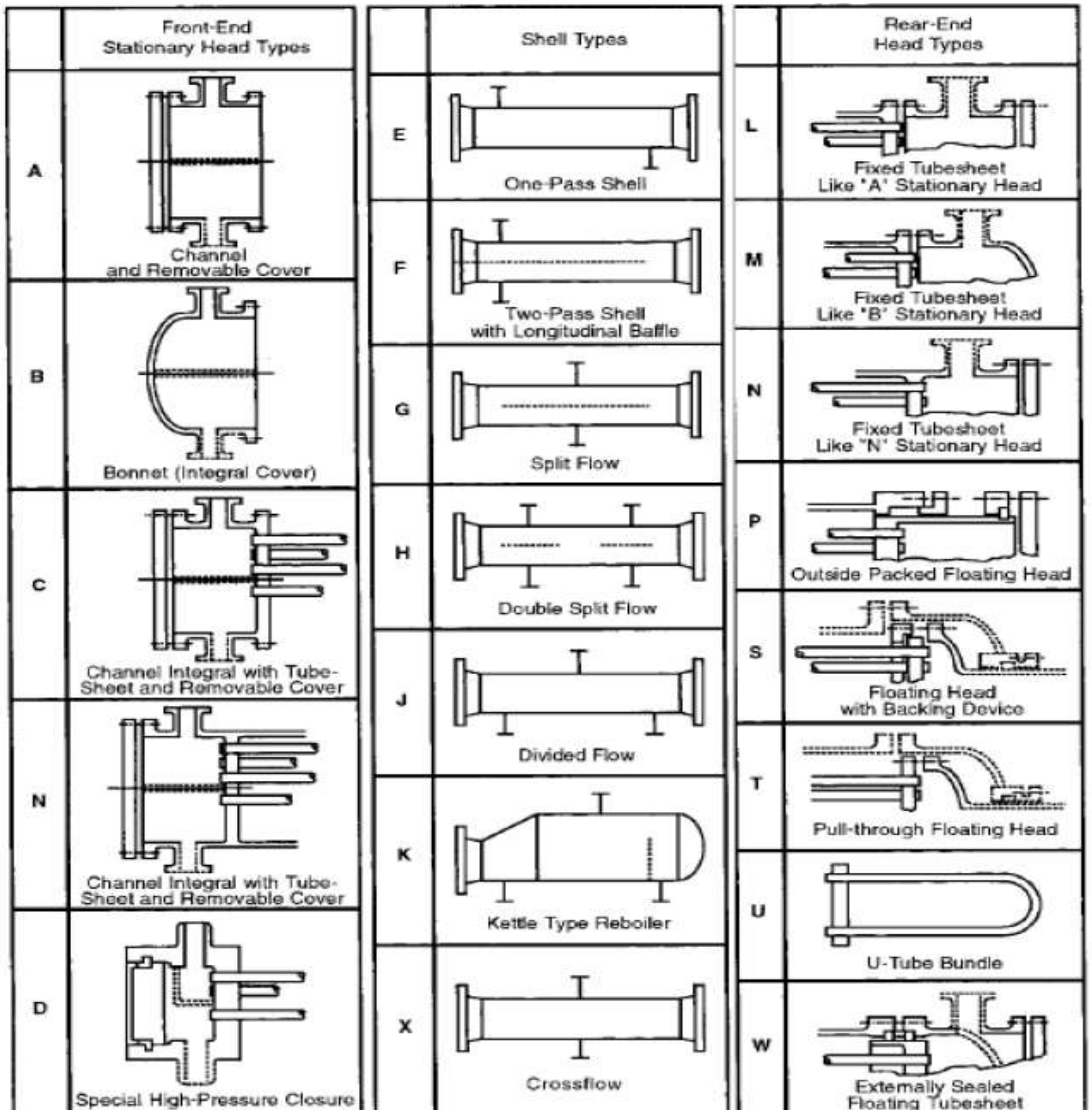


$(k_{fin,o}, k_{fin,i})$: $(outer, inner)$ $fin\ thermal\ conductivity$

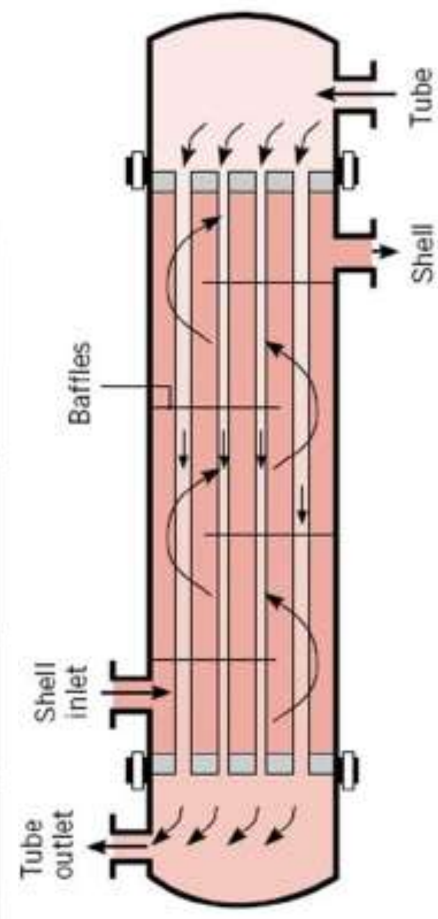
The Overall Heat Transfer Coefficient…5



International Engineering Standards…1



Standard shell types and front- and rear-end head types (From TEMA, 1999).



Shell-and-tube heat exchanger with one shell pass and one tube pass (cross-counterflow mode of operation).

International Engineering Standards…2

Heat Exchanger and Condenser Tube Data

Nominal Pipe Size (in.)	Outside Diameter (in.)	Schedule Number or Weight	Wall Thickness (in.)	Inside Diameter (in.)	Surface Area: Outside ($ft.^2/ft.$)	Surface Area: Inside ($ft.^2/ft.$)	Cross-Sectional Area: Metal Area ($in.^2$)	Cross-Sectional Area: Flow Area ($in.^2$)
		40	0.113	0.824	0.275	0.216	0.333	0.533
3/4	1.05	80	0.154	0.742	0.275	0.194	0.434	0.432
		40	0.133	1.049	0.344	0.275	0.494	0.864
1	1.315	80	0.179	0.957	0.344	0.250	0.639	0.719
		40	0.140	1.38	0.434	0.361	0.668	1.496
1-1/4	1.660	80	0.191	1.278	0.434	0.334	0.881	1.283
		40	0.145	1.61	0.497	0.421	0.799	2.036
1-1/2	1.900	80	0.200	1.50	0.497	0.393	1.068	1.767
		40	0.154	2.067	0.622	0.541	1.074	3.356
2	2.375	80	0.218	1.939	0.622	0.508	1.477	2.953
		40	0.203	2.469	0.753	0.646	1.704	4.79
2-1/2	2.875	80	0.276	2.323	0.753	0.608	2.254	4.24
		40	0.216	3.068	0.916	0.803	2.228	7.30
3	3.5	80	0.300	2.900	0.916	0.759	3.106	6.60
		40	0.226	3.548	1.047	0.929	2.680	9.89
3-1/2	4.0	80	0.318	3.364	1.047	0.881	3.678	8.89
		40	0.237	4.026	1.178	1.054	3.17	12.73
4	4.5	80	0.337	3.826	1.178	1.002	4.41	11.50
		10 S	0.134	5.295	1.456	1.386	2.29	22.02
5	5.563	40	0.258	5.047	1.456	1.321	4.30	20.01
		80	0.375	4.813	1.456	1.260	6.11	18.19
		10 S	0.134	6.357	1.734	1.664	2.73	31.7
6	6.625	40	0.280	6.065	1.734	1.588	5.58	28.9
		80	0.432	5.761	1.734	1.508	8.40	26.1
		10 S	0.148	8.329	2.258	2.180	3.94	54.5
8	8.625	30	0.277	8.071	2.258	2.113	7.26	51.2
		80	0.500	7.625	2.258	1.996	12.76	45.7
		10 S	0.165	10.420	2.81	2.73	5.49	85.3
10	10.75	30	0.279	10.192	2.81	2.67	9.18	81.6
		Extra heavy	0.500	9.750	2.81	2.55	16.10	74.7
		10 S	0.180	12.390	3.34	3.24	7.11	120.6
	12.75	30	0.330	12.09	3.34	3.17	12.88	114.8
		Extra heavy	0.500	11.75	3.34	3.08	19.24	108.4
		10	0.250	13.5	3.67	3.53	10.80	143.1
14	14.0	Standard	0.375	13.25	3.67	3.47	16.05	137.9
		Extra heavy	0.500	13.00	3.67	3.40	21.21	132.7
		10	0.250	15.50	4.19	4.06	12.37	188.7
16	16.0	Standard	0.375	15.25	4.19	3.99	18.41	182.7
		Extra heavy	0.500	15.00	4.19	3.93	24.35	176.7
		10 S	0.188	17.624	4.71	4.61	10.52	243.9
18	18.0	Standard	0.375	17.25	4.71	4.52	20.76	233.7
		Extra heavy	0.500	17.00	4.71	4.45	27.49	227.0

Source: Courtesy of the Tubular Exchanger Manufacturers Association.

International Engineering Standards…3

Dimensional Data for Commercial Tubing

OD of Tubing (in.)	BWG Gauge	Thickness (in.)	Internal Flow Area (in.²)	Sq. Ft. External Surface per Ft. Length	Sq. Ft. Internal Surface per Ft. Length	Weight per Ft. Length, Steel (lb.)	ID Tubing (in.)	OD/ID
1/4	22	0.028	0.0295	0.0655	0.0508	0.066	0.194	1.289
1/4	24	0.022	0.0333	0.0655	0.0539	0.054	0.206	1.214
1/4	26	0.018	0.0360	0.0655	0.0560	0.045	0.214	1.168
3/8	18	0.049	0.0603	0.0982	0.0725	0.171	0.277	1.354
3/8	20	0.035	0.0731	0.0982	0.0798	0.127	0.305	1.233
3/8	22	0.028	0.0799	0.0982	0.0835	0.104	0.319	1.176
3/8	24	0.022	0.0860	0.0982	0.0867	0.083	0.331	1.133
1/2	16	0.065	0.1075	0.1309	0.0969	0.302	0.370	1.351
1/2	18	0.049	0.1269	0.1309	0.1052	0.236	0.402	1.244
1/2	20	0.035	0.1452	0.1309	0.1126	0.174	0.430	1.163
1/2	22	0.028	0.1548	0.1309	0.1162	0.141	0.444	1.126
5/8	12	0.109	0.1301	0.1636	0.1066	0.602	0.407	1.536
5/8	13	0.095	0.1486	0.1636	0.1139	0.537	0.435	1.437
5/8	14	0.083	0.1655	0.1636	0.1202	0.479	0.459	1.362
5/8	15	0.072	0.1817	0.1636	0.1259	0.425	0.481	1.299
5/8	16	0.065	0.1924	0.1636	0.1296	0.388	0.49s	1.263
5/8	17	0.058	0.2035	0.1636	0.1333	0.350	0.509	1.228
5/8	18	0.049	0.2181	0.1636	0.1380	0.303	0.527	1.186
5/8	19	0.042	0.2298	0.1636	0.1416	0.262	0.541	1.155
5/8	20	0.035	0.2419	0.1636	0.1453	0.221	0.555	1.136
3/4	10	0.134	0.1825	0.1963	0.1262	0.884	0.482	1.556
3/4	11	0.120	0.2043	0.1963	0.1335	0.809	0.510	1.471
3/4	12	0.109	0.2223	0.1963	0.1393	0.748	0.532	1.410
3/4	13	0.095	0.2463	0.1963	0.1466	0.666	0.560	1.339
3/4	14	0.083	0.2679	0.1963	0.1529	0.592	0.584	1.284
3/4	15	0.072	0.2884	0.1963	0.1587	0.520	0.606	1.238
3/4	16	0.065	0.3019	0.1963	0.1623	0.476	0.620	1.210
3/4	17	0.058	0.3157	0.1963	0.1660	0.428	0.634	1.183
3/4	18	0.049	0.3339	0.1963	0.1707	0.367	0.652	1.150
3/4	20	0.035	0.3632	0.1963	0.1780	0.269	0.680	1.103
7/8	10	0.134	0.2892	0.2291	0.1589	1.061	0.607	1.441
7/8	11	0.120	0.3166	0.2291	0.1662	0.969	0.635	1.378
7/8	12	0.109	0.3390	0.2291	0.1720	0.891	0.657	1.332
7/8	13	0.095	0.3685	0.2291	0.1793	0.792	0.685	1.277
7/8	14	0.083	0.3948	0.2291	0.1856	0.704	0.709	1.234
7/8	16	0.065	0.4359	0.2291	0.1950	0.561	0.745	1.174
7/8	18	0.049	0.4742	0.2291	0.2034	0.432	0.777	1.126
7/8	20	0.035	0.5090	0.2291	0.2107	0.313	0.805	1.087
1	8	0.165	0.3526	0.2618	0.1754	1.462	0.670	1.493
1	10	0.134	0.4208	0.2618	0.1916	1.237	0.732	1.366
1	11	0.120	0.4536	0.2618	0.1990	1.129	0.760	1.316
1	12	0.109	0.4803	0.2618	0.2047	1.037	0.782	1.279
1	13	0.095	0.5153	0.2618	0.2121	0.918	0.810	1.235
1	14	0.083	0.5463	0.2618	0.2183	0.813	0.834	1.199
1	15	0.072	0.5755	0.2618	0.2241	0.714	0.856	1.167
1	16	0.065	0.5945	0.2618	0.2278	0.649	0.870	1.119

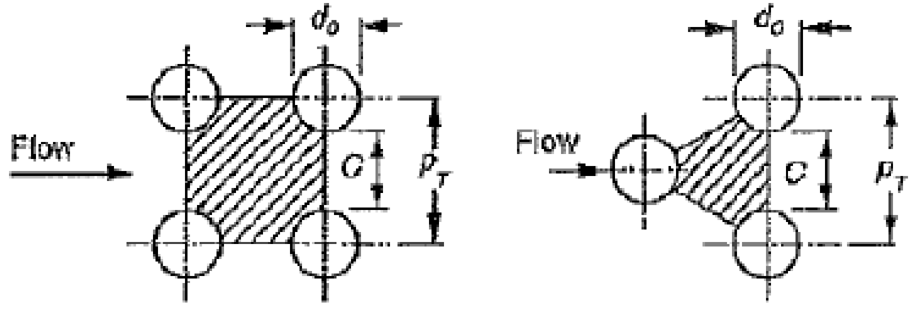
Dimensional Data for Commercial Tubing

OD of Tubing (in.)	BWG Gauge	Thickness (in.)	Internal Flow Area (in.²)	Sq. Ft. External Surface per Ft. Length	Sq. Ft. Internal Surface per Ft. Length	Weight per Ft. Length, Steel (lb.)	ID Tubing (in.)	OD/ID
1	18	0.049	0.6390	0.2618	0.2361	0.496	0.902	1.109
1	20	0.035	0.6793	0.2618	0.2435	0.360	0.930	1.075
1-1/4	7	0.180	0.6221	0.3272	0.2330	2.057	0.890	1.404
1-1/4	8	0.165	0.6648	0.3272	0.2409	1.921	0.920	1.359
1-1/4	10	0.134	0.7574	0.3272	0.2571	1.598	0.982	1.273
1-1/4	11	0.120	0.8012	0.3272	0.2644	1.448	1.010	1.238
1-1/4	12	0.109	0.8365	0.3272	0.2702	1.329	1.032	1.211
1-1/4	12	0.095	0.8825	0.3272	0.2773	1.173	1.060	1.179
1-1/4	14	0.083	0.9229	0.3272	0.2838	1.039	1.084	1.153
1-1/4	16	0.065	0.9852	0.3272	0.2932	0.823	1.120	1.116
1-1/4	18	0.049	1.042	0.3272	0.3016	0.629	1.152	1.085
1-1/4	20	0.035	1.094	0.3272	0.3089	0.456	1.180	1.059
1-1/2	10	0.134	1.192	0.3927	0.3225	1.955	1.232	1.218
1-1/2	12	0.109	1.291	0.3927	0.3356	1.618	1.282	1.170
1-1/2	14	0.083	1.398	0.3927	0.3492	1.258	1.334	1.124
1-1/2	16	0.065	1.474	0.3927	0.3587	0.996	1.370	1.095
2	11	0.120	2.433	0.5236	0.4608	2.410	1.760	1.136
2	13	0.095	2.573	0.5236	0.4739	1.934	1.810	1.105
2-1/2	9	0.148	3.815	0.6540	0.5770	3.719	2.204	1.134

Source: Courtesy of the Tubular Exchanger Manufacturers Association.

International Engineering Standards…4

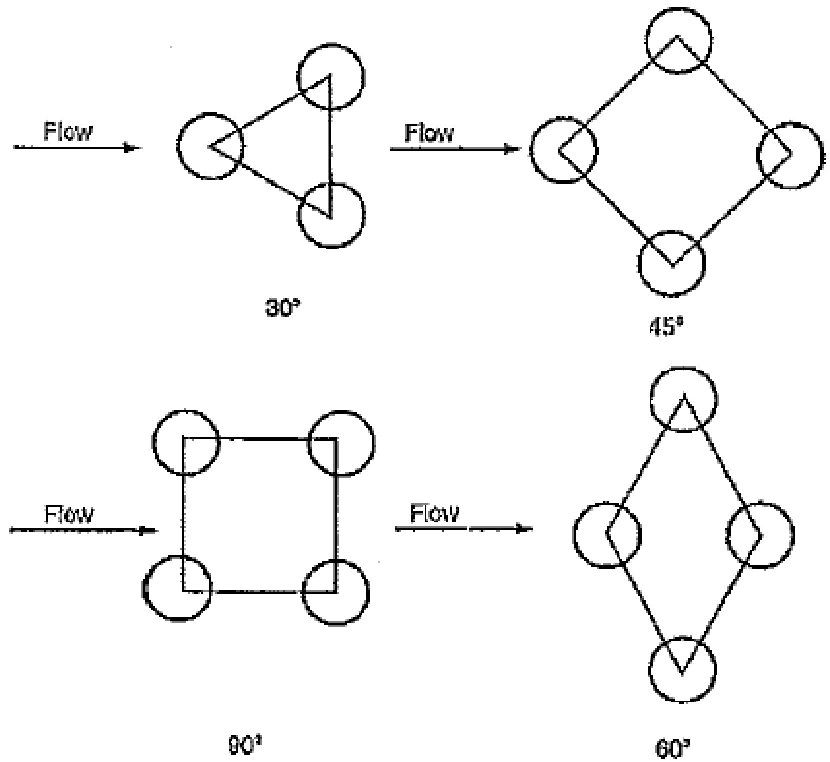
Tube layouts



Square and triangular pitch-tube layouts

P_T: tube pitch; C: clearence; $C = P_T - d_o$

$C \geq 7\ mm$: cleaning requirment for square pitch



Tube layout angles

$1.25 \leq \frac{P_T}{d_o} \leq 1.5$: to avoid weak structurally tube sheets while enhancing heat transfer

$$(N_t)_{max} = f(D_i, d_o, N_p, P_T, tube\ layout)$$

$(N_t)_{max}$: Maximum tubes to be fit inside the shell – (Tube count)

International Engineering Standards…5

Fouling Resistances for Water

Temperature of Heating Medium	Up to 115°C		R_f ($m^2 \cdot K/W$) 115 to 205°C	
Temperature of Water	50°C		Over 50°C	
Water Velocity (m/s)	0.9 and Less	Over 0.9	0.9 and Less	Over 0.9
Seawater	0.000088	0.000088	0.000176	0.000176
Brackish water	0.000352	0.000176	0.000528	0.000352
Cooling tower and artificial spray pond				
Treated make up	0.000176	0.000176	0.000352	0.000352
Untreated	0.000528	0.000528	0.000881	0.000705
City or well water	0.000176	0.000176	0.000352	0.000352
River water				
Minimum	0.000352	0.000176	0.000528	0.000352
Average	0.000528	0.000352	0.000705	0.000528
Muddy or silty	0.000528	0.000352	0.000705	0.000528
Hard (over 15 grains/gal)	0.000528	0.000528	0.000881	0.000881
Engine jacket	0.000176	0.000176	0.000176	0.000176
Distilled or closed cycle				
Condensate	0.000088	0.000088	0.000088	0.000088
Treated boiler feedwater	0.000176	0.000088	0.000176	0.000176
Boiler blowdown	0.000352	0.000352	0.000352	0.000352

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International Engineering Standards…6

TEMA Design Fouling Resistances for Industrial Fluids

Industrial Fluids	R_f ($m^2 \cdot K/W$)
Oils	
Fuel oil no. 2	0.000352
Fuel oil no. 6	0.000881
Transformer oil	0.000176
Engine lube oil	0.000176
Quench oil	0.000705
Gases and Vapors	
Manufactured gas	0.001761
Engine exhaust gas	0.001761
Steam (nonoil bearing)	0.000088
Exhaust steam (oil bearing)	0.000264–0.000352
Refrigerant vapors (oil bearing)	0.000352
Compressed air	0.000176
Ammonia vapor	0.000176
CO_2 vapor	0.000176
Chlorine vapor	0.000352
Coal flue gas	0.001761
Natural gas flue gas	0.000881
Liquids	
Molten heat transfer salts	0.000088
Refrigerant liquids	0.000176
Hydraulic fluid	0.000176
Industrial organic heat transfer media	0.000352
Ammonia liquid	0.000176
Ammonia liquid (oil bearing)	0.000528
Calcium chloride solutions	0.000528
Sodium chloride solutions	0.000528
CO_2 liquid	0.000176
Chlorine liquid	0.000352
Methanol solutions	0.000352
Ethanol solutions	0.000352
Ethylene glycol solutions	0.000352

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Simplified Heat Exchanger Design Calculations…..1

- **If Inlet temperatures, mass flow rates and one of the outlets temperatures are known**

1. Calculate Q and the outlet temperature using energy conservation
2. Calculate ΔT_{lm} by obtaining F and $\Delta T_{lm,cf}$
3. Calculate the overall heat transfer coefficient U
4. Determine the surface area using the Q_ ΔT_{lm} relationship

Simplified Heat Exchanger Design Calculations…..2

- **If Inlet and outlet temperatures and one mass flow rate are known**

1. Calculate Q and the remaining mass flow rate using energy conservation
2. Calculate Q_{max} and ε
3. Find out NTU from the NTU- ε relationships for different types of heat exchangers
4. Determine the surface area

Basic Algorithms for Design of Heat Exchangers…(1)

<u>Problem Identification</u>
- converting users needs into outputs
- Identifying imposed constraints
- Determining the required quality of the design

<u>Selection of Tentative set of Design Parameters</u>
- Type of heat exchanger
- Initial size of heat exchanger

<u>Rating of Tentative Design</u>
- Finding the outputs
- Checking the constraints

Modify the Design Parameters

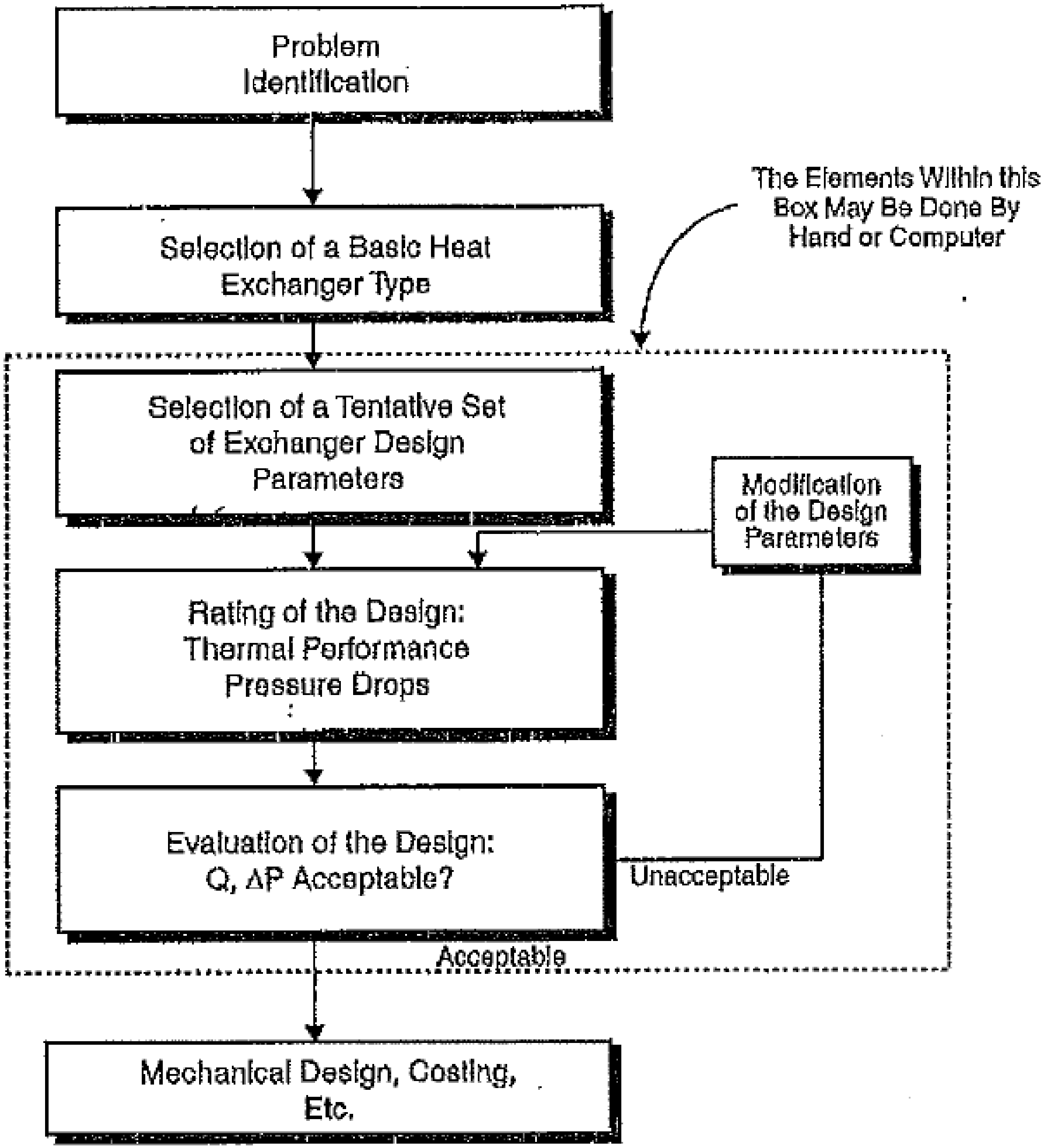
Is Rating of Heat Exchanger satisfying Outputs, Constraints and Required Quality?

No

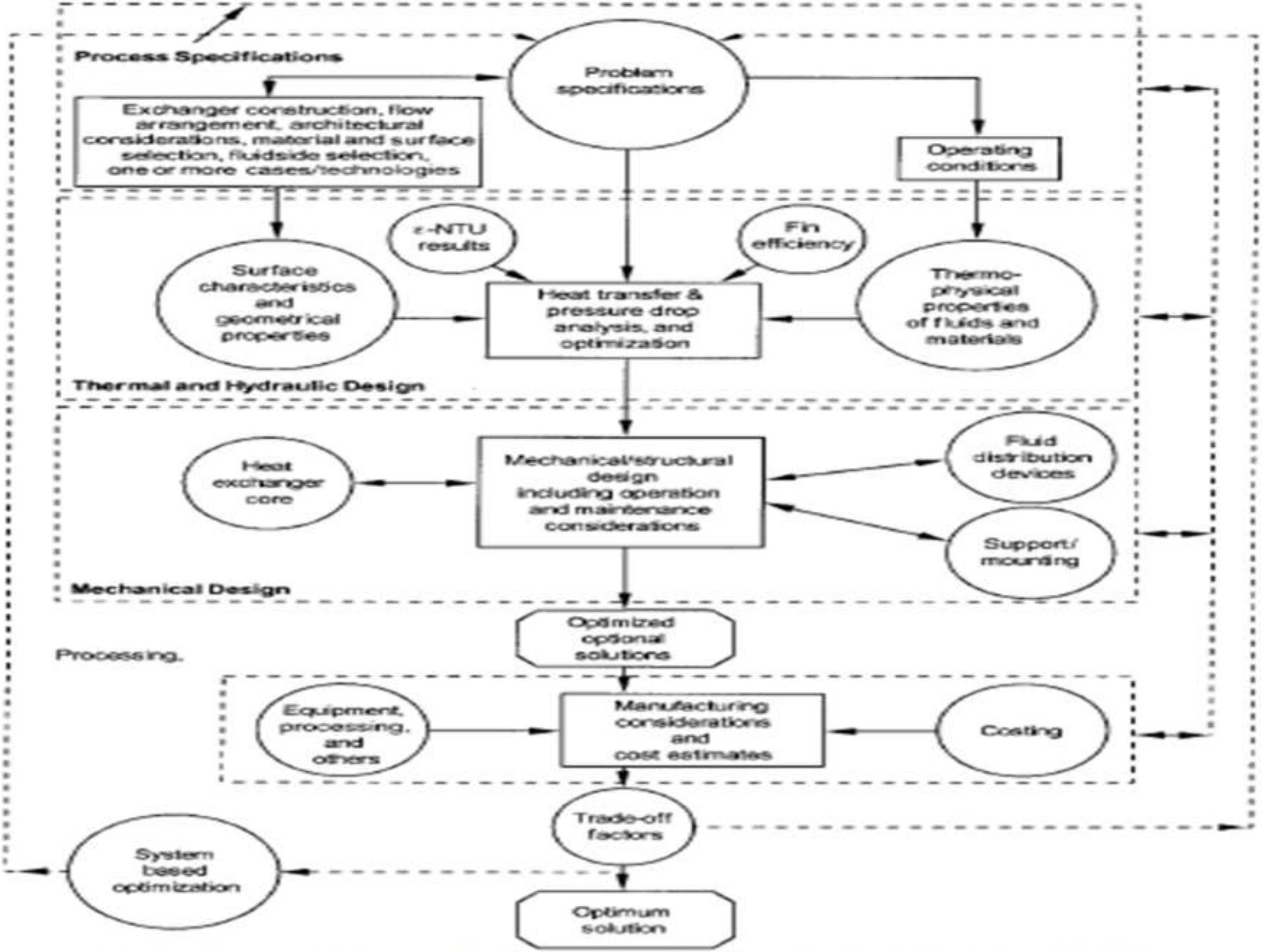
Yes

Mechanical Design Stage

Manufacturing Stage



Basic logic structure for process heat exchanger design. (Based on Bell, K. J. [1981] *Heat Exchangers: Thermal-Hydraulic Fundamentals and Design*, Taylor and Francis, Washington, D.C.)



Heat exchanger design methodology. (Modified from Shah, 1982; Taborek, 1988; and Kays and London, 1998.)

Basic Iterative Numerical Methodology

Example: Double pipe and Shell-and-Tube Heat Exchangers

1) Problem identification.
2) Calculation of heat exchanger effectivness (ε).
3) Selection of the heat exchanger type alternative (Counter flow or multi pass tube flow).
4) Calculation of Number of Transfer Units (NTU) based on $NTU - \varepsilon$ relationships.
5) The length of the heat exchanger is assumed ($L_{assumed}$).
6) Convection heat transfer coefficients h_i and h_o are calculated based on ($L_{assumed}$).
7) The estimated overall heat transfer coefficient ($U_{of,est}$) is calculated.
8) The estimated heat transfer area ($A_{of,est} = C_{min}\, NTU/U_{of,est}$) is calculated.
9) The length of the heat exchanger surface ($L_{corrected} = \frac{A_{of,est}}{\pi\, d_o N_t}$) is corrected.
10) The procedure starting from step (5) to step (9) is repeated by letting $L_{assumed}$=$L_{corrected}$ until the following convergence criterion is satisfied :

$$\left|\frac{L_{assumed} - L_{corrected}}{L_{assumed}}\right| * 100 < 0.1\%$$

11) The size of heat exchanger is checked against the different realistic constraints.
12) The optimum size among the acceptable sizes is selected based on minimum annual cost.

Cost of Heat Exchanger

Cost of Energy (CE):

$$CE = \left(\frac{\dot{P}_i + \dot{P}_o}{1000} \right) \times W_{hrs} \times W_{days} \times Unit\ Price$$

W_{hrs}: Working hours per day; W_{days}: Working days per year;
Unit Price: price of 1 kWhr

Cost of Manufacturing (CM):

$$CM = Unit\ Price\ per\ meter \times Length$$

Total Annual Cost (TAC):

$$TAC = CE + CM \times \{A/P(i,n)\}$$

$$\boxed{A/P(i,n) = \frac{i(i+1)^n}{(i+1)^n - 1}}$$

i: interest rate;

n: worth years of the heat exchanger

Heat Exchanger Design Example..(a)

Objective:

Design a double pipe heat exchanger with bare inner multi-tubes that can be used to cool engine oil with cold sea water. The following are the design specification:

Fluid	Engine Oil	Sea Water
Inlet Temperature, °C	65	20
Outlet Temperature, °C	55	25
Heat Load, kW	117.9	

Preliminary design options:

Three parallel x two series hairpin heat exchangers are used.

The engine oil is selected to flow inside the tubes.

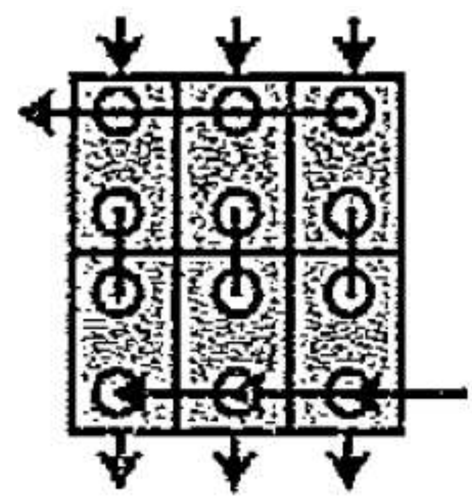
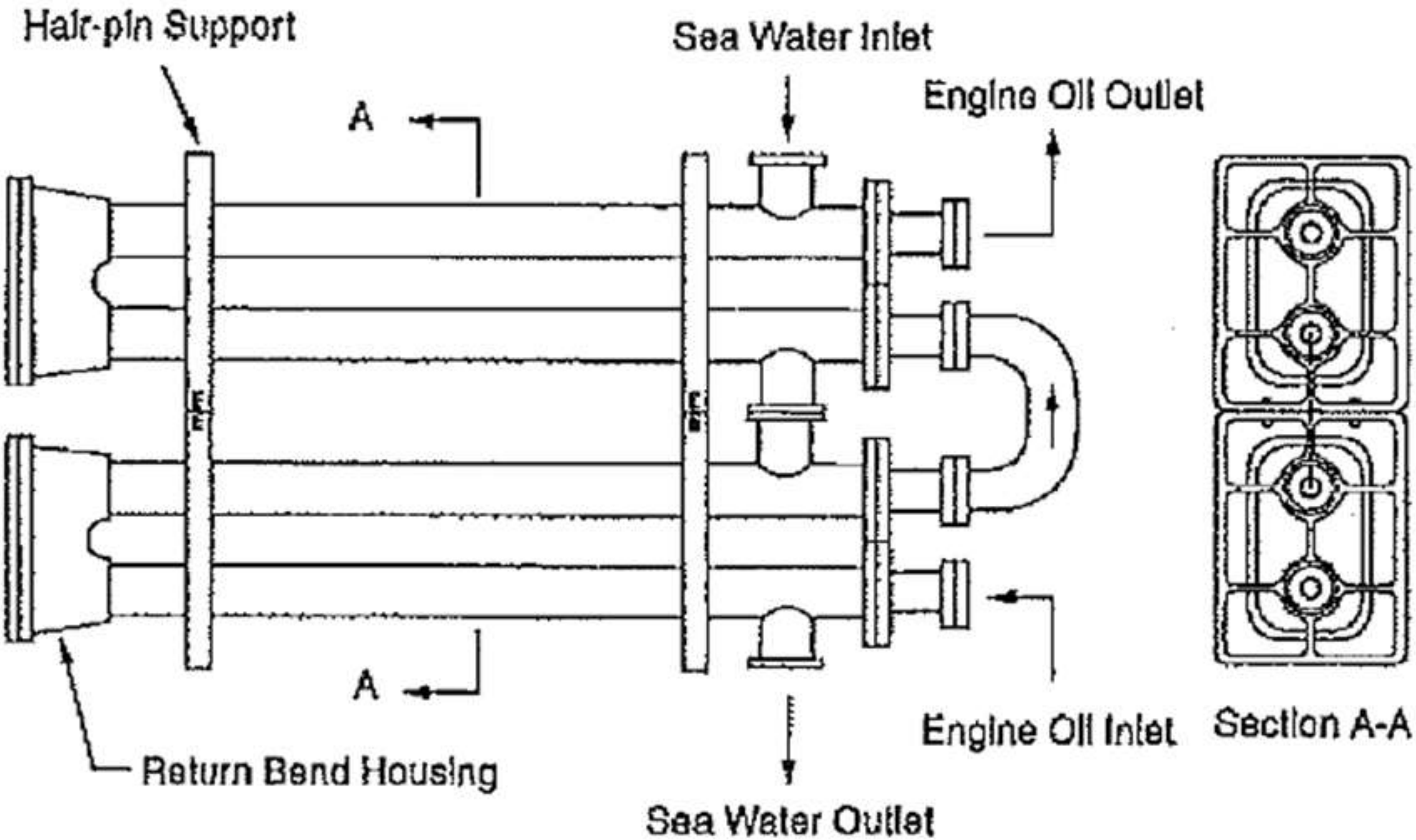


Fig. 1: Preliminary design option for the hairpin sections

Heat Exchanger Design Example..(b)



Two hairpin sections arranged in series.

Heat Exchanger Design Example..(c)

<u>Design constraints:</u>

Pressure drop constraints

(related to mechanical and operational cost constraints)

- The maximum pressure drop of oil must be smaller than 80 kPa.
- The maximum pressure drop of sea water side must be smaller than 10 kPa.

Spatial constraint

(related to capital cost constraints)

The maximum dimension of the heat exchanger must be smaller than 2.0 m.

Cost constraint

(related to capital and operational cost constraints)

The operating cost including manufacturing cost must be smaller than 15,000 SR/year. (**Take:** the price of 1kWhr of electrical energy is 0.2 SR, the pumps efficiency is 0.7, no. of working hours per day for the heat exchanger is 10 hrs/day, no. of working days per year for the heat exchanger is 350 days/year)

Material constraint

(related to environmental constraints)

Tubes must be made of steel, k_{steel}=18 W/mK.

Heat Exchanger Design Example..(d)

Standards to be used:

- The tubes and pipe dimensions are according to "**Steel Pipe Dimensions AISI Schedule 40**".
- The fouling factors are to be taken according to "**TEMA**" standards.

Steel Pipe Dimensions AISI Schedule 40

Pipe Size (in)	d_o (mm)	d_i (mm)
0.375	17.272	12.446
½	21.336	15.748
¾	26.67	20.828
1	33.528	26.67
1 ¼	42.164	35.052
1 ½	48.26	40.894
2	60.452	52.578
2 ½	73.152	62.738
3	88.9	77.978
3 ½	101.6	90.17
4	114.3	102.362
5	141.224	128.27
6	168.402	154.178
8	219.202	202.692

Heat Exchanger Design Example..(e)

Alternative Solutions:

In the market, the following pipe dimensions are available and their expected unit prices are listed:

Sol. no.	D (inch)	d (inch)	N_t	Unit price per meter* (SR/m)
1	3 sch.40	0.5 sch.40	9	1500
2	4 sch.40		14	2300
3	6 sch.40		23	3800
4	8 sch.40		30	5000
*Consider the no. of worth years for the heat exchanger is 4 years with zero interest rate (i=0, n=4)				

Heat Exchanger Design Example..(f)

Sizing Sheets:

Quantity	Engine oil-i	Sea water-o	Unit
mass flow rate	2.066246	1.963037	kg/s
T_1	65.000000	20.000000	°C
T_2	55.000001	25.000000	°C
c_p	1902.000000	4004.000000	J/kg/K
μ	0.075000	0.000964	Pa.s
μ_s	0.197000	0.000703	Pa.s
k	0.144200	0.638900	W/m/K
Pr	1050.000000	6.290000	
ρ	885.270000	1013.400000	kg/m^3

Heat Exchanger Design Example..(g)

Sizing Sheets:

k_t	18.0	W/m/K
Q_{total}	117900.0	W
$N_{HPparallel}$	3	
$N_{HPseries}$	2	
$Q_{\text{per two hairpins}}$	39300.0	W
$\Delta T_{lm.cf}$	37.444379	°C

$L_{estimated}$			%Error	%	less than	
L_1	4.360417	m	0.023470	%	0.10	%
L_2	2.886566	m	0.019095	%	0.10	%
L_3	1.986342	m	0.011529	%	0.10	%
L_4	1.809555	m	0.005738	%	0.10	%

Heat Exchanger Design Example..(h)

Sizing Sheets:

	D_i m	do m	di m	N_t
Size no. (1)	0.077978	0.021336	0.015748	9
Size no. (2)	0.102362	0.021336	0.015748	14
Size no. (3)	0.154178	0.021336	0.015748	23
Size no. (4)	0.202692	0.021336	0.015748	30

u_{mi} m/s	Re_i	fai	Nu_{iavg}	h_i $W/m^2/K$
1.331445	247.493057	0.064648	15.907898	145.664142
0.855929	159.102680	0.100564	15.753116	144.246845
0.521000	96.845109	0.165212	15.121994	138.467835
0.399433	74.247917	0.215494	14.277055	130.730968

Heat Exchanger Design Example..(i)

Sizing Sheets:

A_{co} m^2	P_{wo} m	P_{ho} m	D_{ho} m	D_{eo} m
0.001558	0.848236	0.603261	0.007346	0.010330
0.003224	1.259986	0.938406	0.010235	0.013742
0.010446	2.026032	1.541667	0.020624	0.027104
0.021541	2.647646	2.010871	0.032544	0.042850

u_{mo} m/s	Re_o	fa_o	Nu_o	h_o $W/m^2/K$
1.243414	9602.726967	0.007960	73.531205	4547.975888
0.600845	6464.660397	0.008928	50.428540	2344.526224
0.185432	4020.361861	0.010343	30.715387	724.028688
0.089924	3076.461352	0.011294	22.365887	333.480320

Heat Exchanger Design Example..(j)

Sizing Sheets:

$1/U_{oc}$ m^2K/W	U_{oc} $W/m^2/K$	R_{fi} m^2K/W	R_{fo} m^2K/W	R_{ft} m^2K/W
0.009701	103.082434	0.000176	0.000088	0.000326
0.009999	100.009907	0.000176	0.000088	0.000326
0.011346	88.139550	0.000176	0.000088	0.000326
0.013542	73.843116	0.000176	0.000088	0.000326

$1/U_{of}$ m^2K/W	U_{of} $W/m^2/K$	A_{of} m^2	L m	CF
0.010027	99.726495	10.524352	**4.361441**	0.967444
0.010325	96.847976	10.837157	**2.887118**	0.968384
0.011672	85.674415	12.250527	1.986571	0.972031
0.013869	72.104939	14.555962	1.809659	0.976461

Heat Exchanger Design Example..(k)

<u>Sizing Sheets:</u>

Δp_i Pa	Δp_i kPa	Δp_o Pa	Δp_o kPa	P_i W
230280.968092	**230.280968**	64718.856051	**64.718856**	767.832235
97928.227412	**97.928227**	8651.988187	8.651988	326.524812
40905.782168	40.905782	399.691991	0.399692	136.393287
28475.241873	28.475242	69.851256	0.069851	94.945791

P_o W	P_t W	Elec. Energy consumption kWhr/year	Energy Cost SR/year
179.093725	946.925960	3314.240860	1988.544516
23.942277	350.467089	1226.634811	735.980887
1.106051	137.499337	481.247681	288.748609
0.193296	95.139087	332.986805	199.792083

Heat Exchanger Design Example..(I)

<u>Sizing Sheets:</u>

Unit Price/m SR/m	Annual worth of the unit* SR/year	Total Annual Cost (TAC)** SR/year
1500	9813.241923	11801.786439
2300	9960.555532	10696.536419
3800	11323.454124	11612.202733
5000	13572.443579	13772.235662

	Decision	Reasons	
Size no. (1)	Rejected	dPi>limit, dPo>limit, L>limit	
Size no. (2)	Rejected	dPi>limit, L>limit	
Size no. (3)	**Accept**		**Optimum-size (design) based on minimum cost criterion**
Size no. (4)	**Accept**		

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