UNIVERSITY OF WATERLOO
DEPARTMENT OF ELECTRICAL ENGINEERING

ECE 309 Thermodynamics and Heat Transfer for Electrical Engineering

Mid-Term Examination Spring 1997
M.M. Yovanovich June 14, 1997 4:30-6:30 P.M.

NOTE:

1. Open book examination. You are permitted to use your calculator, the text book and your lecture notes. One crib sheet (8.5 x 11) one side only.
2. Clear systematic solutions are required. Process diagrams and sketches of equipment showing locations referred to in your analysis are both essential. Marks will not be assigned for problems that require unreasonable (in the opinion of your professor) effort for the marker to decipher.
3. Very briefly state the assumptions that are made in each problem.
4. Ask for clarification if any problem statement is unclear.
5. All problems are of equal weight. You must answer all *three* problems.
6. Do not interpolate in the tables. Use the nearest points.

---

1. A single integrated circuit (chip) can consist of approximately 10^4 discrete electrical components which dissipate heat (ohmic heating) which is as high as $30,000\,W/m^2$. The chip which is very thin (assume negligible thickness) is convectively cooled at its outer surface by a coolant whose temperature is $T_{f,o} = 20^0C$ through a film coefficient $h_o = 1000\,W/m^2 \cdot K$. The other surface is in good thermal contact $h_c = 10^4\,W/m^2 \cdot K$ with a circuit board whose thickness is $L = 1\,mm$ and whose effective thermal conductivity is $k_e = 5\,W/m \cdot K$. The other side of the circuit board is exposed to ambient air whose temperature is $T_{f,i} = 20^0C$ and the corresponding film coeffcient is $h_i = 40\,W/m^2 \cdot K$.

(a) Sketch the equivalent thermal circuit showing clearly all relevant thermal resistances, temperature nodes and the heat flow rates.

(b) Calculate the chip temperature T_c for the heat dissipation rate given above.

(c) What fraction of the dissipated heat goes into the coolant?

2. A long stainless-steel wire of diameter $D = 1mm$ is submerged in an oil bath of temperature $T_f = 25^0C$. The wire has an electrical resistance per unit length of $R_e/L = \rho_e/A_c = 0.01\,\Omega/m$. The wire carries a current $I = 100\,A$. The convective heat transfer coefficient is estimated to be $h = 500\,W/m^2 \cdot K$. The wire thermophysical properties are: $\rho = 8000\,kg/m^3, C_P = 500\,J/kg \cdot K$, and $k = 20\,W/m \cdot K$.

   (a) Compute the Biot number for this system and verify that the *lumped* capacitance model can be used.

   (b) Compute the characteristic time t_c of the system.

   (c) Find the value of the steady-state temperature T_{ss}.

   (d) From the time the current is applied, how long does it take the wire to reach a temperature which is within 1^0C of the steady-state value?

3. Two kg of dry air experiences a three process cycle that returns it to its initial state. During the first process the volume is kept constant while the pressure decreases from P_1 to $P_2 = 100\,kPa$. During the second constant pressure process the volume increases from $V_2 = 2\,m^3$ to $V_3 = 5\,V_2$. The third process is isothermal as the system returns to its initial state.

   (a) Provide a simple sketch of the three processes on a $P - V$ diagram.

   (b) What is $\Delta U_{14} = U_4 - U_1$ for the cycle?

   (c) Determine the value of the initial pressure P_1.

   (d) Obtain the relation between W_{14}/M and the system parameters: $P_2, V_1, V_2, V_3, R, T_3$.

   (e) Calculate W_{14}/M and Q_{14}/M. Report the values as kJ/kg.

Some Equations and Relationships

1. $E_1 + W_{1\to 2} + Q_{1\to 2} = E_2$
2. $e = u + \frac{1}{2}\bar{V}^2 + gz + \cdots$
3. $h \equiv u + Pv \qquad u = \frac{U}{M} \qquad v = \frac{V}{M}$
4. $v = (1-x)v_f + xv_g \qquad v_{fg} = v_g - v_f$
5. $\left(\frac{dE}{dt}\right)_{CV} = \dot{Q} + \dot{W} + \sum_{in}(e + Pv)\dot{M} - \sum_{out}(e + Pv)\dot{M}$
6. $\left(\frac{dM}{dt}\right)_{CV} = \sum_{in} \dot{M} - \sum_{out} \dot{M}$
7. $c_v \equiv \left(\frac{\partial u}{\partial T}\right)_V \qquad c_p \equiv \left(\frac{\partial h}{\partial T}\right)_P \qquad c_p = c_v + R$