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NE 533 MOOSE Project Part 2

Problem Set Up: For the second part of the NE 533 MOOSE project, I determined the temperature profile of the cladding inner surface, fuel surface, and fuel centerline computationally, and found the axial location of peak centerline temperature.

For these problems, the fuel pellet has a radius of 0.5 cm, a gap thickness of 0.005 cm, and a cladding thickness of 0.1 cm. Additionally, the fuel pellet has a linear axial heating rate of 350 W/cm. The inlet coolant temperature is 500 Kelvin. Figure 1 below shows a 2D cross-section of the fuel rod.

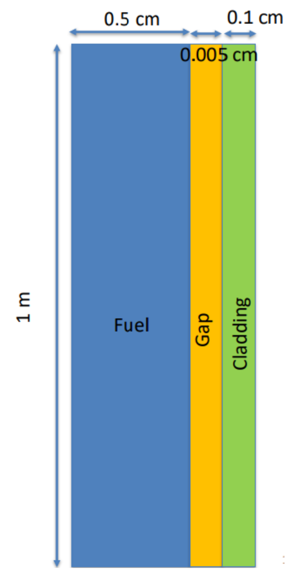

Figure 1. Fuel pellet 2D cross-section.

Corrections From Part 1: In part 1 of the MOOSE assignment I made two key mistakes that were corrected for this model:

a. Incorrect cladding thickness: I inadvertently used a cladding thickness of 0.01 cm instead of 0.1 cm. I updated my model to use the correct cladding thickness. While I made this change, I also defined all of my cladding features in variables at the beginning of the input file so I can generally change the parameters and the mesh will match the defined parameters.

b. Non-convergent transient model: For the final part of the assignment, I modeled the transient response of the fuel rod to determine the peak centerline temperature. I could not get my solver to converge for the full 100 seconds. I was only able to converge out to about 50 seconds. For this follow-on assignment, while I did not use a transient solver, I was able to converge the model by reducing the mesh detail, and modifying the convergence criteria. I increased the time step tolerance and decreased the minimum step time so that the smallest time step was within the time step tolerance. Contrary to the professor's suggestions in my previous assessment, I did originally use the HeatConductionTimeDerivative kernel in the input file; however, I forgot to show the change to the kernel component when writing my report. I attached the corrected transient file to the assignment submission.

c. Mesh Justification: For the model in part 2, I selected 20 nodes within the fuel, 20 nodes in the gap, and 4 nodes in the cladding. I chose the number of nodes to keep a consistent temperature increase between nodes to avoid missing subtle temperature variation effects, but minimize run time. A higher resolution solution could be performed if desired.

Model Changes To Add Coolant Flow As A Factor: To meet the problem statement for the second part of this assignment, I modified my boundary condition to account for a cooling flow in the channel. In the first part of the assignment, I was directed to set a constant cladding outer temperature of 550 K. I accomplished this using the following assumptions and steps:

1. Function Derivation: I used a FunctionDirichletBC boundary condition, which requires a function that defines the condition as a function of t, x, y, and z, instead of a DirichletBC boundary condition which sets a fixed value condition. To define that function I used the convective heat transfer equation as defined in class (Eq. 1) as a function of axial height to set the cladding outer temperature.

$$T_{OC}(z) = \frac{LHR}{2\pi R_f h_{cool}} + T_{bulk}(z) \qquad \text{(Eq. 1)}$$

This equation required me to define the channel bulk fluid temperature as a function of axial height as well. I used the heat capacity equation (Eq. 2) to determine the overall temperature rise across the channel. Using Equations 3 and 4, I was able to put Equation 2 into a useful form for the information provided in this problem (Eq. 5)

$$\dot{Q} = \dot{m} C_v \Delta T \qquad \text{(Eq. 2)}$$

$$\dot{Q} = \dot{q} V = \dot{q} \pi R_f^2 core_{height} \qquad \text{(Eq. 3)}$$

$$\dot{m} = v_{coolant} A_{flow} \rho = v_{coolant} (rod_{pitch}^2 - \pi rod_{radius}^2) \rho \qquad \text{(Eq. 4)}$$

$$\Delta T = \frac{\dot{q} \pi R_f^2 core_{height}}{v(rod_{pitch}^2 - \pi rod_{radius}^2) \rho C_v} \qquad \text{(Eq. 5)}$$

Then I linearized it in the channel because there is a linear heat input in this problem (Eq. 6). This bulk fluid temperature equation could be modified to account for any axial distribution by integrating the heat input into the channel up to the axial position, but that approach was not used in this problem. Substituting in Equation 5 and Equation 6 into Equation 1 produces the forms Equation 7, which was used in the code.

$$T_{bulk}(z) = \Delta T \frac{z}{core_{height}} + T_{in} \quad \text{(Eq. 6)}$$

$$T_{OC}(z) = \frac{LHR}{2\pi R_f h_{cool}} + \frac{\dot{q}\pi R_f^2 core_{height}}{v(rod_{pitch}^2 - \pi rod_{radius}^2)\rho C_v} \frac{z}{core_{heigh}} \quad \text{(Eq. 7)}$$

2. Variable Definitions: Realistic variables were then defined based on scaling common Westinghouse AP 1000 reactor parameters to match this sized reactor. These values could be modified to match a specific design to assess core thermal performance. SI units were used for this simulation to simplify calculations.

a. Given parameters: fuel radius (0.5 cm), gap thickness (0.005 cm), clad thickness (0.1 cm), core height (1 m), LHR (350 W/cm), and inlet temperature (500 K) were given.

b. Calculated parameters: Rod diameter (0.605 cm) was computed geometrically and volumetric heat production rate (445.6 W/cm3) can be calculated using Equation 8.

$$Q_{ave} = \frac{LHR}{\pi R_f^2} \quad \text{(Eq. 8)}$$

c. Assumed parameters:

i. Material Thermal Conductivities: I selected to use a gap thermal conductivity of 0.00236 W/cm-K and a cladding thermal conductivity of 0.15 W/cm-K consistent with the first in class exercise. Additionally, I used the fuel thermal conductivity correlation as a function of temperature as described in class (Eq. 9).

$$k_0 = \frac{100}{7.5408_{17.629T} + 3.6142T^2} + \frac{6400}{T^{5/2}} exp\left(\frac{-16.35}{T}\right) \quad \text{(Eq. 9)}$$

ii. Rod Pitch: I used the ratio of rod pitch to rod diameter (1.326) from reference (a) to scale the rod pitch for this problem. Rod pitch was 1.60446 cm.

iii. Coolant Average Velocity: I scaled the coolant average velocity for this problem to match the mass flow rate per rod per unit power from the reference (a) AP 1000 reactor to the power generated by a rod in this assignment. This resulted in an average coolant velocity of 1.264 m/s. For reference, this is roughly a quarter of the average coolant velocity of the AP 1000 reactor. However, it results in the same 80 K temperature rise over the height of the core as desired.

iv. Water Heat Transfer Coefficient: For this problem, I used a common heat transfer coefficient of 30 kW/m2-K as stated in reference (b) for light water reactors. More specific heat transfer coefficients can be calculated using the Dittus-Bölter correlation, but that approach was beyond the scope of this assignment.

v. Core pressure and average temperature: I matched the 2250 psia core pressure of the AP 1000 reactor from reference (c). I used an average temperature of 550 Kelvin to set water properties for the whole channel because there is a 80 Kelvin temperature rise across the channel in an AP 1000 reactor as stated in reference (a). The temperature of 550 Kelvin, while not the exact average temperature, was convenient to use with a steam table. Ultimately, I used a water property calculation, reference (d), to determine the water properties shown in Table I.

Table I. Water material properties for the selected reactor condition.

Property	Value	Unit
medium :	water, fluid	
pressure :	155.1375	[bar]
temperature :	276.85	[Celsius]
density :	769.71815384007	[kg / m^3]
dynamic viscosity :	9.7661703428876E-5	[Pa s]
kinematic viscosity :	0.12687982340243	[10^{-6} m^2 / s]
specific inner energy :	1196.5505899213	[kJ / kg]
specific enthalpy :	1216.7056946471	[kJ / kg]
specific entropy :	3.0101860744483	[kJ / kg K]
specific isobar heat capacity : cp	5.0268704880304	[kJ / kg K]
specific isochor heat capacity : cv	3.0768769263483	[kJ / kg K]
thermal conductivity :	0.60123176341873	[W / m K]
speed of sound :	1094.9450982938	[m / s]

Results: Using the equations and assumptions described above, the MOOSE model produced a temperature profile that was consistent with my expectations as described below:

a. Cladding Surface Temperature Profile: The temperature profile for the outer cladding surface varies linearly from 535 K to 620 K from the bottom to the top of the core as shown in Figure 1. This shows a 35 K temperature increase on the cladding surface relative to the 500 K inlet coolant temperature to produce the heat flux needed to reach steady state. The temperature profile for the inner cladding surface varies linearly from 605 K to 685 K from the bottom to the top of the core as shown in Figure 2. This shows a 70 K temperature rise across the 0.1 cm thick cladding.

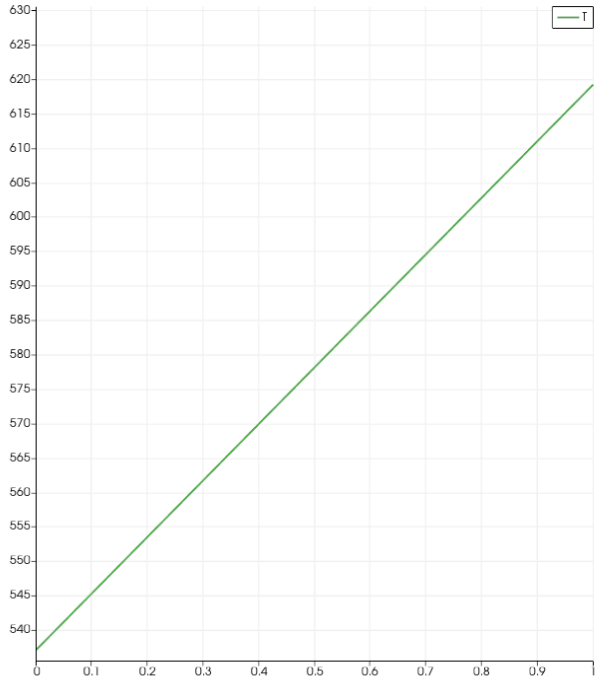

Figure 1. Outer cladding surface temperature (K) as a function of axial position (m).

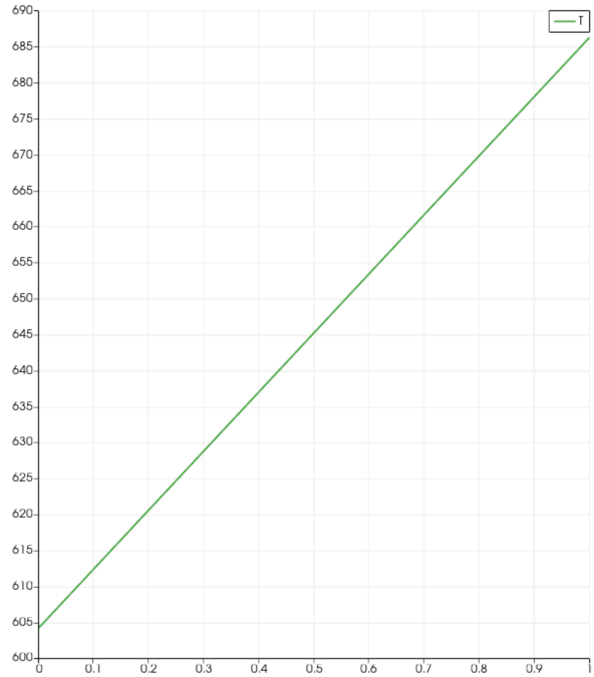

Figure 2. Inner cladding surface temperature (K) as a function of axial position (m).

b. Fuel Surface Temperature Profile: The temperature profile for the fuel surface varies linearly from 840 K to 920 K from the bottom to the top of the core as shown in Figure 3. This shows a 235 K temperature increase across the 0.005 cm gap between the cladding and fuel. This is larger than expected, but is reasonable given the low thermal conductivity of helium at the beginning of life.

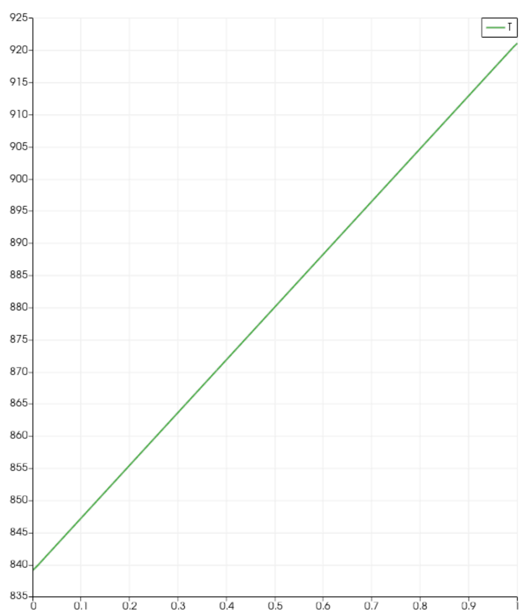

Figure 3. Fuel surface temperature (K) as a function of axial position (m).

c. Fuel Centerline Temperature Profile: The temperature profile for the fuel centerline varies linearly from 1835 K to 1990 K from the bottom to the top of the core as shown in Figure 4. This shows a temperature rise of 995 K at the bottom of the core and rise of 1070 K at the top of the core. This is the only material in the model that shows a non-constant temperature rise axial, which is due to the variable thermal conductivity of the fuel set up in the first part of this MOOSE assignment.

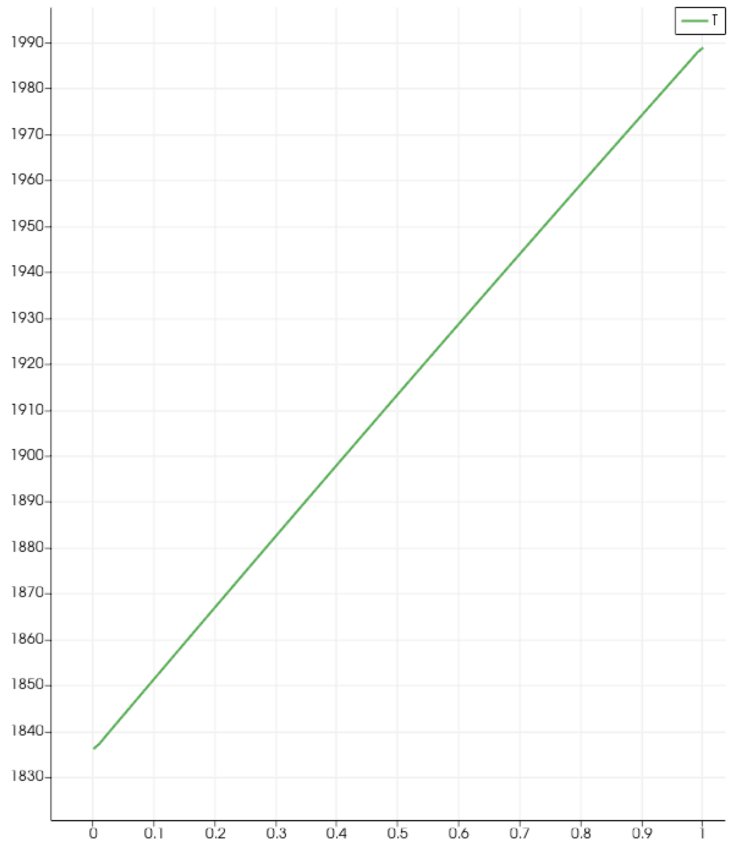

Figure 4. Fuel Centerline Temperature (K) as a function of axial location (m).

d. Axial Location of Peak Centerline Temperature: As shown in Figure 4, the location of peak centerline temperature in the fuel is at the top of the core (z = 1 m). At this location, the fuel is 1988.84 K. At this height, the cladding temperature is the highest, because the coolant temperature in the channel has increased to store the heat generated from the fuel. This is consistent with expectations for a linear axial heat distribution in a core. This solution can vary if the axial power profile for the core was non-linear. Figure 5 shows the radial heat profile for this axial height, demonstrating the largest heat increase across the 0.5 cm thick fuel pellet.

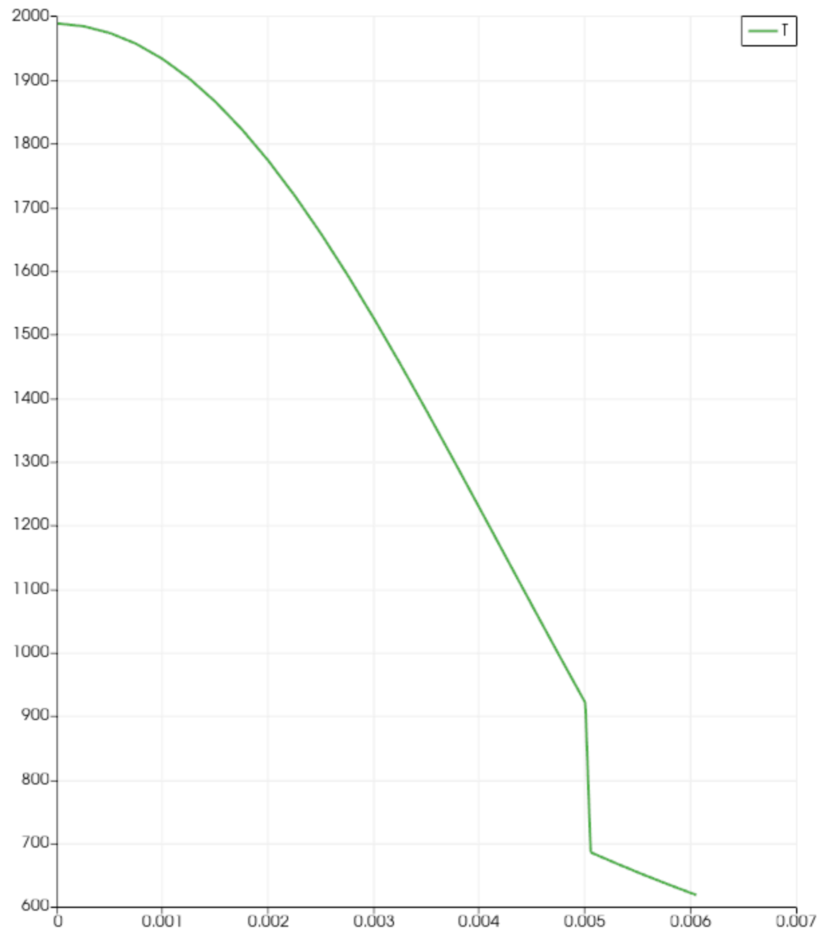

Figure 5. Radial temperature profile (K) as a function of radial position (m) at a height of 1 m, which is the axial location of the peak centerline temperature.

References

a. https://www.nrc.gov/docs/ML0715/ML071580895.pdf
b. https://www.sciencedirect.com/topics/earth-and-planetary-sciences/heat-transfer-coefficient#:~:text=Conditions%20achieved%20in%20a%20generic,m2%20K)%E2%88%92%201.
c. https://westinghousenuclear.com/energy-systems/ap1000-pwr/operations-and-maintenance/
d. https://www.peacesoftware.de/einigewerte/wasser_dampf_e.html