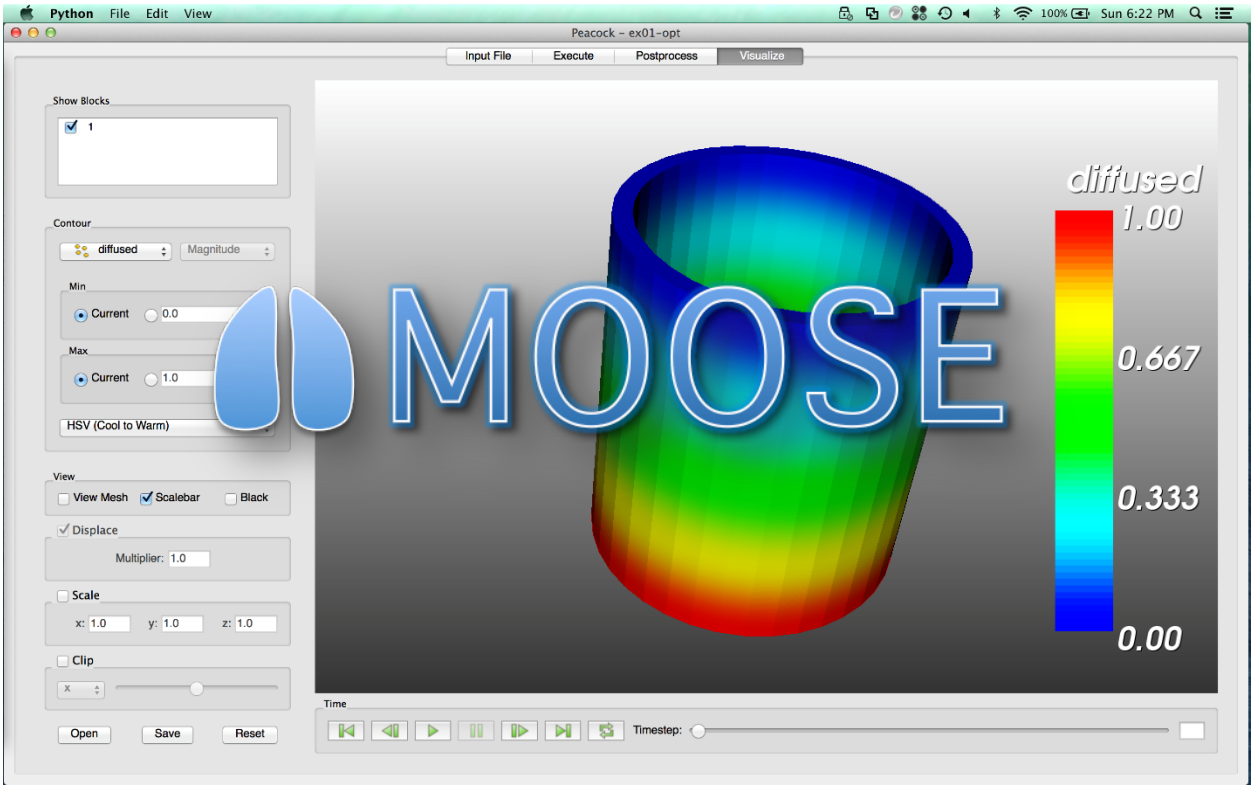
NE 533 Nuclear Fuel Performance

MOOSE Final Project



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April 29th, 2022

Introduction

Multiphysics Object Oriented Simulation Environment – commonly referred to as MOOSE – is a finite element Multiphysics framework that simplifies the development of advanced numerical applications, providing a high-level interface to sophisticated nonlinear solvers and massively parallel computational capability [1]. One of the capabilities of MOOSE is in the heat conduction simulations. In this project, MOOSE was accessed utilizing the RDFMG cluster at NC State University to perform 1- and 2-dimensional steady state and transient state heat conduction simulations for a fuel pin of given dimensions. The scripts used produced an output showcasing the temperature gradients of the fuel pin in each given case.

Fundamentals of Heat Conduction in a Nuclear Reactor [2]

Energy is removed from a reactor by two fundamentally different heat transfer processes – conduction and convection. In conduction, heat is transmitted from one location in a body to another as a result of a temperature difference existing in the body – there is no macroscopic movement of any portion of the body. It is by this mechanism that heat produced in a fuel rod is transferred to the surface of the rod. Heat convection involves the transfer of heat to a moving liquid or gas, again as the result of a temperature difference and the later rejection of this heat at another location. Thus, the heat conducted to the surface of a fuel rod is carried into the coolant and out of the system by convection [2].

Procedure

The equation for heat conduction is:

$$\vec{\nabla} \cdot k(T)\vec{\nabla}T + q'''(\vec{r},t) = \rho C_p \frac{\partial T}{\partial t}$$

Where:

k = thermal conductivity of the material(s)

q''' = volumetric heating rate of the fuel

ρ = density of the material(s)

C_p = specific heat capacity of the material(s)

This equation can be simplified by assuming a steady state (no change in time). Table 1 shows the various equations and boundary conditions used for different parts of the fuel pin.

Table 1. Heat Conduction Equations

	Material Choice	Steady State	Transient State
Fuel	Uranium Oxide (UO2)	$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_f\frac{\partial T}{\partial r}\right)+q'''=0$ Boundary conditions: $T(r=0)=T_0, T(r=r_f)=T_f$ $\frac{dT}{dr}(r=0)=0$ $T_0-T_f=\frac{q'''r_f^2}{4k}$	$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_f\frac{\partial T}{\partial r}\right)+q''' = \rho_{UO_2}C_p^{Fuel}\frac{\partial T}{\partial t}$
Gap	Helium Gas (He)	No q''' in the gap: $\frac{1}{r}\frac{\partial}{\partial r}\left(rk_g\frac{\partial T}{\partial r}\right)=0$ Boundary conditions: $q''=\frac{q'''r_f}{2}$ $T_g-T_f=\frac{LHR}{4\pi k_g}\ln\left(\frac{r_g}{r_f}\right)$	No q''' in the gap: $\frac{1}{r}\frac{\partial}{\partial r}\left(rk_g\frac{\partial T}{\partial r}\right) = \rho_{gap}C_p^{gap}\frac{\partial T}{\partial t}$
Cladding	Zirconium (Zr)	No q''' in the cladding: $\frac{1}{r}\frac{\partial}{\partial r}\left(rk_c\frac{\partial T}{\partial r}\right)=0$ Boundary conditions: $q''=-k_c\frac{dT}{dr}(r=r_f)\frac{q'''r_f}{2}$ $T_{Co}-T_{Ci}=\frac{LHR}{4\pi k_c}\ln\left(\frac{r_c}{r_g}\right)$	No q''' in the cladding: $\frac{1}{r}\frac{\partial}{\partial r}\left(rk_c\frac{\partial T}{\partial r}\right) = \rho_c C_p^{cladding}\frac{\partial T}{\partial t}$

Material Properties

Table 2 shows the material properties used for the simulations for UO2, Zr, and He:

Table 2. Material Properties

Material	Density ρ (g/cm^3)	Heat Capacity C_p (J/g-K)	Thermal Conductivity k (W/cm-K)
UO2	10.98	0.33	0.03
Zr	6.5	0.35	0.17
He	0.000178	5.193	0.00149

Tables 3 and 4 shows the functions and boundary conditions placed in the simulations for each given state – 1D steady, 1D transient, 2D steady, and 2D transient:

Table 3. 1D Functions and Boundary Conditions

	1-Dimensional	
	Steady State	Transient State
Volumetric Heat Rate (W/cm^3)	150	$150\left(1 * e^{(-0.05t)}\right) + 150$
Boundary Condition 1	$T_{Co} = 500\ K$	
Boundary Condition 2	$\frac{dT}{dr}(r = 0) = 0$	

Table 4. 2D Functions and Boundary Conditions

	2-Dimensional	
	Steady State	Transient State
Volumetric Heat Rate (W/cm^3)	150	$150\left(1 - e^{(-0.1t)}\right) + 50$
Boundary Condition 1	$T_{coolin} = 400\ K$ $T_{cool} = 0.833y * \frac{LHR}{MFRC_p} * [\sin(1.2) * \sin(1.2y - 1)] + 400$ Assumption made for simplicity: $T_{Co} = T_{cool}$ $MFR = 1000\frac{kg}{s}, C_p = 4182\ J/kgs$	
Boundary Condition 2	$\frac{dT}{dr}(r = 0) = 0$	

Results

1. 1D Steady State

Figure 1 shows the simulated temperature profile for the fuel pin using the 1-dimensional steady state conditions. The temperature gradient starts off parabolic in the fuel, then becomes linear near the gap and cladding. The centerline temperature simulated is roughly 883 K.

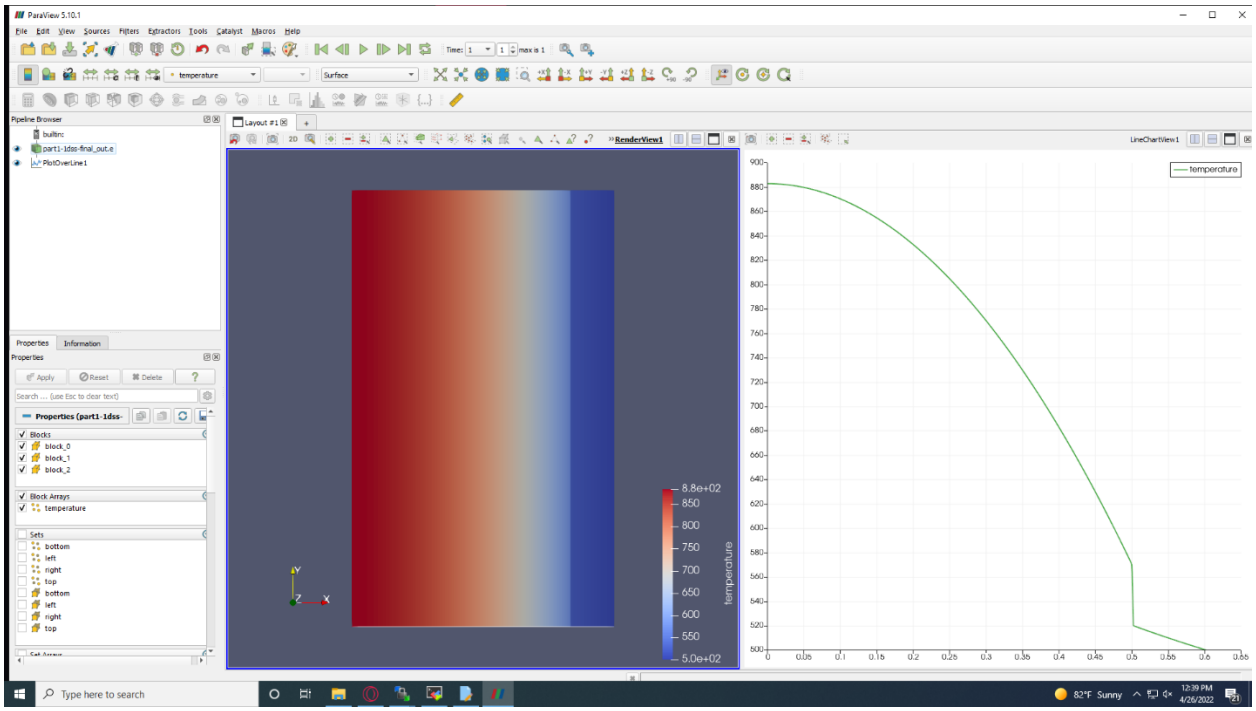

Figure 1. 1D Steady State Fuel Pin Temperature Profile

Results from Figure 1 in comparison to analytical solves are slightly different, likely due to scripting errors:

	MOOSE Results (ΔT)	Analytical Solve
$T_0 - T_f$	310	312.5
$T_f - T_g$	53	50.3
$T_g - T_c$	20	22.1

2. 1D Transient State

Figure 2 shows the simulated temperature profile for the fuel pin using the 1-dimensional transient state conditions. A similar gradient is shown here as well, with the centerline temperature being 1261 K at 100 seconds. As expected, the temperature steadily increased as time increased.

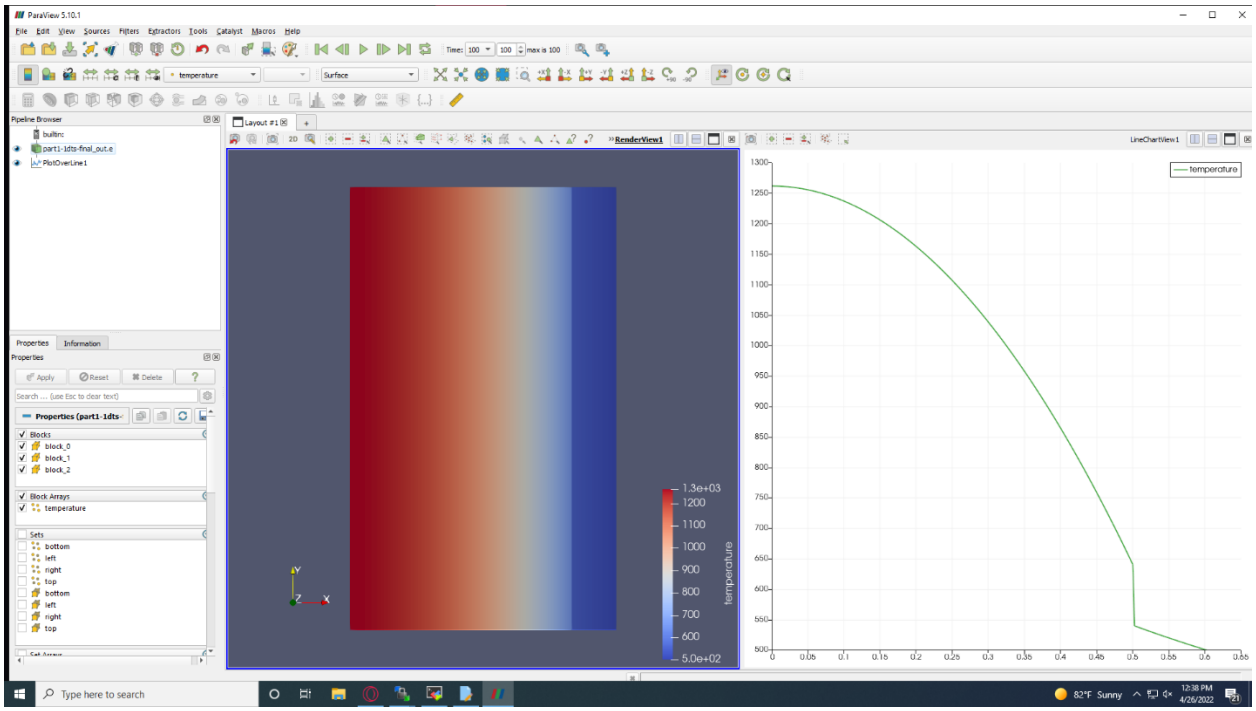

Figure 2. 1D Transient State Fuel Pin Temperature Profile

3. 2D Steady State

Figure 3 shows the simulated temperature profile for the fuel pin using the 2-dimensional steady state conditions. Following suit with the previous profiles, the gradient has a similar parabolic shape. The centerline temperature is 782 K.

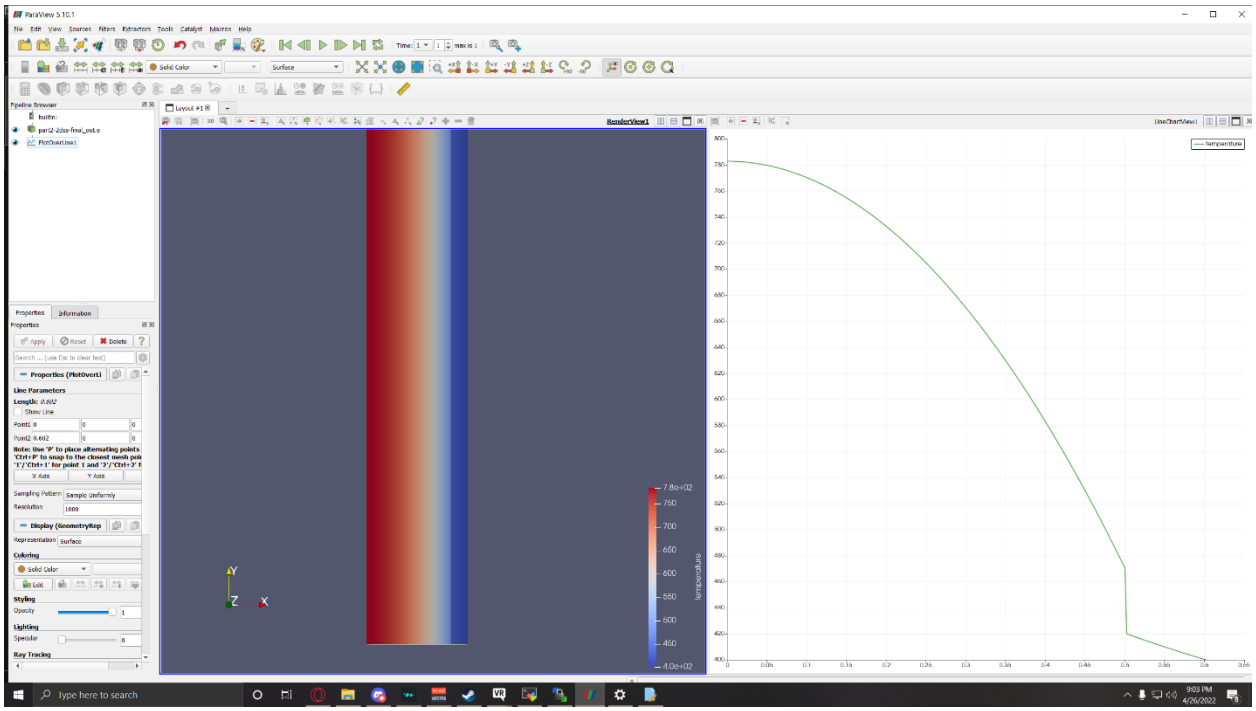

Figure 3. 2D Steady State Fuel Pin Temperature Profile

4. 2D Transient State

Figure 4 shows the simulated temperature profile for the fuel pin using the 2-dimensional transient state conditions. Following suit with the previous profiles, the gradient has a similar parabolic shape. The centerline temperature is 910 K at 100 seconds.

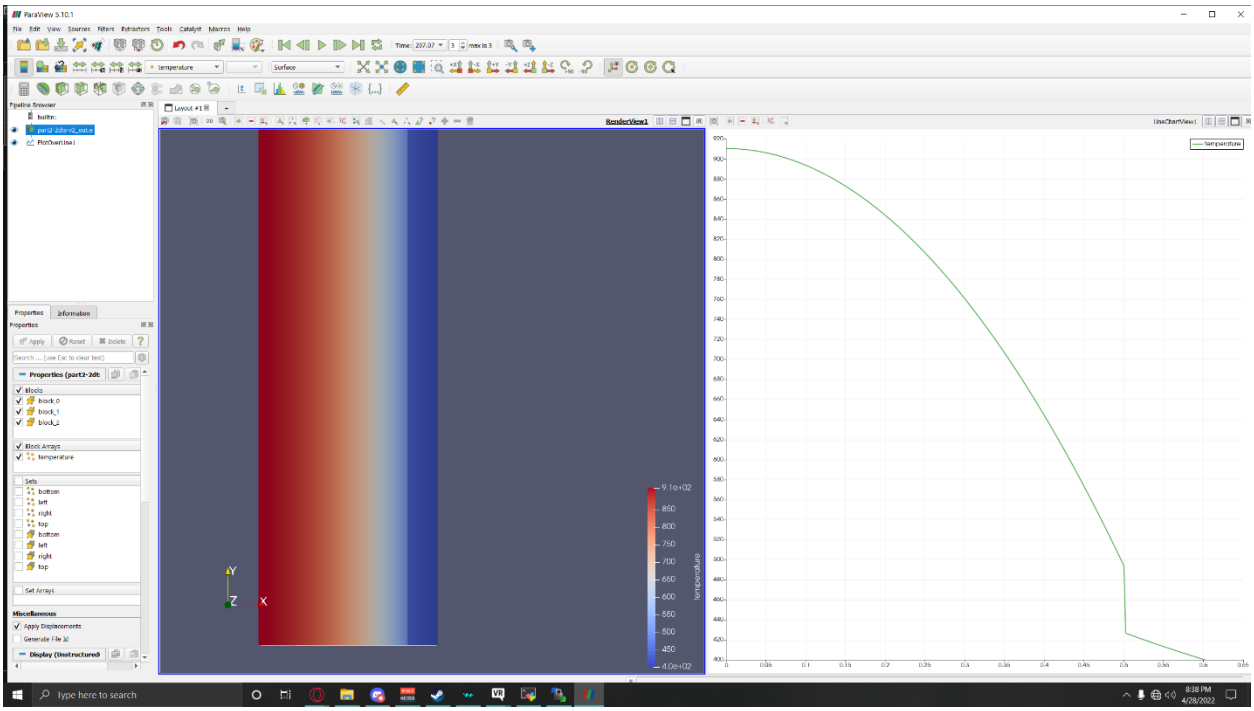

Figure 4. 2D Transient State Fuel Pin Temperature Profile

Conclusion

The 1D transient state showed the highest centerline temperature of the simulations, likely as a result of a higher initial temperature condition. There are likely some errors in the formation of these scripts, resulting in somewhat varying results between the profiles.

References

1. Aagesen, L., Zhang, Y., Schwen, D., Bai, X., Chakraborty, P., Biner, B., Yu, J., Jiang, C., Beeler, B., Jiang, W., Tonks, M., Ahmed, K., & Millet, P. (n.d.). Overview of the MOOSE Framework and Applications to Materials Science . Retrieved April 30, 2022, from https://icmed.engin.umich.edu/wp-content/uploads/sites/176/2016/06/md_lecture2016.pptx

2. Lamarsh, J. R., & Baratta, A. J. (2018). Heat Flow By Conduction. In *Introduction to Nuclear Engineering* (3rd ed., pp. 417–417). essay, Pearson Education, Inc.