Chemical Engineering 612

Reactor Design and Analysis

Lecture 14

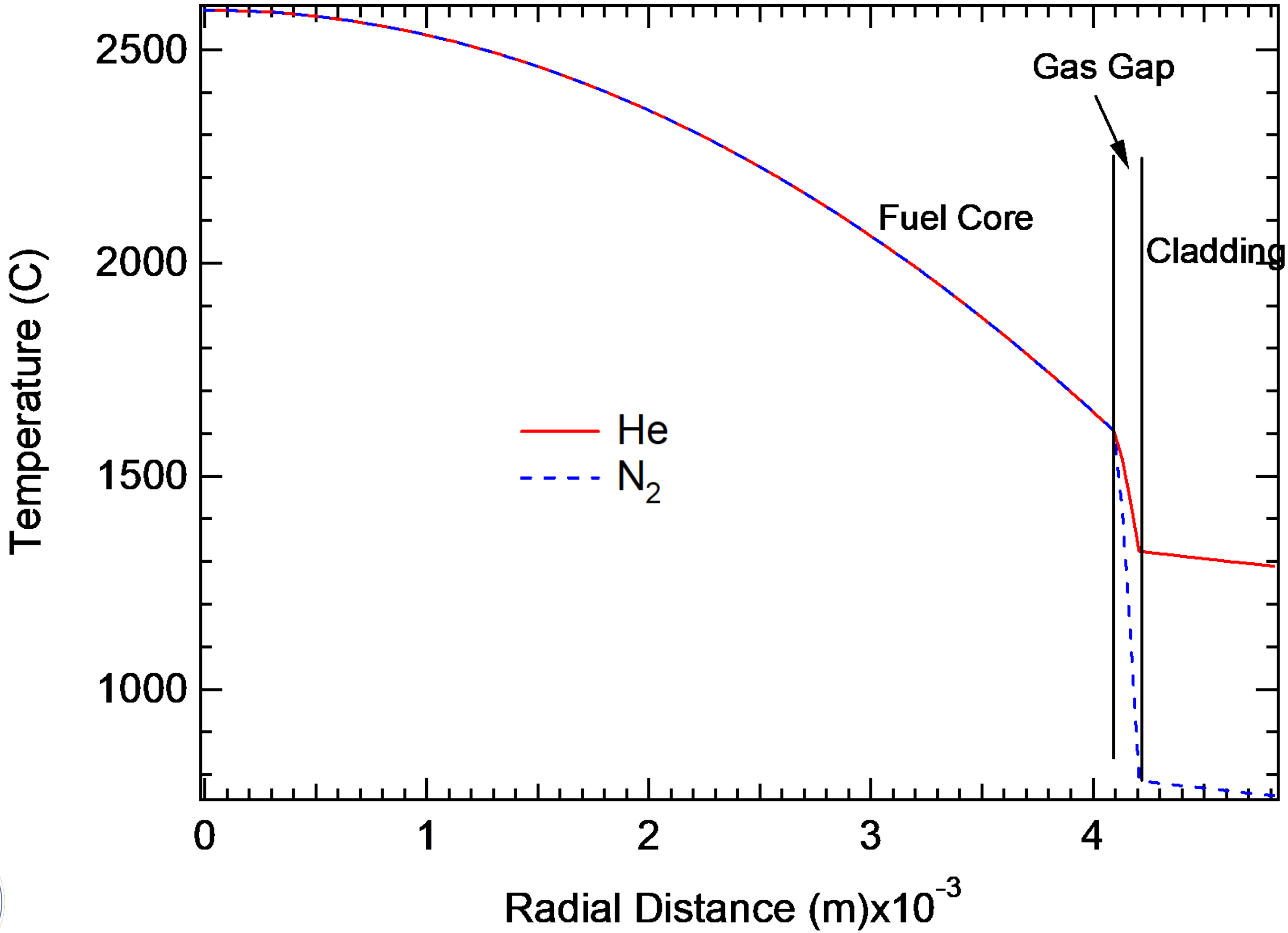
Thermal Assumptions Relaxation

Spiritual Thought

"…Our world needs your goodness and love. Be kind to one another. Jesus taught us to treat others as we want to be treated. As we try our best to be kind, we draw closer to Him. If you are unkind to anyone—individually or with a group—make up your mind now to change. Encourage others to change too."

President Dallin H. Oaks

Temperature Profile in Cylinder

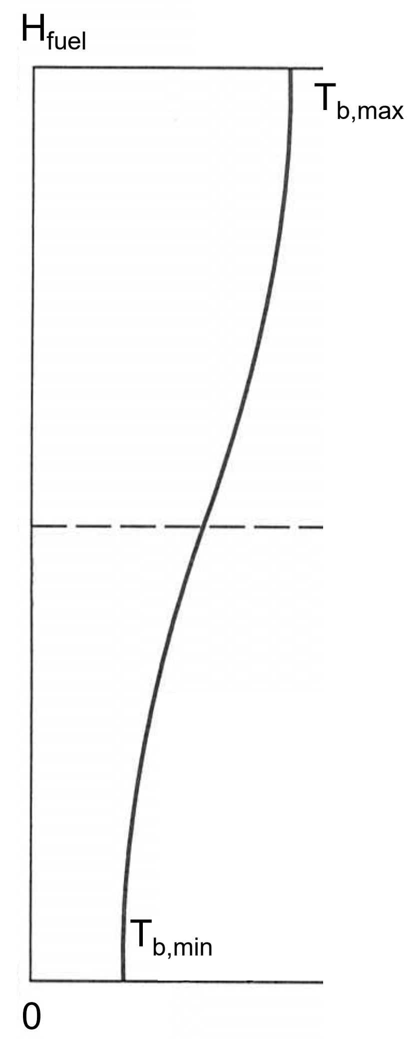


Thermal Resistances

- Conduction
  - Plane Wall – $R_{cond} = \frac{x}{kA}$
  - Cylindrical Wall – $R_{cond} = \frac{\ln\left({}^{r_2}/_{r_1}\right)}{2\pi Lk}$
  - Spherical Wall – $R_{cond} = \frac{r_2 - r_1}{4\pi r_1 r_2 k}$
- Convection – $R_{conv} = \frac{1}{hA}$
- Radiation – $R_{rad} = \frac{1}{h_{rad}A}$
  - $h_{rad} = \varepsilon\sigma(T_1^2 + T_2^2)(T_1 + T_2)$

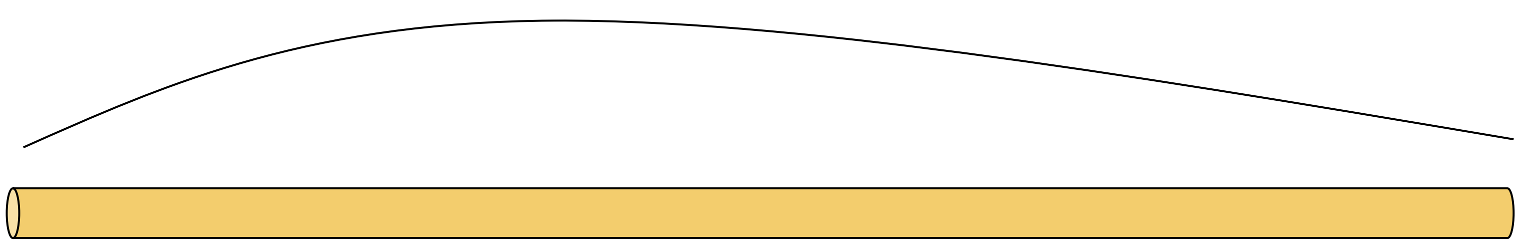
Bulk Flow and Boundary T

- Previous problem → oversimplified!
  - – Tc is rarely constant!
  - – q'' is more likely to be constant
  - – Coolant is ultimate heat sink
  - – Coolant temperature changes!
- 2 ways to relax assumptions
  1. Assume coolant removes heat from fuel rod cladding (4th resistance)
  2. Assume non-linear temperature profile in coolant



Flux Profile

geometry	Buckling (B^2)	Flux	A	$\Omega = \frac{\phi_{max}}{\phi_{av}}$
$plate - 1D$	$\left(\frac{\pi}{a}\right)^2$	$A\cos\frac{\pi x}{a}$	$1.57P / aE_R\Sigma_f$	1.57
$plate - 3D$	$\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2 + \left(\frac{\pi}{c}\right)^2$	$A\cos\frac{\pi x}{a}\cos\frac{\pi y}{b}\cos\frac{\pi z}{c}$	$3.85P / VE_R\Sigma_f$	3.88
$cylinder - 1D$	$\left(\frac{2.405}{R}\right)^2$	$A\,J_0\left(\frac{2.405}{R}\right)$	$0.738P / R^2E_R\Sigma_f$	2.32
$cylinder - 3D$	$\left(\frac{2.405}{R}\right)^2 + \left(\frac{z}{H}\right)^2$	$A\,J_0\left(\frac{2.405}{R}\right)\cos\frac{\pi z}{H}$	$3.63P / VE_R\Sigma_f$	3.64
$sphere$	$\left(\frac{\pi}{R}\right)^2$	$\frac{A}{r}\cos\frac{\pi r}{R}$	$P / 4R^2E_R\Sigma_f$	3.29



Power Distribution

- In reality, not perfect curve… depends on:
  - – Geometry (not perfect cylinder)
  - – Irradiation Cycle (enrichment distribution)
  - – Refueling Schemes
  - – Control Rods
- Interested in highest q''' →max power
  - – Power peaking factor
    - Radial - $\frac{Peak\ FA\ power}{Average\ FA\ power}$
    - Local - $\frac{Peak\ pin\ power\ (in\ FA)}{Average\ pin\ power\ (in\ FA)}$
    - Axial - $\frac{Peak\ linear\ power}{Average\ linear\ power}$

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Example

- Calculate the peak temperature in a sodium (C_p=1.23J/g*K, μ = 0.072cp, ρ=927kg/m^3) fast reactor core (1000 MW) with 10,000 fuel rods (UO_2, Zr metal clad) in which the radial factor is 1.1 and the local peaking factor is 1.2 assume a 1.0 cm fuel pellet, a 0.01cm gap, and a 0.1 cm clad thickness. For simplicity, assume no axial peaking, and coolant inlet temperature of 400C with a flow rate of 5,000 kg/s. The core flow area is roughly 1.5 m^2, while the equivalent diameter of each channel is 1.5 cm.

Heat Transfer Correlations

- For convective cooling:
  1. Find coolant flow regime (laminar vs. turbulent)
  2. Determine appropriate Pr number of fuel $\left(\mathrm{Pr} = \frac{\mu C_p}{k}\right)$
  3. Pick a correct heat transfer correlation (samples given below)
  4. Calculate h $\left(Nu = \frac{hD_{eq}}{k}\right)$
  5. Evaluate the heat transfer resistance and add to sum of resistances in calculation $\left(q'' = \frac{\Delta T}{\sum resistances}\right)$

Seider and Tate: $Nu = 0.023Re^{0.8}Pr^{0.4}\left(\frac{\mu_w}{\mu}\right)^{.014}, 0.7 < Pr < 120, Re > 10{,}000,$

Dittus-Boelter: $Nu = 0.023Re^{0.8}Pr^{0.4}, 0.7 < Pr < 100, Re > 10{,}000, \frac{L}{D} > 60, heated, \mu_w \sim \mu$

$Nu = 0.023Re^{0.8}Pr^{0.4}, 0.7 < Pr < 100, Re > 10{,}000, \frac{L}{D} > 60, cooled, \mu_w \sim \mu$

Colburn: $Nu = 0.023Re^{0.8}Pr^{0.333}, High\ \mu,\ 0.7 < Pr < 100, Re > 10{,}000, \frac{L}{D} > 60, \mu_w \sim \mu$

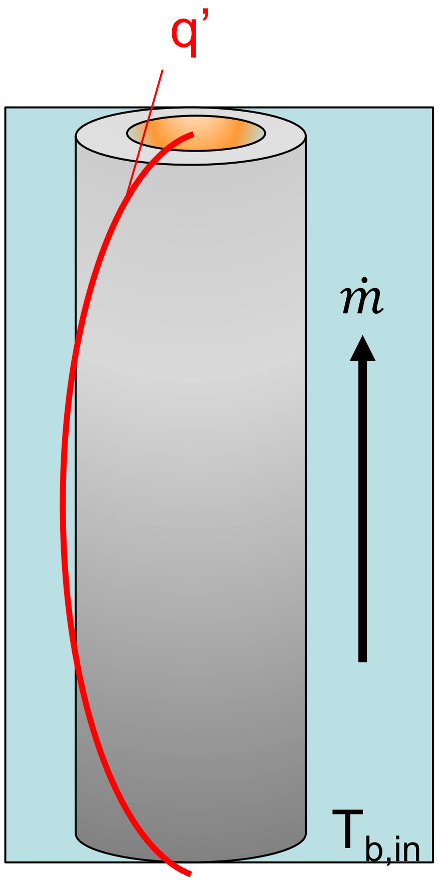
Metallic Fluids: $Nu = 7 + 0.025Pe^{0.8}, constant\ q'' \,\&\, q',\ circular\ tube, fully\ developed$

$Nu = 5.0 + 0.025Pe^{0.8}, constant\ T_{w,axial}\ \&\ q''\ circular\ tube, developed$

$Nu = 5.25 + 0.0188Pe^{0.8}, concentric\ annuli, \frac{D_1}{D_2} > 1.4, developed, q'' = C$

Rod Analysis with non-constant q'

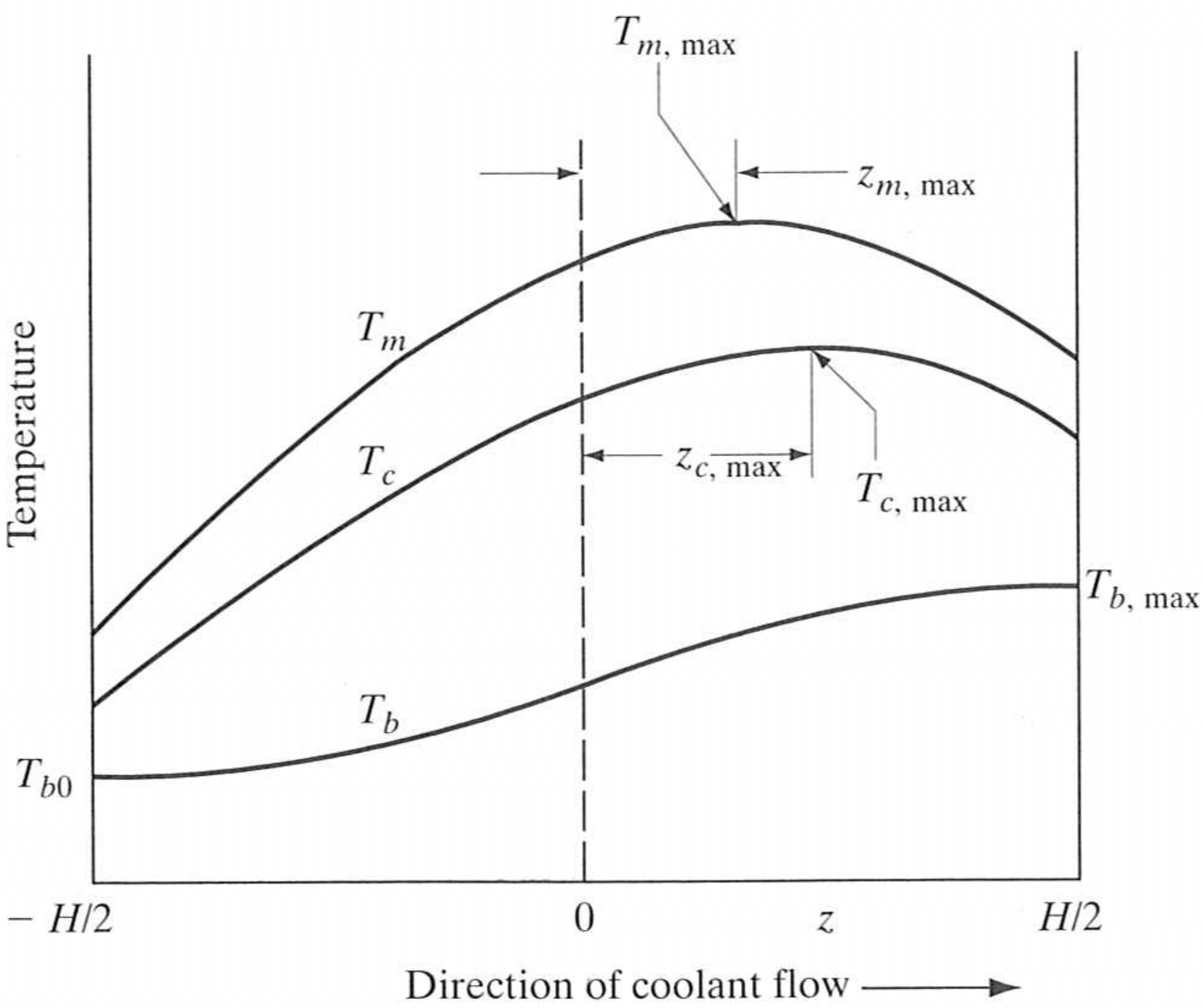
- Now q' = $q'(z) = q'_{max} \sin\left(\frac{\pi z}{L}\right)$
  - Steady state
  - Know $\dot{m}$, $T_{b,in}$
- Develop expressions for:
  - $T_{max}(z)$
  - $T_{fuel}(z)$
  - $T_{clad}(z)$
  - $T_{bulk}(z)$



Bulk Flow

- Energy increase in Flow:
  - $q'(z) = \dot{m}\frac{dh}{dz}$
    - If no phase change, $dh = C_p dT_b$
  - $\dot{m}\frac{dC_pT_b}{dz} = q'(z) = q'_{max}\sin\left(\frac{\pi z}{L}\right)$
  - Solve for T_b
- $T_b(z) = \frac{q'_{max}}{\dot{m}C_p}\frac{L}{\pi}\left[1 - \cos\left(\frac{\pi z}{L}\right)\right]$
- Now apply same method, but $T_b = T_b(z)$

Typical Temperature Profiles



Subscripts *b*, *c*, and *m* represent bulk, cladding, and middle, respectively.

Decay Heat

- Decay of fission products
  - Fuel
  - Moderator
  - time reactor is in operation
  - power
  - time reactor has been shut down, etc
    - For UO_2 fuel, water-moderated reactor
- $\frac{P}{P_o} = 0.066[(\tau - \tau_s)^{-0.2} - \tau^{-0.2}]$