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NE-533: Nuclear Fuel Performance

MOOSE Project: Final

A complete thermo-mechanic model of a fuel rodlet system was developed in MOOSE to determine the temperature profiles of a fuel rodlet assembly and the corresponding stress state of the fuel. This model was developed in three stages including (i) development of a 1D radial temperature profile of a simplified fuel assembly system, (ii) development of a 2D, axially varying temperature profile of a fuel assembly system, and (iii) application of tensor mechanics to the model developed in (i) to determine the von mises stress profile within the fuel. All models were developed in 2D RZ space with a fuel pellet radius of 0.5cm, a gap thickness of 0.002cm, and a cladding thickness of 0.1cm.

The first stage began with development of a steady state model, which was developed using 3 mesh subdomains representing the cladding, gap, and the fuel pellet. The three meshes were stitched together in the model using the StitchedMeshGenerator function. The mesh was split into 100 equal portions in Z for all meshes, and was also split into 30, 10, and 120 equal portions in X for the cladding, gap, and fuel respectively. Grip independence was verified by doubling the grid size in each direction and comparing the results. Minimal changes were observed between each grid size. Conduction in the cladding, gap, and fuel pellet were modeled with the Heat Conduction kernel. The thermal conductivity of the cladding and fuel were assumed to be constant at 0.15 and 0.03 $\frac{W}{cm\ K}$. The gap thermal conductivity was also assumed to be constant at a given temperature for model simplicity, and was calculated at 627 K, given by, $k_{He} = 16 * 10^{-6} T^{0.79}$. A linear heat rate of 350 $\frac{W}{cm}$ was included in the model to account for heat generation within the fuel using a HeatSource kernel.

The steady state model temperature profile, shown in Fig 1, was compared to an analytical solution at four discrete points where r = 0, 0.5, 0.502, and 0.602 cm which correspond to the material boundaries. The model had very good agreement with the analytical solutions, with a 0.2%, 0.5%, and 1.0% underprediction of the temperature at r = 0, 0.5, and 0.502 cm, respectively.

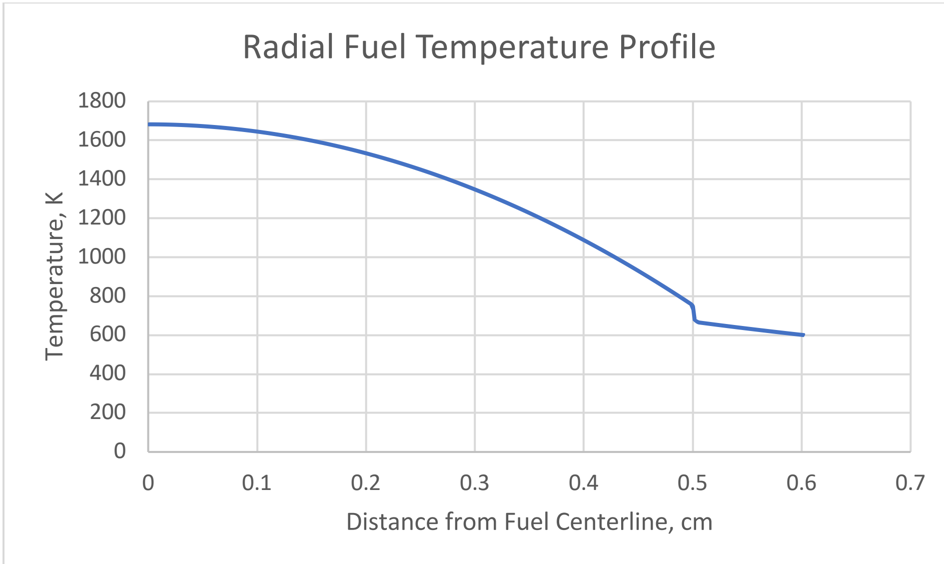

Fig 1. The steady-state temperature profile of a fuel assembly with the centerline a 0 cm.

The steady state model was also used as a framework for development of a transient model where the temperature profile was calculated to t = 100 s, with a maximum time step of dt = 1 s. The linear heat rate in the model was modified to be time-dependent, given by: $LHR = 500\left(\left(\frac{t}{100}\right)^{0.5}\right) * \left(\left(1-\left(\frac{t}{100}\right)\right)^{4}\right) + 150$. The centerline fuel temperature was calculated as a function of time, as shown in Fig 2. The fuel centerline temperature appears to achieve a steady condition around t = 60 s, and levels off at 1063 K. This is a significant change from the steady solution likely due to the different linear heat rate used in the transient model.

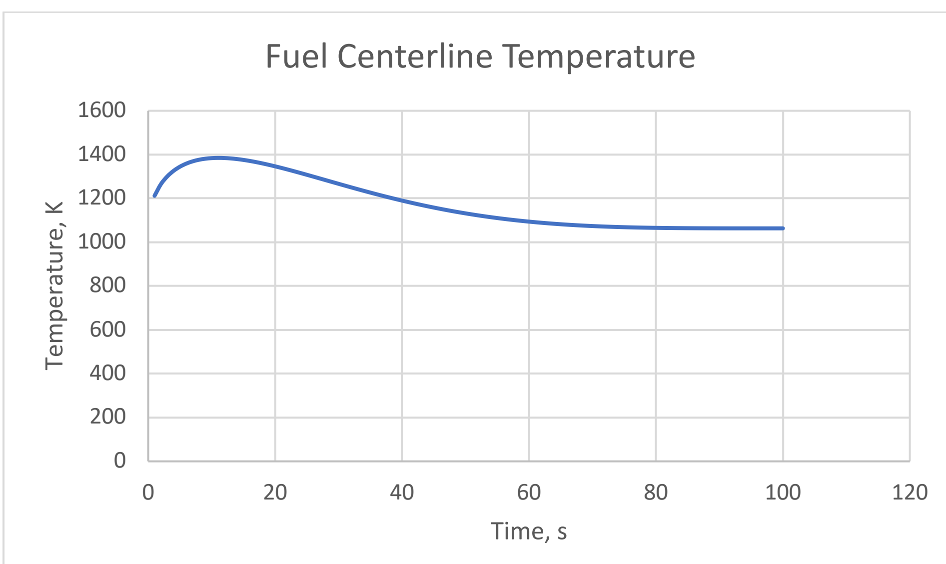

Fig 2. The transient temperature profile of the fuel centerline.

The second stage began with development of a steady-state model with a volumetric heating rate that varied as a function of Z, calculated from the linear heat rate function given by, $LHR\left(\frac{z}{Z_0}\right) = LHR^0 \cos\left[\frac{\pi}{2\gamma}\left(\frac{z}{Z_0} - 1\right)\right]$, where $LHR^0 = 350\frac{W}{cm}$. A non-constant coolant temperature was also included in the steady model, given by $T_{cool} = \frac{1}{1.2}\frac{Z_0 * LHR^0}{\dot{m}C_{PW}}\left[\sin(1.2) + \sin\left[1.2\left(\frac{z}{Z_0} - 1\right)\right]\right] + T_{cool,in}$, where $T_{cool,in}$ = 500 K. The 2D temperature profile of the system was calculated with a maximum Z of 1.0 m. The steady model was then extended to determine the transient temperature profile of the fuel centerline using a transient, initial linear heating rate given by, $LHR^0 = 500(\left(\frac{t}{100}\right)^{0.5}\left(1 - \left(\frac{t}{100}\right)\right)^4 + 150.$ The steady-state radial temperature profile was calculated at z = 0.25m, 0.5m, and 1.0 m, and the transient temperature profile at the centerline of the fuel was also calculated at z = 0.25m, 0.5m, and 1.0m.

The stage 2 steady-state model was developed using the same mesh from stage 1. The mass flow rate and heat capacity of the coolant were assumed to be constant. A coolant convective heat transfer coefficient, h_{cool} of 2.65 $\frac{w}{m^2K}$ was used to account for the heat transfer to the coolant from the cladding. The heat capacity was calculated at 500K based on property tables, and the mass flow rate was assumed to be 0.15 kg/s based on findings in literature[i].

An increase in temperature was observed in the steady-state temperature profiles with an increase in length, as seen in Fig 3. The peak temperature in the steady solution occurred at Z = 1.0m, at the fuel centerline, and was 1652.4 K. A 15.1% and 31.6% reduction in the maximum temperature was observed at 0.5m and 0.25m, respectively, with values of 1402.7 K and 1128.8 K. The heating rate in the cladding and the gap occurred at about the same rate irrespective of length. However, the heating rate inside the fuel varied largely along the length due to the variable volumetric heating.

The transient model was developed by modifying the steady-state model such that the same time-dependency in stage one was added to the linear heat rate. A maximum time of t = 100s was used along with time step of 1s. The centerline fuel temperature evolution at each point was calculated, as shown in Fig 4. The transient temperature profiles at each location along the length shared the same shape, but the maximum temperature profile was observed at Z = 1.0m., with steady a temperature of 1034.5 K. An 11.8% and 24.1% decrease in the steady temperature at t = 100s was observed in the 0.5m and 0.25m cases, respectively, with values of 912.5 K and

785.5 K. The peak centerline temperature at t=100 s was again observed at Z = 1.0m, with a temperature of 1034.5 K.

Both peak centerline temperatures for the steady-state case and the transient case occurred at Z = 1.0m, however it is interesting that the transient case had a 37.4% lower temperature when compared to the steady case. This is likely due to the change in LHR^0 that affects both the volumetric heat generation in the fuel, and the outside cladding surface temperature.

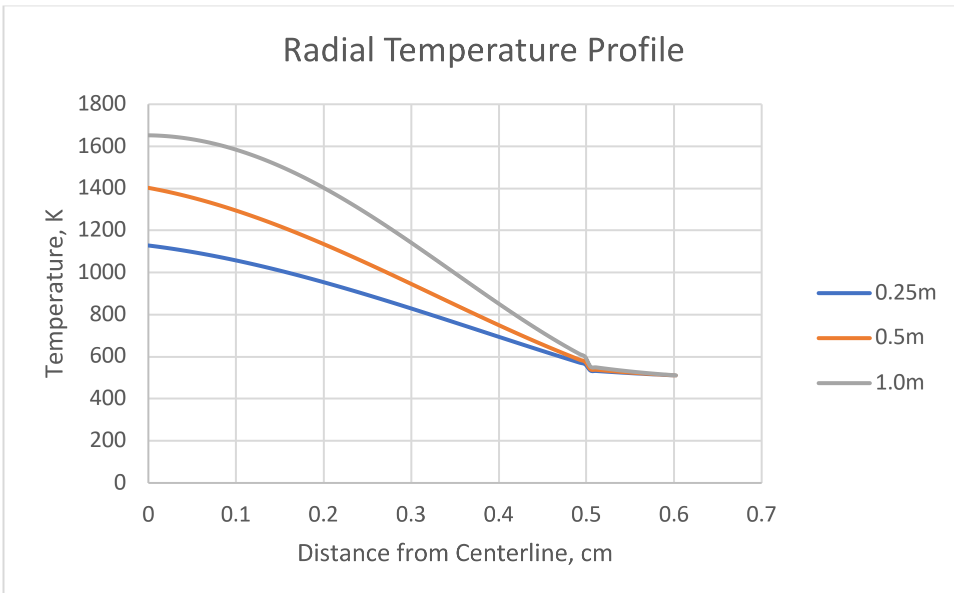

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Fig 3. The steady-state temperature profile of the system at discrete points along the length of the fuel, with the fuel centerline at 0 cm.

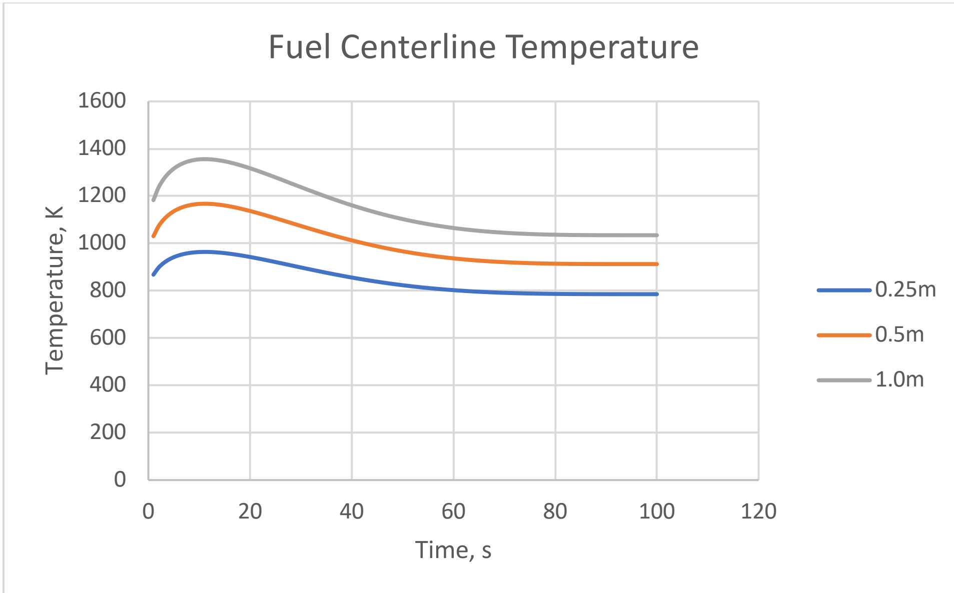

Fig 4. The temperature profile of the fuel centerline as a function of time at discrete points along the length of the fuel.

The third stage calculated thermal stresses in the fuel by implementing tensor mechanics into the model developed in stage 1. Several sections and boundary conditions were added to the model to accommodate the increased computation. The fuel centerline and the top and bottom boundaries were fixed such no displacement occurred at these boundaries. Elastic properties of the fuel and cladding were implemented in the model with a Young's modulus of 200 GPa, and 80 GPa, respectively, and a Poisson's ratio of 0.345 and 0.41, respectively. Thermal expansion coefficients of the fuel and cladding of $11 * 10^{-6}\frac{1}{K}$ and $7.1 * 10^{-6}\frac{1}{K}$, respectively, were used to calculate the thermal expansion within the fuel assembly. The elasticity tensor was also calculated for the fuel and the cladding, however, these calculations were not included for the gap section. The steady solution calculated the stress using the ComputeStrainIncrementBasedStress model within MOOSE. The von mises stress profile varied radially, as shown in Fig 5, with a peak stress of 2.40 GPa observed at the fuel centerline.

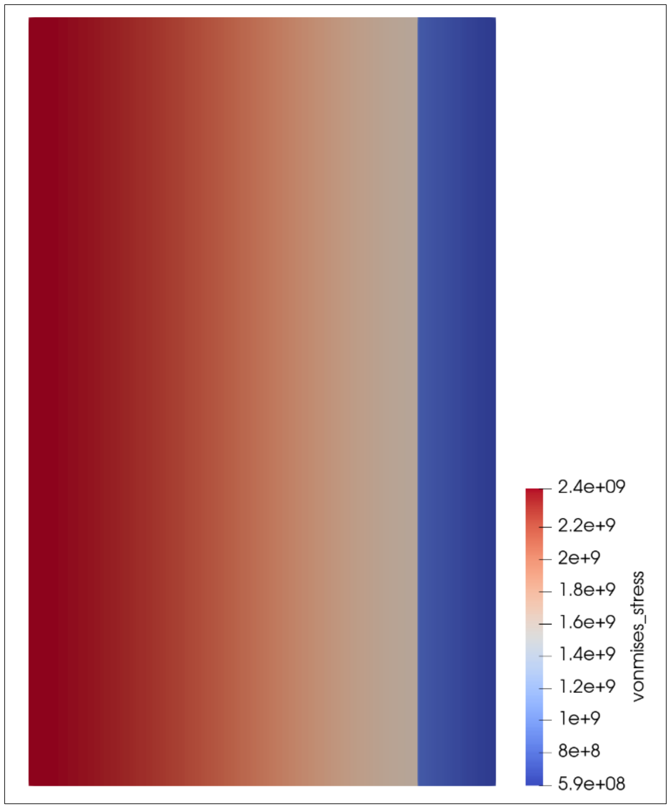

Fig 5. The 2D von mises stress profile within a UO_2 fuel pellet in a fuel rodlet assembly.

The steady solution was calculated only using a constant thermal conductivity, though the framework was created to calculate the solution using temperature-dependent thermal conductivity.

A framework for a transient model was also developed, however the model never sufficiently converged. It is anticipated this is due to how the tensor mechanics of the gap section of the system was calculated. The elasticity of the gap was neglected due to the gap being filled with a compressible fluid. The thermal expansion of the gap was also neglected within the code. Discontinuities between the fuel, gap, and cladding sections of the model likely resulted in a diverging transient solution. The stress was calculated using the ComputeFiniteStrainElasticStress model within MOOSE, rather than the stress model included in the steady solution, which also could have contributed to a diverging solution.

In conclusion, a steady state thermo-mechanical model of a fuel assembly system was developed and corresponding temperature and stress profiles were calculated. Initial steady-state models strongly agreed with calculated analytical solutions, and initial transient models indicated convergence to the steady solution around t = 60 s. A peak fuel centerline temperature of 1034.5

K was observed once the transient models achieved a steady condition. A maximum von mises stress of 2.4 GPa was observed at the fuel centerline using a constant thermal conductivity. A framework was included in the steady model to account for temperature-dependent thermal conductivity. The developed transient models also did not successfully converge to a solution.

Appendix: Analytical Solution Calculations

$$k_f = 0.03, R_F = 0.5\ cm, k_f = 0.15, t_c = 0.1\ cm, t_g = 0.002\ cm$$

$$LHR = 350\frac{W}{cm^2}, T_{co} = 600\ K$$

$$T_{ci} - T_{co} = \frac{LHR}{2\pi R_F}\left(\frac{t_c}{k_c}\right) \rightarrow T_{ci} = 674.3\ K$$

$$T_s - T_{ci} = \frac{LHR}{2\pi R_F}\left(\frac{t_g}{k_g}\right)$$

$$k_g = 16 * 10^{-6} T^{0.79} \rightarrow Assume\ T = T_{ci} \rightarrow k_g = 0.0027\frac{W}{cm\ K}$$

$$T_s = 756.8\ K$$

$$T_c - T_s = \frac{LHR}{4\pi k_f} \rightarrow T_c = 1685.2\ K$$

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[i] Mesquita, Amir Zacarias, and Hugo Cesar Rezende. "Monitoring of coolant flow rate and velocity in the hot channel of the IPR-R1 TRIGA Reactor core." *Científica* 14.2 (2010): 55-60.