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Steady State Heat Transfer in Annular Nuclear Fuel Element Using ANSYS APDL

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ABSTRACT
In this work we studied the analytical solution of steady state analysis of heat conductivity in an annular cylindrical nuclear fuel element. The fuel element used for this modelling was UO2 (Uranium oxide fuel), the cladding material was Zircalloy-2. The model was a simple model where heat transfer in the axial direction is neglected and also, the tiny gap between the outer diameter of the fuel pellet and the inner diameter of the cladding is ignored. Boundary conditions were taken and solution was obtained, the temperature was plotted against the radial distance, the result was compared with the obtained computer-based result using ANSYS APDL, the results were comparable with much accuracy, hence the aim of validating the result was achieved.

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I. INTRODUCTION:

Uranium dioxide fuel is the most widely used fuel in modern nuclear power plants. the positive characteristics that it possesses includes its high melting point, its high dimensional and radiation stability and its chemical compatibility with other reactor components [1]. It also has some disadvantages which includes low thermal conductivity and low fuel density which usually leads to high centre-line temperatures and large volume of the cores. The relatively low thermal conductivity of UO2 gives rise to high temperature gradients during the removal of heat from the fuel.

1.11 Thermal conductivity:

Thermal conductivity of UO2 is an essential parameter in the determination of its behavior, poor thermal conductivity will create a large difference between the centerline temperature and the surface temperature during the removal of fission heat in the reactor. This may create a situation where the centerline temperature gets very close the fuel melting point, thereby reducing the available power [1]. Thermal conductivity is the main thermal parameter when considering steady state heat conduction of fuel.

1.12 Specific heat and Density:

Apart from thermal conductivity, two other thermal parameters that play prominent role in describing heat transfer in fuel rod is the density and specific heat, they are more active in transient case, but less active in steady state, this will be shown later.

1.2Formulation of Analytical result

To formulate the analytical solution of the heat transfer in cylindrical fuel element, the classical equation of heat conduction without the axial and azimuthal terms is used. This is due to the fact that we igore heat losses in axial directions as a result of the large difference between the height and diameter of the fuel element.

$$\frac{1}{R_f}\frac{\partial}{\partial R_f}\left(k_f R_f \frac{\partial T}{\partial R_f}\right)+Q=\rho c_p \frac{\partial T}{\partial t} \quad (1)$$

Where ρ is the density, c_p is the heat capacity at constant pressure, k is the thermal conductivity and Q is the volumetric heat density in thefuel pellet.

Equation (1) is the transient equation of the fuel rod conduction.

If the conduction equation is time independent, then we have heat equation that is in steady state with internal heating (Q), hence the syeady state classical heat equation of heat conduction with internal heat souce is used to represent the pellet and the steady state classical heat equation of heat is used to represent the cladding material.

$$\frac{1}{R_f}\frac{d}{dR_f}\left(k_f R_f \frac{dT}{dR_f}\right)+Q=0 \quad (2)$$

$$\frac{d}{dR_f}\left(R_f\,\frac{dT_{cl}}{dR_f}\right)=0 \quad (3)$$

Where $k_f, T_f, and\, T_{cl}$ are the heat conductivity and temperature of the fuel pellet and temperature of the cladding.
By taking boundary conditions, we can solve the steady state case, analytically.

$$\left(\frac{dT_f}{dR_f}\right)_{R=r}=0 \quad (4)$$

$$k_f\left(\frac{dT_f}{dR_f}\right)_{R=R_1}=k_{cl}\left(\frac{dT_{cl}}{dR_f}\right)_{R=R_1} \quad (5)$$

$$k_{cl}\left(-\frac{dT_{cl}}{dR_f}\right)_{R=R_2}=h\big(T_{cl}(R_2)-T_{cool}\big) \quad (6)$$

$$T_f(R_1)=T_{cl}(R_1) \quad (7)$$

The boundary conditions (4), (5), (6) and (7), shows that (a) temperature is constant at the innermost part of the fuel pellet, hence temperature gradient is zero, (b) at the layer between the pellet outer diameter and the cladding inner diameter, the heat flux is constant or the linear heat density is constant, (c) at the outer boundary between the cladding and the coolant, the thermal flux depends on the temperature difference of the cladding and the coolant, and the heat transfer coefficient of the coolant.
Solving equation (2)

$$\frac{1}{R_f}\frac{d}{dR_f}\left(k_f R_f\,\frac{dT}{dR_f}\right)=-Q \quad (8)$$

$$\frac{dT_f}{dR_f}=-\frac{QR_f}{2k_f}+\frac{A_1}{k_f R_f} \quad (9)$$

Applying boundary condition of equation (4), we have:

$$A_1=\frac{Qr^2}{2}$$

We therefore have:

$$\frac{dT_f}{dR_f}=-\frac{QR_f}{2k_f}+\frac{Qr^2}{2R_f k_f} \quad (10)$$

Solving (3)

$$\frac{d}{dR_f}\left(R_f\,\frac{dT_{cl}}{dR_f}\right)=0$$

$$\frac{dT_{cl}}{dR_f}=-\frac{A_2}{R_f} \quad (11)$$

Applying boundary condition in (5) we have:

$$k_f\left(\frac{-QR_1}{2k_f}\right)+k_f\left(\frac{-Qr^2}{2k_f R_1}\right)=k_{cl}\left(\frac{A_2}{R_1}\right) \quad (12)$$

$$A_2=-\frac{Q(R_1{}^2-r^2)}{2k_{cl}} \quad (13)$$

$$\frac{dT_{cl}}{dR_f}=-\frac{1}{R_f}\frac{Q}{2k_{cl}}\left(R_1{}^2-r^2\right) \quad (14)$$

$$T_{cl} = -\frac{Q}{2k_{cl}}\left(R_1^{\,2} - r^2\right)\ln\left(R_f\right) + A_3 \quad (15)$$

Applying boundary condition in (6) we have:

$$k_{cl}\left(\frac{Q}{2k_{cl}R_2}\left(R_1^{\,2} - r^2\right)\right) = h\left(-\frac{Q}{2k_{cl}}\left(R_1^{\,2} - r^2\right)\ln\left(R_2\right) + A_3 - T_{cool}\right) \quad (16)$$

$$A_3 = \frac{Q}{2hR_2}\left(R_1^{\,2} - r^2\right) + \frac{Q}{2k_{cl}}\left(R_1^{\,2} - r^2\right)\ln\left(R_2\right) + T_{cool} \quad (17)$$

$$T_{cl} = \frac{Q}{2hR_2}\left(R_1^{\,2} - r^2\right) + \frac{Q}{2k_{cl}}\left(R_1^{\,2} - r^2\right)\ln\left(\frac{R_2}{R_f}\right) + T_{cool} \quad (18)$$

Integrating (10), we have:

$$T_f\left(R_f\right) = -\frac{QR_f^{\,2}}{4k_f} + \frac{Qr^2}{2k_f}\ln\left(R_f\right) + A_4 \quad (19)$$

Using the boundary condition (7)

$$\frac{Q}{2hR_2}\left(R_1^{\,2} - r^2\right) + \frac{Q}{2k_{cl}}\left(R_1^{\,2} - r^2\right)\ln\left(\frac{R_2}{R_1}\right) + T_{cool} = -\frac{QR_1^{\,2}}{4k_f} + \frac{Qr^2}{2k_f}\ln\left(R_1\right) + A_4 \quad (20)$$

$$A_4 = -\frac{Qr^2}{2k_f}\ln\left(R_1\right) + \frac{Q}{2hR_2}\left(R_1^{\,2} - r^2\right) + \frac{Q}{2k_{cl}}\left(R_1^{\,2} - r^2\right)\ln\left(\frac{R_2}{R_1}\right) + T_{cool} + \frac{QR_1^{\,2}}{4k_f} \quad (21)$$

We can obtain the fuel pellet temperature distribution thus:

$$T_f\left(R_f\right) = \frac{QR_1^{\,2}}{2k_f}\ln\left(\frac{R_f}{R_1}\right) + \frac{Q}{2hR_2}\left(R_1^{\,2} - r^2\right) + \frac{Q}{2k_{cl}}\left(R_1^{\,2} - r^2\right)\ln\left(\frac{R_2}{R_1}\right) + T_{cool} + \frac{Q}{4k_f}\left(R_1^{\,2} - R_f^{\,2}\right) \quad (22)$$

Fuel geometrical and thermal parameters used for this validation exercise are as follows:

Table 1: table of parameters

Volumetric heat density of fuel (Q)	4000000W/m^3
Heat transfer coefficient (h)	100W/m^2K
Fuel pellet radius (R_1)	0.015m
cladding radius (R_2)	0.018m
Cladding thickness ($R_2 - R_1$)	0.003m
fuel element length (H)	0.01m
coolant tempearture (T_{cool})	300℃
density of the fuel (ρ_f)	10950kg/m^3
density of cladding (ρ_{cl})	6550kg/m^3
specific heat capacity of fuel (c_{pf})	236J/kgK
specific heat capacity of cladding (c_{pcl})	285.8J/kgK
thermal conductivity of fuel (k_f)	6W/mK
thermal conductivity of cladding (k_{cl})	21.5W/mK

1.3 Analytical Results

We can now plot the temperature as a function of radius to observe how it changes within the fuel rod both in the pellet and the cladding, especially at the point where the pellet and the cladding overlap. In this work, our fuel rod is assumed to have infinite length. This is the essence of the boundary condition imposed to ease the analytical calculation. The resulting graph below showed a good behavior of the model, which will be validated using ANSYS APDL.

The PTC-MATHCAD toolbox was used to compute and plot the analytical solution it is user friendly computing environment with a lot of symbolic solution which provides an accurate analysis of result. As can be seen from the graph below, the plotting is quite simple with simple labeling system. Therefore, I can say that while PTC-MATHCAD helped to solve the Analytical solution, ANSYS APDL assisted with the numerical simulation result.

Using PTC-MATHCAD Worksheet We Plotted the Analytical Results

$$q := 4000000 \quad k_f := 6 \quad h := 100 \quad k_{cl} := 21.5 \quad T_{cool} := 300 \quad R_1 := 0.01513 \quad R_2 := 0.01813$$

$$r := 0.002$$

$$T_f(R) = \frac{-q \cdot R^2}{4\ k_f} + \frac{q \cdot \left(R_1{}^2 - r^2\right)}{2\ k_{cl}} \ln\left(\frac{R_2}{R_1}\right) + \frac{q \cdot \left(R_1{}^2 - r^2\right)}{2 \cdot h \cdot R_2} + T_C + \frac{q \cdot R_1{}^2}{4\ k_f} + \frac{q \cdot r^2}{2\ k_f}\ ln\left(\frac{R}{R_1}\right)$$

$$T_{CL}(R) = \frac{q \cdot \left(R_1{}^2 - r^2\right)}{2\ k_{cl}} \ln\left(\frac{R_2}{R}\right) + \frac{q \cdot \left(R_1{}^2 - r^2\right)}{2\ h \cdot R_2} + T_{cool}$$

$$T_f(R_1) := 590 - 1.6667 \cdot 10^5\ R_1{}^2 + 1.3333 \cdot \ln\left(\frac{R_1}{0.01513}\right) \qquad T_{cl}(R_2) := 548.3 + 21\ \ln\left(\frac{0.01813}{R_2}\right)$$

$$R_1 := 0.002, 0.0025..0.01513 \qquad R_2 := 0.01513, 0.016..0.01813$$

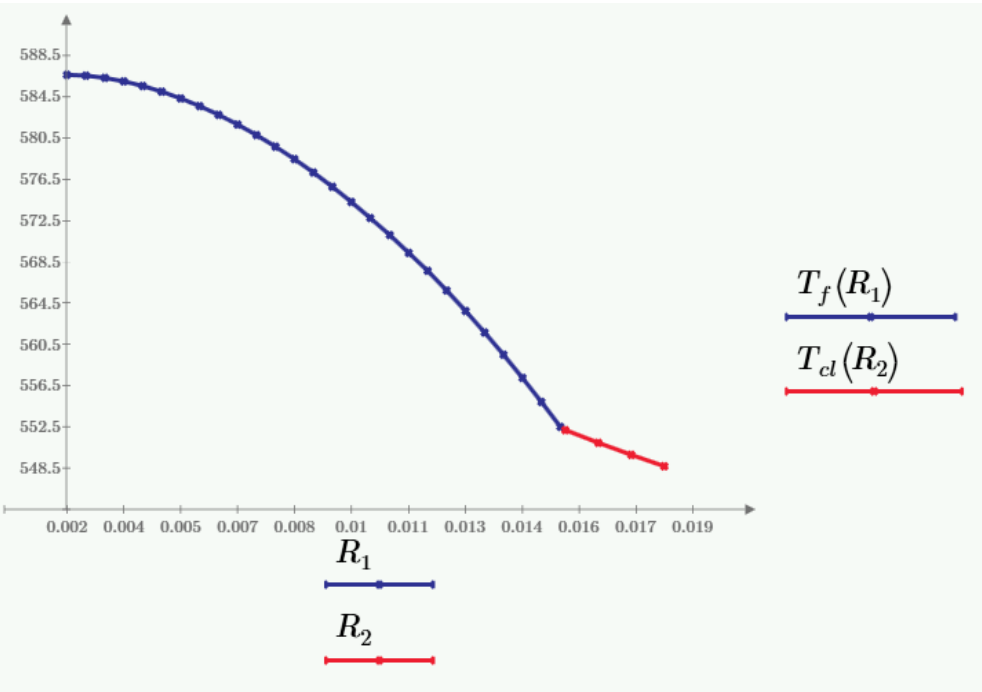

Figure 1: Analytical Result of Steady State Temperature distribution of fuel element

Numerical Simulation of the steady state conduction of nuclear fuel rod using ANSYS APDL
The parameter of the fuel rod are as stated earlier, the simulation was done on 3-D platform

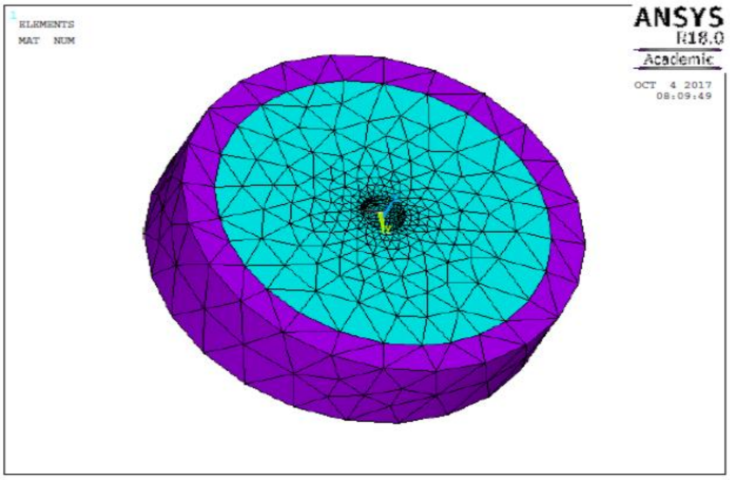

Figure-2: 3D view of Geometrical mesh contour

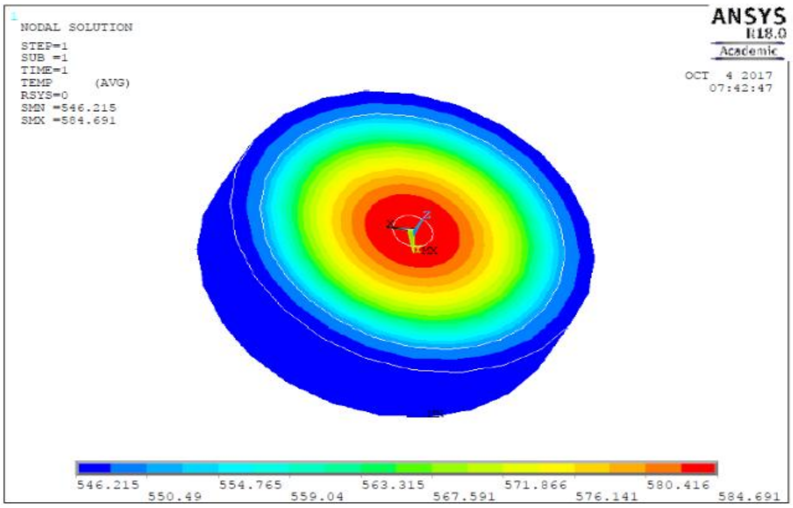

figure-3: 3D view of temperature distribution contour

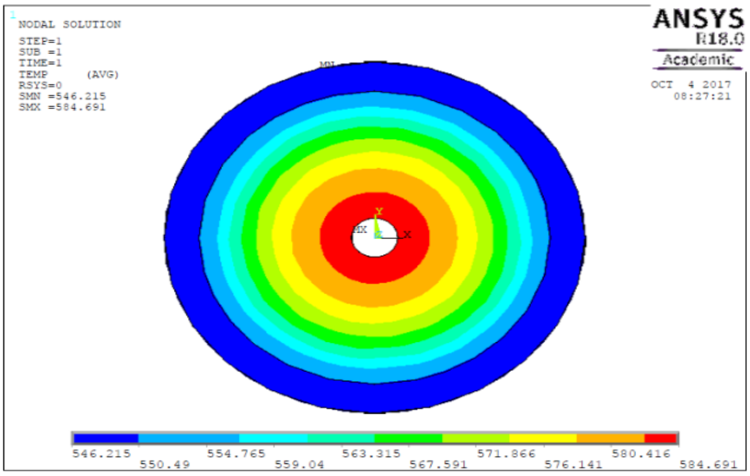

Figure-3:Steady State Temperature Distribution Contour

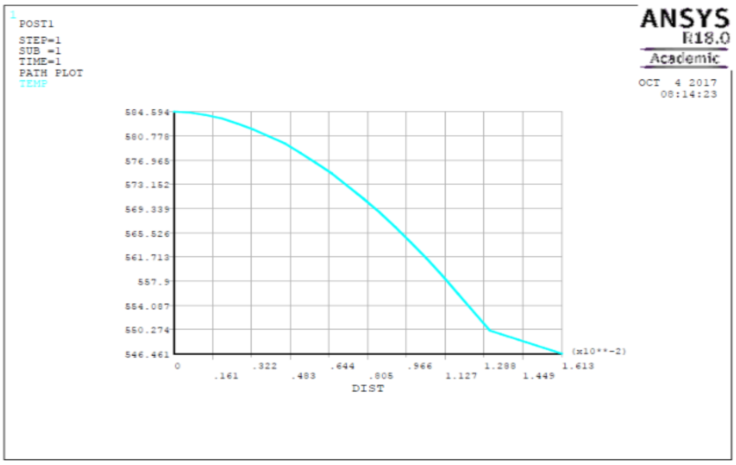

Figure 4: Steady State Temperature Distribution Graph

II. DISCUSSION OF RESULTS AND CONCLUSION

From the results obtained above, we can say that we have been able to authenticate the analytical solution of the problem using ANSYS APDL. The little gap that appeared on the analytical graph was due to geometrical approximation which occurred as a result of the cumbersomeness of the analytical equation. The behavior of each of the contour along the radial direction depicts the four (4) boundary conditions and therefore validates the results of the Analytical solution.

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