



Designing Shell-and-Tube Exchangers

*Will this exchanger do the duty?
Developing a design envelope.
Choosing the best design.*

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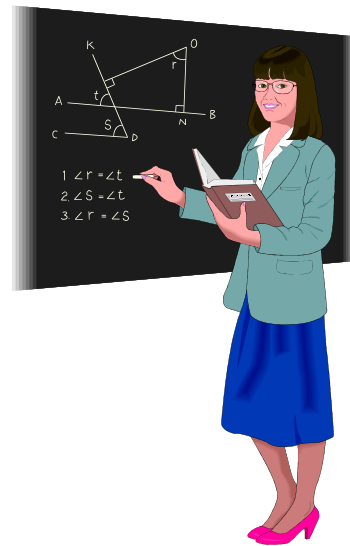
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Lecture series

- Introduction to heat exchangers
- Selection of the best type for a given application
- Selection of right shell and tube
- **Design of shell and tube**



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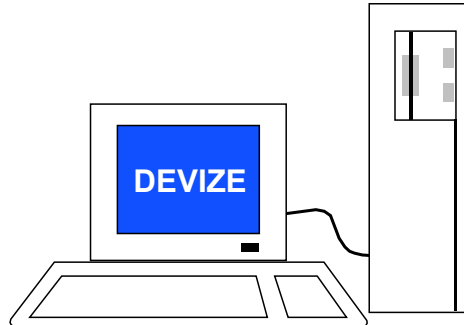
- Overview of design
- Single phase rating methods used in DEVIZE
 - Tube side
 - Shell side
- Design envelope concept in DEVIZE
- Demonstration of DEVIZE

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DEVIZE

- **DE**sign **VI**sualize
- Program which uses visual features to guide you through the design process



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Overall design process

Repeat until satisfied
with design

- Decide fluid allocation (last lecture)
- Decide TEMA type (last lecture)
- Make some guesses about the design
- Generate “design envelope” using DEVIZE
- Do a “rating” using DEVIZE
- Review the envelope and the rating in order to improve your initial guess
- Finally select the best design

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Starting point of rating

We know

- The duty which we need to achieve (i.e. flow rates and temperature changes of the two streams)
- The full exchanger geometry
- The allowable pressure drops for the two streams

We are checking whether that exchanger can do that duty within the imposed constraints

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The thermal rating

- The actual heat transfer area (based on the tube o.d.), A_o is known
- We calculate the required area, A_{req} from

$$A_{req} = \frac{Q}{U_o \Delta T_m}$$

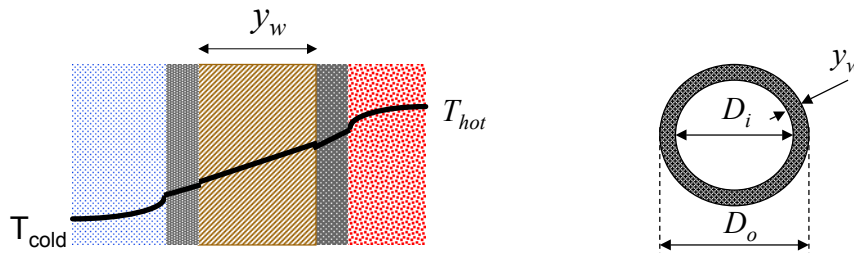
- One output of the thermal rating is the ratio

$$R_A = \frac{A_o}{A_{req}}$$

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Overall coefficient



We have thermal resistances in series

$$\frac{1}{U_o} = \frac{1}{\alpha_i} \frac{D_o}{D_i} + r_i \frac{D_o}{D_i} + \frac{y_w}{\lambda_w} \frac{D_o}{D_w} + r_o + \frac{1}{\alpha_o}$$

$$\text{Where } D_w \approx \frac{1}{2}(D_o + D_i)$$

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Thermal conductivity

Typical values of thermal conductivity

| Material | W/m k |
|------------------|------------|
| Stainless Steel | 15 |
| Copper | 390 |
| Aluminium | 208 |
| Carbon Steel | 50 |
| Gases | 0.02 - 0.3 |
| Liquids | 0.03 - 0.7 |
| Polystyrene foam | 0.003 |
| Pipe Lagging | 0.092 |

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Typical values of stream coefficients

| Fluid | State | htc W/m ² .k |
|---------|-------------------------|-------------------------|
| Water | Single Phase | 5000 - 7500 |
| Water | Boiling <5Bar | 3000 - 10000 |
| Steam | Condensing 1 Bar | 10000 - 15000 |
| Organic | Single Phase 0.5-2.5 cp | 750 -1500 |
| Organic | Boiling 0.5-2.5 cp | 1000 - 3500 |
| Organic | Condensing 0.5-2.5 cp | 1500 - 4000 |
| Gas | 1 Bar | 80 - 125 |
| Gas | 10 Bar | 250 - 400 |

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Typical fouling resistance

| Fluid | State | r (m ² .k/W) |
|---------|-------------------------|-------------------------|
| Water | Single Phase | 0.0001 - 0.00025 |
| Water | Boiling <5Bar | 0.0001 - 0.0002 |
| Steam | Condensing 1 Bar | 0 - 0.0001 |
| Organic | Single Phase 0.5-2.5 cp | 0.0002 - 0.001 |
| Organic | Boiling 0.5-2.5 cp | 0.0001 - 0.0003 |
| Organic | Condensing 0.5-2.5 cp | 0.0001 - 0.0003 |
| Gas | 1 Bar | 0 - 0.0001 |
| Gas | 10 Bar | 0 - 0.0001 |

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Single phase exchangers

- We will now concentrate on a single phase in both streams
- This is a limitation of DEVIZE
- But the principles of the design process are similar for boiling and condensing streams
- In single phase
 - coefficients do not vary much and can be treated as constant
 - and $\Delta T_m = F_T \Delta T_{LM}$

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Tube side heat transfer coefficient

$$Nu = 0.023 Re^{0.8} Pr^{0.4}, Re \geq 8000$$

$$Re < 2000$$

$$Nu = 3.66, Gz \leq 9$$

$$Nu = 1.75 Gz^{1/3}, Gz > 9$$

$$Gz = \frac{\pi}{4} Re Pr \frac{d_i}{L}$$

In the transition region, Nu is calculated from a linear interpolation with Re of the values at Re = 2000 and 8000

Note: wall-to-bulk property variations and natural convection effects are neglected

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Tube side pressure drop

General equation

$$\Delta p = 4f \frac{L \rho u^2}{d_i}$$

Laminar flow

(transition taken as
crossover with
turbulent equation)

$$f = \frac{16}{\text{Re}}, \text{Re} \leq 837$$

Turbulent flow in a
commercial rough
tube

$$f = 0.0035 + \frac{0.264}{\text{Re}^{0.42}}, \text{Re} > 837$$

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Nozzle, tube entry and return losses

$$\Delta p = K \frac{\rho u^2}{2}$$

- K is taken as 1.8 per tube-side pass to allow for tube entry, tube exit and header losses
- 10% of the total pressure drop is assumed to occur in the nozzles

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Shell side - the “Bell Method”

- DEVIZE uses the Bell-Delaware method as set out by Taborek in HEDH
- This method starts with the coefficients and pressure drops for “ideal” cross flow and then corrects these for the non-idealities which occur in real shell-side flows
- The method gives reasonable accuracy while remaining simple
- More accurate proprietary methods have been developed based on network models

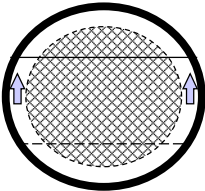
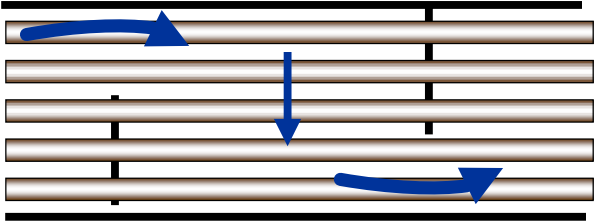
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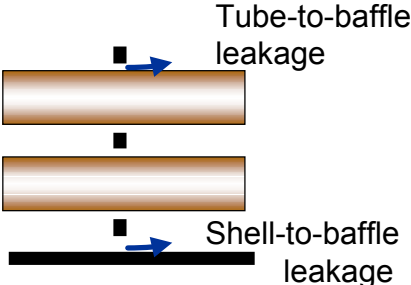
HEDH is the Heat Exchanger Design Handbook available from
Ray Johnson
HEDU office
3 St. Peter’s Street, Wallingford, OX10 0BQ, UK
Tel: +44 (0)1491 834930

Shell-side non-idealities

Window effects



Bypass



Bell method for heat transfer

$$\alpha = \alpha_{Ideal} J_W J_L J_B J_{Lam}$$

Where

J_W corrects for some tubes being in the window

J_L corrects for leakage through and around the baffle

J_B corrects for flow around the bundle

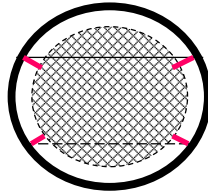
J_{Lam} corrects for special effects which occur at very low Reynolds numbers (not applied in DEVIZE)

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What do the factors depend upon?

- J_w - ratio of tubes in cross flow to tubes in windows
- J_L - ratio of leakage areas to cross-flow area
- J_B - ratio of bypass flow area to cross flow area and the number of pairs of sealing strips

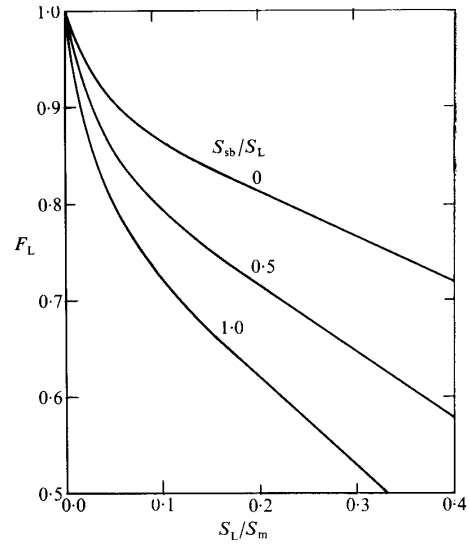
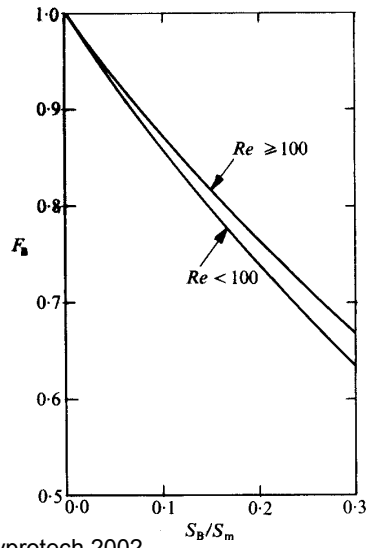


Sealing strips to reduce bypass

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Example correction factor - bypass



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Ideal crossflow coefficient

$$\alpha_{Ideal} = \rho u C_p j \text{Pr}^{-2/3}$$

The j-factor is given as a function of Reynolds number, defined by

$$\text{Re} = \rho u_{min} d_i / \eta$$

Where u_{min} is the velocity calculated at the minimum flow area near the equator of the bundle (assuming no leakage and bypass)

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Shell-side pressure drop and vibration

Pressure drop

The Bell method for pressure drop is similar to that for heat transfer but with some extra complications in the end zones

An additional 10% is assumed for the nozzles

Vibration

DEVIZE uses the methods in ESDU Data Item 87019 for fluid-elastic instability

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London, N1 6UA
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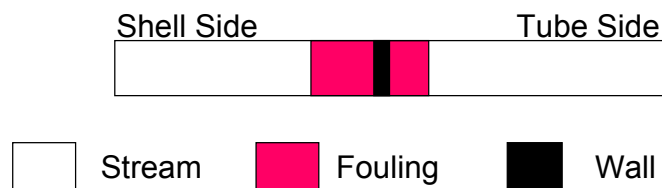
Outputs of rating

- Area ratio (already discussed): $R_A = A_o / A_{req}$
- Pressure drop ratios for the shell side and the tube side: $R_p = \Delta p_{calc} / \Delta p_{spec}$
- Velocity ratio for vibration ratio: $R_v = u / u_{crit}$
- For an acceptable design,
 $R_A > 1, R_{pT} < 1, R_{pS} < 1, R_v < 1$
- The closer these ratios are to 1, the tighter the design (i.e. the lower the safety margins)

Thermal resistance diagram

- Good way of viewing where the main resistances lie and therefore where it is best to make changes to improve the design

$$\frac{1}{U_o} = \frac{1}{\alpha_o} + r_o + \frac{y_w D_o}{\lambda_w D_w} + r_i \frac{D_o}{D_i} + \frac{1}{\alpha_i} \frac{D_o}{D_i}$$



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Heat transfer engineers talk in terms of heat transfer coefficients for streams but thermal resistances for fouling. It is helpful to put this all on the same bases and the best way to do this is in terms of resistances as in the little diagram which is output in a DEVIZE rating. During the design, it is usually best to find ways of lowering the highest resistance.

In addition to showing where the main resistances are, this illustrate the proportion of the heat exchanger surface area required to cope with each resistance. Often, this diagram shows dramatically that a large proportion of the surface area is required to overcome the fouling. In such cases, the choice of fouling resistance should be questioned.

Another useful way of looking at this diagram is that each part is proportional to the temperature difference resulting from the thermal resistance. Hence, the diagram can be used a s quick guide to what the wall temperature is. This may be important if high wall temperatures must be avoided (to prevent scale formation, say).

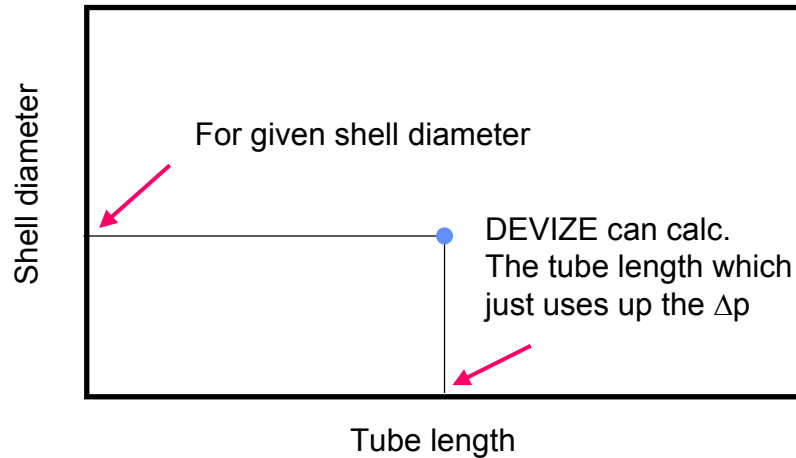
Envelope design concept

- Description of the envelope design concept and the demonstration of DEVIZE
- Starting point is to make guesses about key geometrical features
 - number of passes
 - baffle pitch (say as factor on the shell diameter)
 - baffle cut (say to equalise the cross-flow and window-flow areas)

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Tube side pressure drop



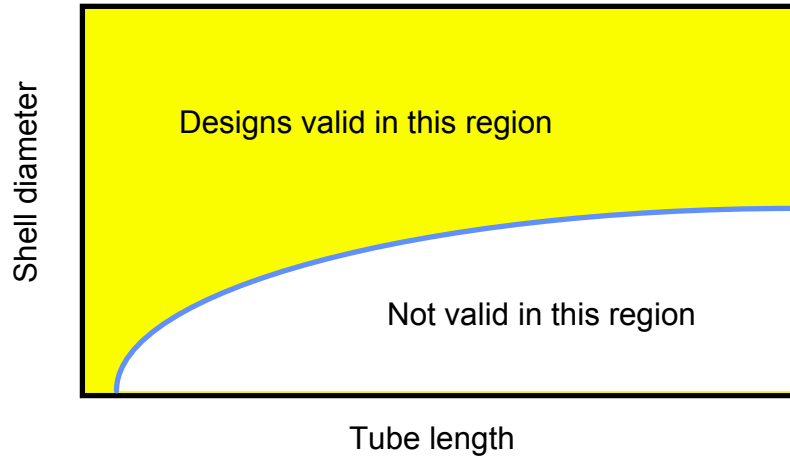
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Take the case of a single pass, as an example, for a known shell diameter we can calculate the number of tubes that fit in the shell. Hence, we can calculate the velocity in the tubes and the pressure gradient along the tubes. From the gradient, we can calculate the exact tube length to just use up the allowable pressure drop.

Tube-side pressure drop limit

Repeating for range of shell diameters gives curve



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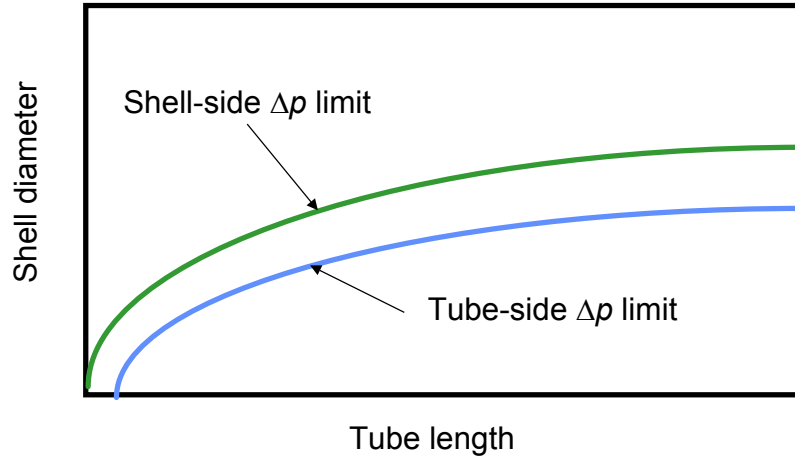
Repeating the calculation for different shell diameters gives the locus shown by the blue curve.

Remember, blue equals tube from now on in this lecture.

The region for valid designs is shown yellow here. This convention is used again later in the lecture but is dropped for the next few slides.

Shell-side pressure drop limit

We can do similar thing for the shell side



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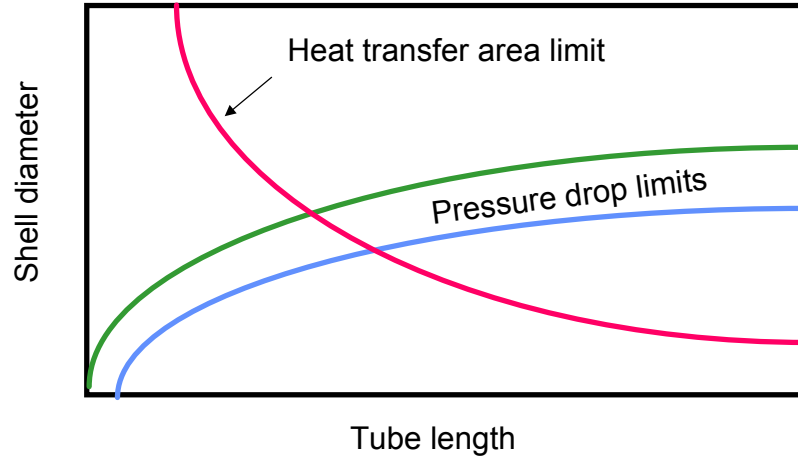
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A similar set of calculations may be done for the shell side pressure drop thus giving the green curve.

Immediately we see that the tube side pressure drop is no longer having an effect on the design in this case. Hence we **might** be able to improve the design by introducing tube side enhancement of increasing the number of tube side passes. We might not for other reasons but these curves are already giving us useful clues for improving the design.

Heat transfer limit

And then for the heat transfer

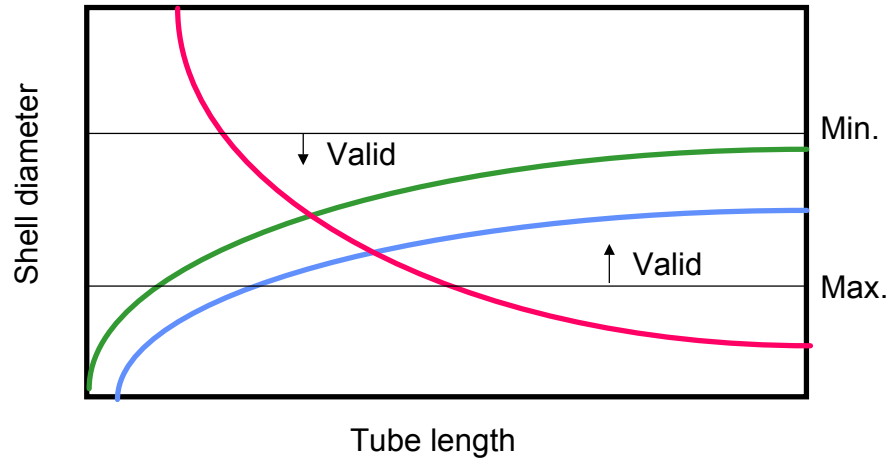


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We can do the same thing for the heat transfer area thus giving the red curve.

Add limits on tube-side velocity

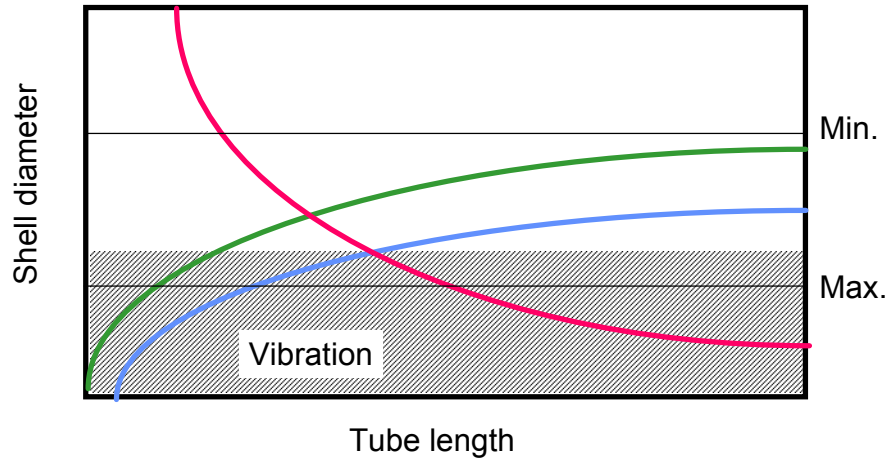


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Often we set limits on the maximum and minimum velocities in the tubes. The minimum may be to avoid fouling while the maximum would be to avoid erosion.

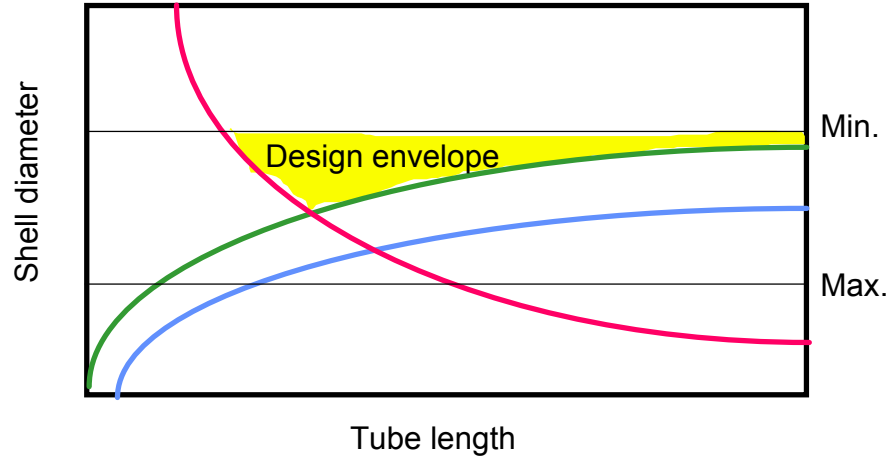
Danger areas for vibration may also be shown



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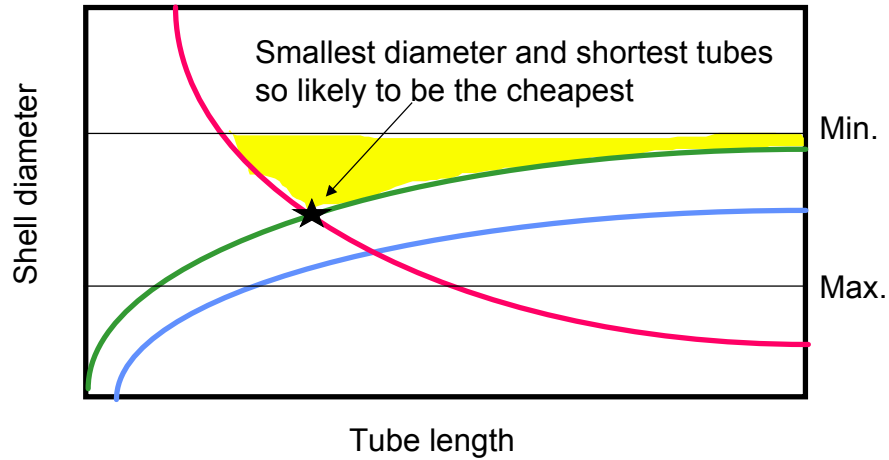
Highlight valid design region



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Rating at optimum point

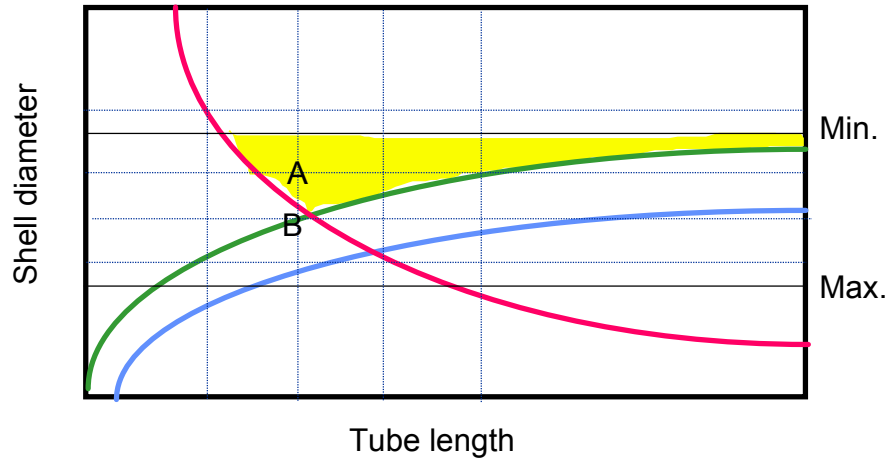


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Doing a rating at this point will generate a resistance diagram which will give more clues on how to improve the design.

Preferred shell diameters and tube lengths



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If you are working with fixed tube lengths and shell diameters, you can introduce the grid of these as shown and select the point closest to the optimum. This is point A but a good designer might think of ways of modifying the design so that point B falls within the yellow area.

Design process

- Start with a set of assumptions about number of passes, baffle configuration, etc.
- Generate envelope
- Change initial assumptions to obtain better envelopes
- Then “*Rate*” good geometries within the best envelopes
- Consider advantages of ratings outside the envelope assuming constraint may be relaxed
- Select the best *Rating*

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Demonstration of DEVIZE



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All this will become clear by using DEVIZE and by producing a demonstration.

There is an article in Chemical Technology Europe, July/August 1996 which takes you through a design example.