

Thursday, November 12th, 2015

OPEN BOOK

QUIZ 2

TAKE HOME

Problem 1 (65%) – Helium-cooled fast reactor with molten fuel within steel rods

A new fast reactor concept uses a molten solution of $\text{UCl}_3/\text{PuCl}_3/\text{NaCl}$ as the fuel. This fuel is contained within cylindrical rods made of steel (see Figure 1). The reactor coolant is helium gas which flows along the fuel rods. The nominal core power is 1,500 MW. The mass flow rate of helium is 1,440 kg/s and the inlet temperature of helium is $T_{in} = 400$ °C. The total number of rods in the core is 30,000 and their length is $L = 3$ m. The rods have an outer diameter $d_{co} = 10$ mm, and are arranged in square-lattice fuel assemblies with an unknown rod-to-rod pitch p . The thickness of the steel cladding is $t_c = 0.5$ mm. The thermo-physical properties of all relevant materials are shown on the next page.

- i) Find the core outlet temperature and the average linear power in the core. (5%)
- ii) Find the minimum allowable value of p if the total pressure drop in the core must be limited to 120 kPa. Please consider only friction and gravity pressure drops. In calculating the friction factor, please use a correlation for smooth tubes with the equivalent diameter concept. Neglect entrance region effects. (25%)

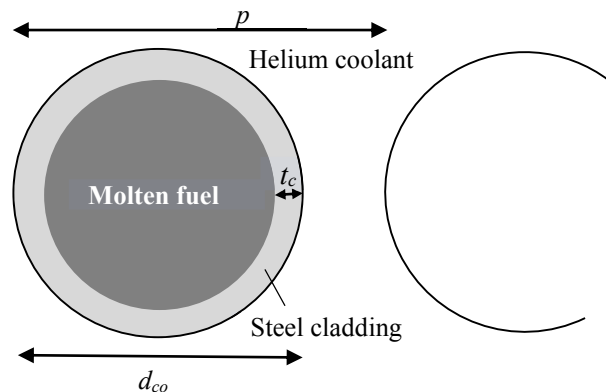


Figure 1. Cross-sectional view of a fuel rod under normal operating conditions.

Normally all the fuel is molten, however when the reactor operates at reduced power, a frozen fuel annulus develops within the rods, as shown in Figure 2. At a certain time during a slow power descent, the core power is 500 MW, while the helium inlet temperature and mass flow rate are the same as before.

- iii) Find and plot the radius of the molten fuel region, R_m , as a function of the axial coordinate z . The melting point of the fuel is $T_m = 460$ °C. You may still assume steady state, and neglect convective motion of the molten fuel within the fuel rods. You may also assume that the linear power is uniform everywhere in the core. (35%)

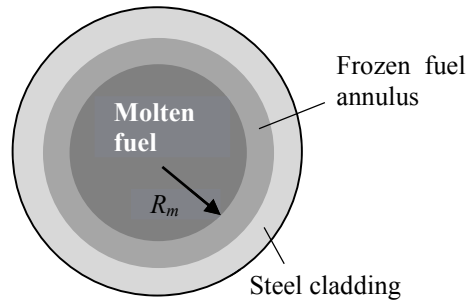


Figure 2. Fuel rod with a frozen fuel annulus.

Properties (all assumed independent of temperature and pressure)

Helium: $c_p = 5,200 \text{ J/kg}^\circ\text{C}$, $\rho = 4.81 \text{ kg/m}^3$, $k = 0.22 \text{ W/m}^\circ\text{C}$, $\mu = 2.8 \times 10^{-5} \text{ Pa}\cdot\text{s}$

Steel: $c = 500 \text{ J/kg}^\circ\text{C}$, $\rho = 7,700 \text{ kg/m}^3$, $k = 19 \text{ W/m}^\circ\text{C}$

UCl₃/PuCl₃/NaCl fuel (both liquid and solid): $c = 950 \text{ J/kg}^\circ\text{C}$, $\rho = 2,350 \text{ kg/m}^3$, $k = 0.7 \text{ W/m}^\circ\text{C}$

Problem 2 (35%) – Passive Residual Heat Removal System

In a small modular Pressurized Water Reactor (PWR) the decay heat is removed by the Residual Heat Removal System (RHRS) shown in Figure 3. The RHRS consists of an external water loop, which removes heat from the Reactor Pressure Vessel (RPV) via the RHRS heat exchanger and discharges it to an atmospheric pool at a higher elevation. The system operates based entirely on natural circulation.

Calculate the flow of water in the core and in the RHRS loop at a time when the decay power is 9 MW. Calculate also the core inlet and outlet temperatures. Use the following assumptions:

- Steady-state operation
- Coolant is single-phase water throughout the system. The relevant properties of water are given in the table at the end.
- Neglect all pressure losses in the primary system except for the friction loss in the core (friction factor = 0.02; flow area = 1 m²; fuel length = 3 m; hydraulic diameter = 1.2 cm)
- The pressure losses in the RHRS loop are equivalent to a single form loss (K = 40; pipe diameter = 15 cm)
- The relative elevation of the core and RHRS heat exchanger is 10 m; the relative elevation of the RHRS heat exchanger and RHRS pool is also 10 m.
- There is a 10°C temperature difference between the hot leg in the primary system and the hot leg in the RHRS loop
- The cold leg temperature in the RHRS loop is 100°C

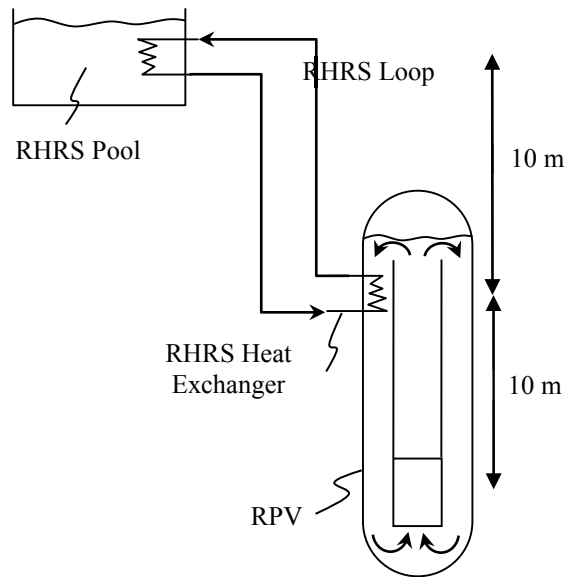


Figure 3: Schematic of the RHRS

Properties of Water in Primary System and RHRS

Parameter	Value
ρ	800 kg/m ³
β	2×10^{-3} 1/°C
c	5.0 kJ/kg°C
μ	9×10^{-5} Pa·s

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22.312 Engineering of Nuclear Reactors
Fall 2015

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