22.312 ENGINEERING OF NUCLEAR REACTORS

Tuesday, December 15th, 2015, 9:00 a.m. – 12:00 p.m.

OPEN BOOK FINAL EXAM 3 HOURS

Problem 1 (35%) – Containment Heat Transfer and Structural Mechanics

Please answer the following short questions related to a hypothetical PWR containment:

i) Determine the maximum possible heat rejection rate through a steel containment wall (thermal conductivity 40 W/m°C) whose thickness is 25 mm and surface area is 50,000 m^2 if it is desired to limit the temperature inside the containment to 150°C or less. Assume the external side is cooled by natural convection of air (heat transfer coefficient is 5 $W/m^2°C$) to an ambient temperature of 30°C. The internal side of the containment experiences condensation heat transfer with a heat transfer coefficient of 1,000 $W/m^2°C$. Assume steady state. (10%)

ii) Would it make sense to build the containment out of a material with higher thermal conductivity to increase the heat rejection rate in Part 'i'? Answer qualitatively. (5%)

iii) Assuming that the initial gas in the containment is dry air at atmospheric pressure and at 30 °C, what is the pressure in the containment if hot steam is ejected into it until the gas temperature reaches 150°C? Assume saturated steam is present in the containment at the final state. (Water properties are in the table below) (10%)

iv) If the containment building volume is 75,000 m^3 what is the mass of steam that will be present inside the containment when the temperature is 150°C? (5%)

v) Consider the building to be of cylindrical geometry, with a radius equal to 20 m. What is the maximum allowable internal pressure if it is desired to limit the hoop stress in the steel wall to 500 MPa? (5%)

Data for saturated water:

T (°C)	P (kPa)	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	4	1.0×10^{-3}	32.9	126	2556	0.4	8.4
100	101	1.0×10^{-3}	1.7	419	2676	1.3	7.3
150	476	1.1×10^{-3}	0.39	632	2747	1.8	6.8

Problem 2 (40%) – Creating a Two-Phase Mixture from Flashing of Pressurized Water

Pressurized water at 10 MPa and 300°C (the corresponding specific enthalpy and entropy are 1343 kJ/kg and 3.1 kJ/kg-K, respectively) is throttled to 6 MPa, to induce flashing and generate a two-phase mixture. The resulting two-phase mixture now flows in a horizontal, smooth, adiabatic tube which is 10-m long and has a diameter of 10 cm. The mass flow rate is steady at 10 kg/s.

i) Calculate the steam quality in the tube assuming thermal equilibrium exists at the outlet of the throttle. (5%) (*Hint*: depressurization in the throttle is a highly irreversible, isenthalpic process)

ii) Using the map in Fig. 1, determine which two-phase flow regime is present in the tube. (5%)

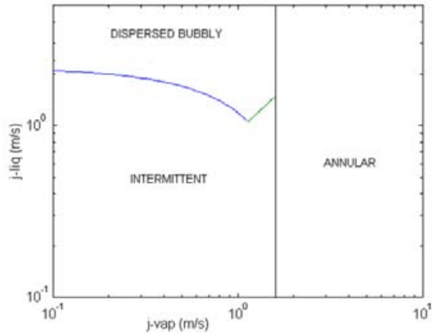

Figure 1. Simplified flow map for water at 6 MPa. The x and y axes are vapor and liquid superficial velocity, respectively. "Intermittent" means plug/churn flow.

Table 1. Properties of water at 6 MPa

Parameter	Value
T_{sat}	275.4 °C
ρ_f	758.5 kg/m^3
ρ_g	30.6 kg/m^3
h_f	1213 kJ/kg
h_g	2785 kJ/kg
s_f	3.0 kJ/kg-K
s_g	5.9 kJ/kg-K
μ_f	1×10^{-4} Pa·s
μ_g	2×10^{-5} Pa·s
k_f	0.58 W/(m°C)
k_g	0.06 W/(m°C)
σ	0.02 N/m

iii) Calculate the void fraction and friction pressure drop in the tube using models/correlations appropriate for the conditions of interest. (15%)

The two-phase mixture finally enters a heated test section, which also comprises a tube, 3-m long, 10-cm diameter, and has a heat flux $q'' = 600$ kW/m^2, axially uniform, but applied only to the top half of the tube (see Fig. 2). There is a concern that dryout may occur in the test section.

iv) Calculate the critical power for the heated test section using the CISE-4 correlation for the critical quality (assume it is suitable for the conditions of interest). (15%) (*Hint:* you may approximate the boiling length with the distance from the inlet of the adiabatic tube).

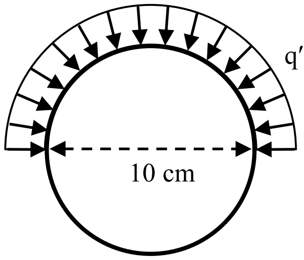

Figure 2. Cross-section of the tube

Bonus question (extra 5%):

v) Calculate the entropy generation rate in the throttle.

Problem 3 (25%) – Sizing the fuel pin of a Liquid Metal Fast Breeder Reactor (LMFBR)

An LMFBR operates with an average specific power in the fuel of 120 W/g. It is desired to upgrade the capability of the reactor so that the specific power becomes 200 W/g. There is a requirement that the temperature drop across the fuel pellet radius remains the same. The present fuel pellet diameter is 0.51 cm.

i) What fuel pellet diameter should be used in the upgraded core? (10%)

ii) If an annular fuel pellet of outer diameter 0.51 cm were to be used, what would be the diameter of the hole in the middle of the pellet? Develop (but do not solve) an equation that would give you the answer. (10%)

iii) Now back to a solid cylindrical pellet. If the fuel pellet diameter is not to change, but the fuel material is to be changed to one of 20% higher density, what is the ratio of the needed fuel thermal conductivity to the conductivity of the present fuel? (5%)

In all questions above assume the fuel thermal conductivity is independent of temperature.

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