Simulation of steady state and transient heat conduction in fuel-gap-cladding systems using MOOSE

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1 Problem Descriptions

We have two fuel-gap-cladding systems. Both systems have 2-D geometries specifying the portion of each type of material. These geometries are axisymmetric, and they only differ in the axial height.

1.1 ”1-D” MOOSE Problem

Figure 1 specifies the dimensions of this problem. In this geometry, the fuel pellet radius is 0.5 cm. The width of both the gap and the cladding is 0.1 cm. It is assumed that the materials have constant thermal properties. The axial height for this system is 1 cm.

There are two boundary conditions for this problem. Firstly, Neumann boundary condition applies at the center of the fuel pellet, i.e., the spatial derivative of temperature is zero. The second boundary condition determines the outer cladding temperature, which is 500 K. As there is no spatial variance in the boundary conditions, the solutions do not have any axial variance. Consequently, this problem can be seen as a 1-D problem even though the geometry is 2-D.

This system is to be solved for steady state and transient conditions. The given volumetric heating rate for the steady state is 250 W/cm^2. For transient state, the volumetric heating rate is determined by the expression $Q = 150(1 - e^{-0.01t}) + 250$ W/cm^2.

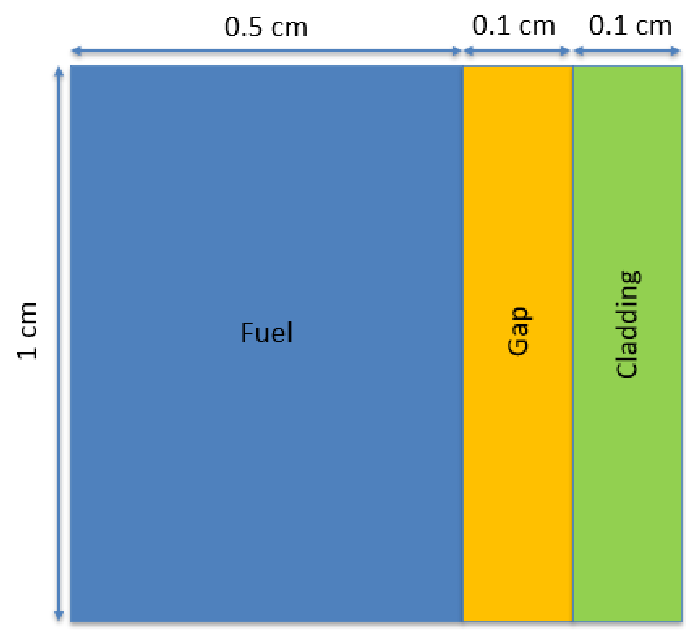

Figure 1: 1-D Moose Problem.

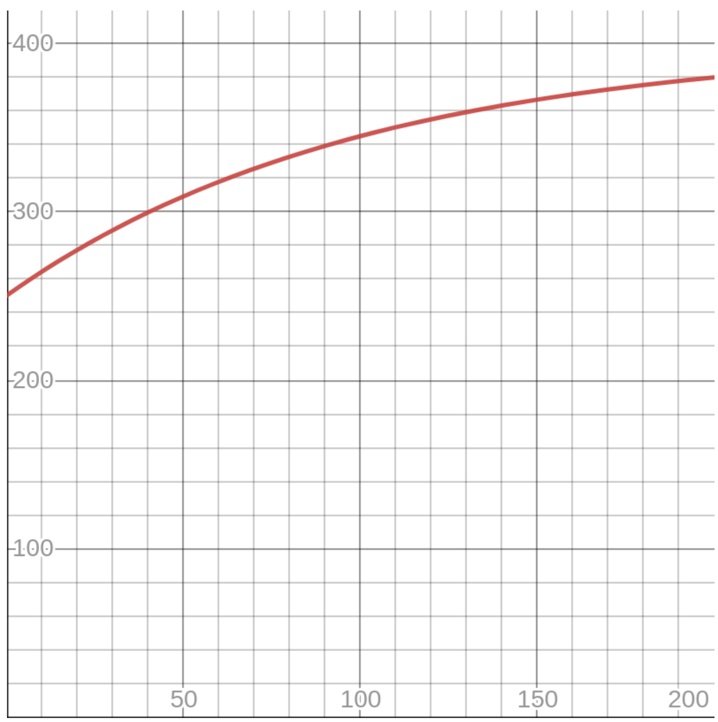

Figure 2: Temporally varying volumetric heat rate.

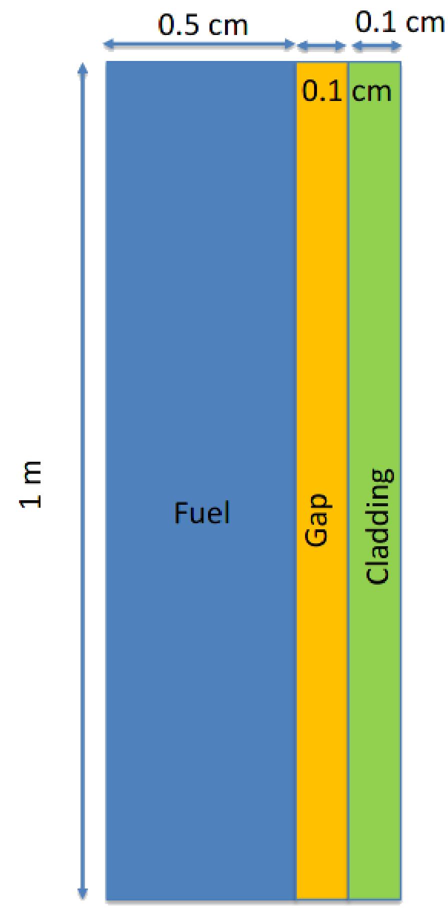

Figure 3: 2-D Moose Problem.

1.2 2-D MOOSE Problem

Figure 3 depicts the 2-D problem. This 2-D system has an axial height of 100 cm. All the other geometric properties for this system are similar with the 1-D system. This system is also to be solved for steady state and transient conditions.

The 2-D system also has Neumann BC for the centerline. However, the right boundary condition, which determines the outer cladding temperature, varies temporally and spatially for this problem. To be able to express cladding temperature as a function of space and time, we need to incorporate the spatial dependence of the linear heating rate and the temporal dependence of the volumetric heating rate.

2 Solution Approach

To solve for the systems described in the given problems, we need to solve the heat equation with appropriate boundary and initial conditions.

For our axisymmetric systems, the equation is

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial}{\partial r}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial}{\partial z}\right) + Q = \rho C_p \frac{\partial T}{\partial t}$$

The MOOSE program can solve such equations numerically with its built-in functions. It also utilizes finite element method to solve for spatial dependence and finite difference method to solve for temporal variation.

As a result, specifying the geometry, boundary conditions and the equation to solve is enough to produce solutions from MOOSE.

For the 2-D case, we also need to incorporate spatial and temporal dependence in our boundary condition. The following equations are utilized to come up with the expressions for the boundary conditions.

$$\begin{aligned}
(LHR)_{avg} &= \pi R^2 Q \\
(LHR)^0 &\approx 2(LHR)_{avg} \\
LHR &= (LHR)^0 \cos\left(\frac{\pi}{2\gamma}\left(\frac{z}{Z_0} - 1\right)\right) \\
T_{CO} &= T_{cool} + \frac{LHR}{2\pi R h_{cool}} \\
T_{cool} &= T_{cool}^{in} + \frac{1}{1.2}\frac{Z_0 \times (LHR)^0}{\dot{m} C_\rho}\left[\sin(1.2) + \sin\left(1.2\left(\frac{z}{Z_0} - 1\right)\right)\right]
\end{aligned}$$

where $\gamma \approx 1.3$ and Z_0 is half of the axial height. Also, $\dot{m}$ is the coolant flow rate, C_ρ is the specific heat of the coolant.

For the transient cases, we will solve the systems for 200 timesteps with $dt = 1$ for each.

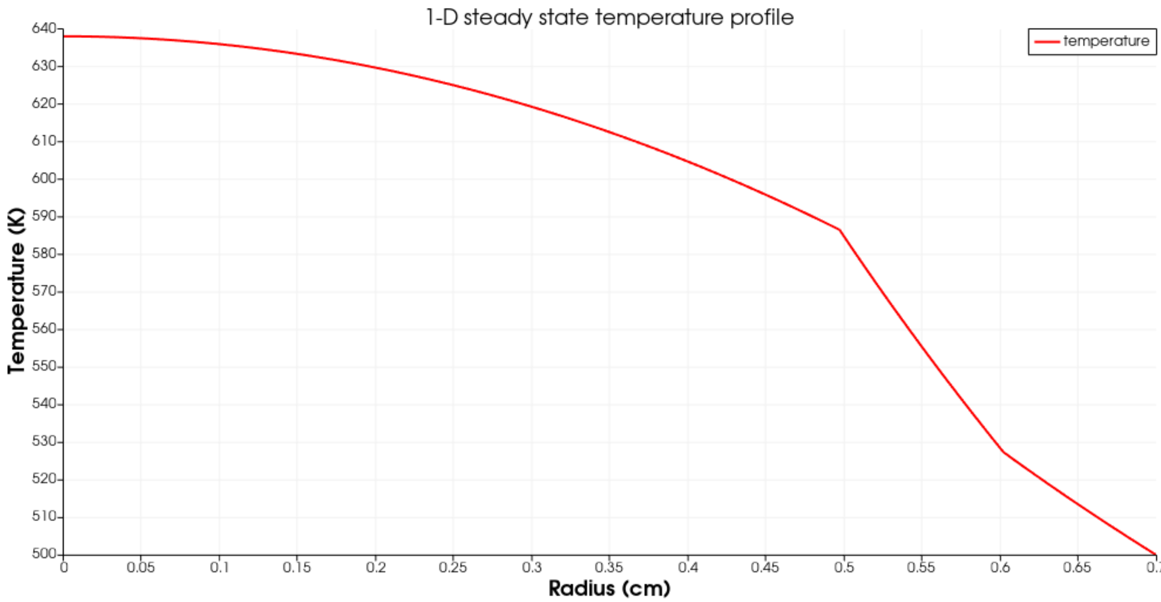

Figure 4: Steady state temperature profile for the 1-D problem.

3 Results

3.1 1-D Problem

Figure 4 shows the steady state temperature profile for the 1-D problem. The centerline has the maximum temperature. The temperature decreases slowly with increasing radius. Temperature drop in the gap and the cladding is almost linear. Also, the maximum temperature drop happens in the gap region, which is expected due to the gap's low thermal conductivity.

In Figure 5, we see the change of the centerline temperature with time. This curve follows the volumetric heat rate curve except in the very beginning. This is due to our choice of initial condition of 500 K. The centerline temperature jumps from the initial value to higher value commensurate with our boundary condition. After that the centerline temperature follows the trend of the volumetric heat rate almost exactly.

3.2 2-D Problem

Figures 6, 7 and 8 depict the temperature profiles of the 2-D problem at $z = 25, 50, 100$ cm . The curves follow the same trend as 4. The most significant variation is in the magnitude of the temperature. The temperatures for $z = 25$ cm and $z = 100$ cm are almost same, whereas the temperature for $z = 50$ cm has higher value. This behavior is well defined in the Figure

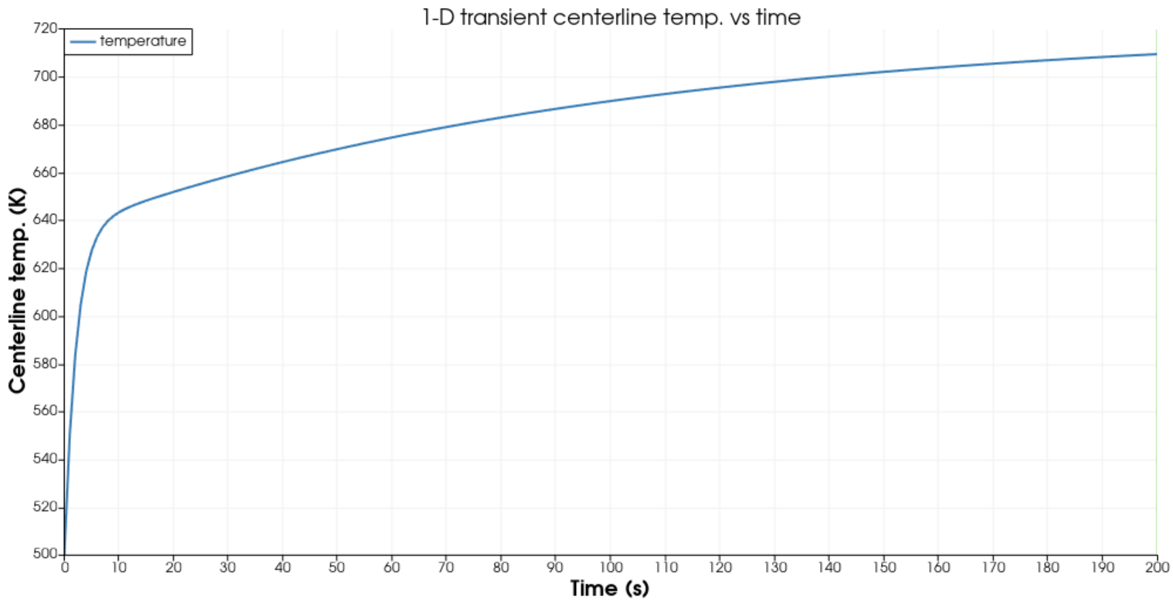

Figure 5: Temporal variance of centerline temperature of the 1-D problem.

9. From this graph, we also see that the peak centerline temperature is 691 K at $z = 64$ cm.

Figures 10, 11 and 12 show the centerline temperatures against time for $z = 25, 50, 100$ cm. These graphs are similar (also to Figure 5) except for the magnitude of the temperature.

We also notice that $z = 25$ and $z = 100$ cm have almost exact values, and $z = 50$ cm has higher temperatures. This trend is apparent in Figure 13, where we see the same behavior as in Figure 9. The peak centerline temperature here is 795 K, which occurs at $z = 62$ cm.

4 Conclusion

The trends of the results from the MOOSE program agree to the general profiles of mainstream nuclear core geometries.

We notice that the temperature drop in fuel is almost parabolic, whereas the drops in gap and cladding is almost linear. We also see that the temporal variation in centerline temperatures follows the volumetric heat rate, and the axial variation follows the boundary condition or the outer cladding temperature. All these results are intuitive as well.

As such, the MOOSE program can provide numerical solutions to heat conduction problems of detailed nuclear core geometries with very little computational overhead.

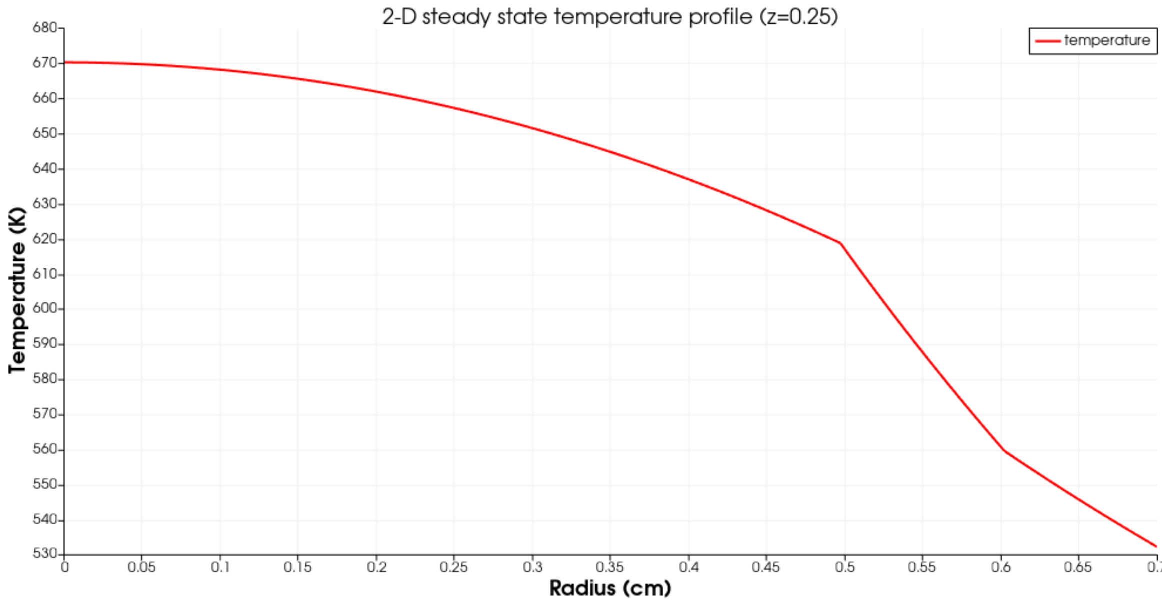

Figure 6: Steady state temperature profile for the 2-D problem at z=0.25 m.

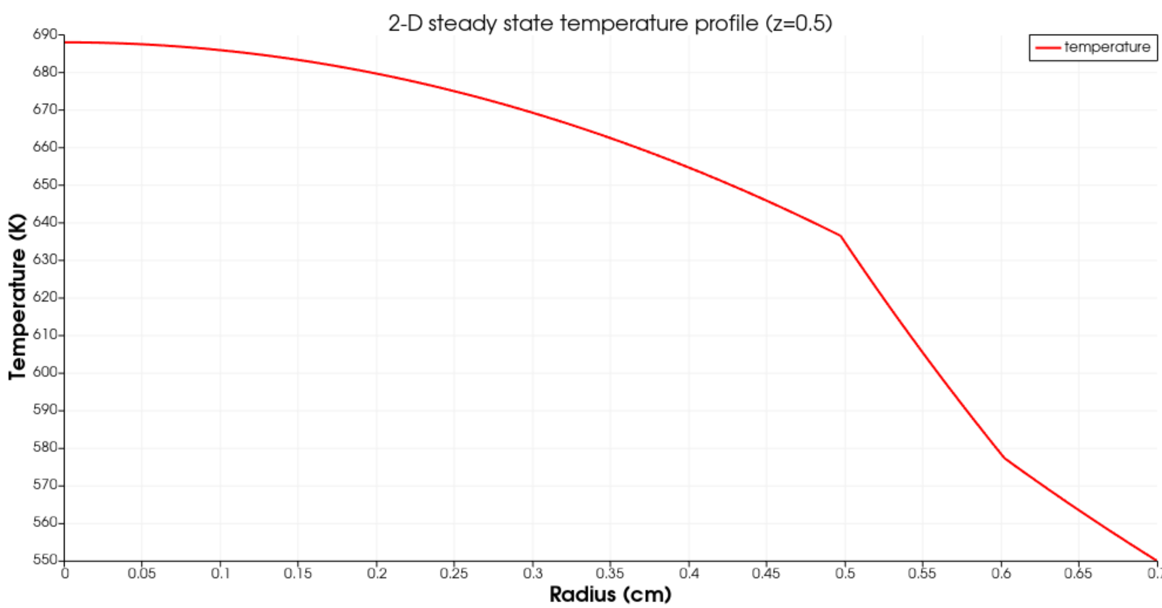

Figure 7: Steady state temperature profile for the 2-D problem at z=0.5 m.

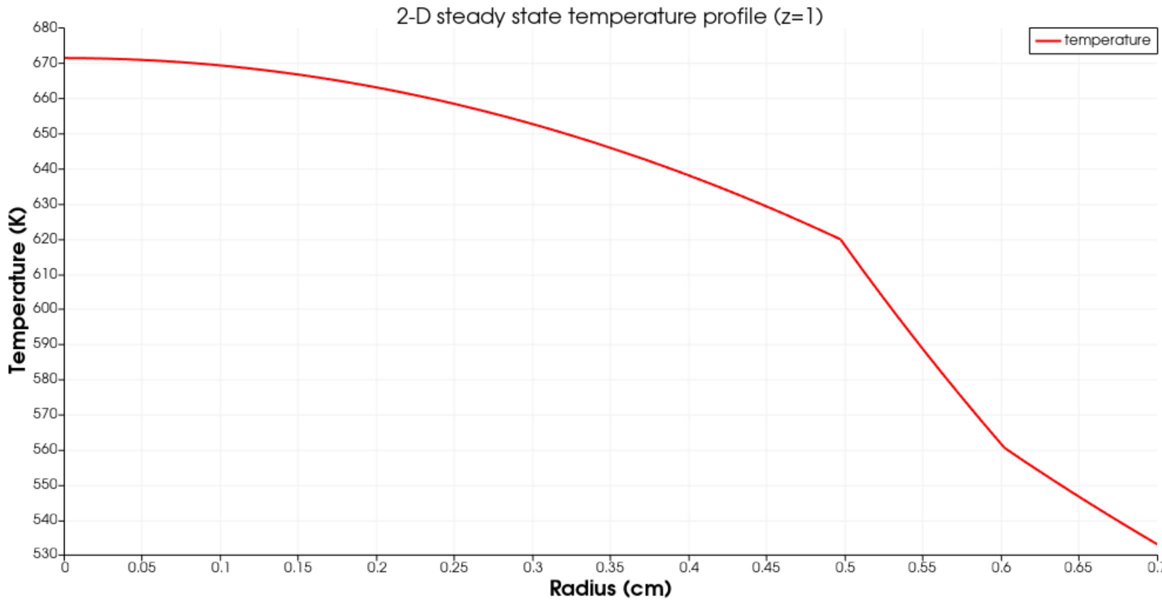

Figure 8: Steady state temperature profile for the 2-D problem at z=1 m.

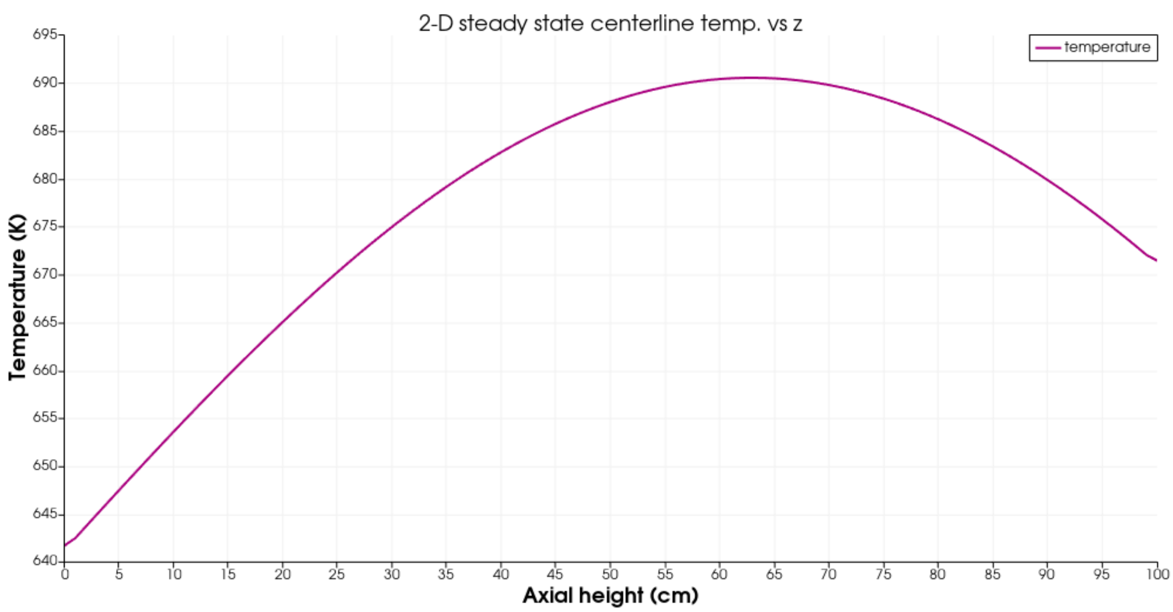

Figure 9: Centerline temperature vs axial height for 2-D steady state case.

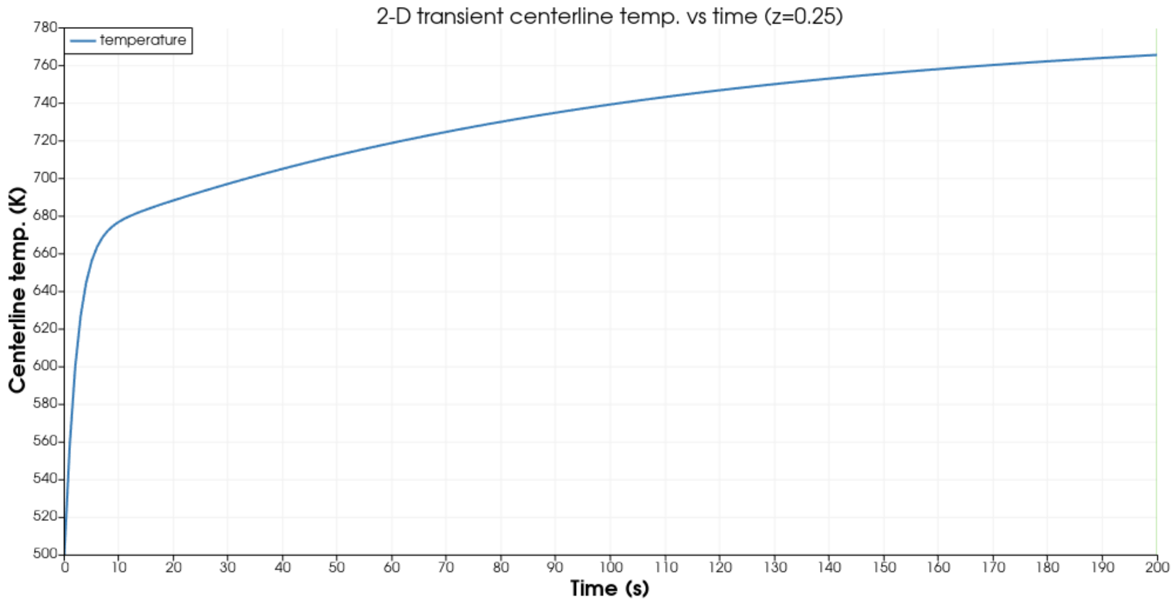

Figure 10: Centerline temperature vs time for 2-D transient case at z=0.25 m.

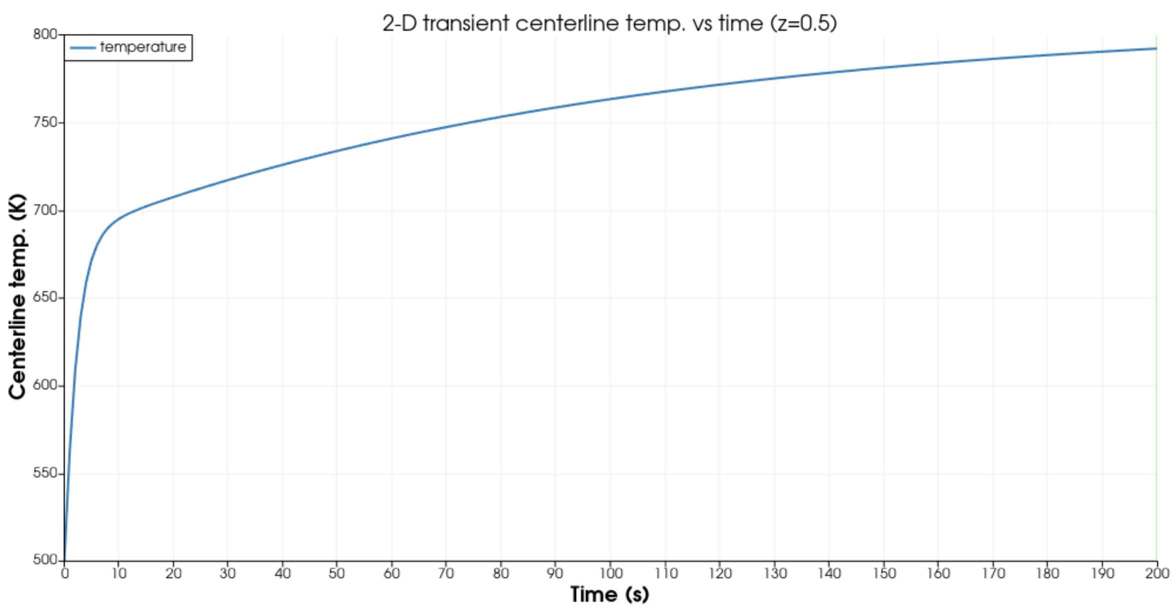

Figure 11: Centerline temperature vs time for 2-D transient case at z=0.5 m.

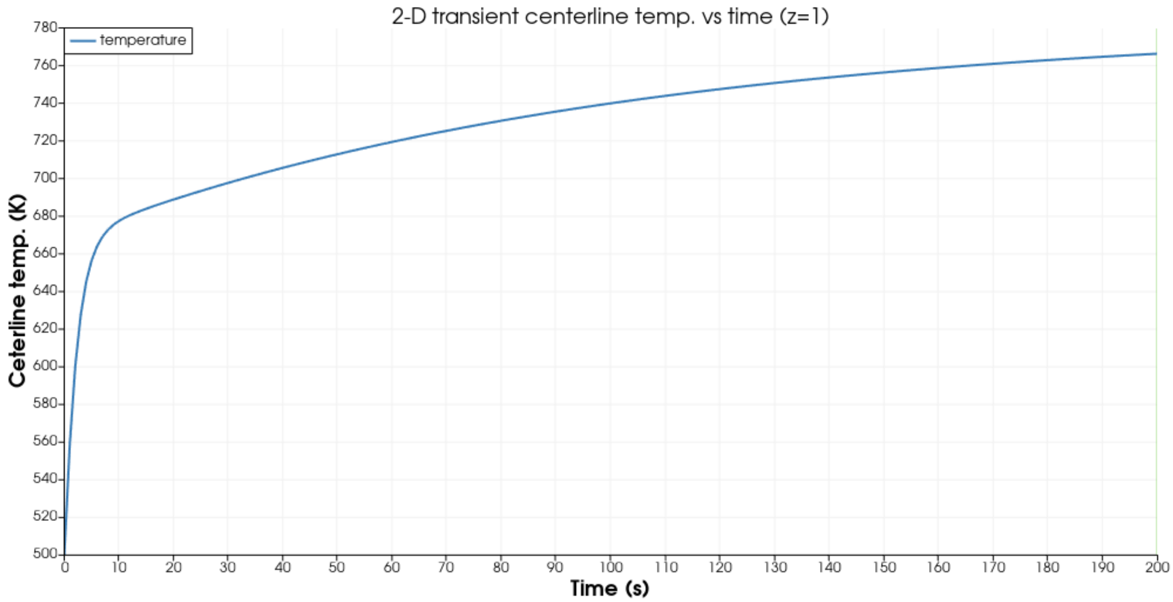

Figure 12: Centerline temperature vs time for 2-D transient case at z=1 m.

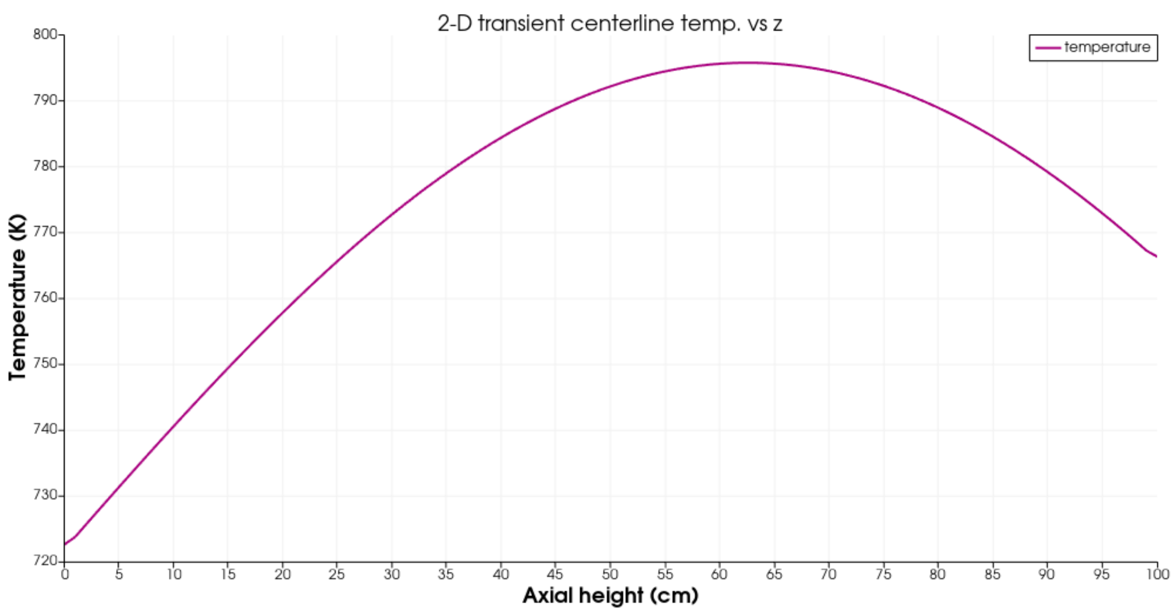

Figure 13: Centerline temperature vs axial height for 2-D transient case.