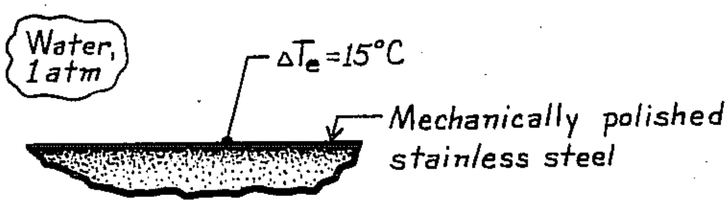
PROBLEM 10.6

KNOWN: Water boiling on a mechanically polished stainless steel surface maintained at an excess temperature of 15 °C; water is at 1 atm.

FIND: Boiling heat transfer coefficient.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Nucleate pool boiling occurs.

PROPERTIES: *Table A-6,* Saturated water (1 atm): $T_{sat} = 100\,°C$, $\rho_\ell = 957.9\ kg/m^3$, $\rho_v = 0.596\ kg/m^3$, $c_{p,\ell} = 4217\ J/kg \cdot K$, $\mu_\ell = 279 \times 10^{-6}\ N \cdot s/m^2$, $Pr_\ell = 1.76$, $\sigma = 58.9 \times 10^{-3}\ N/m$, $h_{fg} = 2257\ kJ/kg$.

ANALYSIS: The heat transfer coefficient can be expressed as

$$h = q''_s / \Delta T_e$$

where the nucleate pool boiling heat flux can be estimated using the Rohsenow correlation.

$$q''_s = \mu_\ell h_{fg} \left[\frac{g(\rho_\ell - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{c_{p,\ell} \Delta T_e}{C_{s,f} h_{fg} Pr_\ell^n} \right)^3 .$$

From Table 10.1, find for this liquid-surface combination, $C_{s,f} = 0.013$ and $n = 1$, and substituting numerical values,

$$q''_s = 279 \times 10^{-6}\ N \cdot s/m^2 \times 2257 \times 10^3\ J/kg \left[\frac{9.8 m/s^2 (957.9 - 0.596)\ kg/m^3}{58.9 \times 10^{-3}\ N/m} \right]^{1/2} \times$$

$$\left(\frac{4217\ J/kg \cdot K \times 15\,°C}{0.013 \times 2257\ kJ/kg \times 1.76} \right)^3$$

$$q''_s = 461.9\ kW/m^2 .$$

Hence, the heat transfer coefficient is

$$h = 461.9 \times 10^3\ W/m^2 / 15\,°C = 30,790\ W/m^2 \cdot K . \qquad \triangleleft$$

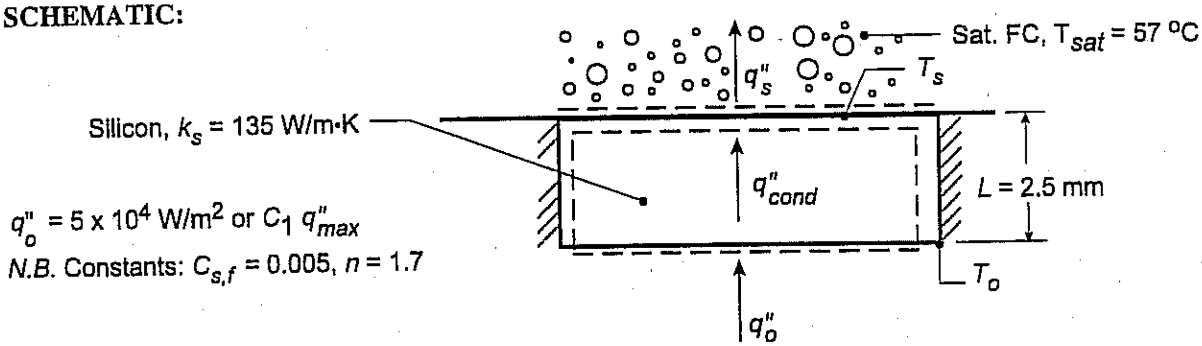
COMMENTS: Note that this value of q''_s for $\Delta T_e = 15\,°C$ is similar to the typical boiling curve, Fig. 10.4.

PROBLEM 10.20

KNOWN: Thickness and thermal conductivity of a silicon chip. Properties of saturated fluorocarbon liquid.

FIND: (a) Temperature at bottom surface of chip for a prescribed heat flux and 90% of CHF, (b) Effect of heat flux on chip surface temperatures; maximum allowable heat flux.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Uniform heat flux and adiabatic sides, hence one-dimensional conduction in chip, (3) Constant properties, (4) Nucleate boiling in liquid.

PROPERTIES: Saturated fluorocarbon (given): $c_{p,\ell} = 1100$ J/kg·K, $h_{fg} = 84{,}400$ J/kg, $\rho_\ell = 1619.2$ kg/m^3, $\rho_v = 13.4$ kg/m^3, $\sigma = 8.1 \times 10^{-3}$ kg/s^2, $\mu_\ell = 440 \times 10^{-6}$ kg/m·s, $Pr_\ell = 9.01$.

ANALYSIS: (a) Energy balances at the top and bottom surfaces yield $q''_o = q''_{cond} = k_s\left(T_o - T_s\right)/L = q''_s$; where T_s and q''_s are related by the Rohsenow correlation,

$$T_s - T_{sat} = \frac{C_{s,f} h_{fg} Pr_\ell^n}{c_{p,\ell}}\left(\frac{q''_s}{\mu_\ell h_{fg}}\right)^{1/3}\left[\frac{\sigma}{g(\rho_\ell - \rho_v)}\right]^{1/6}$$

Hence, for $q''_s = 5 \times 10^4$ W/m^2,

$$T_s - T_{sat} = \frac{0.005(84{,}400\,\text{J/kg})9.01^{1.7}}{1100\,\text{J/kg}\cdot\text{K}}\left(\frac{5\times10^4\,\text{W/m}^2}{440\times10^{-6}\,\text{kg/m}\cdot\text{s}\times 84{,}400\,\text{J/kg}}\right)^{1/3}$$

$$\times\left[\frac{8.1\times10^{-3}\,\text{kg/s}^2}{9.807\,\text{m/s}^2\,(1619.2-13.4)\,\text{kg/m}^3}\right]^{1/6} = 15.9^\circ\text{C}$$

$$T_s = (15.9 + 57)^\circ\text{C} = 72.9^\circ\text{C}.$$

From the rate equation,

$$T_o = T_s + \frac{q''_o L}{k_s} = 72.9^\circ\text{C} + \frac{5\times10^4\,\text{W/m}^2\times 0.0025\,\text{m}}{135\,\text{W/m}\cdot\text{K}} = 73.8^\circ\text{C}$$ <

For a heat flux which is 90% of the critical heat flux ($C_1 = 0.9$), it follows that

$$q''_o = 0.9 q''_{max} = 0.9\times0.149 h_{fg}\rho_v\left[\frac{\sigma g(\rho_\ell - \rho_v)}{\rho_v^2}\right]^{1/4} = 0.9\times0.149\times84{,}400\,\text{J/kg}\times13.4\,\text{kg/m}^3$$

Continued...

$$\times\left[\frac{8.1\times10^{-3}\,\text{kg/s}^2\times9.807\,\text{m/s}^2\,(1619.2-13.4)\,\text{kg/m}^3}{\left(13.4\,\text{kg/m}^3\right)^2}\right]^{1/4}$$

$$q''_o = 0.9\times15.5\times10^4\ \text{W/m}^2 = 13.9\times10^4\ \text{W/m}^2$$

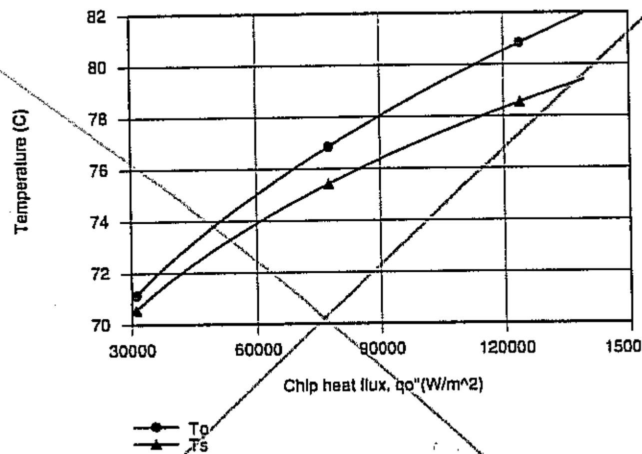
From the results of the previous calculation and the Rohsenow correlation, it follows that

$$\Delta T_e = 15.9^\circ\text{C}\left(q''_o/5\times10^4\ \text{W/m}^2\right)^{1/3} = 15.9^\circ\text{C}(13.9/5)^{1/3} = 22.4^\circ\text{C}$$

Hence, $T_s = 79.4°C$ and

$$T_o = 79.4^\circ\text{C} + \frac{13.9\times10^4\ \text{W/m}^2\times0.0025\,\text{m}}{135\,\text{W/m·K}} = 82^\circ\text{C} \quad <$$

(b) Using the energy balance equations with the *Correlations* Toolpad of IHT to perform the parametric calculations for $0.2 \le C_l \le 0.9$, the following results are obtained.



The chip surface temperatures, as well as the difference between temperatures, increase with increasing heat flux. The maximum chip temperature is associated with the bottom surface, and $T_o = 80°C$ corresponds to

$$q''_{o,max} = 11.3\times10^4\ \text{W/m}^2 \quad <$$

which is 73% of CHF ($q''_{max} = 15.5\times10^4$ W/m^2).

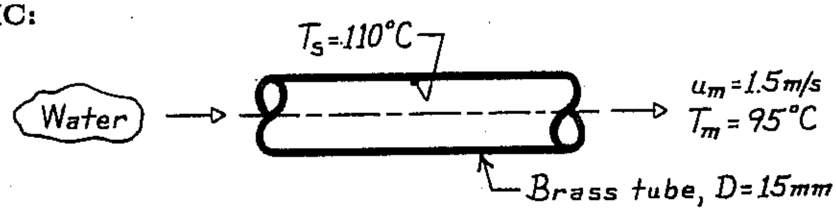
COMMENTS: Many of today's VLSI chip designs involve heat fluxes well in excess of 15 W/cm^2, in which case pool boiling in a fluorocarbon would not be an appropriate means of heat dissipation.

PROBLEM 10.33

KNOWN: Forced convection and boiling processes occur in a smooth tube with prescribed water velocity and surface temperature.

FIND: Heat transfer rate per unit length of the tube.

SCHEMATIC:



ASSUMPTIONS: (1) Fully-developed flow, (2) Nucleate boiling conditions occur on inner wall of tube, (3) Forced convection and boiling effects can be separately estimated.

PROPERTIES: *Table A-6,* Water ($T_m = 95\,^\circ C = 368K$): $\rho_\ell = 1/v_f = 962\,kg/m^3$, $\rho_v = 1/v_g = 0.500\,kg/m^3$, $h_{fg} = 2270\ kJ/kg$, $c_{p,\ell} = 4212\ J/kg{\cdot}K$, $\mu_\ell = 296\times10^{-6}\ N{\cdot}s/m^2$, $k_\ell = 0.678\ W/m{\cdot}K$, $Pr_\ell = 1.86$, $\sigma = 60\times10^{-3}\ N/m$, $\nu_\ell = 3.08\times10^{-7}\ m^2/s$.

ANALYSIS: Experimentation has indicated that the heat transfer rate can be estimated as the sum of the separate effects due to forced convection and boiling. On a per unit length basis,

$$q' = q'_{fc} + q'_{boil}\ .$$

For *forced convection,* $Re_D = u_m D/\nu_\ell = 1.5\,m/s \times 0.015m/3.08\times10^{-7}\,m^2/s = 73{,}052$. Since $Re > 2300$, flow is turbulent and since fully developed, use the Dittus-Boelter correlation but with the 0.023 coefficient replaced by 0.019 and $n = 0.4$,

$$Nu_D = hD/k = 0.019\,Re_D^{4/5}\,Pr^n$$

$$h = \frac{k}{D}Nu_D = \frac{0.678\,W/m{\cdot}K}{0.015m}\times 0.019\,(73{,}052)^{4/5}\,(1.86)^{0.4} = 8563\,W/m^2{\cdot}K\ .$$

$$q'_{fc} = h\pi D\,(T_s - T_m) = 8{,}563\,W/m^2{\cdot}K\cdot\pi(0.015m)(110-95)\,^\circ C = 6052\,W/m\ .$$

For *boiling,* $\Delta T_e = (110-100)\,^\circ C = 10\,^\circ C$ and hence nucleate boiling occurs. From the Rohsenow equation, with $C_{sf} = 0.006$ and $n = 1.0$,

$$q''_{boil} = \mu_\ell h_{fg}\left[\frac{g(\rho_\ell - \rho_v)}{\sigma}\right]^{1/2}\left[\frac{c_{p,\ell}\,\Delta T_e}{C_{sf}\,h_{fg}\,Pr_\ell^n}\right]^3$$

$$q''_{boil} = 296\times10^{-6}\,\frac{N{\cdot}s}{m^2}\times 2270\times10^3\,\frac{J}{kg}\left[\frac{9.8\,m/s^2\,(962-0.5)\,kg/m^3}{60\times10^{-3}\,N/m}\right]^{1/2}\left[\frac{4212\,J/kg{\cdot}K\times 10K}{0.006\times 2270\times10^3\,\frac{J}{kg}\times(1.86)^{1.0}}\right]^3$$

$$q''_{boil} = 1.22\times10^6\,W/m^2 \qquad q'_{boil} = q''_{boil}(\pi D) = 1.22\times10^6\,W/m^2\,(\pi\times 0.015m) = 57{,}670\,W/m\ .$$

The total heat rate for both processes is

$$q' = (6052 + 57{,}670)\,W/m = 6.37\times10^4\,W/m\ . \qquad \lhd$$

COMMENTS: Recognize that this method provides only an estimate since the processes are surely coupled.