22.313J, 2.59J, 10.536J THERMAL-HYDRAULICS IN POWER TECHNOLOGY

Tuesday, May 22nd, 2007, 9 a.m. – 12 p.m.

OPEN BOOK	FINAL	3 HOURS

Problem 1 (35%) – Steady-state natural circulation in a steam generation system

Saturated steam at 3 MPa (properties in Table 1) is used in a certain factory. The steam is generated by the system shown in Figure 1, which consists of a natural gas-fired heater, a riser of height *L*, a steam separator of form loss *K*, and a downcomer. The makeup flow can be assumed to be saturated water at 3 MPa. The riser and the steam separator have the same flow area, *A*.

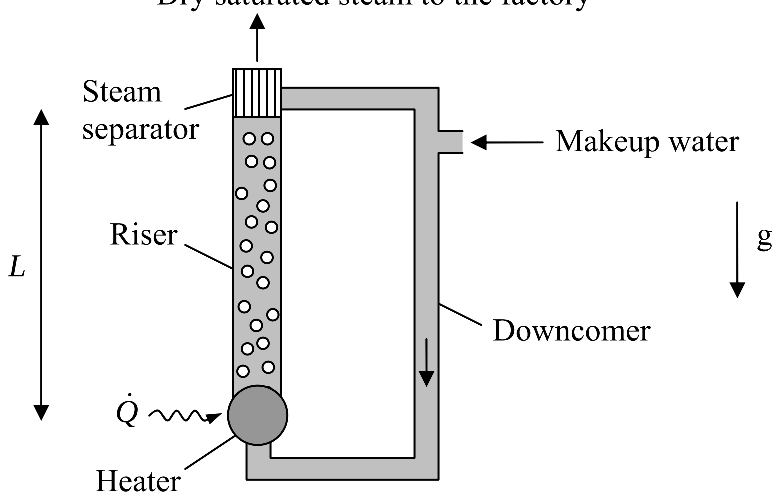

Figure 1. Schematic of the steam generation loop

i) Using the conservation equations and their constitutive relations, find a single equation from which the mass flow rate in the loop, $\dot{m}$, could be found as a function of the heat rate, $\dot{Q}$, and the parameters *A*, *L* and *K*, i.e., $f(\dot{m}, \dot{Q}, A, L, K)=0$. (20%)

ii) Find $\dot{m}$ for the two limit cases $\dot{Q}=0$ and $\dot{Q}=\dot{m}\,h_{fg}$. Do you think the $\dot{m}$ vs $\dot{Q}$ curve (with fixed *A*, *L* and *K*) could have a maximum between these two limits? Explain your answer qualitatively. (10%)

iii) For a given $\dot{Q}$, how does $\dot{m}$ change if *K* increases or *L* increases or *A* increases? (5%)

Assumptions:

- Steady state
- Steam separator efficiency is one
- Use HEM for the void fraction in the riser
- Neglect all acceleration and friction terms in the loop momentum equation
- Use the HEM multiplier for the form loss in the separator, $\phi_{\ell o}^2 = 1 + x\left(\frac{\rho_f}{\rho_g} - 1\right)$

Table 1. Properties of saturated water at 3 MPa.

Parameter	**Value**
T_{sat}	234°C (507 K)
ρ_f	822 kg/m^3
ρ_g	15 kg/m^3
h_f	1,008 kJ/kg
h_g	2,803 kJ/kg
$C_{p,f}$	4.7 kJ/(kg°C)
$C_{p,g}$	3.6 kJ/(kg°C)
μ_f	1.1×10^{-4} Pa·s
μ_g	1.7×10^{-5} Pa·s
k_f	0.638 W/(m°C)
k_g	0.047 W/(m°C)
σ	0.030 N/m

Problem 2 (55%) – Water boiling during a loss-of-flow transient in a home heating system

A large condo building uses a water forced-convection heating system. The heater consists of hundreds of round channels of diameter D=2.54 cm and length L=1 m in which water is heated by an axially uniform heat flux, q''=200 kW/m^2 (see Figure 2). The system operates at 1 MPa and the water temperature at the inlet of the heater channel is T_{in}=90°C (h_{in}=365.6 kJ/kg). Under normal operating conditions the mass flux is G_o=1000 kg/m^{2}s and no boiling occurs in the channel. A pump malfunction occurs at t=0, so that the mass flux in the heater channel starts to decay exponentially, i.e., $G(t) = G_o e^{-t/\tau}$, where τ=10 s. Assume that the heat flux, pressure and inlet temperature remain constant throughout the transient.

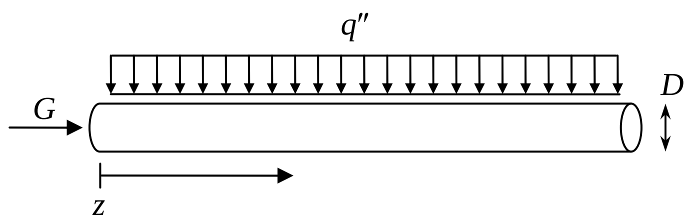

Figure 2. A heater channel.

Table 2. Properties of saturated water at 1 MPa.

Parameter	**Value**
T_{sat}	180°C (453 K)
ρ_f	887 kg/m^3
ρ_g	5.1 kg/m^3
h_f	763 kJ/kg
h_g	2,778 kJ/kg
$C_{p,f}$	4.4 kJ/(kg°C)
$C_{p,g}$	2.6 kJ/(kg°C)
μ_f	1.5×10^{-4} Pa·s
μ_g	1.4×10^{-5} Pa·s
k_f	0.677 W/(m°C)
k_g	0.034 W/(m°C)
σ	0.042 N/m
R^*	462 J/kg·K

i) Using a simplified version of the energy conservation equation, $G\dfrac{\partial h}{\partial z} = \dfrac{q'' P_h}{A}$, calculate the fluid enthalpy and equilibrium quality as functions of z and t. (5%)

ii) At what time does the bulk temperature reach saturation? Assume the specific heat does not change with temperature. (5%)

iii) At what time does nucleate boiling start? Use the Davis and Anderson model for ONB and assume that the single-phase forced convection heat transfer coefficient, H, is proportional to the mass flux, i.e., $H = H_o \frac{G(t)}{G_o}$, where H_o=9.3 kW/m^{2}K. (10%)

iv) At what time does a significant amount of vapor first appear in the channel? (10%)

v) Qualitatively sketch the MDNBR vs. time. (5%)

vi) Qualitatively sketch the bulk and wall temperatures vs. time at the channel outlet. (10%)

vii) Estimate the time at which two-phase density-wave oscillations appear in the channel. Use the stability map of Figure 3 below. (10%)

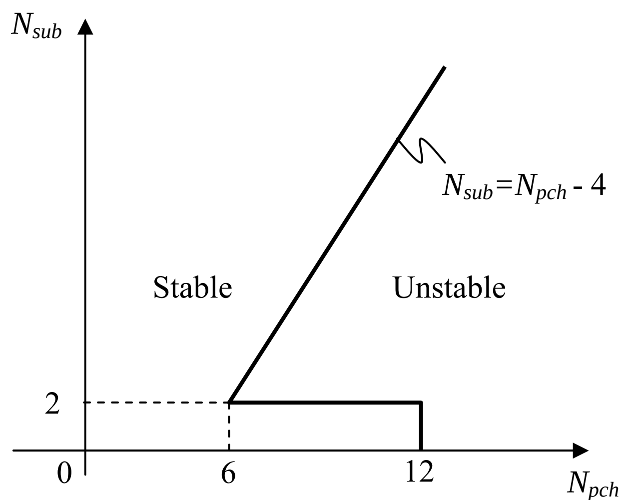

Figure 3. Stability map for the heater channel.

Problem 3 (10%) – Short questions on bubble nucleation

i) A steam bubble grows at a cavity with the geometry shown in Figure 4. What can you say about the steam temperature in this situation? (5%)

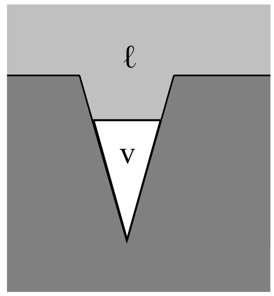

Figure 4. Steam bubble growing within a wall cavity.

ii) To obtain bubble nucleation at a cavity of radius 1 μm on a copper surface, a certain fluid (of contact angle 135° with copper) requires a 2°C superheat. What would the required superheat be for bubble nucleation at a cavity of radius 3 μm on steel, if the fluid contact angle with steel were 45°? (5%)