1. Introduction

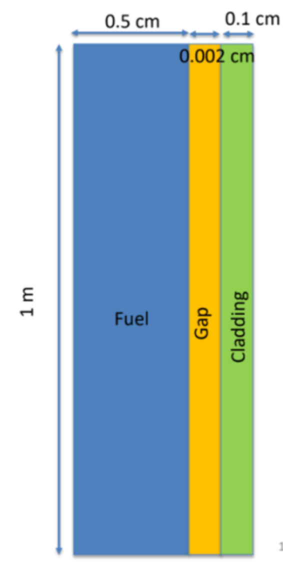

Figure 1 Fuel rod dimensions

This project uses MOOSE framework to calculate the temperature gradient using heat conduction module and to calculate the thermal stresses using the tensor mechanics module along the fuel rod shown in Figure 1. UO_2 [1] is selected as fuel material with thermal conductivity ($k_f = 0.03W/(cm.K)$). The Helium gap thermal conductivity ($k_g = 0.0026W/(cm.K)$). The cladding material selected for our simulation is Zirconium[1] with thermal conductivity ($k_c = 0.17W/(cm.K)$). The simulation is conducted on 3 parts. the simulation is in 2-D in RZ coordination, in part 1 aims to calculate temperature gradient over a fuel pellet using steady state and transient state, given an outer cladding temperature of 600K and pellet height equals $1cm$. Part 2 calculates the temperature gradient of the coolant along a fuel pin, getting the centerline temperature profile at z = 25cm, 50cm and100cm. (noted that the problem doesn't explicitly show z units). and getting the z-point corresponding to the highest centerline temperature. In part 3 the stresses resulting from the thermal expansion are calculated and shown in the results section.

2. Results

2.1 Part 1: Temperature Profile across the fuel pellet

a) Steady State

The simulation results in a centerline temperature of 1693.23 Kelvin, while the analytical solution shows a centerline temperature of 1679.6 Kelvin. In Figure 2, the curve shows how the temperature decreases with the pellet radius till it reaches the outer cladding temperature (600 K).

b) Transient State

The result obtained shows a centerline temperature of 1069.11, and Figure 3 shows 4 timesteps (t=18 sec, t=26 sec, t=75sec, and t=100sec) as LHR is a function of time governed by Eq (1) .

$$LHR = 500 \times (\frac{t}{100})^{0.5} \times (1 - \frac{t}{100})^4 + 150 \; (1)$$

The material properties are defined for each block using HeatConductionMaterial which identifies the thermal conductivity and specific heat and GenericConstantMaterial to set the density values [2] for the transient state to calculate the time derivative heat equation. However, in the steady state thermal conductivity only is needed to solve the heat transfer equation. Figure 4 shows the change of centerline temperature with time at z=0.5 cm

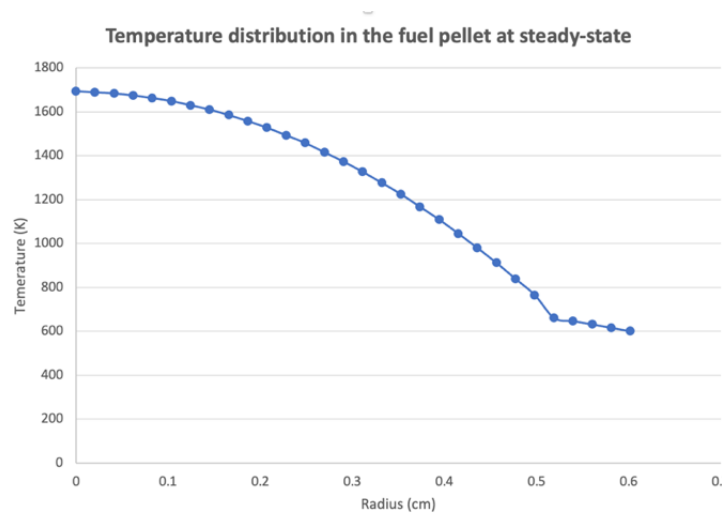

Figure 2 Temperature profile in the fuel rod at steady state

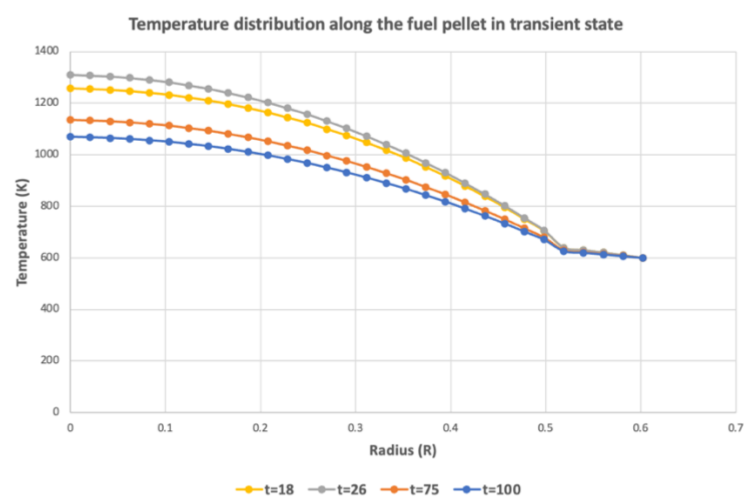

Figure 3 Temperature profile in the fuel pellet with different time

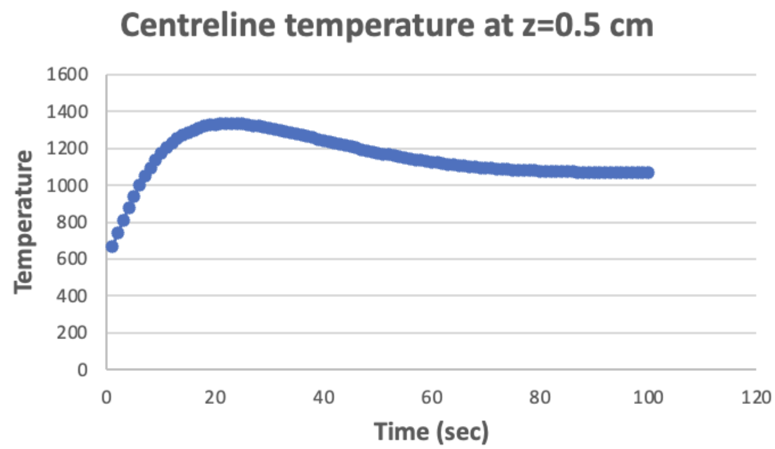

Figure 4 Centerline temperature profile with time

2.2 Part 2: Temperature gradient of the coolant along a fuel pin

The simulation is performed in a steady state and transient state indicating the location of the highest centerline temperature. The given coolant is water [1] with flow rate $m^{\cdot} = 0.3\ kg/s$, Inlet temperature = 500K, and heat capacity $c_p = \frac{4200J}{kg}.K$. The water heat transfer coefficient is 2.65 W/$cm^2K$and the initial linear heat rate is 350 W/cm.

a) Steady State

The simulation results in the outlet coolant temperature $T_{cool} = 1650.15K$ at the end of the simulation and the temperature profile along the fuel pellet radius at z = 0.25cm, 0.5cm and 1cm in Figure 5 using Fourier heat transfer equation. Figure 6 illustrates the location of peak centerline temperature, to be around the middle of the fuel rod which is z =50cm.

b) Transient State

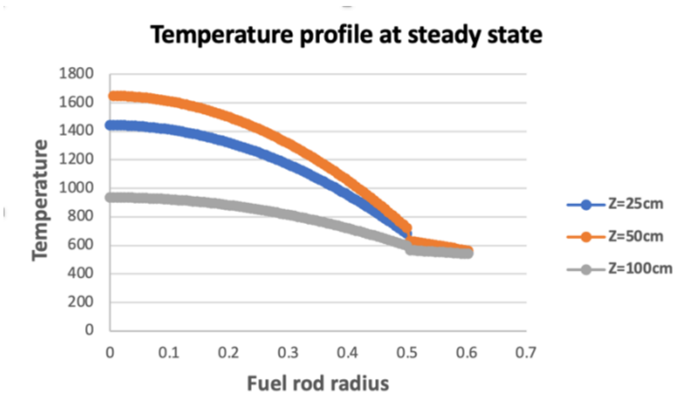

Figure 5 Temperature profile along the fuel rod at different z points

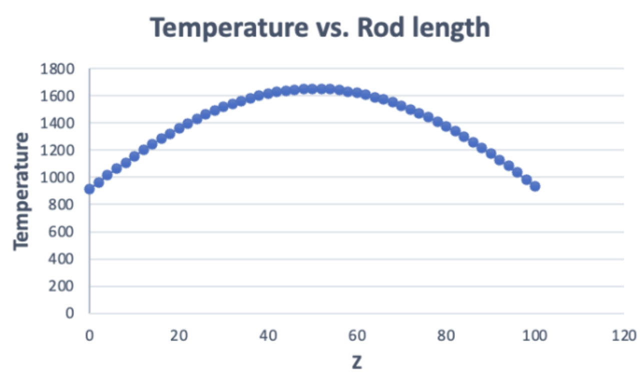

Figure 6 centerline temperature along the fuel rod length

Figure 7 shows the centerline temperature varying with time at different locations of along the fuel rod. Figure 8 shows the location of the peak centerline temperature at time = 100sec.

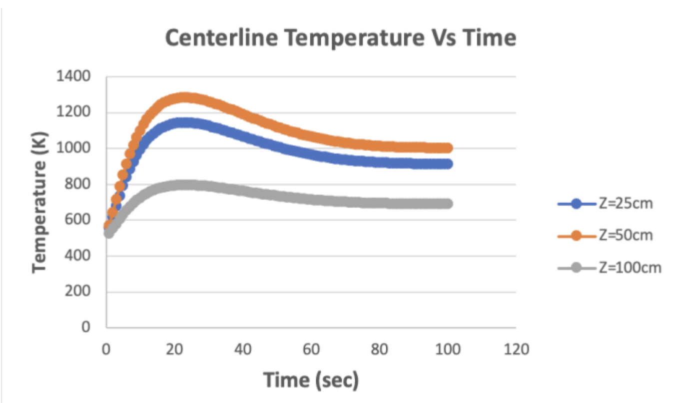

Figure 7 Centerline temperature with time at different z points

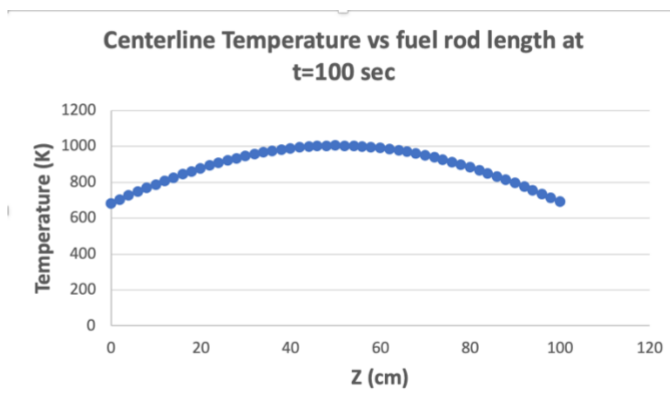

Figure 8 centerline temperature along the fuel rod length

2.3 Part 3: Thermal stresses in the fuel pin

In this part, we are only concerned with the fuel, so the clad and gap meshes are ignored and the fuel surface temperature is set as 633k calculated from part 1 for the constant LHR value.

Three different codes are performed to calculate the stresses corresponding to different LHRs. The elastic constant was assumed to be 200 GPa and Poisson's ratio to be 0.34 with thermal expansion coefficient equals $11x10^{-6}$1/k [3]. All three codes are conducted as a transient as this the only case MOOSE calculate the stresses. However, only one code has an LHR as a function of time.

A new mesh is added to this code "Pin" to fix a point of the fuel mesh so the stresses resulted from the thermal expansion doesn't rotate or translate to negative x or y directions. The boundary conditions also prevent the translation in the negative direction of y and x, and the stresses are calculated at the middle of the fuel rod at z=50 cm.

a) Constant LHR with Temperature-dependent thermal conductivity

Using AnisoHeatConductionMaterial to provide the thermal conductivity which is governed by $k(T) = k_{0x}\left(1+\propto (T - Tref)\right)$[4], where $k_{0x} = \frac{1}{A+BT}$, $A = 3.8$, B= 0.0217 [5] a python code was conducted to calculate a fitted value for k_{0x} and $\propto$
$k_{0x} = 0.713$ and $\propto = -0.000416$, while $Tref$ was assumed to be zero.

Figure 9 , 10 and 11 show the thermal stresses and as shown stress_xx corresponds to the radial stress , stress_yy corresponds to the axial stress and stress_zz corresponds to the hoop stress

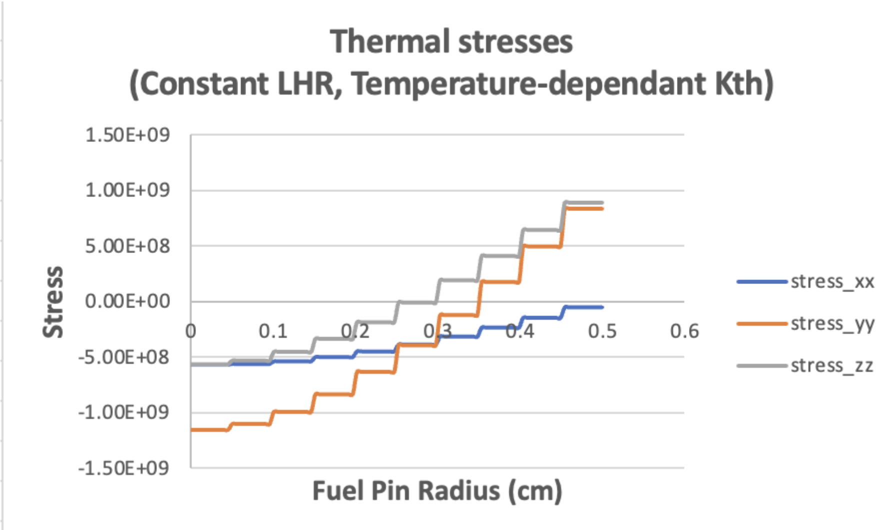

Figure 9 Thermal stresses variations with fuel radius

b) Axially variant LHR with constant thermal conductivity

LHR follows this equation

$$LHR(\frac{z}{Z_0}) = LHR^0 \cos\left(\frac{\pi}{2\gamma}\left(\frac{z}{Z_0} - 1\right)\right)$$

where $LHR^0 = 350 \frac{w}{cm}$,with the thermal conductivity used in part 1 and part two.

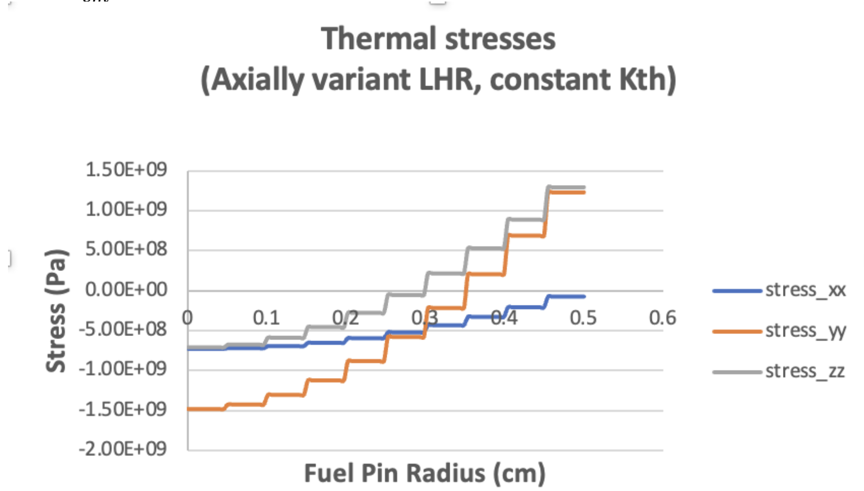

Figure 10 Thermal stresses variations with fuel radius

c) Axially and Time Variant LHR with constant thermal conductivity

LHR follows these equations

$$LHR(\frac{z}{Z_0}) = LHR^0 \cos\left(\frac{\pi}{2\gamma}\left(\frac{z}{Z_0} - 1\right)\right), \text{ and}$$

$$LHR^0 = 500 \times (\frac{t}{100})^{0.5} \times (1 - \frac{t}{100})^4 + 150$$

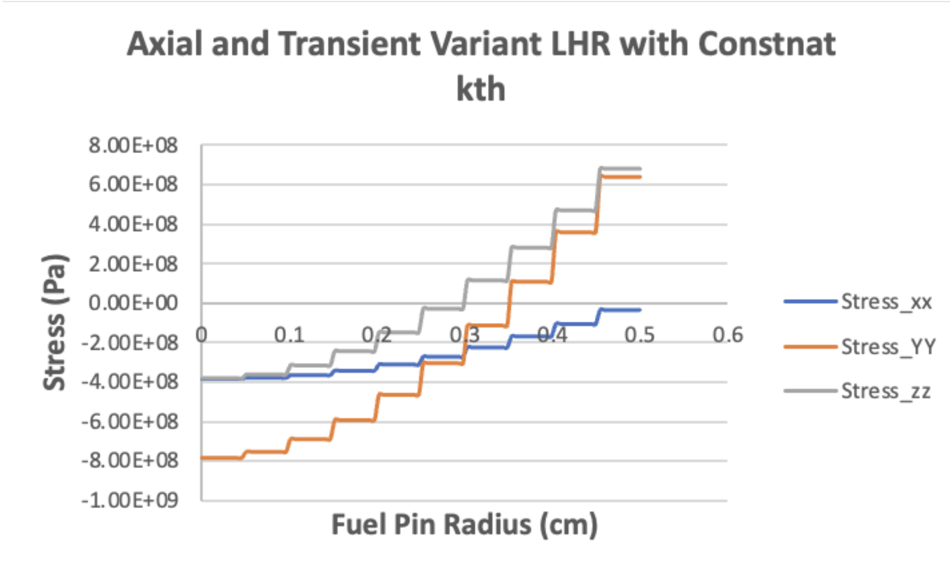

Figure 11 Thermal stresses variations with fuel radius

These results show that the maximum axial and hoop stress value corresponds to the constant thermal conductivity and axial variant LHR case, the value ranges from -1.5 GPa to more than 1 GPa and from -0.4 GPa to more than 1 GPa for the axial and hope stresses respectively, while the radial stress is varying in the same range for the three different cases.

3. References

1. [1] Lecture 4 heat analytical, fuel performance course 533
2. [2] Engineers Edge, L. L. C. (n.d.). Thermal conductivity, heat transfer. Engineers Edge - Engineering, Design and Manufacturing Solutions. Retrieved March 31, 2023, from https://www.engineersedge.com/heat_transfer/thermal-conductivity-gases.htm
3. [3] Lecture 9 thermomechanics, fuel performance course 533
4. [4] AnisoHeatConductionMaterial, MOOSE framework documentation

5. [5] Lecture 5 thermal conductivity, fuel performance course 533