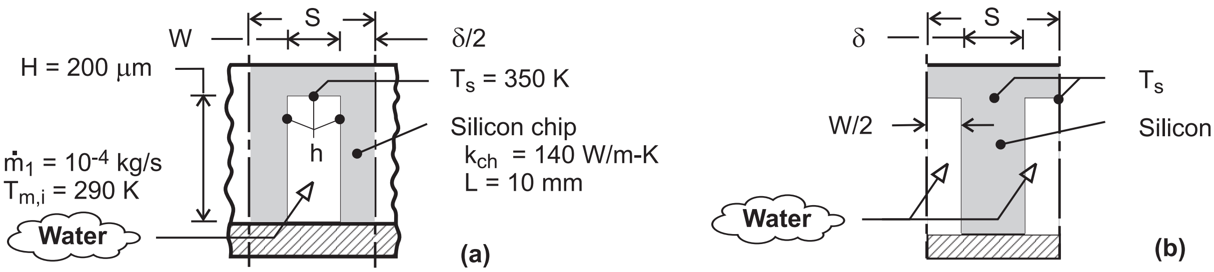
PROBLEM 8.109

KNOWN: Chip and cooling channel dimensions. Channel flow rate and inlet temperature. Temperature of chip at base of channel.

FIND: (a) Water outlet temperature and chip power, (b) Effect of channel width and pitch on power dissipation.

SCHEMATIC:



ASSUMPTIONS: (1) Incompressible liquid with negligible viscous dissipation, (2) Flow may be approximated as fully developed and channel walls as isothermal for purposes of estimating the convection coefficient, (3) One-dimensional conduction along channel side walls, (4) Adiabatic condition at end of side walls, (5) Heat dissipation is exclusively through fluid flow in channels, (6) Constant properties.

PROPERTIES: *Table A-6*, Water ($\overline{T}_m$ = 300K): c_p = 4179 J/kg·K, $\mu = 855 \times 10^{-6}$ kg/s·m, k = 0.613 W/m·K, Pr = 5.83.

ANALYSIS: (a) The channel sidewalls act as fins, and a *unit* channel/sidewall combination is shown in schematic (a), where the total number of unit cells corresponds to N = L/S. With N = 50 and L = 10 mm, S = 200 μm and δ = S – W = 150 μm. Alternatively, the unit cell may be represented in terms of a single fin of thickness δ, as shown in schematic (b). The thermal resistance of the unit cell may be obtained from the expression for a fin array, Eq. (3.108), $R_{t,o} = (\eta_o h A_t)^{-1}$, where $A_t = A_f + A_b$ = L (2 H + W) = 0.01m ($4 \times 10^{-4} + 0.5 \times 10^{-4}$) m = 4.5×10^{-6} m^2. With D_h = 4 (H × W)/2 (H + W) = 4 (2 × 10^{-4}m × 0.5 × 10^{-4}m)/2 (2.5 × 10^{-4}m) = 8 × 10^{-5}m, the Reynolds number is $Re_D = \rho u_m D_h/\mu = \dot{m}_1 D_h/A_c\mu$ = 10^{-4} kg/s × 8 × 10^{-5}m/(2 × 10^{-4}m × 0.5 × 10^{-4}m) 855 × 10^{-6} kg/s·m = 936. Hence, the flow is laminar, and assuming fully developed conditions throughout a channel with uniform surface temperature, Table 8.1 yields Nu_D = 4.44. Hence,

$$h = \frac{k}{D_h} Nu_D = \frac{0.613\, W/m \cdot K \times 4.44}{8 \times 10^{-5} m} = 34{,}022\, W/m^2 \cdot K$$

With $m = (2h/k_{ch}\delta)^{1/2}$ = (68,044 W/m^2·K/140 W/m·K × 1.5 × 10^{-4}m)$^{1/2}$ = 1800 m^{-1} and mH = 0.36, the fin efficiency is

$$\eta_f = \frac{\tanh\, mH}{mH} = \frac{0.345}{0.36} = 0.958$$

and the overall surface efficiency is

$$\eta_o = 1 - \frac{A_f}{A_t}(1 - \eta_f) = 1 - \frac{4.0 \times 10^{-6}}{4.5 \times 10^{-6}}(1 - 0.958) = 0.963$$

The thermal resistance of the unit cell is then

Continued …

$$R_{t,o} = (\eta_o h A_t)^{-1} = \left(0.963 \times 34{,}022\,\text{W/m}^2\cdot\text{K} \times 4.5\times10^{-6}\,\text{m}^2\right)^{-1} = 6.78\,\text{K/W}$$

The outlet temperature follows from Eq. (8.45b),

$$T_{m,o} = T_s - \left(T_s - T_{m,i}\right)\exp\left(-\frac{1}{\dot{m}_1 c_p\ R_{t,o}}\right) = 350\text{K} - \left(60\text{K}\right)\times$$

$$\exp\left(-\frac{1}{10^{-4}\,\text{kg/s} \times 4179\,\text{J/kg}\cdot\text{K} \times 6.78\,\text{K/W}}\right) = 307.8\text{K}$$ <

The heat rate per channel is then

$$q_1 = \dot{m}_1 c_p\left(T_{m,o} - T_{m,i}\right) = 10^{-4}\,\text{kg/s} \times 4179\,\text{J/kg}\cdot\text{K}\left(17.8\text{K}\right) = 7.46\,\text{W}$$

and the chip power dissipation is

$$q = Nq_1 = 50 \times 7.46\,\text{W} = 373\,\text{W}$$ <

(b) The foregoing result indicates significant heat transfer from the channel side walls due to the large value of η_f. If the pitch is reduced by a factor of 2 ($S = 100\ \mu$m), we obtain

$$S = 100\,\mu\text{m},\ W = 50\,\mu\text{m},\ \delta = 50\,\mu\text{m},\ N = 100:\ q_1 = 7.04\,\text{W},\ q = 704\,\text{W}$$ <

Hence, although there is a reduction in η_f due to the reduction in δ ($\eta_f = 0.89$) and therefore a slight reduction in the value of q_l, the effect is more than compensated by the increase in the number of channels. Additional benefit may be derived by further reducing the pitch to whatever minimum value of δ is imposed by manufacturing or structural limitations. There would also be an advantage to increasing the channel hydraulic diameter and or flowrate, such that turbulent flow is achieved with a correspondingly larger value of h.

COMMENTS: (1) Because electronic devices fail by contact with a polar fluid such as water, great care would have to be taken to hermetically seal the devices from the coolant channels. In lieu of water, a dielectric fluid could be used, thereby permitting contact between the fluid and the electronics. However, all such fluids, such as air, are less effective as coolants. (2) With $L/D_h = 125$ and $L/D_h)_{fd} \approx 0.05\, Re_D\, Pr = 273$, fully developed flow is not achieved and the value of $h = h_{fd}$ underestimates the actual value of $\bar{h}$ in the channel. The coefficient is also underestimated by using a Nusselt number that presumes heat transfer from all four (rather than three) surfaces of a channel.