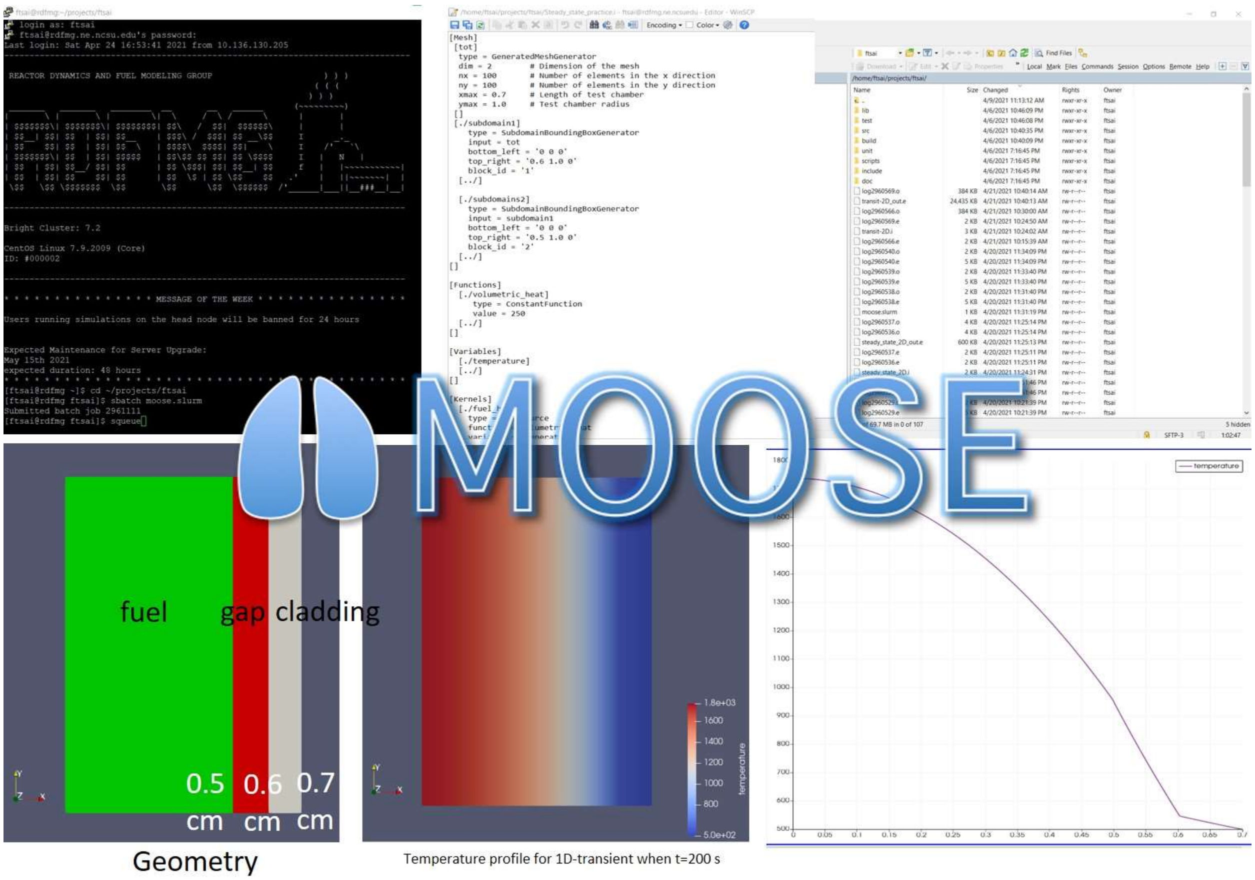
NE591 Nuclear Fuel Performance

Project: 1-D and 2-D Moose Project



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Introduction

From the viewpoint of Thermodynamics, energy is produced in a nuclear reactor and transferred to reactor coolant. If reactor coolant is not able to remove heat adequately, the fuel temperature will increase rapidly and go above the upper limit of the designed temperature. The fuel may melt, resulting in rupture of fuel cladding and fission gas release. A fuel performance code can simulate how heat transfer within the fuel and cladding. The objective of this project is to use MOOSE to predict the temperature profiles in the fuel, gap and cladding at steady state and transient state for both 1D and 2D cases.

Heat Transfer in a Reactor [1]

There are two fundamental different heat transfer processes for energy to remove from the reactor. One is conduction and the other is convection. Heat conduction involves heat transmission from one location to another in a body while heat convection transfers the heat to a moving liquid and gas.

Heat Conduction [1, 2]

Heat conduction equation is shown below.

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

where
k is thermal conductivity of the materials
q''' is volumetric heating rate generated in the fuel
ρ is density of the materials
C_p is specific heat capacity of the reactor materials

Simplified heat conduction equation can be obtained by assuming steady state of heat conduction, heat conduction is predominately in the radial direction and constant thermal conductivity.

	Steady state	Transient state
Fuel	For a cylindrical fuel with volumetric heat source q''': $$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_f\frac{\partial T}{\partial r}\right) + q''' = 0$$ where k_f is thermal conductivity of the fuel q''' is volumetric heating rate generated in the fuel Boundary conditions: (i) $T(r=0) = T_0$; $T(r=r_f) = T_f$ (ii) $\frac{dT}{dr}(r=0) = 0$	For a cylindrical fuel with volumetric heat source q''': $$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_f\frac{\partial T}{\partial r}\right) + q''' = \rho_{UO_2} C_p^{Fuel}\frac{\partial T}{\partial t}$$ where k_f is thermal conductivity of the fuel q''' is volumetric heating rate generated in the fuel ρ_{UO_2} is density of UO_2 C_p^{Fuel} is capacity of UO_2

	Steady state	Transient state
	$T_0 - T_f = \frac{q'''{r_f}^2}{4k_f}$	
Gap	There is no heat generation in the gap. $$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_g\frac{\partial T}{\partial r}\right) = 0$$ where k_g is thermal conductivity of the gap Boundary conditions: According to continuity of heat flux at the fuel surface. $q'' = -k_g\frac{dT}{dr}(r = r_f) = \frac{q'''r_f}{2}$ $T_g - T_f = -\frac{q'''{r_f}^2}{4k_g}\ln\left(\frac{r_g}{r_f}\right)$ where $r_g = r_f + t_g$; t_g is the gap thickness.	There is no heat generation in the gap. $$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_g\frac{\partial T}{\partial r}\right) = \rho_{gap}C_p^{gap}\frac{\partial T}{\partial t}$$ where k_g is thermal conductivity of the gap ρ_{gap} is the density of helium C_p^{gap} is the capacity of helium
Clad ding	There is no heat generation in the cladding. $$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_c\frac{\partial T}{\partial r}\right) = 0$$ where k_c is thermal conductivity of the cladding Boundary conditions: According to continuity of heat flux at the fuel surface. $q'' = -k_c\frac{dT}{dr}(r = r_f)\frac{q'''r_f}{2}$ $T_{CO} - T_{CI} = -\frac{q'''{r_f}^2}{4k_c}\ln\left(\frac{r_c}{r_g}\right)$ where T_{CO} is the temperature of outer cladding, T_{CI} is the temperature of inner cladding $T_{CI} = T_g$	There is no heat generation in the cladding. $$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_c\frac{\partial T}{\partial r}\right) = \rho_c C_p^{cladding}\frac{\partial T}{\partial t}$$ where k_c is thermal conductivity of the cladding ρ_c is the density of cladding $C_p^{cladding}$ is the capacity of cladding

Thermal properties of materials

1. Thermal conductivity of UO_2 fuel

Table.1showed the thermal properties of fuel rod and cladding at room temperature before irradiation.

Table.1 Thermal properties of materials of fuel rod and cladding at room temperature [3]

Material	*Density ρ (g/cm³) [kg/m³]*	*Specific heat C_p (J/g.K) [J/kg.K]*	*Thermal conductivity k (W/cm.K)*	*Thermal expansion coefficient α (K^{-1})*
UO_2	10.98 [10980]	0.33 [330]	0.037* [3.7]	1.45×10^{-5}
Zircaloy	6.5 [6500]	0.35 [350]	0.17 [1.7]	$5\text{–}10 \times 10^{-6}$
Steel	8.0 [8000]	0.5 [500]	0.17 [1.7]	9.6×10^{-6}

Mush [4] mentioned thermal conductivity of UO_2 fuel (k_f) is dependent of fuel temperature.

$$k_f = \frac{1}{11.8 + 0.0238T_f} + 8.775 \times 10^{-13}{T_f}^3$$

where k_f is thermal conductivity of UO_2 (W/cm-K); T_f is fuel temperature (K).
If T_f=500K, k_f = 0.0423W/cm-K.
If T_f=700K, k_f = 0.0354W/cm-K.

Rozhgar [2] indicated thermal conductivity of UO_2 is a function of temperature and burnup as shown in Fig.1.

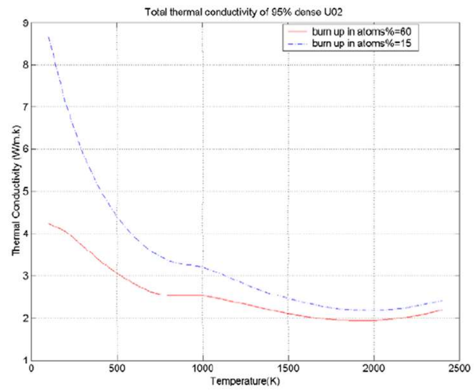


Fig.1 Thermal conductivity of UO_2

2.Thermal conductivity of gap

Assume helium existed in the gap when fabricated. Thermal conductivity of helium is dependent of temperature. [3]

$$k_{He} = 16 \times 10^{-4} \times T^{0.79} \left(\frac{W}{m} - K\right)$$

If T=500K, $k_{He} = 0.2169 \left(\frac{W}{m} - K\right)$

3.Thermal conductivity of cladding

Rozhgar [2] indicated thermal conductivity of Zircaloy-2 is a function of cladding temperature as shown in below equation and in Fig.2.

$$k_c = 7.51 + 2.09 \times 10^{-2}T - 1.45 \times 10^{-5}T^2 + 7.67 \times 10^{-9}T^3$$

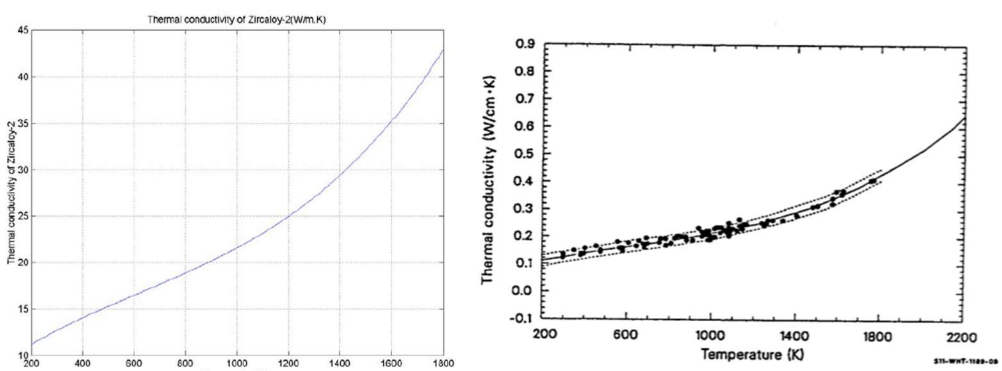


Fig.2 Thermal conductivity of Zircaloy-2 [2] [5]

According to the literature, calculate the thermal conductivity of the materials when the temperature is 500K. Assume all thermal properties are a constant in the given 1D and2D moose projects. Calculate helium density is shown as below [6].

So all we need now are the value of Helium pressure and (average) temperature inside the pellet-clad gap. Some typical value of those data for PWR fuel rods are as follow:

- p = 3 MPa
- T = 650 K

Calculate..

$$\rho = \frac{pM}{RT} = \frac{3\times10^{6}\times4.002602\times10^{-3}}{8.314472\times650} = 2.22185457985879 \text{ kg/m}^3$$

$$\rho = 2.22185 \text{ kg/m}^3$$

So Helium density inside pellet-clad gap is roughly about **0.00222185 g/cc**.

Table.2 Thermal properties used in the moose projects [2, 3, 6]

	Thermal conductivity (W/cm-K)	Specific heat capacity(J/g-K)	Density(g/cm^3)
Fuel	0.03	0.28	10.90
Gap	0.02169	5.193	0.0022
Cladding	0.15	0.35	6.525

Heat generation and boundary conditions functions

Table.3 Volumetric/Areal heating rate and boundary conditions for 1D and 2D moose projects

<table>
<tr><td rowspan="2"></td><td colspan="2">1D</td><td colspan="2">2D</td></tr>
<tr><td>Steady state</td><td>Transient state</td><td>Steady state</td><td>Transient state</td></tr>
<tr><td>Volumetric/Areal heating rate (W/cm^3)</td><td>250</td><td>150(1-Exp(-0.01t)) +250</td><td>250</td><td>150(1-Exp(-0.01t)) +250</td></tr>
<tr><td>Boundary conditions (i)</td><td colspan="2">T_{CO}=500K</td><td colspan="2">$T_{CO} - T_{cool} = \frac{LHR}{2\pi r_f h_{cool}}$
$T_{cool} - T_{cool}^{in} = \frac{Z_0 \times LHR^0}{1.2\,\dot{m}C_p^w}\{\sin(1.2) + \sin[1.2(\frac{z}{Z_0} - 1)]\}$
Assume $T_{cool}^{in} = 566K$, $C_p^w = 4.2\frac{J}{g-K}$
$Z_0 = 50\ cm; \dot{m} = 250\ g/s; h_{cool} = 2.5\frac{W}{cm^2 - K}$</td></tr>
<tr><td>Boundary conditions (ii)</td><td colspan="4">$\frac{dT}{dr}(r = 0) = 0$</td></tr>
</table>

Results

1. <u>1D-steady state</u>

Fig.3 shows temperature profile in the fuel pin for 1D steady state. The results show parabolic shapes in fuel while linear dependence in gap and cladding. Since the thermal conductivity of the gap is smaller than that of cladding, more rapid temperature decreases in the gap. The centerline temperature is 1318.59 K.

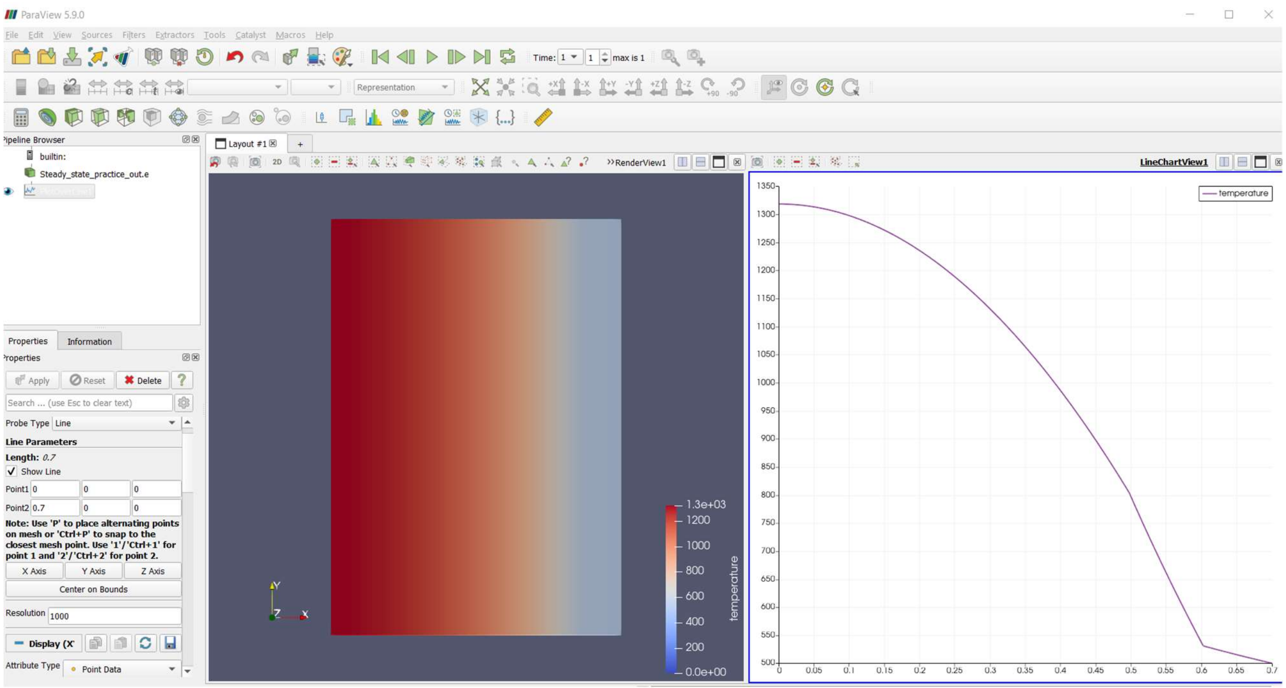


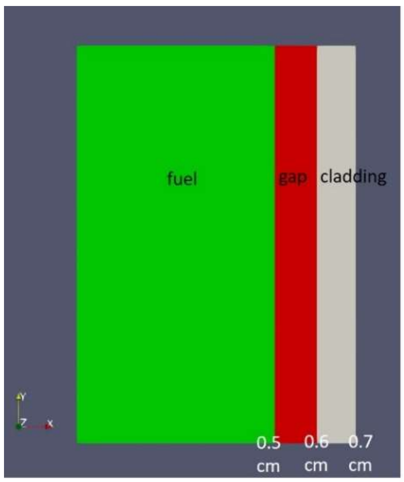
Fig.3 Temperature profile in the fuel pin for 1D steady state

Compare moose results with calculation results on analytical equations. They are pretty closed.

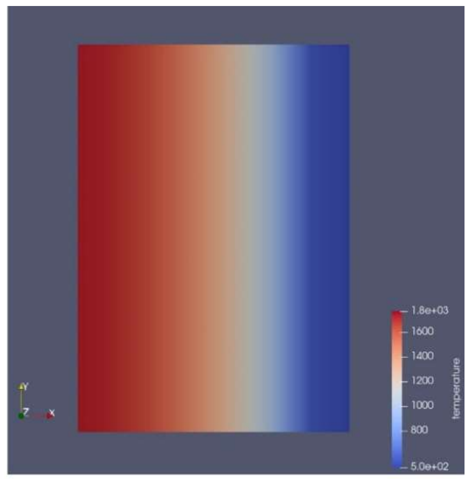
	Moose results	Calculation
$T_0 - T_{fuel}$	1318.59-793.929 =521.661 K	$\frac{q'''{r_f}^2}{4k_f} = \frac{(250\frac{W}{cm^3})(0.5\ cm)^2}{4 \times 0.03\frac{W}{cm-K}} = 520.83\ K$
$T_{fuel} - T_{gap}$	793.929-536.04 =257.89 K	$\frac{q'''r_f}{2h_{gap}} = \frac{q'''r_f}{2\frac{k_{gap}}{t_{gap}}} = \frac{(250\frac{W}{cm^3})(0.5\ cm)}{2 \times \frac{0.02169}{0.1}\frac{W}{cm-K}} = 288.15\ K$
$T_{gap} - T_{caldding}$	536.04-500 =36.04 K	$\frac{q'''r_f t_{cladding}}{2k_{cladding}} = \frac{(250\frac{W}{cm^3})(0.5\ cm)(0.1\ cm)}{2 \times 0.15\frac{W}{cm-K}} = 41.67\ K$

2. <u>1D-transient state</u>

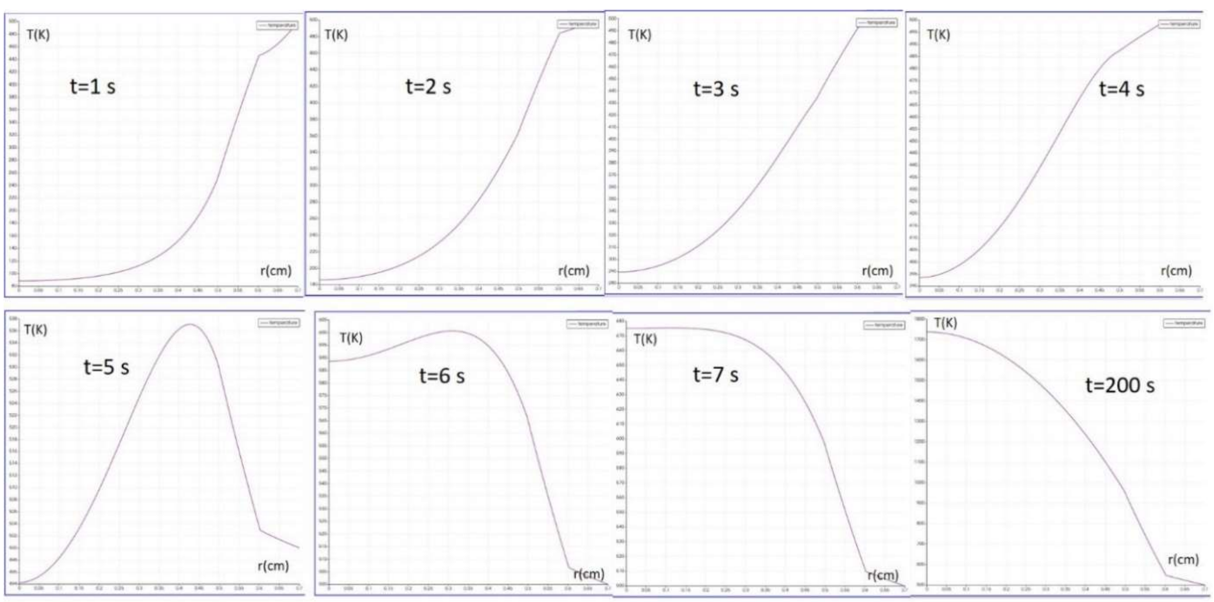
Fig.4 shows the temperature profile in the fuel pin for 1D transient state. In the beginning there is not much heat generated in the fuel. Since we assume the temperature of other cladding is 500K, the temperature profiles showed fuel temperature is less than cladding temperature when t=1~4 sec. As the time increases, fuel temperature increases immediately. When t=5 sec, the highest temperature exists on the surface of the fuel. After t=7 sec, the temperature profile shows the highest temperature happens in the centerline of the fuel. At t=200 s, the centerline temperature is 1765.99 K.



Geometry



Temperature profile for 1D-transient when t=200 s



1D-transient

Fig.4 Temperature profile in the fuel pin for 1D transient state

3. <u>2D-steady state</u>

Fig.5 shows the temperature profile in the fuel pin for 2D steady state.

At z=0 cm, centerline temperature is 1484.67 K.

At z=25 cm, centerline temperature is 1496.04 K.

At z=50 cm, centerline temperature is 1513.64 K.

At z=100 cm, centerline temperature is 1542.61 K.

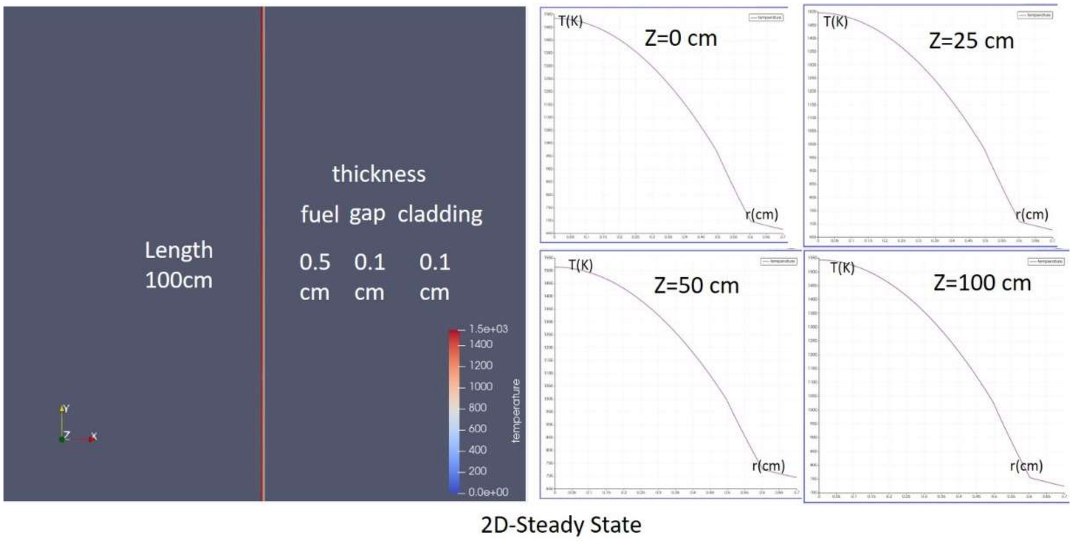


Fig.5 Temperature profile in the fuel pin for 2D steady state

Fig.6 shows the temperature profile of the outer cladding along z axis. Since the boundary conditions of outer cladding temperature is higher than 500K used for 1D case, the centerline temperature in 2D case is higher than that in 1D case.

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In[7]:= Plot[100 + 566 + ((1 / 1.2) * 50 * (250 * 2 * Pi * 0.5) / (4.2 * 250)) *
     (Sin[1.2] + Sin[1.2 * (x / 50 - 1)]), {x, 0, 100},
    PlotLabel → "outer cladding temperature vs. fuel length", AxesLabel → {"Z(cm)", "T(K)"}]
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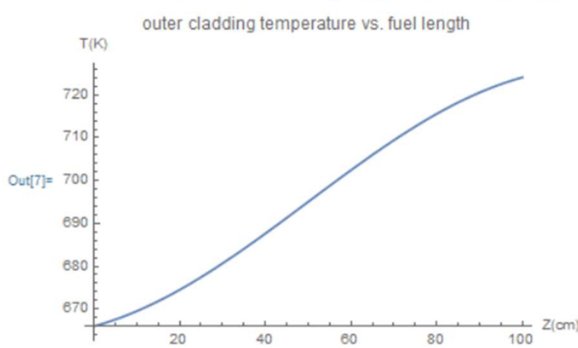


Fig.6 The temperature profile of the outer cladding along z axis (Plotted by Mathematica)

4. <u>2D-transient state</u>

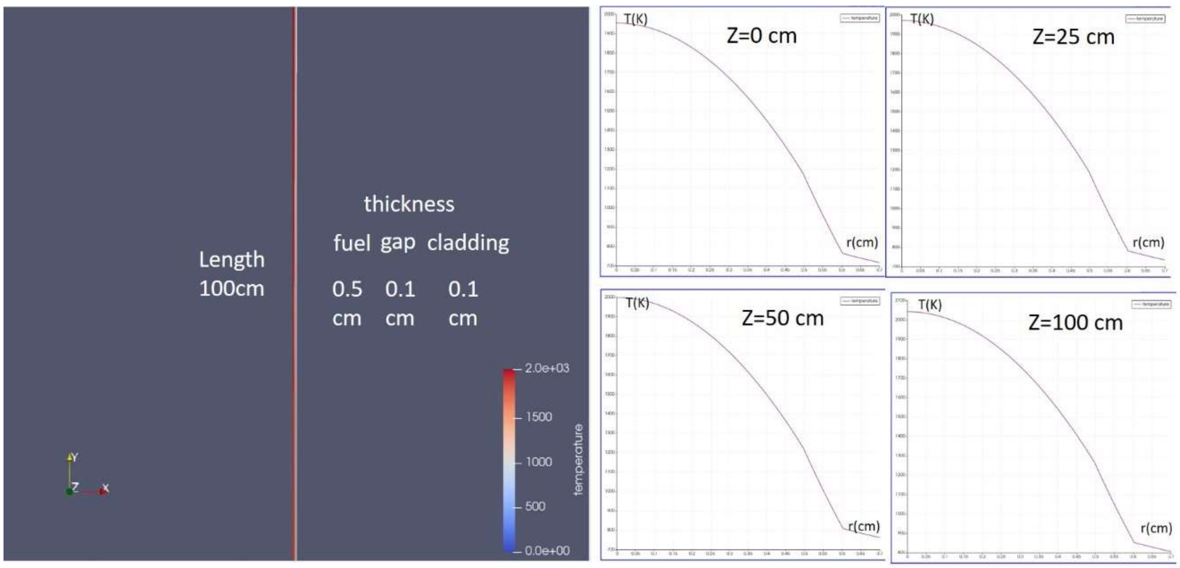
Fig.7 shows the temperature profile in the fuel pin for 2D transient state.

At z=0 cm, centerline temperature is 1954.74 K.

At z=25 cm, centerline temperature is 1971.89 K.

At z=50 cm, centerline temperature is 1998.46 K.

At z=100 cm, centerline temperature is 2041.21 K.



2D-Transient State when t=200 s

Fig.7 Temperature profile in the fuel pin for 2D transient state (t=200 s)

Fig.8 shows heat generation rates as function of time. Since the heat generation rates is higher than 250 (W/cm^3) used for steady state case, the centerline temperature in 2D-transient case is higher than that in 2D-steady state case.

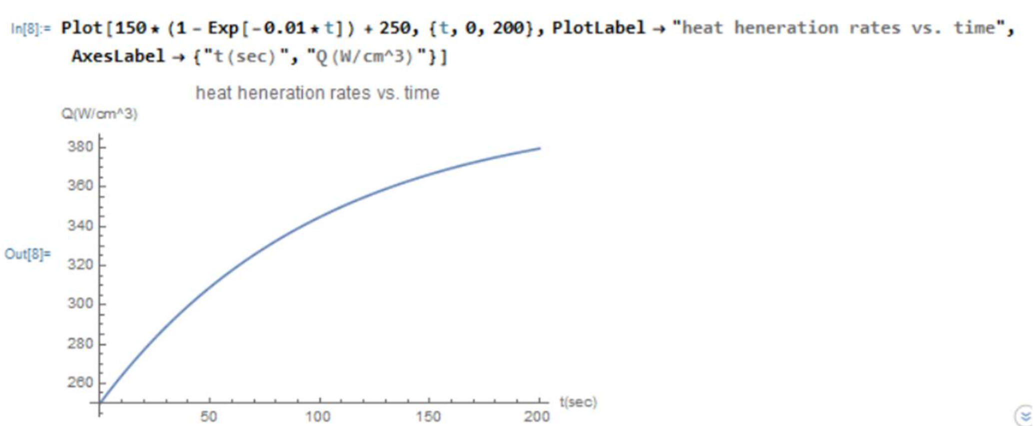


Fig.8 The temperature profile of heat generation rates as function of time (Plotted by Mathematica)

Conclusion

Fig.9 shows comparison results of temperature profiles for 1D and 2D steady state and transient state. The 2D transient result has higher temperature profile than others since not only the boundary conditions of outer cladding temperature but also heat generation rates are higher than other cases. The highest cladding temperature is around 800 K which is bound by the melting temperature of Zircaloy-2 of 1850℃ (2123 K) [7].

Furthermore, the highest centerline temperature is 2041.21 K which is less than the melting temperature of UO_2 2865℃ (3138 K). However, fuel is usually operated at much lower peak centerline temperature (less than 1673 K) [7].

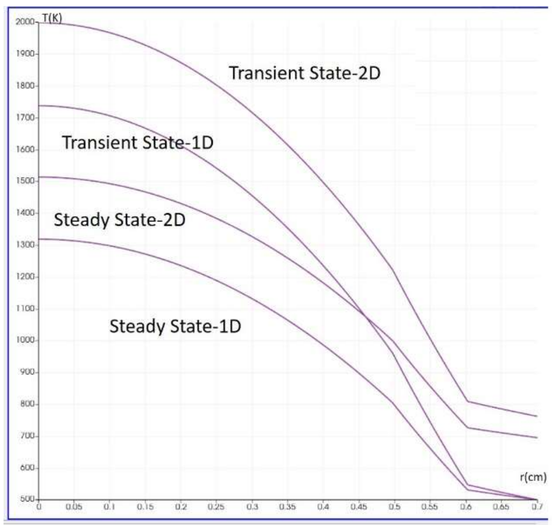


Fig.9 Comparison results of temperature profiles for 1D and 2D steady state and transient state

Reference

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7. Neil E. Todreas, M.K., *Nuclear Systems Volume I : Thermal Hydraulic Fundamentals, Second Edition.* 2011.