Heat Transfer Fundamentals & Equipment (Supplemental Chapter 9)

Topics

Fundamentals of heat transfer & exchange

- Heat transfer across boundaries
  - Conduction
  - Convection
  - Radiation
- Coupled with internal energy changes
  - Sensible heat effects
  - Phase change

Equipment – heat exchangers

- Combines information about fluid flow & heat transfer across internal boundaries
- Considerations
  - When do I need to know the specifics of the heat exchange configuration?
  - How is the heat transfer area related to the outlet temperatures?
  - What is the difference between in-tank heat exchange & an external heat exchanger?

Updated: November 13, 2017
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Heat Transfer – Modes of heat transfer

Conduction

- Flow of heat through material with no bulk movement of the material itself
- Usually thought of through solid, but can also be through a stagnant fluid
- In general

$$\bar{\mathbf{q}} = -k\nabla T \quad \text{and} \quad \frac{\partial}{\partial t}\left(\rho\hat{U}\right) = -\nabla\cdot\left(k\nabla T\right)$$

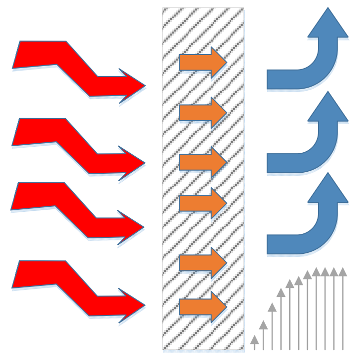
- Integrated steady-state version for flat sold:

$$\frac{\dot{Q}}{A} = k\frac{T_{hot} - T_{cold}}{\Delta x}$$

- … through a circular pipe:

$$\frac{\dot{Q}}{L} = \frac{2\pi}{\ln\left(D_o/D_i\right)}k\left(T_{hot} - T_{cold}\right)$$

$$\frac{\dot{Q}}{A} = \frac{\bar{D}_{LM}}{D_o}k\frac{T_{hot} - T_{cold}}{\Delta x}$$



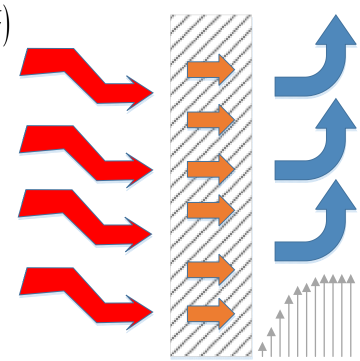
Heat Transfer – Modes of heat transfer

Convection

- Equation of change for internal energy – includes convective effect

$$\frac{\partial}{\partial t}\left(\rho\hat{U}\right) = -\left(\nabla\cdot\rho\hat{U}\bar{\mathbf{v}}\right) - \left(\nabla\cdot\bar{\mathbf{q}}\right) - p\left(\nabla\cdot\bar{\mathbf{v}}\right) - \left(\bar{\bar{\boldsymbol{\tau}}}:\nabla\bar{\mathbf{v}}\right)$$

- Include terms for…
  - Convective transport
  - Conductive energy transfer
  - Reversible energy transformation from compression effects
  - Irreversible energy transformation from viscous effects



Heat Transfer – Modes of heat transfer

Boundary conditions to relate flow of heat to/from fluid from the heat transfer surface

Convection

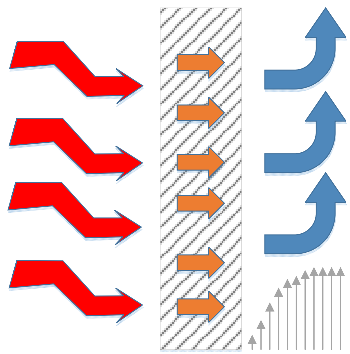
- Flow of heat associated with fluid movement – natural & forced convection

$$\frac{\dot{Q}}{A} = h\left(T_{hot} - T_{cold}\right)$$

Radiation

- Heat transferred via electromagnetic radiation

$$\frac{\dot{Q}}{A} = \varepsilon\sigma\left(T_{hot}^4 - T_{cold}^4\right) = \left[\varepsilon\sigma\left(T_{hot}^2 + T_{cold}^2\right)\left(T_{hot} + T_{cold}\right)\right]\left(T_{hot} - T_{cold}\right)$$



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Heat Exchangers – Some Basics

Focus is on the system to have heat flow from the hot fluid(s) to the cold fluid(s) usually without direct contact

- Use bulk flow parameters to relate the heat conduction across the flow barrier to the change in energy of the hot & cold fluids
- Account for the series of resistances to heat transfer between the hot & cold fluids

Heat exchangers

- Heat to & from flowing fluids through impermeable barrier(s)
- Driving force for heat through barriers is the temperature difference between the two fluids on opposite sides of the barrier
- Relate the heat effects in the flowing fluids to the change in enthalpy
  - Often this can be related to the difference in the inlet & outlet temperatures for the fluids

$$\dot{Q}_H = \dot{m}_H\left(\hat{H}_{H,in} - \hat{H}_{H,out}\right) \Rightarrow \dot{Q}_H = \dot{m}_H\hat{C}_{p,H}\left(T_{H,in} - T_{H,out}\right) \text{ for constant } \hat{C}_{p,H}$$

$$\dot{Q}_C = \dot{m}_C\left(\hat{H}_{C,out} - \hat{H}_{C,in}\right) \Rightarrow \dot{Q}_C = \dot{m}_C\hat{C}_{p,C}\left(T_{C,out} - T_{C,in}\right) \text{ for constant } \hat{C}_{p,C}$$

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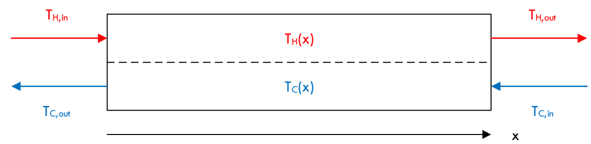
Heat Exchangers – Some Basics

- Relate the heat across the barrier to the temperature difference across the barrier



$$\frac{d(\dot{Q}/L)}{dx} = U\left(T_h - T_c\right) \quad \Rightarrow \quad Q = (UA)\overline{\left[T_h - T_c\right]}_{\text{AREA AVERAGED}}$$

- It can be shown that for many typical configurations the AREA AVERAGED temperature difference is the LMTD (Log Mean Temperature Difference)

$$\dot{Q} = (UA)\overline{(\Delta T)}_{LM} \quad \text{where} \quad \overline{(\Delta T)}_{LM} \equiv \frac{\left(T_{H,0} - T_{C,0}\right) - \left(T_{H,1} - T_{C,1}\right)}{\ln\left(\frac{T_{H,0} - T_{C,0}}{T_{H,1} - T_{C,1}}\right)}$$

Heat Exchangers – Some Basics

LMTD is a prescribed calculation – calculating the LMTD from the procedure is <u>always</u> correct.

$$LMTD = \frac{(\Delta T)_1 - (\Delta T)_2}{\ln\left[\frac{(\Delta T)_1}{(\Delta T)_2}\right]}$$

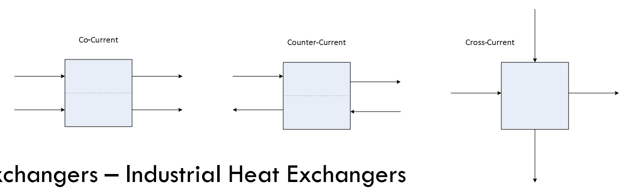
LMTD is appropriate for use as the area averaged temperature difference when temperature vs. heat released/absorbed is a straight line

- 1-1 co-current & counter-current flow and …
- Both hot & cold sides have a constant heat or …
- <u>Only</u> pure component phase change on one side or the other (no subcooling or superheating)

Heat Exchangers – Some Basics

Heat exchanger configurations – Co-Current vs. Counter-Current vs. Cross-Current flows

- Counter-current flow allows the outlet temperatures to approach more closely to the inlet temperature of the other fluid
- Cross-current flow is complicated & requires knowledge of the actual flow patterns



Heat exchangers – Industrial Heat Exchangers

- Industrial heat exchangers have a combination of heat transfer through multiple barriers and a combination of counter-current & co-current flow
  - LMTD must be "corrected" to give the actual area-averaged temperature difference (i.e., driving force)

Heat Exchanger – Example 1

Given the heat exchanger configuration shown

Determine duty & unknown temperature if…

- counter-current flow
- co-current flow

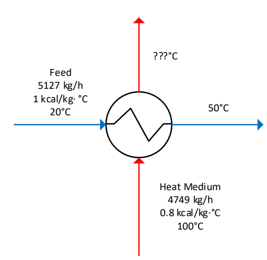
These values do not depend on the flow configuration

Duty from the cold side…

$$\dot{Q} = \dot{m}_C C_{p,C} \left(T_{C,out} - T_{C,in} \right)$$
$$= (5127)(1)(50 - 20) = 153{,}810 \text{ kcal/h}$$

Hot side outlet temperature to close energy balance…

$$\dot{Q} = \dot{m}_H C_{p,H} \left(T_{H,out} - T_{H,in} \right) \quad \Rightarrow \quad T_{H,out} = \frac{\dot{Q}}{\dot{m}_H C_{p,H}} + T_{H,in}$$
$$= \frac{-153810}{(4749)(0.8)} + 100 = 61.9°\text{C}$$



Heat Exchanger – Example 2

Given the heat exchanger configuration shown

Determine

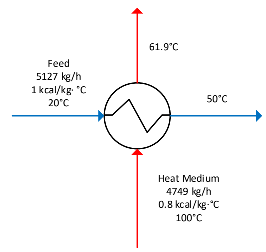
- LMTD if counter-current flow
- LMTD if co-current flow

Counter-current flow

$$LMTD = \frac{(100-50)-(61.9-20)}{\ln\left[\frac{(100-50)}{(61.9-20)}\right]} = 45.8°C$$

Co-current flow

$$LMTD = \frac{(100-20)-(61.9-50)}{\ln\left[\frac{(100-20)}{(61.9-50)}\right]} = 35.7°C$$



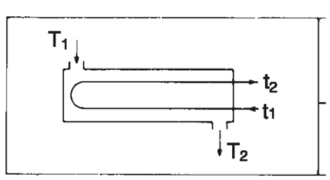
Heat Exchangers – Complicated Flow

Many industrial heat exchangers have complicated flow paths consisting of multiple shell & tube passes

The area-averaged temperature difference has needs to include configuration information

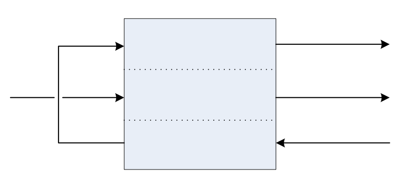
- For example, a 1-2 (1 shell & 2 tube passes) exchanger combines both counter & co-current flow

  The fluid in the shell pass transfers heat separately to the two tube banks



Ref: *GPSA Data Book*, 13th ed.

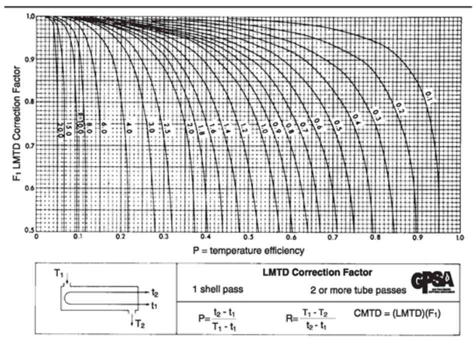
1-2 Co & Counter-Flow



Heat Exchangers – Complicated Flow

- 1-2 exchanger calculations require a configuration correction to relate the area-averaged temperature difference to the LMTD
- Base the LMTD on counter-current flow & apply correction to this

FIG. 9-4
LMTD Correction Factor (1 shell passes; 2 or more tube passes)



$$F_1 = \frac{\sqrt{R^2+1}\,\ln\left[\frac{1-P}{1-RP}\right]}{(R-1)\ln\left[\frac{2-P\left(R+1-\sqrt{R^2+1}\right)}{2-P\left(R+1+\sqrt{R^2+1}\right)}\right]}$$

Ref: Kern, *Process Heat Transfer*, McGraw-Hill, 1965

Ref: *GPSA Data Book*, 13th ed.

Heat Exchanger – Example 2

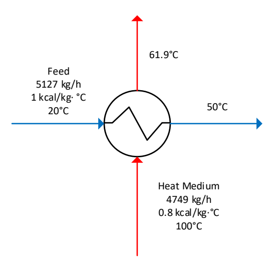
Given the heat exchanger configuration shown as a 1-2 shell & tube exchanger

Determine

- Corrected LMTD if hot stream on the shell side
- Corrected LMTD if cold stream on the shell side

For both cases, LMTD for pure counter-current flow

$$LMTD = \frac{(100-50)-(61.9-20)}{\ln\left[\frac{(100-50)}{(61.9-20)}\right]} = 45.8°C$$



Heat Exchanger – Example 2

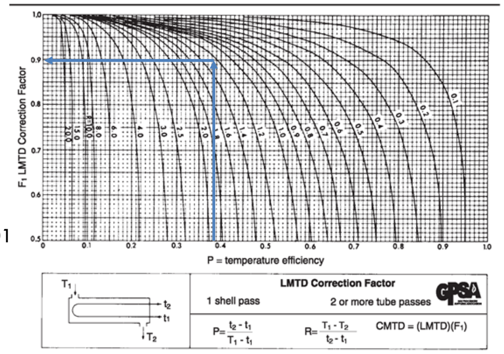
Hot stream on the shell side

$$P=\frac{t_2-t_1}{T_1-t_1}=\frac{50-20}{100-20}=0.375$$

$$R=\frac{T_1-T_2}{t_2-t_1}=\frac{100-61.9}{50-20}=1.27$$

$$F_1=\frac{\sqrt{R^2+1}\ln\left[\frac{1-P}{1-RP}\right]}{(R-1)\ln\left[\frac{2-P\left(R+1-\sqrt{R^2+1}\right)}{2-P\left(R+1+\sqrt{R^2+1}\right)}\right]}=0.901$$

FIG. 9-4
LMTD Correction Factor (1 shell passes; 2 or more tube passes)



Ref: *GPSA Data Book*, 13th ed.

$$CMTD=F\cdot \text{LMTD}=(0.901)(45.8)=41.3°\text{C}$$

Heat Exchanger – Example 2

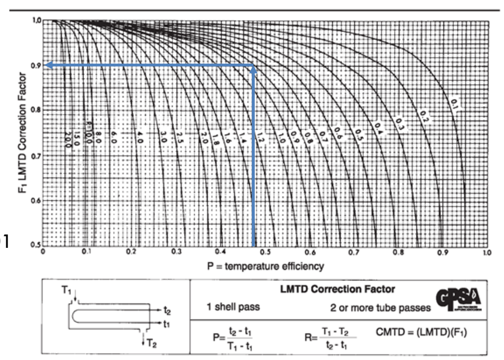
Cold stream on the shell side

$$P=\frac{t_2-t_1}{T_1-t_1}=\frac{61.9-100}{20-100}=0.476$$

$$R=\frac{T_1-T_2}{t_2-t_1}=\frac{20-50}{61.9-100}=0.787$$

$$F_1=\frac{\sqrt{R^2+1}\ln\left[\frac{1-P}{1-RP}\right]}{(R-1)\ln\left[\frac{2-P\left(R+1-\sqrt{R^2+1}\right)}{2-P\left(R+1+\sqrt{R^2+1}\right)}\right]}=0.901$$

FIG. 9-4
LMTD Correction Factor (1 shell passes; 2 or more tube passes)



Ref: *GPSA Data Book*, 13th ed.

$$CMTD=F\cdot \text{LMTD}=(0.901)(45.8)=41.3°\text{C}$$

Heat Transfer – What if there is pure component phase change?

If there is only phase change then the LMTD is still the appropriate area-averaged temperature difference

- If there is superheating and/or subcooling the situation is more complicated

For a pure component only with phase change …

- The temperature will remain constant
- The heat released/absorbed will be related to the enthalpy of phase change at the exchanger conditions (pressure & temperature)

$$\dot{Q}_H = \dot{m}_H \left(\Delta \hat{H}_{vap} \right)$$

- Since the temperature vs. heat released/absorbed curve is a straight line then the LMTD is appropriate for the area-averaged temperature difference

Heat Exchanger – Example 3

This time provide the heat by condensing saturated 50 psig steam (4.46 bar-a, 147.6°C/297.7°F, ΔH_{vap} = 506.63 kcal/kg)

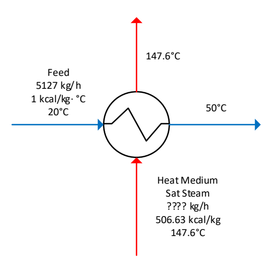
Determine duty, steam flowrate, & LMTD

Duty from the cold side…

$$\dot{Q} = \dot{m}_C C_{p,C} \left(T_{C,out} - T_{C,in} \right)$$
$$= (5127)(1)(50-20) = 153{,}810 \text{ kcal/h}$$

Hot side outlet temperature to close energy balance…

$$\dot{Q} = \dot{m}_H \Delta H_{vap} \quad \Rightarrow \quad \dot{m}_H = \frac{\dot{Q}}{\Delta H_{vap}}$$
$$= \frac{153810}{506.63} = 303.5 \text{ kg/h}$$

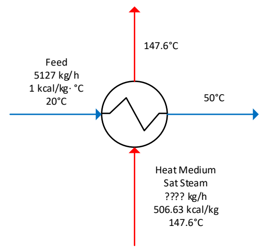


Heat Exchanger – Example 3

LMTD?

- Since the steam has a constant temperature it does not matter whether it is consider co-current or counter-current

$$LMTD = \frac{(147.6-50)-(147.6-20)}{\ln\left[\frac{(147.6-50)}{(147.6-20)}\right]} = 111.9°C$$



Heat Transfer – What if there are coils in a well-mixed tank?

An ideal well-mixed tank has then same temperature at any point in the tank – it is the same as the outlet temperature from the tank

The outside of the coils will experience this single temperature

Since the temperature is constant it will lead to the applicability of the LMTD as the area-averaged temperature difference

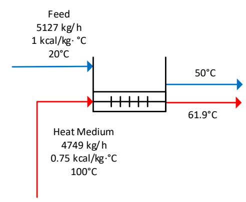
Heat Exchanger – Example 4

Given the heat coil configuration in a well mixed tank

Determine LMTD

- The outside of the coils experience a single temperature, that of the outlet

$$LMTD = \frac{(100-50)-(61.9-50)}{\ln\left[\frac{(100-50)}{(61.9-50)}\right]} = 26.5°C$$



Heat Transfer – Some Basics

Thermal resistances are added when in series

- Can be combined into an overall heat transfer coefficient
- Across a flat plate (i.e., constant cross sectional area)

$$\frac{1}{U} = \frac{1}{h_i} + \frac{L}{k} + \frac{1}{h_o}$$

- For radial heat transfer (e.g., through the wall of a tube) must also take into account the change in area with respect to radius
  - Overall heat transfer coefficient must also be related to a reference area or diameter

$$\frac{1}{U_o A_o} = \frac{1}{h_i A_i} + \frac{L}{k A_{ave}} + \frac{1}{h_o A_o}$$

$$\frac{1}{U_o} = \frac{1}{h_i}\frac{A_o}{A_i} + \frac{L}{k}\frac{A_o}{A_{ave}} + \frac{1}{h_o} = \frac{1}{h_i}\frac{D_o}{D_i} + \frac{2D_o}{k}\ln\left(\frac{D_o}{D_i}\right) + \frac{1}{h_o}$$

Typical Film Coefficients

TABLE 9.2 Individual Heat Transfer Coefficients

Process	Range of values of h ($W\ m^{-2}\ °C^{-1}$)	($Btu\ h^{-1}\ ft^{-2}\ °F^{-1}$)
Forced convection		
Heating or cooling air	10–500	2–100
Heating or cooling water	100–20,000	20–4000
Heating or cooling oil	60–2000	10–400
Boiling water flowing		
In a tube	5000–100,000	880–17,600
In a tank	2500–35,000	440–6200
Condensing steam, 1 atm		
On vertical surfaces	4000–11,300	700–2000
Outside horizontal tubes	9500–25,000	1700–4400
Condensing organic vapour	1100–2200	200–400
Superheating steam	30–110	5–20

Note: To convert from $W\ m^{-2}\ °C^{-1}$ to $Btu\ h^{-1}\ ft^{-2}\ °F^{-1}$, multiply by 0.176.
Data from L.C. Thomas, 1992, Heat Transfer, *Prentice Hall, Upper Saddle River, NJ.; J.P. Holman, 1997,* Heat Transfer, *8th ed., McGraw-Hill, New York; and W.H. McAdams, 1954,* Heat Transmission, *3rd ed., McGraw-Hill, New York.*

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Heat Transfer – Correlations for Film Coefficients

Flow in tubes with no phase change

$$N_{Nu} = 0.023\, N_{Re}^{0.8}\, N_{Pr}^{0.4} \quad \Rightarrow \quad \left(\frac{hD}{k}\right) = 0.023 \left(\frac{D\, v\, \rho}{\mu}\right)^{0.8} \left(\frac{C_p\, \mu}{k}\right)^{0.4}$$

When there is a significant difference between wall & bulk fluid

$$N_{Nu} = 0.023\, N_{Re}^{0.8}\, N_{Pr}^{0.33} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad \Rightarrow \quad \left(\frac{hD}{k}\right) = 0.023 \left(\frac{D\, v\, \rho}{\mu}\right)^{0.8} \left(\frac{C_p\, \mu}{k}\right)^{0.33} \left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

Stirred liquids, heat transfer from coil …

$$N_{Nu} = 0.9\, N_{Re,i}^{0.62}\, N_{Pr}^{0.33} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad \Rightarrow \quad \left(\frac{hD}{k}\right) = 0.9 \left(\frac{N_i\, D_i^2\, \rho}{\mu}\right)^{0.62} \left(\frac{C_p\, \mu}{k}\right)^{0.33} \left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

… from tank jacket

$$N_{Nu} = 0.36\, N_{Re,i}^{0.66}\, N_{Pr}^{0.33} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad \Rightarrow \quad \left(\frac{hD}{k}\right) = 0.36 \left(\frac{N_i\, D_i^2\, \rho}{\mu}\right)^{0.67} \left(\frac{C_p\, \mu}{k}\right)^{0.33} \left(\frac{\mu_b}{\mu_w}\right)^{0.14}$$

Heat Transfer – What if we have fouling of the heat transfer surface(s)?

Add fouling into the sum of thermal resistances

- Across a flat plate (i.e., constant cross sectional area)

$$\frac{1}{U}=\frac{1}{h_i}+\frac{L}{k}+\frac{1}{h_o}+R_{f,i}+R_{f,o}=\frac{1}{h_i}+\frac{L}{k}+\frac{1}{h_o}+\frac{1}{h_{f,i}}+\frac{1}{h_{f,o}}$$

- Over a radial tube

$$\frac{1}{U_o}=\frac{1}{h_i}\frac{D_o}{D_i}+\frac{2D_o}{k}\ln\left(\frac{D_o}{D_i}\right)+\frac{1}{h_o}+\frac{1}{h_{f,i}}\frac{D_o}{D_i}+\frac{1}{h_{f,o}}$$

Typical Fouling Coefficients

TABLE 9.3 Fouling Factors for Scale Deposits

Source of deposit	Fouling factor $(W\ m^{-2}\ {}^\circ C^{-1})$	Fouling factor $(Btu\ h^{-1}\ ft^{-2}\ {}^\circ F^{-1})$
Water (temperatures up to 52°C, velocities over 1 m s^{-1})		
River water	2800	500
City or well water	5700	1000
Hard water	1900	330
Brackish water	5700	1000
Untreated cooling tower water	1900	330
Seawater	11,400	2000
Steam		
Good quality, oil free	11,400	2000
Liquids		
Industrial organic	5700	1000
Caustic solutions	2800	500
Vegetable oil	1900	330
Fuel oil	1100	200
Gases		
Compressed air	2800	500
Solvent vapour	5700	1000

Note: To convert from $W\ m^{-2}\ {}^\circ C^{-1}$ to $Btu\ h^{-1}\ ft^{-2}\ {}^\circ F^{-1}$, multiply by 0.176.
Data from A.C. Mueller, 1985, Process heat exchangers. In: Handbook of Heat Transfer Applications, *2nd ed., W.M. Rohsenow, J.P. Hartnett, and E.N. Ganic (Eds.), pp. 4-78–4-173, McGraw-Hill, New York.*

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Heat Exchanger Design

Combine process considerations (flow rates, temperatures, properties of fluids) with the configuration to obtain the area-averaged temperature difference (usually the LMTD)

Determine the required UA

$$\dot{Q} = (UA)\overline{(\Delta T)}_{LM} \quad \Rightarrow \quad UA = \frac{\dot{Q}}{\overline{(\Delta T)}_{LM}}$$

Determine the overall heat transfer coefficient & determine the required area

- Heat transfer area usually associated with the bare outside area of the tubes

Heat Exchanger – Example 5

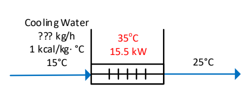
Given a batch fermenter @ 35°C that is generating 15.5 kW heat to be removed by cooling water (15°C heated to 25°C)

The overall heat transfer coefficient is 340 W/m^2K.

Determine…

- LMTD?
- How much heat transfer area is needed?
- What length of 4 cm diameter stainless steel pipe is needed to provide this area?

$$LMTD = \frac{(35-15)-(35-25)}{\ln\left[\frac{(35-15)}{(35-25)}\right]} = 14.4°C$$



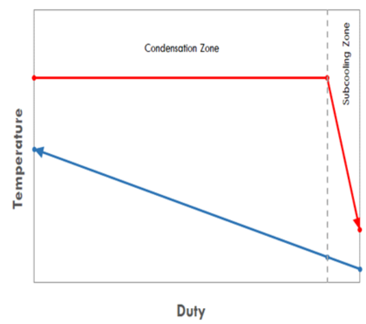
$$\dot{Q} = (UA)\overline{(\Delta T)}_{LM} \quad \Rightarrow \quad A = \frac{15500}{(340)(14.4)} = 3.16 \text{ m}^2$$

$$A = \pi D L \quad \Rightarrow L = \frac{A}{\pi D} = \frac{3.16}{\pi(0.04)} = 25.1 \text{ m}$$

Heat Exchangers – What if there is phase change and sensible heat change?

Superheating and/or subcooling with phase change gives a complicated heat exchange situation & LMTD is no longer the applicable area-averaged temperature difference

- Each zone will generally have different film coefficients, leading to different overall heat transfer coefficients
- Best to treat as sequential heat exchangers

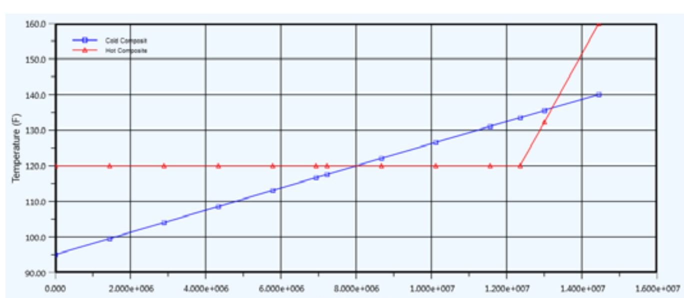


Heat Exchangers – What if there is phase change and sensible heat change?

Bigger issue if there is superheated vapor followed by condensation

Internal "pinch point" will limit the ΔT driving force

- May even have a "cross over" – design will not work as intended!



Summary

Analysis of heat exchangers builds on the understanding of the basics of heat transfer by conduction, convection, and/or radiation

Different configurations will lead to different area-averaged temperature differences, leading to different required heat transfer areas

- Typically the LMTD

Stirred vessels will have a single temperature against the heat transfer area

Supplemental Slides

Updated: November 13, 2017
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Typical Tank Heating Configurations

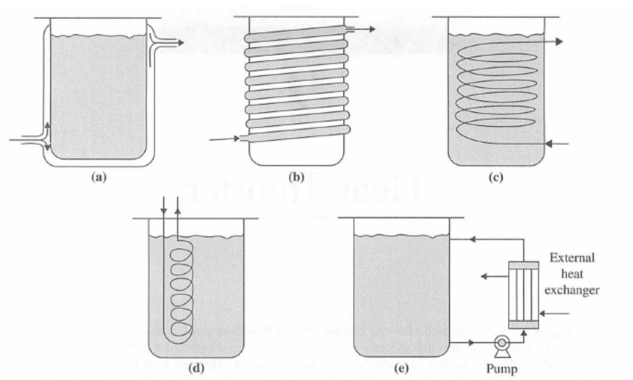

FIGURE 9.1 Heat transfer configurations for bioreactors: (a) jacketed vessel; (b) external coil; (c) internal helical coil; (d) internal baffle-type coil; (e) external heat exchanger.

Bioprocess Engineering Principles, 2nd ed
Pauline Doran, Elsevier Science & Technology

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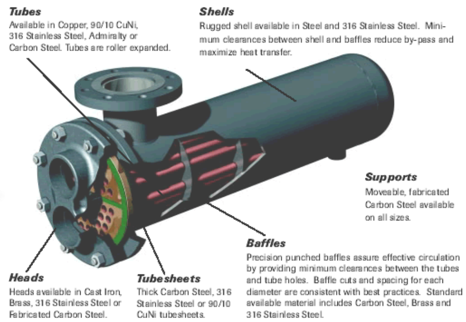
Shell & Tube Heat Exchangers



http://www.apiheattransfer.com/Product/54/Type-ST-U-Tube-Shell-Tube-Heat-Exchangers

Shell & Tube Heat Exchangers

Shell side

- Baffles used in the shell side to minimize channeling

Tube side

- Manifolds allow for even distribution of fluids into the tubes & collection/mixing of fluids out of the tubes
- Multiple tube passes make it easier to pull the tube bundle for maintenance/cleaning and…
- … have better allowance for thermal expansion effects

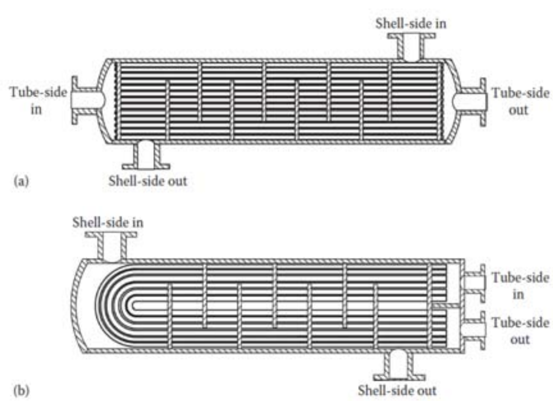
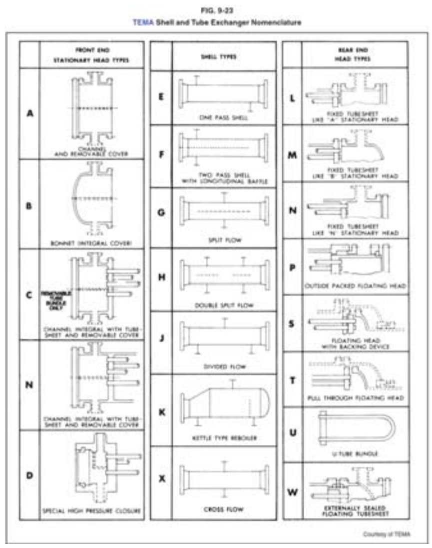


Fig. 3.6, *Fundamentals of Natural Gas Processing*, 2nd ed., Kidnay, Parrish, & McCartney, 2011

Shell and Tube Heat Exchangers (Types)



Ref: *GPSA Data Book*, 13th ed.

Kettle Reboiler

Shell & tube heat exchanger with the tubes submerged in boiling liquid on the shell side

- Main resistance to heat transfer is on the tube side since boiling is occurring on the shell side

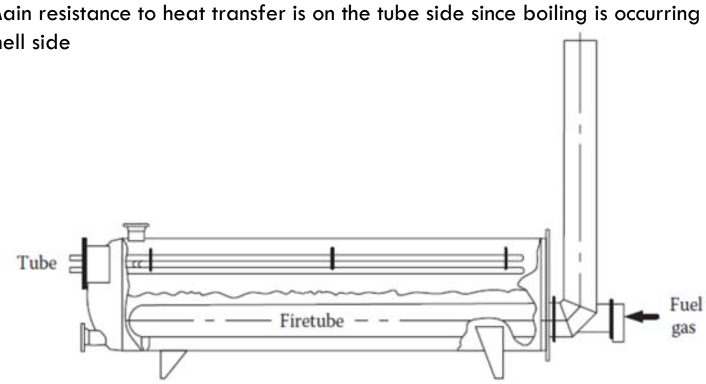


Fig. 3.7, *Fundamentals of Natural Gas Processing*, 2nd ed., Kidnay, Parrish, & McCartney, 2011

Air Cooled Heat Exchangers

Fans either push air through (forced draft) or pull air through (induced draft) tube bundle

- Can control the air flow rate either with a variable speed motor or with louviers

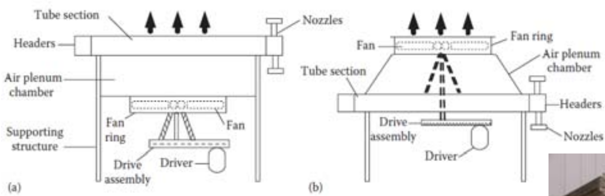


Fig. 3.8, *Fundamentals of Natural Gas Processing*, 2nd ed., Kidnay, Parrish, & McCartney, 2011

http://spxcooling.com/products/detail/air-cooled-heat-exchangers

Plate Frame Heat Exchangers

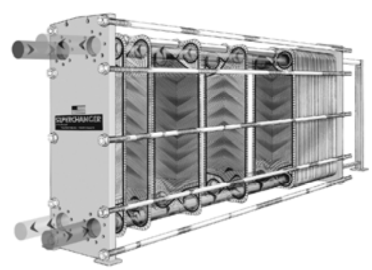


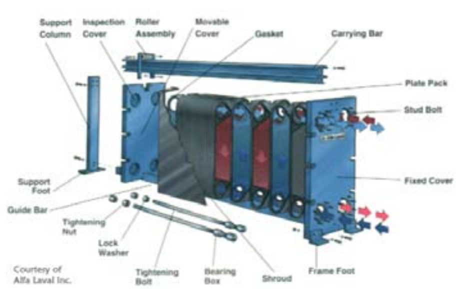
Fig. 3.9, *Fundamentals of Natural Gas Processing*, 2nd ed., Kidnay, Parrish, & McCartney, 2011

Positives

- Low cost
- Compact – high area per weight & volume
- Can get very close approach temperatures (5°F or lower)
- Can be disassembled to clean

Negative considerations

- Limited maximum allowable working pressure
- Susceptible to plugging

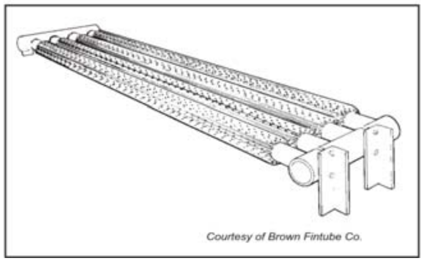


http://www.cheresources.com/content/articles/heat-transfer/plate-heat-exchangers-preliminary-design

Tank Heaters

Integrated into existing equipment (i.e., tanks or vessels)

FIG. 9-32
Prefabricated Tank Heater



https://www.chromalox.com/en/global/case-studies/pocket-heater-reduces-costs-and-downtime

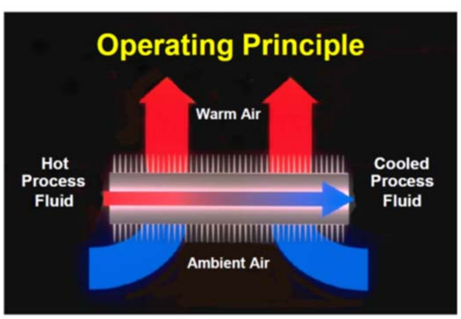
Ref: *GPSA Data Book*, 13th ed.

Air-Cooled Exchangers – Fundamentals

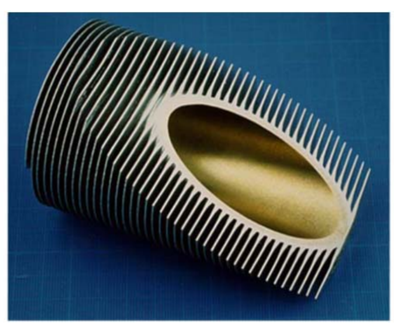
Air cooled exchangers cool fluids with ambient air

- Seasonal variation can greatly impact performance

Utilize finned tube in increase heat transfer surface area



www.hudsonproducts.com



www.hudsonproducts.com

Air-Cooled Exchangers – Types

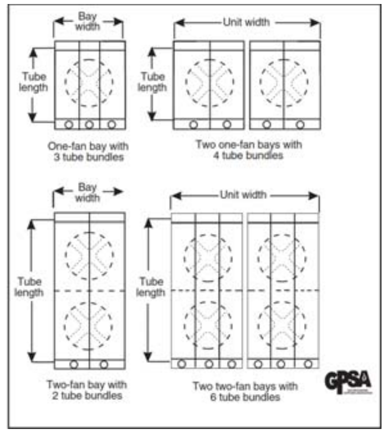
Horizontal air-cooled exchangers

- One or more tube sections served by one or more axial flow fans
- An enclosing / supporting structure.

Classified as forced draft or induced draft depending on the tube/fam location

EDB Pgs 10-2 to 10-4

- Basic design considerations
- Layout of tubes / fans
  EDB Fig 10-3 →
- Typical tube and fan sizes / selection
- Header design **EDB Fig 10-5**



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Air-Cooled Exchangers – Types

Forced Draft vs. **Induced Draft**

Forced Draft

Advantages:

- Slightly lower horsepower
- Better maintenance accessibility
- Easily adaptable for warm air recirculation
- Most common in gas industry

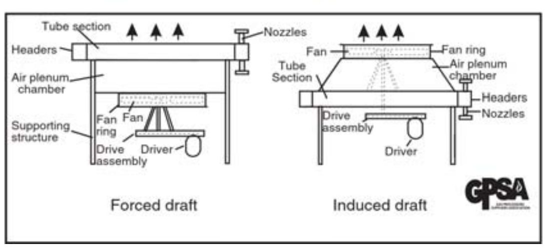
Induced Draft

Advantages

- Better distribution of air
- Less possibility of air recirculation
- Less effect of sun, rain, or hail
- Increased capacity in the event of fan failure

FIG. 10-2

Typical Side Elevations of Air Coolers



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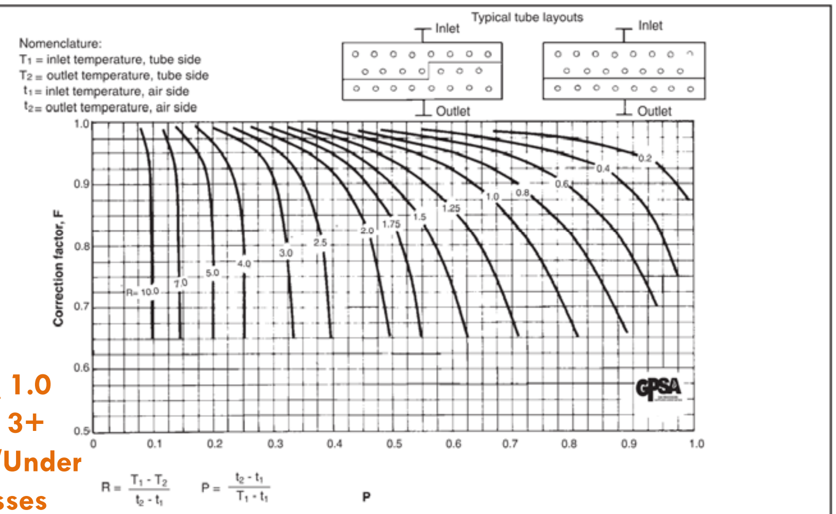
Air-Cooled Exchanger – Thermal Design (Δ Temperature – CMTD Figs 10-8 & 9)

FIG. 10-9
MTD Correction Factors (2 Pass — Cross Flow, Both Fluids Unmixed)



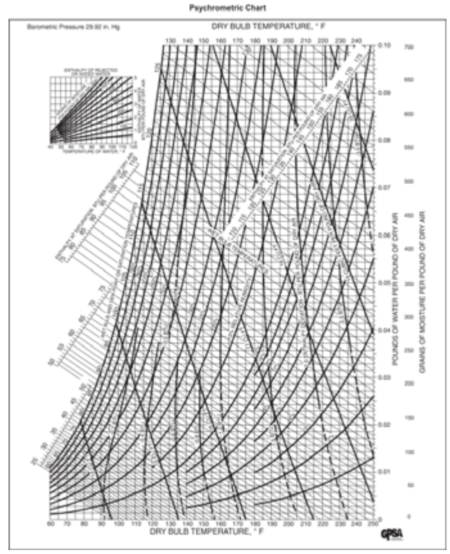
F $\simeq$ 1.0 for 3+ Over/Under Passes

Cooling Tower Principles

Evaporative cooling (Psychrometry)

- Dry Bulb versus Wet Bulb Temperature
  - Contact dry air with water
  - Saturation of air (vaporization of some water) takes energy
  - Air is cooled below ambient – to "Wet Bulb" temperature
- Takes advantage of air below 100% humidity
  - Wet Bulb MUST be lower than Dry Bulb temperature

FIG. 11-2
Psychrometric Chart



Cooling Tower Principles

Evaporative cooling (Psychrometry)

- Wet bulb and dry bulb data for various locations around the world Fig 11-3

FIG. 11-3

Dry Bulb/Wet Bulb Temperature Data for Selected Locations[2]

Meaning of acronyms:
DB: Dry bulb temperature, °F
MCWB: Mean coincident wet bulb temperature, °F
The Dry Bulb and Wet Bulb temperatures which are equalled or exceeded by the given percentage, on average, of the time during the warmest consecutive four months.

Lat: Latitude, °
Long: Longitude, °
MCDB: Mean coincident dry bulb temperature, °F
WB: Wet bulb temperature, °F
Elev: Elevation, ft

Station	Lat	Long	Elev	Cooling DB/MCWB 1% DB	Cooling DB/MCWB 1% MCWB	Cooling DB/MCWB 2% DB	Cooling DB/MCWB 2% MCWB	Evaporation WB/MCDB 0.4% WB	Evaporation WB/MCDB 0.4% MCDB	Evaporation WB/MCDB 1% WB	Evaporation WB/MCDB 1% MCDB
United States of America											
Alabama											
AUBURN OPELIKA ROBE	32.62N	85.43W	778	91.4	74.2	90.2	73.9	78.0	88.4	77.0	87.2
BIRMINGHAM MUNI	33.56N	86.75W	630	93.0	74.5	90.9	74.3	78.4	88.5	77.5	87.6
CAIRNS AAF	31.28N	85.71W	302	94.2	76.5	92.2	76.1	81.1	89.4	79.8	88.3
GADSDEN MUNI	33.97N	86.08W	568	91.3	74.5	90.0	74.3	78.1	89.1	77.1	88.0
HUNTSVILLE/MADISON	34.64N	86.79W	643	92.8	74.6	90.6	74.1	78.4	88.4	77.6	87.6
MAXWELL AFB	32.38N	86.36W	171	95.4	76.6	93.5	76.3	80.6	91.2	79.7	90.2
MOBILE/BATES FIELD	30.69N	88.25W	220	92.0	76.5	90.5	76.1	80.1	88.5	79.1	87.3
MONTGOMERY/DANNELLY	32.30N	86.39W	203	94.5	76.0	92.6	75.7	79.7	90.7	78.6	89.2
TUSCALOOSA RGNL	33.21N	87.62W	187	94.3	75.9	92.3	75.6	79.5	90.8	78.5	89.3
Alaska											
FAIRBANKS INTL ARPT	64.82N	147.86W	453	78.3	60.0	74.8	58.6	63.2	76.9	61.6	74.2
FT. RICHARDSON/BRYA	61.27N	149.65W	377	71.6	58.9	68.3	57.1	61.7	72.7	59.6	69.5

Example:

How cold can you get?

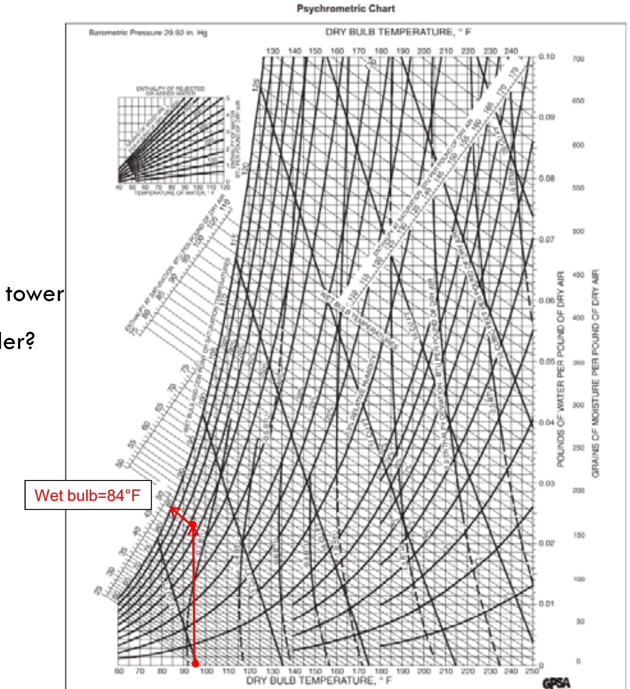
Air temperature: 95° F

RH = 65%

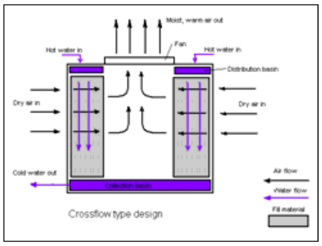
Temperature with cooling tower

Temperature with air cooler?

FIG. 11-2
Psychrometric Chart



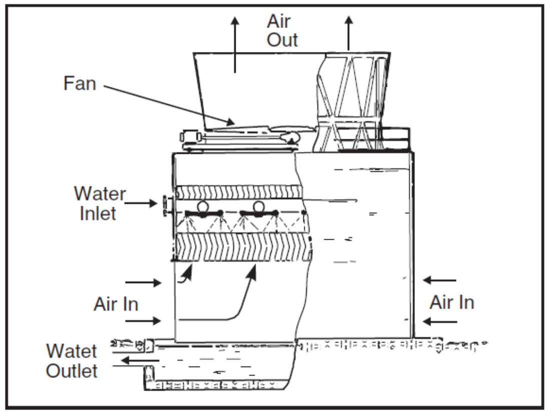
Cooling Towers – Mechanical Induced Draft



www.iklimnet.com

www.rjdesjardins.com

FIG. 11-7
Mechanical Induced Draft Counterflow Tower



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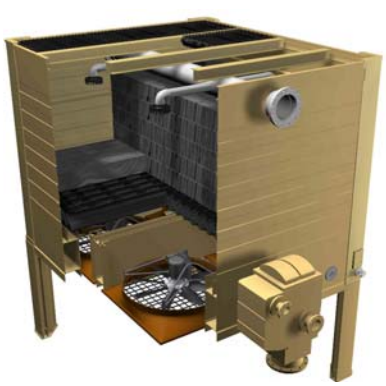
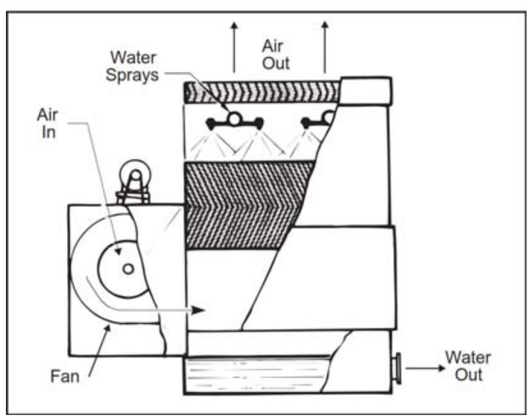
Cooling Towers – Mechanical Forced Draft



Towertechinc.com

FIG. 11-6
Mechanical Forced Draft Counterflow Tower



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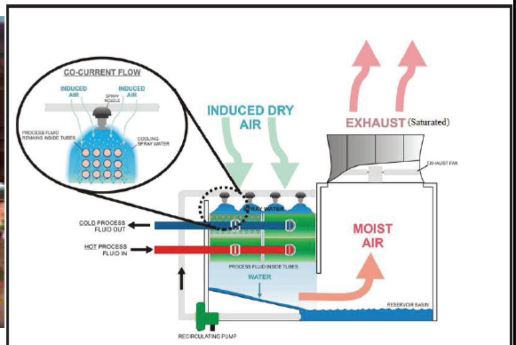
Cooling Towers – Wet Surface Air Cooler

www.niagarablower.com

FIG. 11-12

Wet Surface Air Cooler



Courtesy of Niagara Blower

Heat Exchanger – Example S-1

Exchanger duty & hot fluid outlet temperature determined from energy balance around exchanger

$$Q = \dot{m}_c \hat{C}_{p,c} \left(T_{c,out} - T_{c,in} \right) = (291800)(0.704)(145 - 80) = 13{,}353{,}000 \text{ Btu/hr}$$

$$T_{h,out} = T_{h,in} - \frac{Q}{\dot{m}_h \hat{C}_{p,h}} = 240 - \frac{13353000}{(191600)(0.828)} = 155.8°\text{F}$$

Determination of UA requires configuration information

- 1-1 counter-current flow

$$(\Delta T)_{LMTD} = \frac{(240-145)-(155.8-80)}{\ln\left(\frac{240-145}{155.8-80}\right)} = 85.1°\text{F}$$

$$UA = \frac{Q}{(\Delta T)_{LMTD}} = \frac{13353000}{85.1} = 157{,}000 \frac{\text{Btu}}{\text{hr°F}}$$

1-1 co-current flow

$$(\Delta T)_{LMTD} = \frac{(240-80)-(155.8-145)}{\ln\left(\frac{240-80}{207.7-105}\right)} = 55.4°\text{F}$$

$$UA = \frac{Q}{(\Delta T)_{LMTD}} = \frac{13353000}{55.4} = 241{,}000 \frac{\text{Btu}}{\text{hr°F}}$$

Heat Exchanger – Example S-1

- 1-2 exchanger

$$(\Delta T)_{LMTD} = \frac{(240-145)-(155.8-80)}{\ln\left(\frac{240-145}{155.8-80}\right)} = 85.1°F$$

$$P = \frac{145-80}{240-80} = 0.4$$

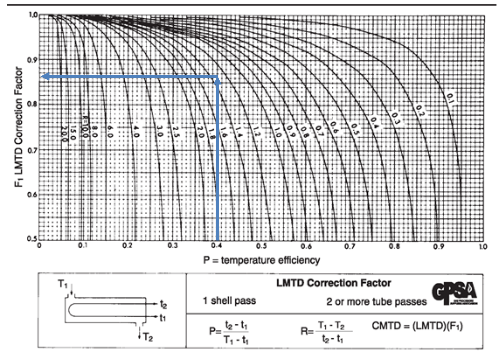
$$R = \frac{240-155.8}{145-80} = 1.3$$

$$F_2 = 0.86 \text{ (from chart)}$$

$$UA = \frac{Q}{F_2(\Delta T)_{LMTD}}$$

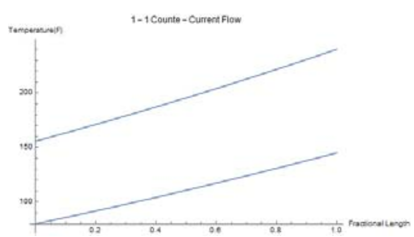
$$= \frac{13353000}{0.86(85.1)} = 182,500 \frac{\text{Btu}}{\text{hr°F}}$$

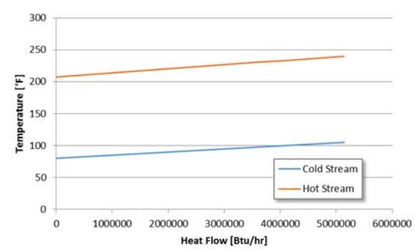
FIG. 9-4
LMTD Correction Factor (1 shell passes; 2 or more tube passes)

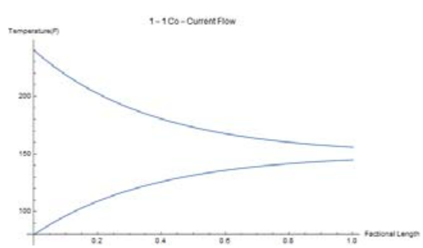


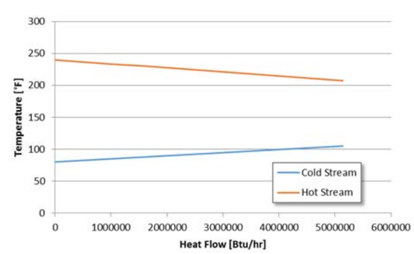
Ref: *GPSA Data Book*, 13th ed.

Heat Exchanger – Example S-1









Heat Exchanger – Example S-1

Representation of temperature profiles with combined flow becomes more complicated.