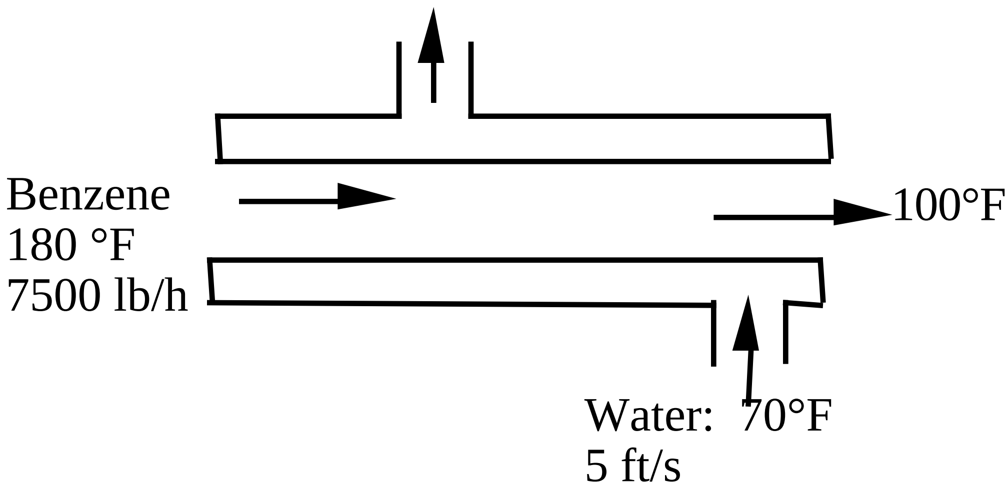
Design of a Parallel Tube Heat Exchanger

The Exchanger



The Design Equation for a Heat Exchanger

$$Q_H = UA\frac{(\Delta T_2 - \Delta T_1)}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} = UA\Delta T_{lm}$$

Problem

Find the Required Length of a Heat Exchanger with Specified Flows: Turbulent Flow in Both Streams

The design constraints are given in the schematic above. We show this as a countercurrent configuration, but we will examine the cocurrent case as well. The benzene flow is specified as a mass flow rate (in pound *mass* units), and the water flow is given as a linear velocity. Heat transfer coefficients are not provided; we will have to calculate them based on our earlier discussions and the correlations presented in earlier lectures.
The inside tube is specified as "Schedule 40—1-14 inch steel."

Pipe "schedules" are simply agreed-upon standards for pipe construction that specify the wall thickness of the pipe. Perry's Handbook specifies the following dimensions for

the inside pipe :
Schedule 40 1 1/4" pipe
D_o = 1.66 in. = 0.138 ft. $S_c = \pi D^2/4 = 0.0104\ ft^2$
D_i = 1.38 in = 0.115 ft. (cross-sectional area for flow)
the outside pipe :
Schedule 40 2" pipe
D_i = 2.07 in = 0.115 ft.

To calculate the heat exchanger area, we must find $A_o = \pi DL$. We know the diameter; what is the length ?

The Design Equation is

$$Q_h = U_o A_o \Delta T_{ln}$$

The overall heat transfer coefficient, U_o, is given by

$$U_o = \frac{1}{r_o}\left[\frac{1}{r_o h_o} + \frac{\ln r_o / r_i}{k} + \frac{1}{r_{ih_i}}\right]^{-1}$$

We can write it as:

$$U_o \frac{A_o}{L} = \left[\frac{1}{h_o\left(A_{o/L}\right)} + \frac{\ln r_o / r_i}{2\pi k} + \frac{1}{h_i\left(A_i / L\right)}\right]^{-1} = \left(\Sigma R\right)^{-1}$$

To evaluate the parameters of the problem, we need the physical and thermal properties and conditions for flow in the system

$T_b = 140^\circ F$ $\rho_b = 52.3\ lb_m/ft^3$ $C_p = 0.45\ BTU/lb\text{-}^\circ F$

$k_b = 0.085\ Btu / h \cdot ft \cdot {}^\circ F$ $Pr = \frac{C_{pb}\mu}{k_b} = 5$

$$\mu_b = 0.39\ cP = \frac{0.39}{1000}\frac{1}{47.88} = 8.1 \times 10^{-6} lb_f \cdot s / ft^2$$
$$= 2.6 \times 10^4 lb_m/ft\cdot s$$

Internal Film Resistance

The Nusselt number on the inside of the inner pipe is given by the Dittus-Boelter equation.

$$Nu = \frac{h_i D_i}{k_b} = 0.023\, Re^{0.8} Pr^{0.3} = 337$$

so that the film heat transfer coefficient

$$h_i = 249 \text{ Btu/h}\cdot\text{ft}^2\cdot{}^\circ\text{F}$$

The heat transfer area per unit length is

$$\frac{A_i}{L} = \pi(0.115) = 0.361 \text{ ft}^2/\text{ft}$$

so that the inner film resistance is :

$$\left(h_i \frac{A_i}{L}\right)^{-1} = \left[249\,(0.361)\right]^{-1} = 0.011 \text{ h}\cdot\text{ft}\cdot{}^\circ\text{F / Btu}$$

The other tube dimensions are

$$D_{oi} = 0.138 \text{ ft} \quad \text{and} \quad D_{io} = 0.172 \text{ ft}$$

Calculation of the Water Flow Rate

The hydraulic diameter is

$$D_{eq} = 4\frac{\pi\left(D^2_{i,o} - D^2_{o,i}\right)/4}{\pi\left(D_{i,o} + D_{o,i}\right)} = D_{i,o} - D_{o,i} = 0.034 \text{ ft}$$

Given the water velocity of 5 ft/s, we can solve for the water flow rate

$$W_{water} = 9300 \text{ lb}_m\text{/h}$$

The Overall Energy balance

$$(wC_p\,\Delta T)_{benz} = (wC_p\Delta T)_{water}$$

Solving for the outlet water temperature:

$$7500\,(0.45)\,(100 - 180) = 9300\,(1)\,(70 - T_{out})$$

gives the exit temperature as:

$$T_{out} = 99^\circ\text{F}$$

External Film Resistance

The physical properties of the water must be estimated in order to determine the film heat transfer coefficient in the annular shell. The average water temperature T_b is calculated as 84.7 °F

μ = 0.8 cp   k = 0.34 BTU/h-ft-°F ρ = 62.4lb/ft³

so that the Reynolds number can be calculated.

$$Re \equiv \frac{\rho V D_{eq}}{\mu} = \frac{\dfrac{62.4\ lb_m/ft^3}{32.2\ lb_m \cdot f/lb_f \cdot s^2}(5\ ft/s)\ 0.034\ ft}{1.67\ x\ 10^{-5} lb_f \cdot s/ft^2} = 2\ x\ 10^4$$

From the Dittus-Boelter equation, the Nusselt number is given as:

$$Nu = 0.023\ Re^{0.8} Pr^{0.4} = 127$$

so that the external film coefficient, h_o , is

$$h_o = 1270\ Btu/h \cdot ft^2 \cdot {}^\circ F$$

The external area/length is

$$\frac{A_0}{L} = \pi(0.138) = 0.434\ ft^2/ft$$

so that the external film resistance is

$$\left(h_0 \frac{A_0}{L}\right)^{-1} = \left[1270\ (0.434)\right]^{-1} = 0.00181 \cdot hft \cdot {}^\circ F/\ Btu$$

Conduction Resistance

The last term in the equation for the overall heat transfer coefficient is

$$\frac{\ln r_0 / r_i}{2\pi k} = 0.00116\ h \cdot ft \cdot {}^\circ F / Btu$$

Overall Heat Transfer Coefficient

The overall resistance is

$$(UA)^{-1} = \Sigma R = \underset{benzene}{0.011} + \underset{wall}{0.00116} + \underset{water}{0.00181} + = 0.014$$

Log-Mean ΔT

$$\Delta T_{ln} = \frac{(180 - 99) - (100 - 70)}{\ln (81 / 30)} = 51°F$$

Heat Load

$Q_h = wC_p\Delta T$

$= 7500\ (0.45)\ (180 - 100) = 2.7 \times 10^5$ Btu/h

Heating Rate/unit Length

$$\frac{Q_h}{L} = \frac{UA}{L}\Delta T_{ln} = (\Sigma R)^{-1}\Delta T_{ln} = 3640 \text{ Btu / h} \cdot \text{ft}$$

Given the heat load, we can calculate the length of tubing so that

$$L = \frac{Q_h}{3640} = \frac{2.7 \times 10^5}{3640} = 74 \text{ ft}$$

The case we considered was countercurrent flow, but we noted in an earlier example that in co-current flow we could be more fluid. Now is the pipe longer or shorter ?

A Co-current Flow Heat Exchanger

The Design Equation for a Heat Exchanger

$$Q_H = UA\frac{\left(\Delta T_2 - \Delta T_1\right)}{\ln\left(\frac{\Delta T_2}{\Delta T_1}\right)} = UA\Delta T_{lm}$$

The heat loads are identical, the Overall Resistances to heat transfer $(UA)^{-1}$ are no different since the film coefficients do not change, but the ΔT_{lm} are different.

Counter current	Co-current
T_1 (water) = 99	T_1 (water) = 70
T_1 (benzene) = 180	T_1 (benzene) = 180
T_2 (water) = 70	T_2 (water) = 99
T_2 (benzene) = 100	T_2 (benzene) = 100
ΔT_1 = 81	ΔT_1 = 110
ΔT_2 = 30	ΔT_2 = 1
ΔT_{ln} = 51	ΔT_{ln} = 23.2
L = 74	L = 163 ft

There are two observations to be made. First that the tube length required for co-current flow is more than twice as long. Secondly that the approach temperature for co-current flow becomes diminishingly small.

Questions

Question 1.
To have a single concentric pipe heat exchanger 73 ft. long may be impractical. Why ?

Question 2.
What are the alternatives and can you make a rapid evaluation of the their requirements ?

Question 3.
What if we use more tubes, do I need more area ? How do I estimate the number of tubes and the required area for a single pass heat exchanger.

Question 4.
If we use more tubes, should we specify the tubes to be smaller. Why? How do we estimate the effect ?

Question 1.

To have a single concentric pipe heat exchanger 73 ft. long may be impractical. Why ?

Where do I put a 73 ft. piece of pipe ? Can I fold it up? Can I cut it into shoter pieces and have them in parallel. ?

Question 2.

What are the alternatives and can you make a rapid evaluation of the their requirements ?

One alternative is to cut the pipe into 12 equal length, place them in a header and put a shell around the bundle of tubes.

Question 3.

If we use more tubes, do I need more area ? How do I estimate the number of tubes and the required area for a single pass heat exchanger.

If we use N identical tubes, $Re_{new} = Re_{old}/N$ since

$$Re = \frac{\rho UD}{\mu} = \frac{\rho Q}{4\pi D\mu}$$

From the Dittus-Boelter equation we have

$$Nu = 0.023\, Re^{0.8} Pr^{0.4} = 127$$

The internal film heat tarnsfer coefficient $h_i \sim Q$
If the new flow rate is Q/N then $h_i \sim (1/N_{new})^{0.8}$
So that for 12 identical tubes $h_{inew} = 0.137\, h_{iold}$
The overall resistance is now

$\Sigma R = 0.011/(0.137) + 0.00181 + 0.00116 = 0.0833$

The required length is $L_{new}/L_{old} = R_{new}/ R_{old}/ = 0.0833/0.014 = 5.95$
so that L_{new} is 73(5.95) = 434.2 ft.

Question 4.

If we use more tubes, should we specify the tubes to be smaller. Why?
How do we estimate the effect ?

When we introduced the use of multiple tubes, we decreased the Re to significantly reduce the internal film resistance. We can then use similar arguments in decreasing the tube diameter, but we have the following consequences

1. we reduce the area/length for heat transfer.
2. we increase the Reynolds number and the heat transfer coefficient
3. we increase the pressure drop
4. we make it harder to clean

How do we do evaluate the trade-offs ?