22.06 **ENGINEERING OF NUCLEAR SYSTEMS - Fall 2010**

Problem Set 4

Thermal Analysis of Fuel + Core Temperature Distributions

Reference Textbooks:

[RAK] = Knief, R. A. *Nuclear Engineering: Theory and Technology of Commercial Nuclear Power*. 2nd ed. La Grange Park, IL: ANS, 2008. ISBN: 9780894484582.

[T&K] = Todreas, N. E., and M. Kazimi. *Nuclear Systems Volume I: Thermal Hydraulic Fundamentals*. New York, NY: Taylor & Francis, 1989. ISBN: 9781560320517.

1) [RAK] Chapter 7, Problem 7-6

2) [RAK] Chapter 7, Problem 7-7

3) Consider an annular cylindrical annular fuel pellet of length L, inside radius, R_V, and outside radius R_{foc}. It is operating at q_c''', such that for a given outside surface temperature, T_{fo}, the inside surface temperature, T_V, is just at the fuel melting limit T_{melt}. A fellow engineer claims that if the same volume of fuel is arranged as a sphere with an inside voided region of radius R_V and operated between the same two surface temperature limits, i.e., T_V and T_{fo}, more power can be extracted from the spherical fuel volume then from a cylindrical fuel pellet. In both cases volumetric generation rate is radially constant.

Is the claim correct? Prove or disprove it. Please use the nomenclature of Fig. 1. Assume no sintering occurs.

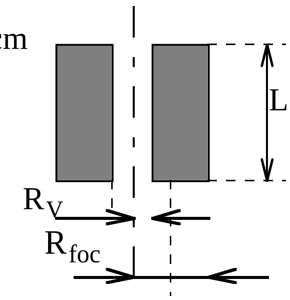
Given:

The one dimensional heat conduction equation in the radial direction in spherical coordinates is: $\frac{1}{r^2}\frac{d}{dr}\left(kr^2\frac{dT}{dr}\right) + q''' = 0$

For a sphere: $V_S = \frac{4}{3}\pi R^3$ and $A_S = 4\pi R^2$

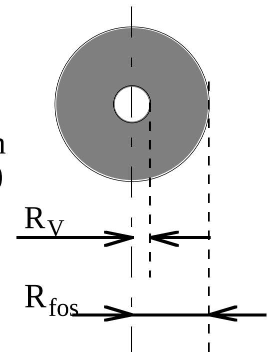
Cylindrical Annular Fuel Pellet:

q_c'''
R_V = 0.25 cm
R_{foc} = 1 cm
L = 1 cm



Spherical Hollow Fuel Pellet:

q_s'''
R_V = 0.25 cm
R_{fos} = ?
(to be determined from the problem statement)



Courtesy of Todreas, N. E. and Kazimi, M. S. Used with permission.

4) Effect of internal cooling on fuel temperatures

Consider the following three UO_2 pellets:

- Solid pellet
- Annular pellet with only external cooling
- Annular pellet with simultaneous internal and external cooling

The dimensions for all three pellets are in the table below. Assume that the fuel thermal conductivity is k_f=3 W/m·K (independent of temperature), the pellet surface temperature is 700°C and the linear power is q'= 40 kW/m in all three cases.

Geometry of the pellets

	ID (mm)	OD (mm)
Solid pellet	N/A	8.2
Annular pellet with only external cooling	2.0	8.44
Annular pellet with internal and external cooling	9.9	14.1

i) Calculate the maximum temperature for the solid pellet.
ii) Calculate the maximum temperature for the annular pellet with only external cooling.
iii) Calculate the maximum temperature for the annular pellet with simultaneous external and internal cooling.
iv) For the annular pellet with simultaneous internal and external cooling calculate also the heat flux at the inner and outer surfaces.
v) What are in your judgment the advantages and drawbacks of the annular fuel pellet with simultaneous internal and external cooling?

5) Heated channel power limits (from T&K book)

Consider a PWR with the following geometry and operating conditions:

Pressure: 15.5 MPa
Coolant inlet temperature: 286°C
Mass flow rate per fuel rod: 0.341 kg/s
Total number of fuel rods: 50,952
Fuel rod OD: 9.5 mm
Clad thickness: 0.57 mm
Gap: 0.08 mm
Active fuel height: 3.66 m

Properties
Coolant specific heat: 5.6 kJ/kg-K
Fuel thermal conductivity (assumed constant): 2.163 W/m-K
Clad thermal conductivity (assumed constant): 13.85 W/m-K

Other useful input
Heat transfer coefficient: 34 kW/m^2-K
Gap conductance: 5.7 kW/m^2-K

Assuming a typical cosine-shaped axial power profile, how much power can be removed from this PWR, if:

i) The coolant exit temperature is to remain below 344.9°C (i.e. the boiling point of water at 15.5 MPa)?
ii) The maximum clad temperature is to remain below 344.9°C (i.e. the boiling point of water at 15.5 MPa)?
iii) The fuel maximum temperature is to remain below 2400°C (i.e. the melting point of UO_2 fuel)?

(Adapted from Todreas and Kazimi text.)

6) Specification of power profile for a given clad temperature (from T&K book)

Consider a fuel rod whose cladding outer radius is a. Heat is transferred from the fuel rod to the coolant with constant heat transfer-coefficient h. The coolant mass flow rate along the rod is $\dot{m}$. The coolant specific heat c is independent of temperature. It is desired that the temperature of the outer surface of the fuel rod T (at radius a) be constant, independent of distance z from the coolant inlet end of the fuel rod.
Derive a formula showing how the linear power of the fuel rod q' should vary with z if the temperature at the outer surface of the fuel rod is to be constant.

(Adapted from Todreas and Kazimi text.)

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