MOOSE Project Part II

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NE 533: Nuclear Fuel Performance

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Chapter 1

Introduction

In the rapidly evolving field of nuclear energy, the optimization of fuel rod design remains an important concern for enhancing efficiency and safety within Pressurized Water Reactors (PWRs). The MOOSE (Multiphysics Object-Oriented Simulation Environment) project designed for completion of 'NE 533: Nuclear Fuel Performance' builds upon foundational analyses to understand thermal behaviors exhibited within a nuclear fuel pin. This segment of the project is dedicated to a comprehensive study of temperature profiles across various axial positions within a fuel rod, employing the MOOSE framework to simulate conditions reflective of operational PWR environments.

The dimensions of the fuel pin, including the fuel itself, the gap, and the cladding, are critically considered, alongside assumed values for thermal conductivities, to establish a realistic model. A specific focus is placed on the axial temperature distribution of the coolant, where coolant inlet temperature is 500 K, and the linear heat rate (LHR) at fuel centerline is 350 w/cm, aiming to uncover the axial location of peak centerline temperature.

To facilitate this analysis, the project assumes reasonable values for key parameters such as thermal conductivities, flow rates, and heat capacities, enabling a detailed simulation of temperature profiles at axial positions of 0.25 m, 0.5 m, and 1 m.

This report presents the findings from Part 2 of the MOOSE Project, incorporating insights gained from Part 1, and further refining the understanding through the choice of materials, mesh details, and the resolution of previously identified issues.

Chapter 2

Methodology

This section outlines the systematic approach adopted in this part of the project to analyze the thermal behavior within a nuclear fuel pin. The study is designed to simulate temperature profiles across various axial positions within a fuel rod, leveraging the capabilities of the MOOSE framework. The methodology encompasses the selection of materials, determination of thermal properties, equations which have been used, computational mesh design, and the implementation of boundary conditions reflective of operational conditions in PWRs.

2.1 Selection of Materials and their Properties

The fuel rod analyzed in this study consists of three primary components: the nuclear fuel, the gap, and the cladding. The dimensions specified for these components are a fuel radius of 0.5 cm, a gap thickness of 0.005 cm, and a cladding thickness of 0.1 cm, with the entire rod extending to a length of 1 m. Table 2.1 shows all of the materials that have been used with their respective properties.

Table 2.1: Selected Materials and their Properties

Materials	Region	Heat Capacity $(J/g-K)$	Thermal Conductivity $(w/cm-K)$
UO_2	Fuel	0.33	Temperature Dependent
Zr	Cladding	0.17	0.35

Here, thermal conductivity of UO_2 as a function of temperature has been considered which can be expressed as:

$$k(T) = \frac{1}{3.8 + 0.0217 \times T} \tag{2.1}$$

where, T is temperature and $k(T)$ is thermal conductivity as a function of temperature.

2.2 Equations and other Parameters

Neutron flux varies axially, so does the linear heat rate (LHR). Let, a fuel rod which has a length of $2Z_0$, so the midpoint is Z_0. Then, the equation for axial LHR can

be expressed by equation 2.2:

$$LHR\ (\frac{z}{Z_0}) = LHR^{\circ}\ cos\ [\ \frac{\pi}{2\gamma}\ (\frac{z}{Z_0 - 1})\ ] \tag{2.2}$$

Here, LHR° is the midpoint linear heat rate. A typical value for γ is 1.3 which reduces $\frac{\pi}{2\gamma}$ to 1.2. Coolant temperature varies axially as well which can be expressed by equation 2.3:

$$T_{cool} - T_{cool}^{in} = \frac{1}{1.2}\frac{Z^{\circ} \times LHR^{\circ}}{\dot{m}C_{pw}}\left\{sin(1.2) + sin\left[1.2\left(\frac{z}{Z^{\circ} - 1}\right)\right]\right\} \tag{2.3}$$

Here, T_{cool} is coolant temperature varying axially, T_{cool}^{in} is the coolant inlet temperature, $\dot{m}$ is mass flow rate and C_{pw} is specific heat capacity of coolant which is water.

Table 2.2 refers to the parameters used in equations 2.2 and 2.3.

Table 2.2: Given/Assumed Parameters

Parameter	Given/Assumed	Value	Unit
Linear heat rate, LHR	Given	350	w/cm
Coolant inlet temperature, T_{cool}^{in}	Given	500	K
Coolant flow rate, $\dot{m}$	Assumed	0.24	kg/s
Specific heat capacity of ccolant, C_{pw}	Assumed	4200	$J/kg - K$

2.3 Mesh Design

A structured mesh was carefully designed to capture the complexities of the fuel rod geometry, ensuring sufficient resolution in areas of interest. Mesh sensitivity analysis was conducted to ascertain the impact of mesh density on simulation accuracy. The detailed information on mesh convergence analysis will be included at the results and discussion section.

Side sets between the fuel and cladding subdomains were set up to delete the gap region which was included in the previous segment. Then, a thermal contact block was set up to include the gap heat transfer. Here, gap thermal conductivity was assumed as 0.0026 $w/cm - K$.

Chapter 3

Results & Discussion

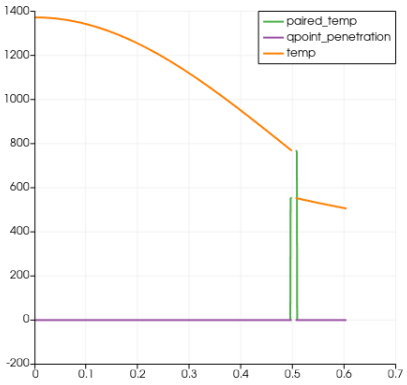
One of the issues that was in the previous part of the project was 'use of a very refined mesh'. Mesh convergence analysis was not done in the previous segment of the project and it has been addressed in this part. The process of mesh convergence involves decreasing the element size and analysing the impact of this process on the accuracy of the solution. Typically, the smaller the mesh size, the more accurate the solution as the behavior of the design or product is better sampled across its physical domain. Goal here is to achieve the result with a coarse mesh which is closer to the result achieved by a very refined mesh. Table 3.1 shows the results obtained at various mesh sizes. The result obtained from $nx \times ny = 1000 \times 1000$ has been assumed as standard and the deviations have been calculated with respect to that. Axial location for peak temperature at $nx \times ny = 150 \times 7$ is around 57 cm which is not representative of the results obtained at finer mesh structures, so deviation has not been calculated at this mesh size. Considering the deviation, $nx \times ny = 200 \times 300$ has been considered for the analysis.

Table 3.1: Analysis of Mesh Convergence

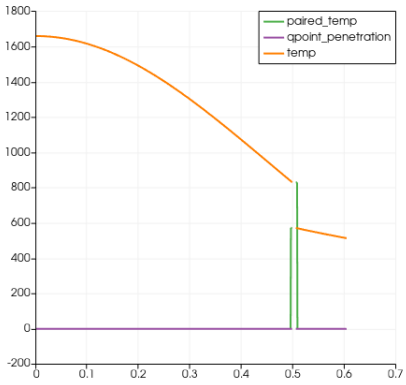
$nx \times ny$	Axial location for peak temperature (cm)	Temperature (K)	Deviation (%)
150×7	57	1507.23	N/A
150×200	51	1510.4	6.6
200×300	51	1659.87	2.6
200×500	51	1659.87	2.6
1000×1000	51	1616.52	-

Fig. 3.1 shows temperature profiles at different axial positions. The results express the trend of temperature rising from $z = 0$ to fuel centerline and then falling to a lower level at $z = 1$ which is expected. In all graphs, the presence of the sharp drop-off in the temperature profile near the edge of the fuel suggests a consistent thermal boundary where the heat is being transferred from the fuel to the coolant, cladding or other mediums.

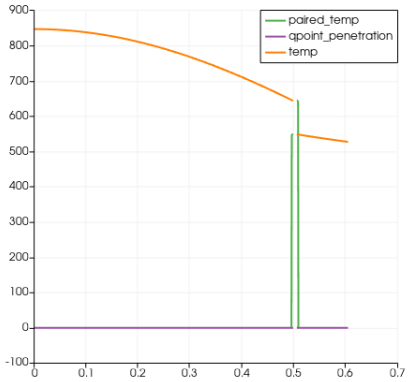
Fig. 3.2 depicts the axial position for peak fuel centerline temperature. It has been found at $z = 0.51$. Ideally, it should have been around $z = 0.6$. The deviation from the ideal result can be due to many reasons. Flow rate can be adjusted to simulate a more ideal result. Nonetheless, the temperature profile, if compared with the profile obtained from part I, seems reasonable. The peak centerline temperature was around 1758 K in part I and the result of part II agrees well with it.



(a) $z = 0.25$

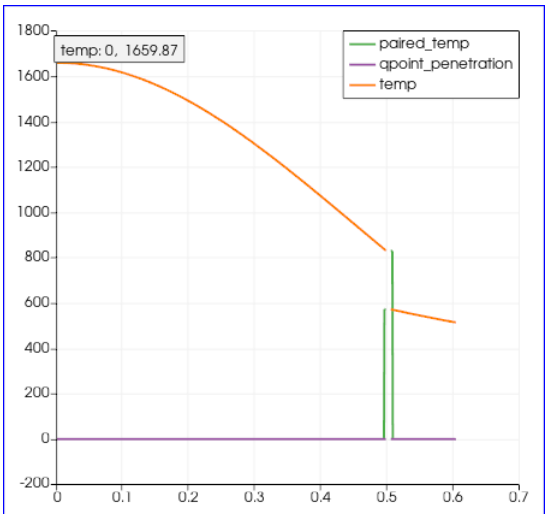


(b) $z = 0.5$

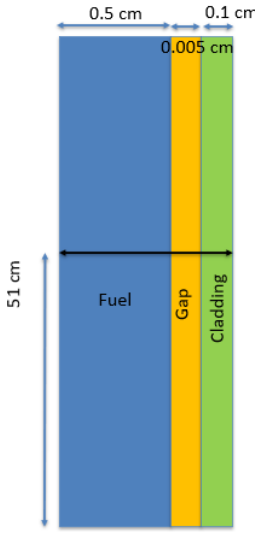


(c) $z = 1$

Fig. 3.1: Temperature profiles at different axial positions



(a) Temperature profile at $z = 0.51$



(b) Schematic diagram of the fuel pin

Fig. 3.2: Axial location of peak fuel centerline temperature

Chapter 4

Conclusion

Through the simulation of temperature profiles at axial positions $z = 0.25, z = 0.5$ and $z = 1$, a mapping of thermal behavior axially throughout the fuel has been established. With a coolant inlet temperature (T^{in}_{cool}) set at 500 K and a linear heat rate at fuel centerline, LHR° of 350 W/cm, the simulations have pinpointed the axial location of peak centerline temperature, thereby identifying potential hot spots and regions of thermal significance.

The temperature profiles across the different axial positions have remained consistent with the anticipated distribution of heat within a fuel rod. The peak temperature at almost the mid-length (z=0.51) suggests a higher thermal load in this region, aligning with the core's expected power peaking factors. This central hot spot necessitates further attention to ensure the integrity of the fuel rod over its operational life.