Design constraints – Maximum clad temperature, linear power rating

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Table of Contents

1 DESIGN CONSTRAINTS ...........................................................................................................3
   1.1 Maximum Temperature of Clad .................................................................................. 3
   1.2 Linear (heat/power) Rating ....................................................................................... 5

2 REFERENCE/ADDITIONAL READING ...............................................................................7
In this lecture, we shall discuss the constraints in design of fast reactor core with respect to maximum temperature of clad and linear power rating.

At the end of this lecture, the learners will be able to

(i) understand the importance of clad temperature with respect to plant efficiency
(ii) understand the meaning of linear power rating
(iii) understand the role of thermal conductivity of fuel in influencing linear power rating

The design of fast breeder reactor core is a challenging task. The requirements of power generation, breeding and operational safety have to be borne in mind during the design. Responses to transients both intentional and unintentional must be factored in the design as well. This imposes several constraints during the design most of which are related to material aspects. In particular these constraints are imposed by possible changes in the physical and chemical nature of materials including fuel, cladding, coolant and structural materials. The economics must also be taken into account.

### 1 Design Constraints

Some of the design constraints are listed below with their significance and their influence on reactor characteristics:

#### 1.1 Maximum temperature of clad

From the thermodynamic point of view, higher temperature of clad is advantageous. This would in turn increase the outlet temperature of primary sodium, and in turn that of secondary sodium and in turn that of steam. The efficiency of thermal to electrical energy conversion increases with increase in steam temperature.

However the properties of clad material impose constraints on the maximum permissible clad temperature. Another problem in achieving higher clad temperature is the resistance for heat conduction within the pellet and that in the fuel gap.

As discussed earlier the thermal conductivity of mixed oxide fuel is low. Hence to achieve a fixed rate of heat transfer, the temperature gradient required is high. In other terms the difference in temperature between the centre of fuel pin and that at the outer surface will be high. If one considers the resistance in the fuel-clad gap and in the clad
also, the difference between the temperature at the centre of the fuel pin and the
temperature at the outer surface of the clad will be very high.

The net result of all these resistances is that to obtain higher temperature on the outer
surface of the clad, higher temperature at the centre of fuel pin is required. If this
temperature exceeds the melting point of the fuel, catastrophic consequences would
set in. Hence, this too limits the maximum temperature on the outer surface of the
cladding.

Under steady-state condition, the cladding material is exposed to temperatures in the
range of 673-973 K. However during transient conditions, the temperature may reach
1273 K. One can understand this, by looking at the following examples.

Example – 1: The average temperature of coolant in fast breeder reactor is 470°C.
If the coolant-side heat transfer coefficient is 15000 W/m²K, determine the
temperature on the outer surface of the cladding, if the diameter of pin is 6 mm
and cladding is 0.5 mm thick. The rate of heat generation is 1000 MW/m³.

Data: Volumetric rate of heat generation = q’ = 1x10⁹ W/m³

Converting ‘q’ in terms of per unit surface area of pins, we get heat flux (q’’) as
follows:

q’’(surface area of pins) = q’ (Volume of pins)

q’’(NL²πR)=q’(NLπR²)

q’’ = q’R/2

Heat flux (q’’) may also be equated to the heat transfer coefficient (h) and driving
force (T_clad-T_coolant) as follows:

q’’=q’R/2=h(T_clad-T_coolant)

Substituting R = 3+0.5 = 3.5 mm = 3.5x10⁻³ m, h = 15000 W/m²K and q’=
1x10⁹W/m³, we get

T_clad = T_coolant+q’R/(2h)

T_clad = T_coolant+q’’/h = 587 °C

Therefore, the temperature on the outer surface of cladding is 587 °C.
Example – 2: In the above problem if the heat transfer coefficient falls to 5000 W/m²K due to reduced coolant flow, determine the temperature on the outer surface of the cladding.

Solution:

In the above problem, if the value of ‘h’ is substituted as 5000 W/m²K, we get

$$T_{\text{clad}} = 820 \degree C$$

This problem illustrates the increased temperature of clad due to transients in the coolant flow rate.

### 1.2 Linear (heat/power) rating

It is defined as the ratio of thermal power to the product of number of fuel pins and the height (or length) of the pin.

$$\text{Linear rating} = \frac{Q}{N \cdot L}$$  \hspace{1cm} (1)

In terms of thermal conductivity of the material, linear rating is expressed as

$$\text{Linear rating} = 4\pi \int_{T_s}^{T_{fc}} k(T) \cdot dT$$  \hspace{1cm} (2)

In Eq. (2), $T_s$ is the temperature on fuel surface and $T_{fc}$ is the temperature at the fuel centre. $k(T)$ is the temperature-dependent thermal conductivity of the fuel.

From the above expression, one may observe that the linear power rating depends on the thermal conductivity of the material and its variation with temperature. Higher linear rating will be obtained for materials that have higher thermal conductivity. This is illustrated in the following examples:

1. Determine the linear rating of an oxide fuel when the temperature at the center of the fuel pin is 800 °C while that at the surface is 600 °C. The thermal conductivity of oxide fuel is related to temperature (in K) as follows:

$$k(T) = \frac{3824}{129.4 + T} + 6.125 \times 10^{-11} (T^3) \; W/mK$$

$$\text{Linear rating} = 4\pi \int_{800+273}^{600+273} \frac{3824}{129.4 + T} + 6.125 \times 10^{-11} (T^3) \; dT$$
Linear rating = \( 4\pi \left[ 3824\ln (129.4 + T) + 6.125 \times 10^{-11} \left( \frac{T^4}{4} \right) \right]^{1073}_{873} \)

From the above equation, Linear rating = 8885.4 W/m

2. Assuming that a metallic fuel has a linear rating of 8885.4 W/m (as calculated above), determine the temperature at the centre of the fuel if the temperature on its outer surface is 600°C. The thermal conductivity of metallic fuel as the function of temperature (in K) is given by

\[
k(T) = 6.945681 + 0.016174(T) + 5.58 \times 10^{-6} (T^2); \ W/mK
\]

Solution:

\[
Linear \ rating = 4\pi \int_{600+273}^{T} 6.945681 + 0.016174(T) + 5.58 \times 10^{-6} (T^2) \ dT
\]

\[
Linear \ rating = 4\pi \left[ 6.945681(T) + 0.016174T^2/2 + \frac{5.58 \times 10^{-6} (T^3)}{3} \right]^{T}_{873}
\]

Solving the above equation, we get T = 900 K

What do we infer from Examples – 1 and 2? For the same linear rating, with metallic fuels the temperature at the centre of the fuel is lower than that of a metal oxide fuel. In other words, the linear power of a metallic fuel can be increased appreciably before the peak fuel temperature or temperature at the centre of the fuel increases beyond permissible limits.

Since linear rating and reactor thermal power are directly proportional, a fuel element with higher linear rating can be used to produce higher thermal power for the same number of fuel pins and for the same length.

Once it is realized that the higher linear rating is advantageous, it must also be realized that for a chosen fuel material, larger difference in temperature between the fuel center and fuel surface would be incurred for higher linear rating. As discussed earlier, there is a limitation to maximum temperature to which a fuel can be heated. This poses a constraint on the maximum linear rating permissible, depending on the type of fuel used. Use of large number of small diameter fuel pins can be used to increase the reactor power without increasing the linear rating. The maximum linear rating for PFBR is 450 W/cm with an active core height of 1 m.
2 Reference/Additional reading