22.312 **ENGINEERING OF NUCLEAR REACTORS**

Tuesday, December 14th, 2004, 1:30-4:30 pm

OPEN BOOK FINAL EXAM 3 HOURS

Problem 1 (55%) – Structural and thermal-hydraulic analysis of a PWR pressurizer

In the primary system of a PWR the pressure is controlled by means of a pressurizer. The pressurizer is a cylindrical steel vessel of 2-m internal diameter, containing water and steam, and is connected to the primary system by a surge line (Figure 1). The pressurizer also has a bundle of submerged electric heaters. When there is an outsurge of water from the pressurizer, the heaters are activated to maintain the nominal pressure.

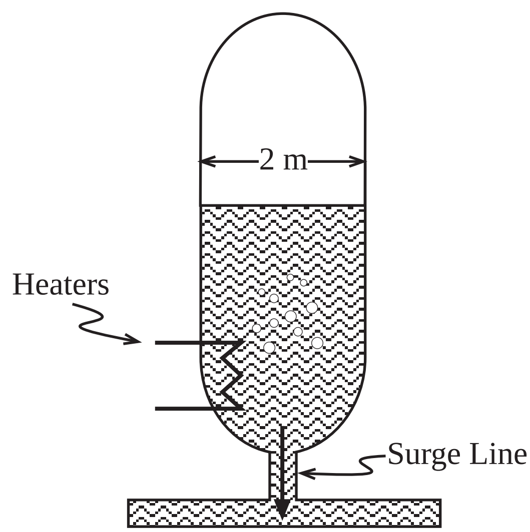

Figure 1. The pressurizer.

i) Calculate the minimum thickness of the pressurizer cylindrical shell to meet the ASME code primary general membrane stress requirements for a design pressure of 17 MPa. (The value of the maximum allowable stress intensity, S_m, is 184 MPa in the temperature range of interest. Use a thin-shell approximation to calculate the stresses) (15%)

ii) Write a complete set of equations to calculate the total amount of heat that needs to be supplied by the heaters to maintain the nominal PWR pressure of 15.5 MPa, following a 3,500 kg liquid water outsurge from the pressurizer. (Assume that thermodynamic equilibrium is maintained throughout the process. The initial conditions for the pressurizer and the thermodynamic properties of water at 15.5 MPa are reported in Table 1. Make clear all assumptions implied in your calculations.) (20%)

iii) Does the answer in "ii" depend on the duration of the process? Explain. (5%)

iv) The electric heater bundle consists of 30 cylindrical resistors of 1 cm diameter, delivering a (total) maximum power of 3 MW. It is desirable that the CHF limit not be exceeded on the surface of the resistors. Calculate the minimum length of the resistors to meet this criterion. (The pool boiling curve for water at 15.5 MPa is shown in Figure 2) (10%)

v) If the pressure in the pressurizer significantly decreased (e.g., to 10 MPa) while the heaters are at full power, would the no-CHF criterion in "iv" still be met? Explain. (5%)

Table 1.

Parameter	**Value**
Pressurizer volume	31 m^3
Initial conditions	
Liquid volume	25 m^3
Vapor volume	6 m^3
Properties of saturated water at 15.5 MPa	
v_f	0.0017 m^3/kg
v_g	0.01 m^3/kg
h_f	1,631 kJ/kg
h_g	2,596 kJ/kg
u_f	1,605 kJ/kg
u_g	2,444 kJ/kg

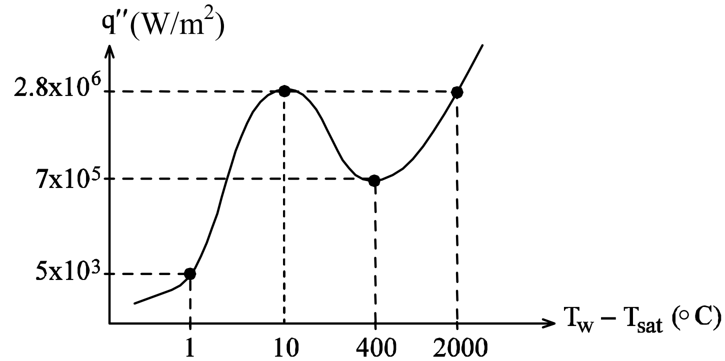

Figure 2. Boiling curve for water at 15.5 MPa.

Problem 2 (35%) – Void fraction and pressure drop in an isolation condenser.

A modern BWR uses an isolation condenser to remove the decay heat from the core following a feedwater pump trip. The isolation condenser receives 50 kg/s of saturated dry steam at 280°C and condenses it completely. The isolation condenser consists of 200 horizontal round tubes of 3-cm inner diameter and 12-m length. The condensing steam flows inside the tubes (Figure 3). The tubes sit in a pool of water at atmospheric pressure.

i) Calculate the isolation condenser heat removal rate. (The properties of saturated water at 280°C are reported in Table 2) (5%)

ii) Using the simplified Chato correlation reported below, estimate the temperature on the inner surface of the tubes. (Assume an axially uniform heat flux in the tubes) (5%)

iii) Sketch the axial profile of the void fraction in the tubes. (Assume linear variation of the quality in the tubes. Use HEM to calculate the void fraction) (10%)

iv) Calculate the acceleration, friction, gravity and total pressure drops within the tubes. (Use the HEM approach with $f_{TP}=f_{\ell o}$ to calculate the friction pressure drop) (10%)

v) How would the acceleration, friction and gravity pressure drops within the tubes change, if the tubes were vertical and the steam flow were downward? (A qualitative answer is acceptable) (5%)

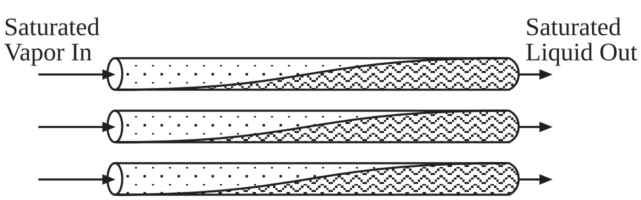

Figure 3. Isolation condenser tubes.

Table 2. Properties of saturated water at 280°C.

Parameter	Value
v_f	0.0013 m^3/kg
v_g	0.03 m^3/kg
h_f	1,237 kJ/kg
h_g	2,780 kJ/kg
μ_f	9.8×10^{-5} Pa·s
μ_g	1.9×10^{-5} Pa·s
k_f	0.574 W/(m°C)
k_g	0.061 W/(m°C)

Simplified Chato correlation for flow condensation inside round tubes:

$$h_D = 0.555\left[\frac{g\rho_f(\rho_f-\rho_g)k_f^3 h_{fg}}{\mu_f(T_{sat}-T_w)D}\right]^{1/4}$$

Problem 3 (10%) – Departure from Nucleate Boiling in a PWR

The departure from nucleate boiling (DNB) heat flux and the operating heat flux in the hot channel of a PWR at 100% power are sketched qualitatively in Figure 4, as functions of the axial location, z. If the reactor power were increased (without changing the mass flow rate, pressure and inlet bulk temperature), how would the curves of Figure 4 change?

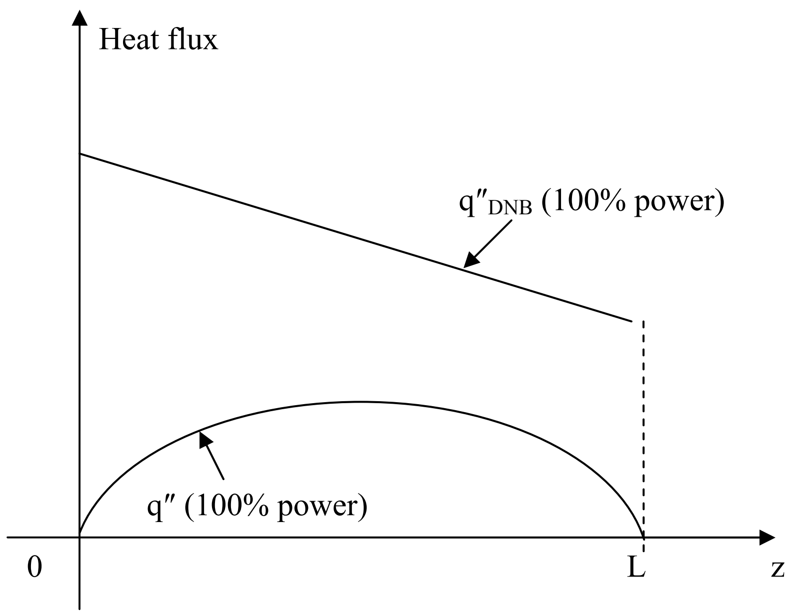

Figure 4. Axial variation of the DNB and operating heat fluxes in the PWR hot channel.