22.312 ENGINEERING OF NUCLEAR REACTORS

Monday, December 17th, 2007, 9:00am-12:00 pm

OPEN BOOK FINAL EXAM 3 HOURS

Problem 1 (45%) – Analysis of Decay Heat Removal during a Severe Accident

Extreme events in which the reactor core melts partially or completely are designated by nuclear engineers as ‘severe accidents’. Consider a severe accident during which the core has completely melted, thus falling to the bottom of the pressure vessel. The situation is illustrated in Figure 1. The molten mixture of fuel (UO_2), fission products, clad (Zr), control rod material (B_4C) and core-supporting structures (steel) is known in severe accident analysis as ‘corium’. In the situation considered here, the corium melt fills the bottom of the vessel up to the junction of the hemispherical lower head with the cylindrical beltline region. There is water above the corium and water outside the vessel. The fuel decay heat is removed by boiling above the corium, and by conduction through the vessel wall (with boiling outside the vessel being the heat sink for this heat removal mechanism). The whole system is at atmospheric pressure.

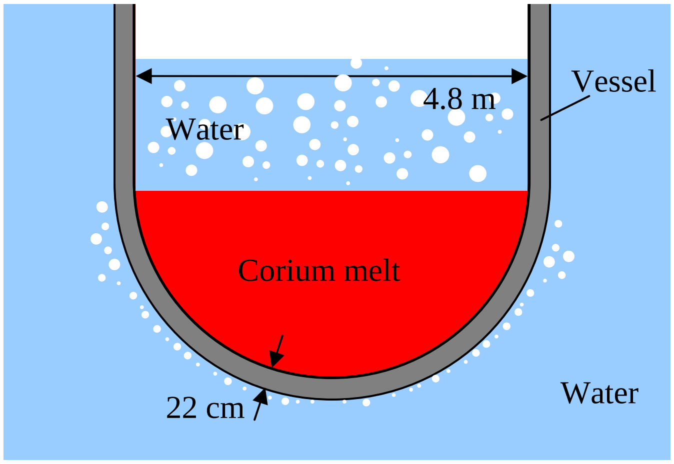

Figure 1. The lower head of the reactor vessel during a severe accident with complete melting of the core.

i) At normal operating conditions the thermal power of this reactor is 3400 MW_t. Three hours after reactor shutdown, the corium melt is at 2000°C, the temperature on the outer surface of the vessel is 120°C and the temperature of the water above the corium is 100°C. At this time is the corium heating up, cooling down or staying at steady temperature? (*Hint:* assume that the temperature distribution within the corium melt is uniform) (20%)

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ii) At a certain time during the accident, the heat flux at the upper surface of the corium melt is 200 kW/m^2. Calculate the average void fraction in the (stagnant) water above the corium melt. (Use the drift-flux model with C_o=1 and the expression of V_{vj} for churn flow. Assume water at saturated conditions) (20%)

iii) With regard to question 'ii', would a HEM approach be acceptable? Why? (5%)

Heat transfer correlations
In solving question 'i' use the following film boiling heat transfer correlation (by Berenson):

$$h_{FB} = h_c + 0.75 h_{rad}$$

$$h_c = 0.425 \left[\frac{g(\rho_f - \rho_g)\rho_g k_g^3 h'_{fg}}{\mu_g (T_w - T_{sat})\lambda_T} \right]^{0.25} \quad , \qquad h_{rad} = \varepsilon \sigma_{SB} \frac{T_w^4 - T_{sat}^4}{T_w - T_{sat}}$$

$$h'_{fg} \equiv h_{fg} + 0.5 C_{p,g}(T_w - T_{sat}) \quad , \qquad \lambda_T \equiv \sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}}$$

Properties for materials of interest in this problem

Corium
Density 8000 kg/m^3, Specific Heat 530 J/kg°C, Emissivity 0.5

Vessel steel
Density 7500 kg/m^3, Thermal Conductivity 30 W/m°C,

Saturated water at atmospheric pressure

Parameter	**Value**
T_{sat}	100°C (373 K)
ρ_f	960 kg/m^3
ρ_g	0.6 kg/m^3
h_f	419 kJ/kg
h_g	2675 kJ/kg
$C_{p,f}$	4.2 kJ/(kg°C)
$C_{p,g}$	2.1 kJ/(kg°C)
μ_f	2.8×10^{-4} Pa·s
μ_g	1.2×10^{-5} Pa·s
k_f	0.68 W/(m°C)
k_g	0.02 W/(m°C)
σ	0.06 N/m

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Problem 2 (15%) – Boiling Crisis on the Vessel Outer Surface during a Severe Accident

With regard to the situation in Problem 1, consider now the water boiling on the outer surface of the vessel. This water actually flows in a hemispherical gap between the surface of the vessel and the vessel insulation (Figure 2). The gap thickness is 20 cm. The system is at atmospheric pressure (the properties of water at atmospheric pressure are given at the end of Problem 1 above).

i) The water inlet temperature is 80°C and the flow rate in the gap is 300 kg/s. The heat flux on the outer surface of the vessel is a uniform 350 kW/m^2 in the hemispherical region ($0 \leq \theta \leq 90°$) and zero in the beltline region ($\theta > 90°$). If a boiling crisis occurred in this system, what type of boiling crisis would it be (DNB or dryout)? (10%)

ii) At what angle θ within the channel would you expect the boiling crisis to occur first and why? (5%)

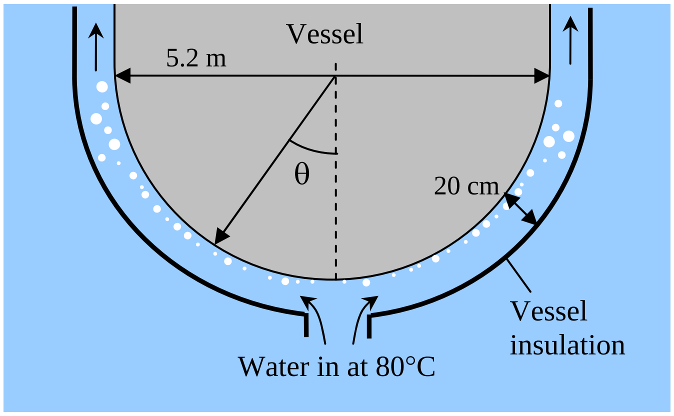

Figure 2. Two-phase flow in the gap between the outer surface of the vessel and the vessel insulation.

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Problem 3 (25%) – Entropy generation in a steam turbine system

Consider a steam turbine driven by 600 kg/s of dry saturated steam at 280°C, which discharges to a condenser operating at 0.04 bar. The isentropic efficiency for this turbine is 0.93. Calculate the rate at which entropy is generated in the turbine in the following two cases:

i) Straight expansion to 0.04 bar. (5%)

ii) Expansion to 10 bar + moisture separation + final expansion to 0.04 bar. (10%)

iii) What is the entropy generation rate in the moisture separator of Part 'ii' above? (5%)

iv) What are the advantages of the approach with moisture separation? Make sure to comment on economics, reliability and efficiency. (5%)

Properties of saturated water

T (°C)	P (bar)	v_f (m^3/kg)	v_g (m^3/kg)	h_f (kJ/kg)	h_g (kJ/kg)	s_f (kJ/kg·K)	s_g (kJ/kg·K)
30	0.04	1.0×10^{-3}	32.9	126	2556	0.4	8.4
180	10	1.1×10^{-3}	0.19	762	2777	2.1	6.7
280	64	1.3×10^{-3}	0.03	1236	2780	3.1	5.9

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Problem 4 (15%) - Sizing the Silicon Carbide Layer in a TRISO Fuel Particle

A TRISO fuel particle can be modeled as a small spherical pressure vessel of radius 300 μm and with the wall made of silicon carbide (SiC). The internal pressure is due to the build-up of fission gases, while the external pressure is a constant 9 MPa (i.e., the pressure of the reactor coolant). At the end of the irradiation cycle the fuel particle contains 0.1 μmol (=10^{-7} moles) of fission gases and operates at 1000°C.

Estimate the minimum required thickness of the SiC wall to prevent failure.

Assumptions

Use a thin-shell approximation and the Von Mises failure criterion for your analysis. Assume the fission gases occupy only 30% of the volume within the fuel particle. The fission gases can be treated as a perfect gas (R=8.31 J/mol-K).

Properties of SiC at 1000°C

Yield strength: 200 MPa
Density: 3200 kg/m^3
Young's modulus: 400 GPa
Poisson's ratio: 0.28

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