458.401 Process & Product Design

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Heuristics ("Rules of Thumb")

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Use of Experienced-Based Principles to:

Check new process designs
Provide equipment size and performance estimates
Help with troubleshooting problems with existing systems
Verify computer simulations and results
Provide initial estimates for simulator inputs
Use as a starting place for initial designs
Develop preliminary process layouts

However, keep in mind that a heuristic:

Doesn't guarantee a solution
May contradict other heuristics
Can reduce the time to solve problems
Depends on the context in which it is used

Examples of Heuristics Usage

What is the density of water in SI units? In English units?

What does a gallon of milk weigh? What about 4 gallons of milk?

What does a cubic meter of air weigh?

The ratio of ρ_L/ρ_v is approximately _____?

Creation of Heuristics / Shortcuts

1. **P**redict. (assumptions, heuristics, back of the envelope calculations)
2. **A**uthenticate/Analyze (equations, simulations, operational data)
3. **R**eevaluate/Rethink (compare, revise)

Example-11.1

Suppose you calculated a turbulent heat transfer coefficient inside a 1.5" pipe as: 5250 W/[m^2·°C], for water at 21°C and a velocity of 1.83 m/s.

Estimate a heat transfer coefficient when the water temperature is 93°C and a velocity of 3.05 m/s.

Solution-11.1

1. **P**redict: assume the velocity and temp. have no effect. Predicted Heat Transfer Coef. = 5250 W/[m²·°C]
2. **A**uthenticate: Find appropriate equation for calculation of Nusselt number.

$$\mathrm{Re} = u\rho D_{pipe}/\mu = (1.83)(997.4)(1.5)(0.0254)/(9.8 \times 10^{-4}) = 71 \times 10^3$$

For highly turbulent flow, use the _____ equation

$$hD/k = (0.023)(Du\rho/\mu)^{0.8}(C_p\mu/k)^{1/3}$$

$$h'/h = (D'/D)^{0.2}(u'/u)^{0.8}(\rho'/\rho)^{0.8}(\mu'/\mu)^{0.47}(C_p'/C_p)^{0.33}(k'/k)^{0.67} \qquad (11.2)$$

$$= (1)(1.50)(0.973)(1.73)(1.00)(1.08) = 2.725$$

$$h' = (2.725)(5250)\ \mathrm{W/m^2{}^\circ C} = 14,300 \mathrm{W/m^2{}^\circ C}$$

Solution-11.1

3. **R**eevaluate/Rethink (compare, revise)

Property	21°C (70°F)	93°C (200°F)	Ratio of (New/Old)
ρ (kg/m³)	997.4	963.2	0.966
k (W/m°C)	0.604	0.678	1.12
C_p (kJ/kg°C)	4.19	4.20	1.00
μ (kg/m/s)	9.8×10^{-4}	3.06×10^{-4}	0.312

- The temperature effect on viscosity must be evaluated.
- The effects of temperature on C_p, ρ, and k are negligible.
- Pipe diameter has a small effect on h (all other things being equal)
- Results are limited to the range where the Sieder-Tate equation is valid

With these assumption, the values for water at 21°C are substituted into Eq. (11.2). This creates a useful heuristic for evaluating the heat transfer coefficients for water

$$h'[\mathrm{W/m^2{}^\circ C}] = 125u'^{0.8}/\mu'^{0.47} \quad \text{for} \quad u'(\mathrm{m/s}), \mu'(\mathrm{kg/m/s})$$

Follow the logic carefully…

From Rules 9 and 12

$$u = 0.0305\sqrt{\frac{850}{8} - 1} = 0.313 \text{ m/s} \qquad u_{\text{act}} = (\quad)(0.313) = 0.23 \text{ m/s}$$

Mass flow rate of vapor = 9200 kg/h = 9200/3600 (kg/s) = 2.56 (kg/s)

$$^2/4 = 2.56 \quad \longrightarrow \quad D = 1.33 \text{ m}$$

From Rule 5, the volume of the liquid = $0.5L\pi D^2/4 = 0.726L \text{ m}^3$

5 min of liquid flow
= (5 min)(60 sec/min)(11,570 kg/hr)/(850 kg/m³)/3600 (hr/sec) = 1.13 m³

Equating the two results above, L = 1.56 m

Table 1.7 Equipment Summary for Toluene Hydrodealkylation PFD

Heat Exchangers	E-101	E-102	E-103	E-104	E-105	E-106
Type	Fl.H.	Fl.H.	MDP	Fl.H.	MDP	Fl.H.
Area (m^2)	36	763	11	35	12	80
Duty (MJ/h)	15,190	46,660	1055	8335	1085	9045

Rule 1: Set F = 0.9

Rule 6: min ΔT = 10°C; but E-105 has 8°C (ignore for now)

Rule 7: Water enters at 30°C and leaves at 40°C

Rule 8: U = 850 W/m²°C

$$\Delta T_{lm} = \boxed{} = 29.1^\circ\text{C}$$

$$Q = 1085\text{MJ/h} = 301\text{kW} \quad \text{from Table 1.7}$$

$$A = \frac{Q}{FU\Delta T_{lm}} = \frac{301,000}{0.9 \times 850 \times 29.1} = 13.52 \text{ m}^2$$

From Rule 9, this heat exchanger should be double-pipe or multiple-pipe design

In Table 1.7, E-105 is multiple-pipe design with the area of 12 m²

Table 11.14

Rule 2: $F_s = u\rho_v^{0.5} = 1.2 - 1.5 \text{ m/s}(\text{kg/m}^3)^{0.5}$ ( )

Rule 3: $\Delta P_{tray} = 0.007 \text{ bar}$

Rule 4: $\varepsilon_{tray} = 60 - 90\%$

$x_{ovhd} = 0.9962, \; x_{bot} = 0.0308$

$\alpha_{ovhd} = 2.44, \; \alpha_{bot} = 2.13, \; \alpha_{geom\ ave} = \sqrt{2.44 \times 2.13} = 2.28$

$N_{\min} = \{\ln[0.9962/(1-0.9962)]/[0.0308/(1-0.0308)]\}/\ln(2.28) = 10.9$

$R_{\min} = (142.2/105.6)/(2.28-1) = 1.05$ 1.26 ≤ R ≤ 1.58

stream 15

N_{theory} = 2 x 10.9 = 21.8 N_{actual} = (21.8 / ε (=0.6)) x 1.1 = 43 trays

Vapor flowrate (Str. 13) = 22,700 kg/h $\rho_v = 6.1 \text{ kg/m}^3$

$$u = (1.2 - 1.5)/6.1^{0.5} = (0.49 - 0.60) \text{ m/s}$$

Vapor flowrate (Str. 13) = 22,700 kg/h

$$22,700 \frac{\text{kg}}{\text{h}} \times \frac{1 \text{ h}}{3,600 \text{ s}} \times \frac{\text{m}^3}{6.1 \text{ kg}} = 1.03 \frac{\text{m}^3}{s} = v$$

$$D_{tower} = [4v/\pi u]^{0.5} = [(4)(1.03)/(3.142)/(0.49 \sim 0.60)]^{0.5} = 1.64 \sim 1.48 \text{ m}$$

$$\Delta P_{tower} = (N_{actual})(\Delta P_{tray}) = (43)(0.007) = 0.30 \text{ bar}$$

	Tables 1.5 and 1.7 and F 1.5	From Heuristics
Tower diameter	1.5 m	1.48 - 1.64 m
Reflux ratio, R	1.75	1.26 - 1.58
Number of trays	42	43
Pressure drop, ΔP_{tower}	0.30 bar	0.30 bar