22.312 ENGINEERING OF NUCLEAR REACTORS

Tuesday, October 20th, 2015, 1:00 – 2:30 p.m.

OPEN BOOK QUIZ 1 1.5 HOURS

Problem 1 (50%) – Cooling tower

The schematic drawing of a draft cooling tower used in a large LWR plant is shown in Figure 1. Hot water from the condenser enters the tower at Point 1, at a flow rate $\dot{m}_{w1}$=17,000 kg/s, temperature T_1 = 35°C and enthalpy h_1 = 146.7 kJ/kg, and is sprayed downward to be cooled by a flow of cold air. The water collected at the bottom of the tower (Point 3) is returned to the condenser. Air entering the tower at Point 2 is perfectly dry (ϕ_2 = 0) at temperature T_2 = 20°C, and with a flow rate $\dot{m}_a$ =16,000 kg/s. The air exiting the tower at Point 4 is at T_4 = 30°C, with 100% humidity (ϕ_4 = 1). The pressure can be assumed atmospheric throughout the system.

i) Find the mass flow rate of water discharged from the cooling tower, $\dot{m}_{w3}$. (15%) (*Hint:* the air and the water in the air at Point 4 have the same volumetric flow rate, m^3/s)

ii) Find the temperature of water discharged from the cooling tower, T_3. (30%)

Now consider a different situation: it is a very hot day, and the air entering the cooling tower is at the same temperature of the water entering the cooling tower, i.e. $T_2 = T_1$.

iii) Will T_3 be higher, lower or equal than T_1? In other words, will the cooling tower still be able to cool the water coming from the condenser? A qualitative answer is acceptable. (5%)

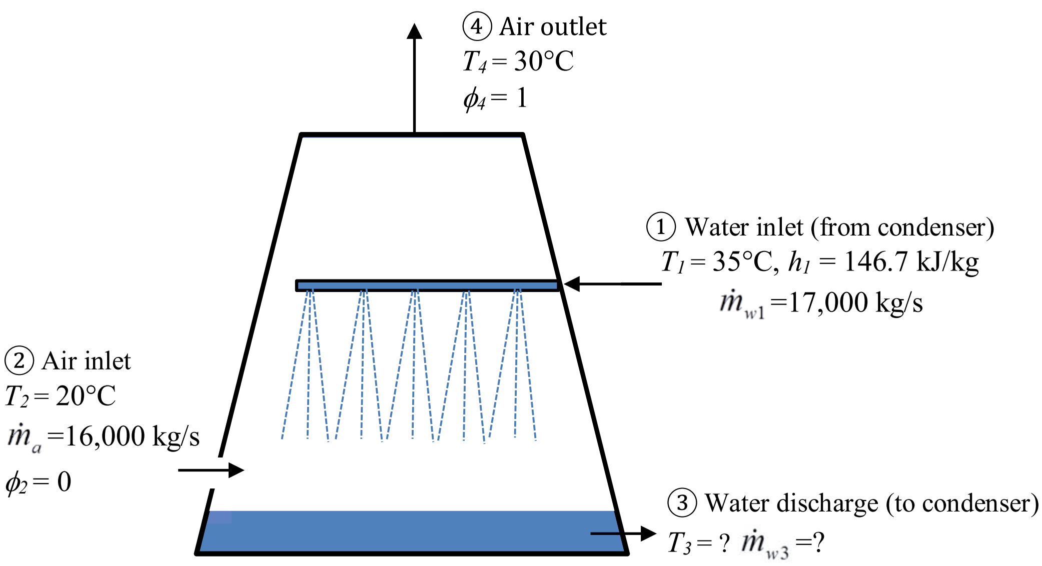

Figure 1. Draft cooling tower

Assumptions:

- Assume steady operation
- Neglect kinetic and gravitational terms in the energy equation
- Neglect solubility of air in water
- Treat air as an ideal gas (R = 287 J/kg-K; c_p = 1005 J/kg-K)
- You may treat subcooled water as an incompressible fluid (ρ =1000 kg/m^3, c =4180 J/kg-K)

Properties of saturated water:

Temperature (°C)	Pressure (kPa)	ρ_f (kg/m^3)	ρ_g (kg/m^3)	h_f (kJ/kg)	h_g (kJ/kg)
30	4.24	995	0.03	126	2556
100	101 (atmospheric)	958	0.6	419	2676

Courtesy of Michael Kappel on Flickr. Used with permission.

iv) Bonus question (extra 5%): in the photo above, why is the plume of humid air at the top of the tower visible?

Problem 2 (50%) – Transient analysis of a firebrick-based energy storage system

NSE's Dr. Forsberg has been developing the concept of Firebrick Resistance-heated Energy Storage, or FIRES. In this approach, excess electric energy from the grid, for example due to a surge in renewable energy generation at a time of low demand, is stored as internal energy in a large stack of firebricks. That energy can be recovered by blowing cooler air through the hot firebrick stack, to provide hot air to industrial furnaces and/or gas turbines at a time of peak power demand. Consider one such stack of firebricks contained within a well-insulated vessel. At first there is no flow of air in or out of the vessel, and electrical power is delivered from the grid to the firebricks at a steady rate 100 MW. The initial temperature and pressure of the system are $T_1 = 950$ K and $P_1 = 2$ MPa, respectively. The mass of firebricks is $M_b = 3.6\times10^6$ kg; the free volume of air in the vessel is $V_a = 180$ m^3.

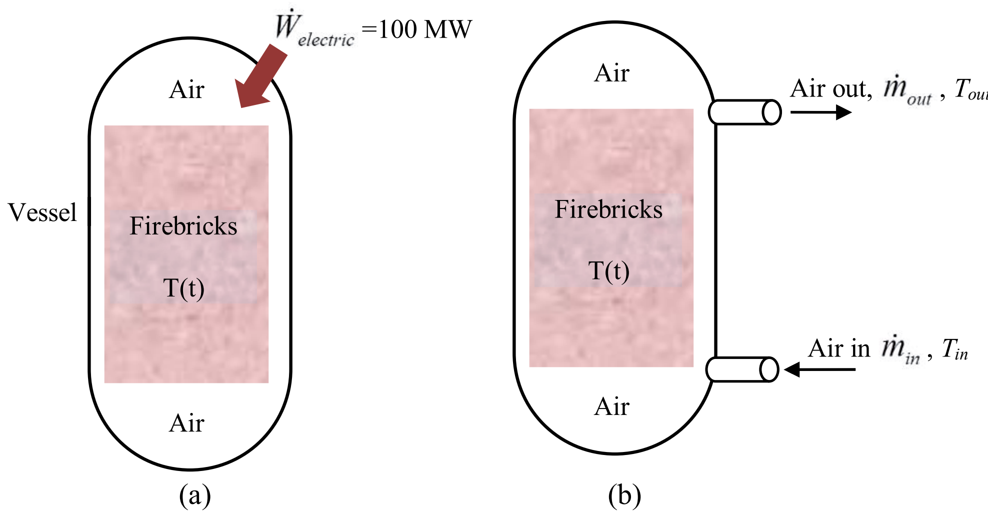

Figure 2. The FIRES system during (a) the charging phase, and (b) when air is forced through the system after t= 3 hours

i) Calculate the thermal capacity (J/K) of the air and compare it to thermal capacity of the bricks. (5%)

ii) Find an expression for and plot the temperature of the system vs. time, *T(t)*, during the charging, and calculate the temperature of the system after 3 hours of charging. You may assume that the air and bricks are in thermal equilibrium at all time. (15%)

At $t = 3$ hours the electrical power is turned off, the intake and discharge valves are open, and a steady air flow in and out of the vessel is established, $\dot{m}_{in} = \dot{m}_{out} = 300$ kg/s. The inlet temperature of the air is $T_{in} = 950$ K constant in time, while you may assume that the temperature of the air at the outlet is equal to the instantaneous temperature of the bricks within the system, $T_{out} = T(t)$.

iii) Find an expression for and plot the temperature of the system vs. time, *T(t)*, for $t>3$ hours. (30%)

Assumptions:

- Neglect kinetic and gravitational terms
- Assume the FIRES vessel is well insulated

Properties:

Firebrick: $c_b = 700$ J/kg-K, $\rho_b = 4000$ kg/m^3
Air (treat as ideal gas): $R_a = 287$ J/kg-K; $c_{va} = 718$ J/kg-K

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