5 Fuel - Coolant Heat Transfer

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Learning Outcomes

Know WHAT (basic comprehension)
- definitions of terms
- physical layout of reactor channel
- typical values
- units
- key physical phenomena
  - conduction
  - convection
  - dryout
  - centreline melting
  - CHF
  - CPR

Know HOW (ability to do)
- model heat conduction in solids
- model heat convection to fluids
- calculate temperature distribution
  - radial
  - axial

Know WHY(high level understanding)
- heat transfer as a limiting factor for power output
- heat transfer dependence on parameters
- crisis prevention

5.1 Introduction

The interface between the fuel and the coolant is centrally important to reactor design since it is here that the limit to power output occurs. Nuclear fission can provide a virtually unlimited heat generation rate, far more than can be transported away by the coolant. Herein we investigate the heat transfer at the fuel site so that this limitation can be factored into the reactor design. The key concepts covered are (see figure 5.1):
- heat is generated in the fuel at a rate proportional to reactor power
- heat is conducted to the coolant as the coolant flows along the fuel
- in the steady state, the fuel temperature is just sufficiently greater than the coolant temperature to transfer the heat generated - ie, fuel temperature "floats" on coolant temperature
- too much power will cause the fuel temperature to be too high and a heat transfer crisis will occur
- heat transfer is a key limiting factor to power output

<u>Examples</u>

Typical values of parameters:

Typical fuel and coolant temperatures:

PWR
BWR
CANDU
HTGCR
LMFBR

<u>Exercises:</u>

WHAT: Describe the fuel heat transfer mechanism. Explain the roles of conduction and convection.

HOW: How does the fuel temperature depend on fluid temperature?

WHY: Why is the reactor power limited by heat transfer?

Overview Concept Map

$$T_{FL}(z) - T_{INLET} = \frac{q_0 H}{\pi c W}\left(\sin\left(\frac{\pi z}{H}\right)+1\right)$$

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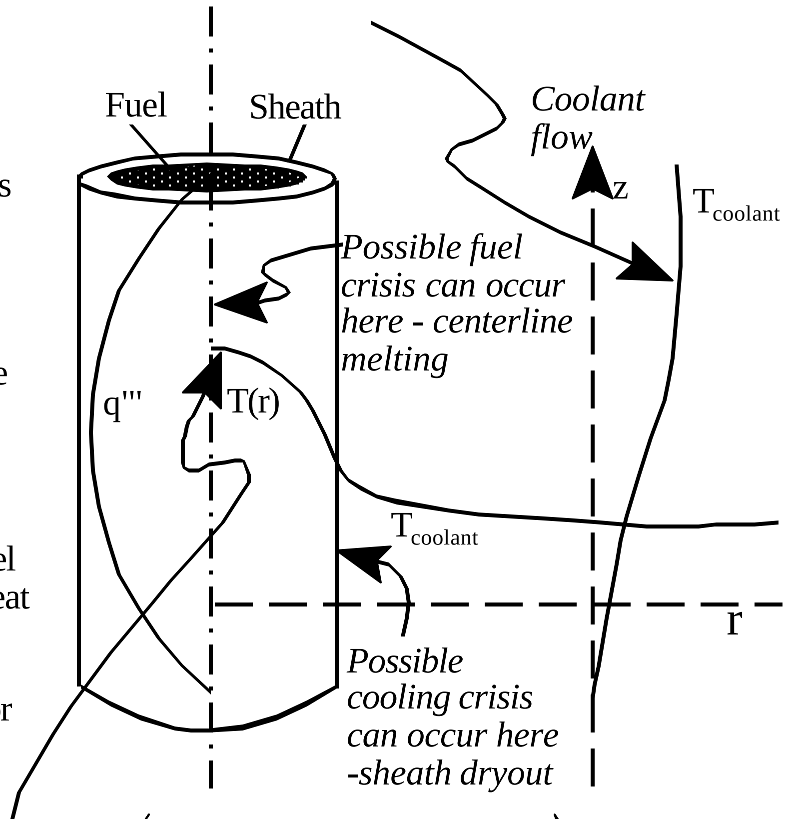

$$T_0 - T_{FL} = \frac{q'}{2\pi}\left(\frac{1}{2\bar{k}_f}+\frac{1}{h_G r_F}+\frac{t_G+t_C}{k_C(r_F+t_G)}+\frac{1}{h_S(r_F+t_G+t_C)}\right)$$

Figure 5.1 Overview of fuel heat transfer

5.2 General Heat Conduction Equation

For a solid, the general energy thermal energy balance equation of an arbitrary volume, $\mathcal{V}$, is:

$$\iiint_{\mathcal{V}} \frac{\partial(\rho e)}{\partial t}\, d\mathcal{V} = \iiint_{\mathcal{V}} q'''(\bar{r},t)\, d\mathcal{V} - \iint_{S} \bar{q}''(\bar{r},t) \cdot \hat{n}\, ds \quad \textbf{(1)}$$

where ρ is the material density, e is the internal energy, $\mathcal{V}$ is the volume, S is the surface area, q''' is the volumetric heat generation, q'' is the heat flux, and $\hat{n}$ is the unit vector on the surface. We replace the internal energy with temperature, T, times the heat capacity, c. Using Gauss' Law to convert the surface integral to a volume integral and dropping the volume integral everywhere:

$$\frac{\partial(\rho c T)}{\partial t} = q'''(\bar{r},t) - \nabla \cdot q''(\bar{r},t) \quad \textbf{(2)}$$

We further need a relation to specify the heat flux in terms of temperature. In a solid, Fourier's law of thermal conduction applies:

$$q''(\bar{r},t) = -k\, \nabla T(\bar{r},t) \quad \textbf{(3)}$$

where and k is the thermal conductivity. This gives the usable form:

$$\frac{\partial(\rho c T)}{\partial t} = q'''(\bar{r},t) + \nabla \cdot k \nabla T(\bar{r},t) \quad \textbf{(4)}$$

The parameters have the following units:

ρ	kg/m^3
c	J/(kg °K)
k	J/(m°K-sec)
q''	J/(m^2-sec) = W/m^2
q'''	J/(m^3-sec) = W/m^3
T	°K
α	defined as k/ρc = m^2/sec.