FORTRAN Assessed Problem 2018/19

School of Physics and Astronomy
MSc Physics and Technology of Nuclear Reactors

You are provided with a data file (flux.txt) that gives the neutron flux distribution from the bottom of a reactor fuel channel (first data value) to the top (last data value).

The task is to write a FORTRAN77 program that can calculate the coolant temperature, outer cladding temperature and maximum fuel temperature as a function of position along a fuel channel for both PWR and AGR fuel pins for the given flux profile.

The fuel type in both reactors is UO_2, with a density of $\rho = 10.97$ gcm^{-3} and a thermal conductivity, $k_f = 2.65$ Wm^{-1}K^{-1}. The microscopic fission cross section for ^{235}U is $\sigma_f = 580$ b, and you may take the recoverable energy released per fission as being 200 MeV. Avogadro's constant is $N_A = 6.022 \times 10^{23}$ mol^{-1}, and the charge of an electron is $e = 1.602 \times 10^{-19}$ C.

The physical parameters for each reactor type are:

	PWR	**AGR**
Coolant	H_2O	CO_2
Total height of channel (m)	4	8
Mass flow rate per channel, $\dot{m}$ (kgs^{-1})	0.35	0.35
Specific Heat Capacity, C_p (Jkg^{-1}K^{-1})	5500	1120
Convective heat transfer coefficient, h_c (Wm^{-2}K^{-1})	30,000	1000
Inlet coolant temperature (°C)	292	339
Enrichment (% ^{235}U)	4	2
Outer diameter of fuel pellet, d_f (mm)	9	14.5
Inner diameter of fuel pellet, d_h (mm)	0	6
Cladding material	Zircaloy	Stainless Steel
Thickness of cladding (mm)	0.5	0.38
Thermal conductivity of cladding, k_c (Wm^{-1}K^{-1})	14	18
Gap conductance, h_g (Wm^{-2}K^{-1})	4000	4000

Theory

There are several ways this can be programmed, but you need to capture the necessary physics whatever method you use. You will cover the details in your Thermal Hydraulics course, and information can be found in Chapter 8 of Lamarsh, J.R. and Baratta, A.J., *Introduction to Nuclear Engineering*, 3rd Edition, Prentice Hall (2001).

Heat generation

The amount of heat per unit volume, $q'''(z)$, generated by the fuel at some position, z, along the channel depends on the fission reaction rate per unit volume of fuel, $RR(z)$, and the recoverable energy produced per fission, E_f:

$$q'''(z) = E_f RR(z) = E_f \Sigma_f \phi(z)$$

where $RR(z) = \Sigma_f \phi(z)$ as usual and $\Sigma(z)$ is the macroscopic fission cross section for the fuel.

As heat cannot be destroyed, all of this heat must be transferred through the fuel pellet to the cladding, across the cladding and then into the coolant. Each of these stages needs to be modelled to determine the temperatures of each component.

Temperature of the coolant

The total amount of heat per second, $q(z)$, generated in a portion of fuel of cross sectional area, A_f, and height Δz at position z along the channel will be $q(z) = q'''(z)A_f\Delta z$. In this time a mass $\dot{m}$ of the coolant will have flowed past this segment of fuel, so the temperature rise of the coolant moving from position z to $z+\Delta z$, , $\Delta T_{cool} = T_{cool}(z+\Delta z) - T_{cool}(z)$, due to the input of heat, q, is given by:

$$\dot{m}C_p\Delta T_{cool}(z) = \dot{m}C_p(T_{cool}(z+\Delta z) - T_{cool}(z)) = q'''(z)A_f\Delta z$$

where C_p is the specific heat capacity of the coolant.

Temperature of the outside of the cladding

The heat gets from the surface of the cladding to the coolant via convective heat transfer. The heat is transferred to the coolant from a surface area of the cladding $A_c = \pi d_c \Delta z$, where d_c is the outer diameter of the cladding. The rate at which heat is transferred is then $q(z) = h_c A_c \Delta T_c(z)$, where h_c is the convective heat transfer coefficient for the coolant. As ΔT_c is the temperature difference between the outside of the cladding, T_{oc}, and the coolant, T_{cool}, we get:

$$\begin{aligned} h_c A_c \Delta T_c(z) &= q'''(z)A_f\Delta z \\ h_c \pi d_c \Delta z\,(T_{oc}(z) - T_{cool}(z)) &= q'''(z)A_f\Delta z \\ \therefore \qquad T_{oc}(z) &= T_{cool}(z) + \frac{A_f}{h_c\pi d_c}q'''(z) \end{aligned}$$

Temperature of the inside of the cladding

The temperature is distributed throughout the cladding according to $\nabla^2 T = 0$. For a cylindrical geometry, the result for the temperature of the inside wall of the cladding, $T_{ic}(z)$, is:

$$T_{ic}(z) = T_{oc}(z) + \frac{A_f}{2\pi k_c}\ln\left(\frac{d_c}{d_f}\right)q'''(z)$$

where k_c is the thermal conductivity of the cladding and d_f is the outer diameter of the fuel pellet (inner diameter of the cladding).

Temperature of the outside of the fuel

There is a small gap between the outside of the fuel and the inside of the cladding, which offers thermal resistance to the flow of heat, As a consequence, there can be a significant temperature difference between the two. The temperature of the outside of the fuel, $T_{of}(z)$, is then given by:

$$T_{of}(z) = T_{ic}(z) + \frac{A_f}{\pi h_g d_f}q'''(z)$$

where h_g is the gap conductance.

Temperature of the fuel

The temperature profile across the radius of a fuel pellet can be determined from $\nabla^2 T = -q'''/k_f$, where k_f is the thermal conductivity of the fuel.

For a solid, PWR type, fuel pellet, the maximum temperature occurs at the centre and is given by:

$$T_{max}(z) = T_{of}(z) + \frac{A_f}{4\pi k_f} q'''(z)$$

with $A_f = \pi r_f^2$ with r_f being the radius of the fuel pellet.

For an AGR fuel pellet, there is a hole in the centre of diameter d_h. This means the maximum temperature occurs at radius $r_h = d_h/2$ from the centre, and is given by:

$$T_{max}(z) = T_{of}(z) + \frac{A_f}{4\pi k_f} q'''(z) - \frac{A_f}{2\pi k_f} \frac{d_h^2}{d_f^2 - d_h^2} \ln\left(\frac{d_f}{d_h}\right) q'''(z)$$

with $A_f = \pi(r_f^2 - r_h^2)$ in this case.

Assessment

What I am looking for is a compact, robust, efficient and user-friendly program that could any similar flux data without modification. It is possible to get a good pass for a basic working program that demonstrates that you have a sound grasp of FORTRAN77 syntax: use of arrays, DO loops and IF blocks, reading data from file. Most of the marks will be reserved for the basic working program.

If the project seems rather daunting, try breaking the problem down into more manageable tasks and test each part before extending your program. This is very much a 'real-life' example of the kind of numerical problem you may face as a professional scientist. You will need to put some thought into finding the best way to tackle the problem before you start programming. Pay particular attention to the user-friendliness of your program and show that you have tested it. If you have time, consider whether your program handles exceptions gracefully. Comment your code well to explain what each section is meant to do.

You should prepare a short (~5 pages excluding appendices) report that briefly describes the work you did to design, write and test your program. It should include, as an Appendix, a printout of the source code. Your results should be clearly recorded, perhaps in graphical form. You should also supply an electronic copy of your source files, so that I can test it for myself. The source files and report can be uploaded to Canvas through the assignment link in the Fortran 16370 section. Like the Numerical Analysis assessment, it is worth half the weight of a laboratory report. A printed copy of your report should be submitted to the Teaching Support Office by 4 pm on **Monday 28th January**.

Please note that this is a formal item of assessment and you must work **individually**. You are not permitted to discuss your solutions with any other student. Collaborative work is not allowed. The solution should be your own and not one copied or modified from the internet.

Good luck!