5.1.3 Fuel rod heat transfer

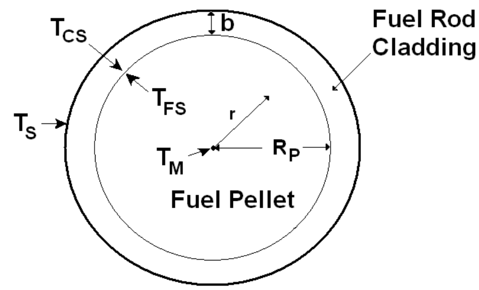

Figure 1: Schematic of the cross-section of a fuel pellet and fuel rod.

Consider first the heat transfer within an individual fuel rod. The cross-section of a fuel pellet is sketched in figure 1. The fuel pellet radius and thermal conductivity are denoted by R_f and k_f and the fuel rod cladding thickness and thermal conductivity by b and k_C. The temperatures in the center of the fuel rod, at the outer surface of the fuel pellet, at the inner surface of the cladding and at the outer surface of the fuel rod will be denoted by T_M, T_{FS}, T_{CS}, and T_S respectively. A small gap and/or a contact resistance is assumed so that $T_{FS} \neq T_{CS}$. It will also be assumed that the gradients of temperature in the axial direction are small compared with those in the radial direction and therefore that the primary heat flux takes place in the radial plane of figure 1. Consequently, if the rate of heat production per unit length of a fuel rod is denoted by $\mathcal{Q}$ and if this is uniformly distributed over the cross-section of the rod, then, in steady state operation, the radially outward heat flux (per unit area) through the radial location, r, must be $\mathcal{Q}r/2\pi R_f^2$. Consequently the heat conduction equation becomes

$$\frac{\mathcal{Q}r}{2\pi R_f^2} = -k\frac{\partial T}{\partial r} \quad (1)$$

where $T(r)$ is the temperature distribution and k is the local thermal conductivity (k_f or k_C). Integrating in the fuel pellet, it follows that for $0 < r < R_f$:

$$T(r) = T_M - \frac{\mathcal{Q}}{4\pi R_f^2 k_f} r^2 \quad (2)$$

where the condition that $T = T_M$ at $r = 0$ has been applied. Consequently the temperature at the surface of the fuel pellet is

$$T_{FS} = T_M - \frac{\mathcal{Q}}{4\pi k_f} \quad (3)$$

As a typical numerical example note that with a typical value of $\mathcal{Q}$ of 500 W/cm and a thermal conductivity of UO_2 of $k_f = 0.03$ $W/cm^\circ K$ the temperature difference between the surface and center of the fuel becomes $1400°K$, a very substantial difference.

Assuming that the small gap and/or contact resistance between the fuel and the cladding gives rise to a heat transfer coefficient, h^*, where

$$k_f \left(\frac{\partial T}{\partial r}\right)_{r = R_f \text{ in fuel}} = k_C \left(\frac{\partial T}{\partial r}\right)_{r = R_f \text{ in cladding}} = -h^* \left\{T_{FS} - T_{CS}\right\} \tag{4}$$

it follows that

$$T_{CS} = T_M - \frac{\mathcal{Q}}{4\pi k_f} - \frac{\mathcal{Q}}{2\pi R_f h^*} \tag{5}$$

Integration of equation 1 in the cladding ($R_f < r < R_f + b$) leads to

$$T(r) = C - \frac{\mathcal{Q}}{4\pi R_f^2 k_C} r^2 \tag{6}$$

where C is an integration constant. Applying the condition that $T = T_{CS}$ at $r = R_f$ yields a value for C and, finally, the fuel rod surface temperature is obtained as

$$T_S = T_M - \frac{\mathcal{Q}}{4\pi}\left[\frac{1}{k_f} + \frac{2}{h^* R_f} + \frac{\left\{(1 + b/R_f)^2 - 1\right\}}{k_C}\right] \tag{7}$$

Typical temperature differences in a LWR, across the fuel/cladding gap, across the cladding and between the cladding surface and the bulk of the coolant might be of the order of $200°K$, $80°K$ and $15°K$ respectively so that the temperature difference between the water and the center of the fuel pellet is dominated by the temperature difference in the fuel and has a magnitude of about $1400°K$. In summary, the radial temperature distribution in a fuel rod is given by equations 2, 3, 5, 6 and 7 and the general form of this distribution is illustrated in figure 2.

Since the objective is to extract heat from the fuel it is desirable to maintain a large heat production rate, $\mathcal{Q}$, using a proportionately large neutron flux. A large $\mathcal{Q}$ and therefore a large power density is desirable for several reasons. First it minimizes the size of the reactor core for a given power production level and thereby reduces the cost of the core and the cost and size of the rest of the structure that contains the core. Second, higher temperature differences across the core lead to higher thermal efficiencies in the turbines driven by the coolant.

However a high $\mathcal{Q}$ implies large temperature differences within the fuel rods and therefore high temperatures. Thus, limiting design factors are the maximum allowable temperature in the fuel, T_M, which must be much less than the melting temperature and, similarly, a maximum temperature in the cladding, T_{CS}. Moreover the temperature of the wall in contact with the coolant, T_S, will also be constrained by boiling limits in the coolant. Any or all of these factors will limit the heat production since the temperature differences are proportional to $\mathcal{Q}$. It is also clear that the temperature differences for a given heat production

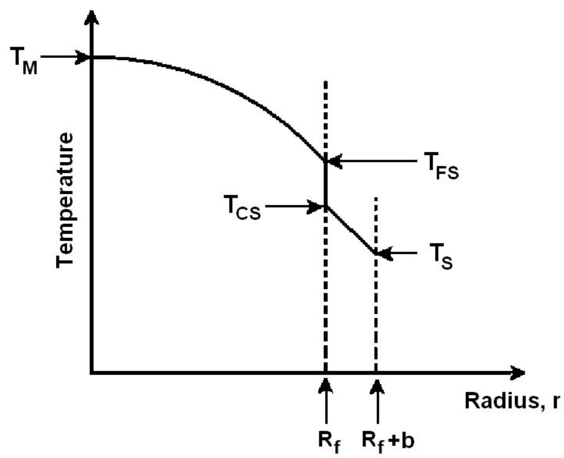

Figure 2: The general form of the radial temperature distribution within a fuel rod.

per unit fuel volume (or a given neutron flux) are reduced by decreasing the size of the fuel pellets, R_f. However to yield the required power from the reactor this means increasing the number of fuel rods and this increases the cost of the core. Consequently a compromise must be reached in which the number of fuel rods is limited but the temperature differences within each rod are maintained so as not to exceed a variety of temperature constraints.

It is valuable to list some secondary effects that must also be factored into this fuel rod analysis:

- The neutron flux in the center of the fuel rod is somewhat less than at larger radii because thermal neutrons that enter the fuel from the moderator or coolant are absorbed in greater number near the surface of the fuel. This helps even out the temperature distribution in the fuel.
- The fuel is often UO_2 whose manufacture causes small voids that decrease the thermal conductivity of the pellet and increase the temperature differences.
- As the fuel is used up the gap between the fuel pellet and the cladding tends to increase causing a decrease in h^* and therefore an increase in the temperature of the fuel.
- The thermal conductivity of the fuel increases with temperature and therefore, as the heat production increases, the temperature differences in the fuel increase with $\mathcal{Q}$ somewhat less than linearly.
- Fission gases are released by nuclear reactions in the fuel and this can lead to significant build up of pressure within the fuel rods that are, of course, sealed to prevent release of these gases. The gas release increases rapidly

with temperature and hence there is an important design constraint on the fuel temperature that is required in order to limit the maximum pressure in the fuel rods. This constraint is often more severe than the constraint that T_M be less than the fuel melting temperature.

Despite these complicating factors, it is useful to emphasize that the leading constraint is the maximum allowable temperature in the center of the fuel as will be discussed in sections 5.3 and 5.4.