BOILING

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General Considerations

- Boiling is associated with transformation of liquid to vapor at a solid/liquid interface due to convection heat transfer from the solid.

- Agitation of fluid by vapor bubbles provides for large convection coefficients and hence large heat fluxes at low-to-moderate surface-to-fluid temperature differences.

- Special form of Newton's law of cooling:

$$q''_s = h\left(T_s - T_{sat}\right) = h\,\Delta T_e$$

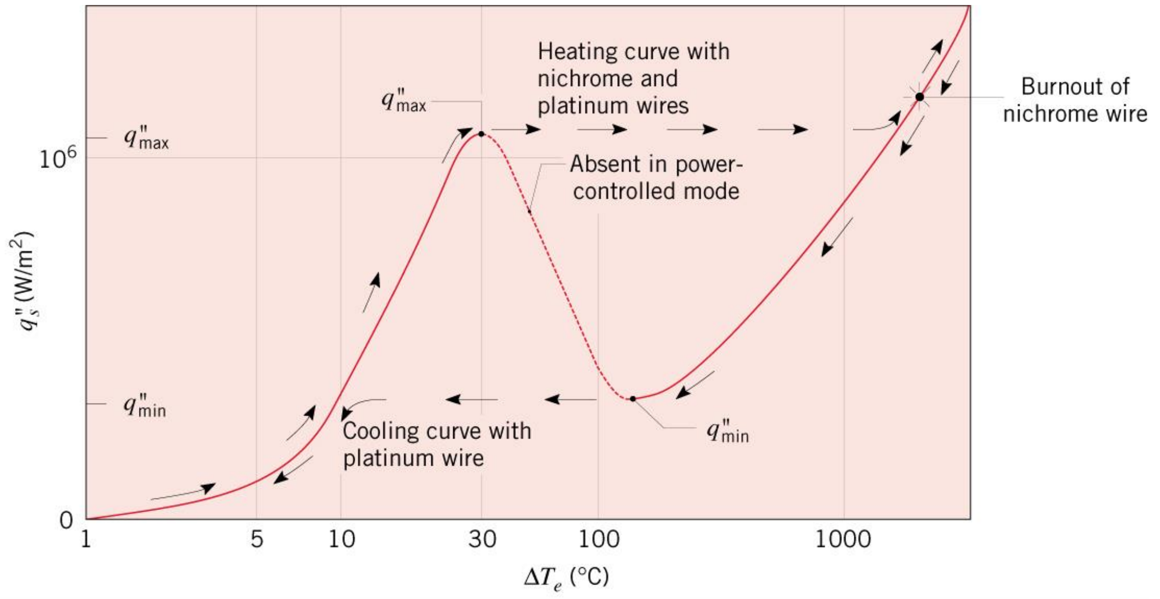
  - $T_{sat} \rightarrow$ saturation temperature of liquid
  - $\Delta T_e \equiv \left(T_s - T_{sat}\right) \rightarrow$ excess temperature

- Special Cases
  - **Pool Boiling**:
    Liquid motion is due to natural convection and bubble-induced mixing.
  - **Forced Convection Boiling**:
    Fluid motion is induced by external means, as well as by bubble-induced mixing.
  - **Saturated Boiling**:
    Liquid temperature is slightly larger than saturation temperature.
  - **Subcooled Boiling**:
    Liquid temperature is less than saturation temperature.

The Boiling Curve

Reveals range of conditions associated with saturated pool boiling on a $q''_s - \Delta T_e$ plot.

Water at Atmospheric Pressure



- Free Convection Boiling $\left(\Delta T_e < 5^\circ C\right)$
  - ➢ Little vapor formation.
  - ➢ Liquid motion is due principally to single-phase natural convection.

- Onset of Nucleate Boiling - $ONB\left(\Delta T_e \approx 5^\circ C\right)$

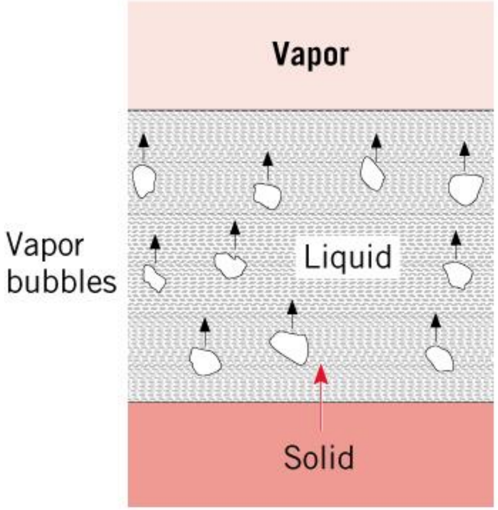
- Nucleate Boiling $\left(5 < \Delta T_e < 30^\circ C\right)$

  - Isolated Vapor Bubbles $\left(5 < \Delta T_e < 10^\circ C\right)$

    – Liquid motion is strongly influenced by nucleation of bubbles at the surface.

    – h and q''_s increase sharply with increasing ΔT_e.

    – Heat transfer is principally due to contact of liquid with the surface (single-phase convection) and not to vaporization.

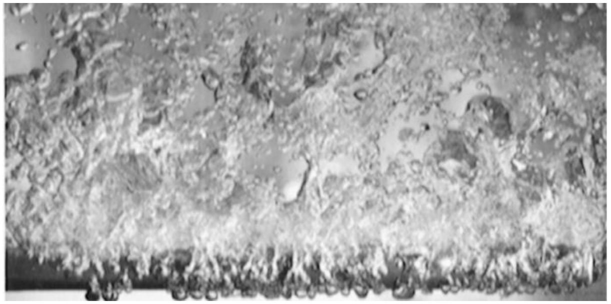


  - Jets and Columns $\left(10 < \Delta T_e < 30^\circ C\right)$

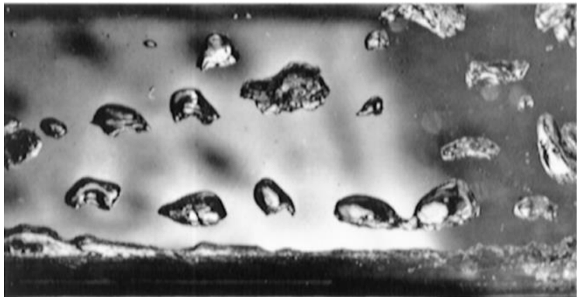
    – Increasing number of nucleation sites causes bubble interactions and coalescence into jets and slugs.

    – Liquid/surface contact is impaired.

    – q''_s continues to increase with ΔT_e while h begins to decrease.



- *Critical Heat Flux - CHF,* $q''_{\max}\left(\Delta T_e \approx 30^\circ C\right)$
  - Maximum attainable heat flux in nucleate boiling.
  - $q''_{\max} \approx 1\ \mathrm{MW/m^2}$ for water at atmospheric pressure.
- Potential Burnout for Power-Controlled Heating
  - An increase in q''_s beyond $q''_{\max}$ causes the surface to be blanketed by vapor, and the surface temperature can spontaneously achieve a value that potentially exceeds its melting point $\left(\Delta T_s > 1000^\circ C\right)$.
  - If the surface survives the temperature shock, conditions are characterized by *film boiling*.
- Film Boiling
  - Heat transfer is by conduction and radiation across the vapor blanket.
  - A reduction in q''_s follows the cooling curve continuously to the Leidenfrost point corresponding to the minimum heat flux $q''_{\min}$ for film boiling.



- A reduction in q''_s below $q''_{\min}$ causes an abrupt reduction in surface temperature to the nucleate boiling regime.

- Transition Boiling for Temperature-Controlled Heating
  - Characterized by a continuous decay of q''_s $\left(\text{from } q''_{\max} \text{ to } q''_{\min}\right)$ with increasing ΔT_e.
  - Surface conditions oscillate between nucleate and film boiling, but portion of surface experiencing film boiling increases with ΔT_e.
  - Also termed unstable or partial film boiling.

Pool Boiling Correlations

- Nucleate Boiling

  - Rohsenow Correlation

$$q_s'' = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{c_{p,l}\, \Delta T_e}{C_{s,f}\, h_{fg}\, \Pr_l^n} \right)^3$$

$C_{s,f}, n \rightarrow$ Surface/Fluid Combination (Table 10.1)

- Critical Heat Flux

$$q''_{\max} = 0.149 h_{fg} \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4}$$

- Film Boiling

The cumulative (and coupled effects) of convection and radiation across the vapor layer ⟶

$$\bar{h}^{4/3} \approx \bar{h}_{conv}^{4/3} + \bar{h}_{rad}\,\bar{h}^{1/3}$$

$$\overline{Nu}_D = \frac{\bar{h}_{conv} D}{k_v} = C\left[\frac{g(\rho_l - \rho_v) h'_{fg} D^3}{\nu_v k_v (T_s - T_{sat})}\right]^{1/4}$$

Geometry	C
Cylinder(Hor.)	0.62
Sphere	0.67

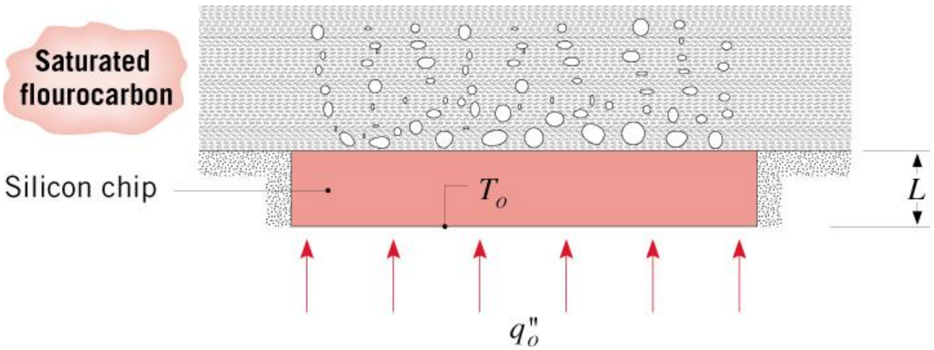
$$h'_{fg} = h_{fg} + 0.80\, c_{p,v}(T_s - T_{sat})$$

$$\bar{h}_{rad} = \frac{\varepsilon\sigma\left(T_s^4 - T_{sat}^4\right)}{T_s - T_{sat}}$$

If $\bar{h}_{conv} > \bar{h}_{rad}$,

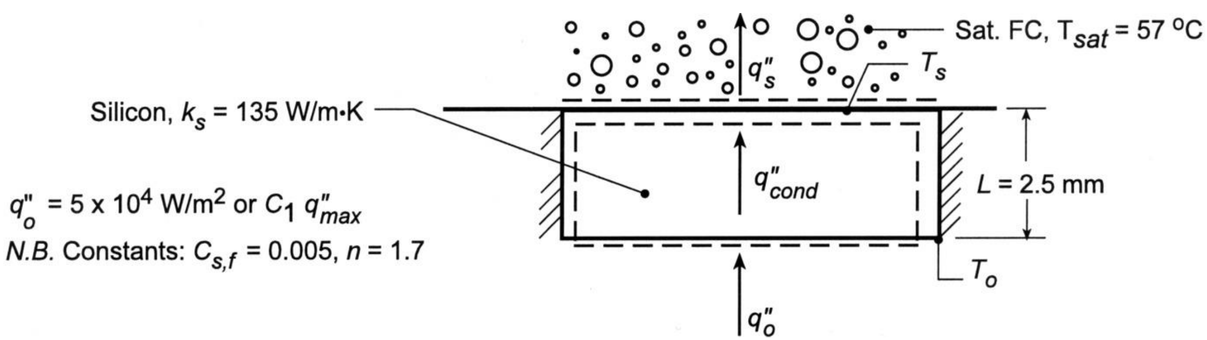
$$\bar{h} \approx \bar{h}_{conv} + 0.75\,\bar{h}_{rad}$$

Problem 10.23: Chip thermal conditions associated with cooling by immersion in a fluorocarbon.



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 for a flux that is 90% of CHF, (b) Effect of heat flux on chip surface temperatures; maximum allowable heat flux for a surface temperature of 80°C.



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, ρ_ℓ = 1619.2 kg/m^3, ρ_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
$q''_o = q''_{cond} = k_s (T_o - T_s)/L = q''_s$; 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,

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

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

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

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

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

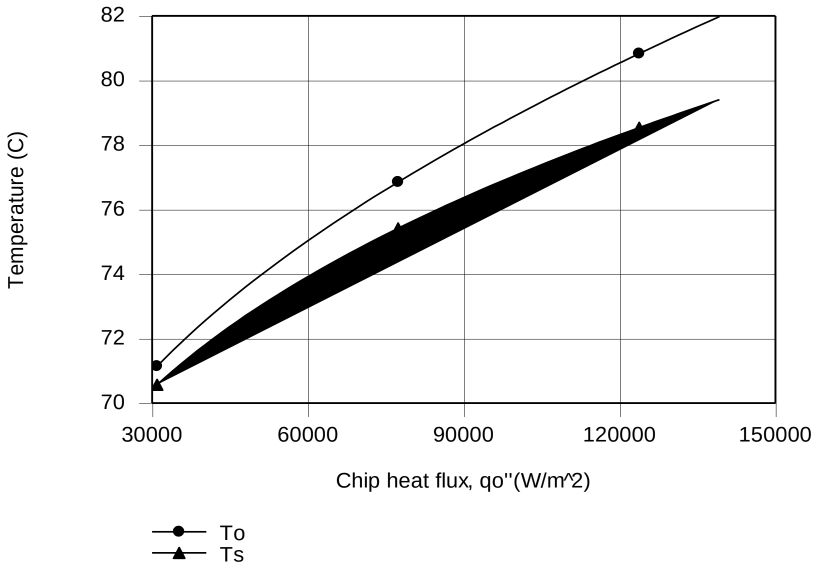
From the results of the previous calculation and the Rohsenow correlation, it follows that

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

Hence, $T_s = 79.4^\circ C$ and

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

(b) Parametric calculations for $0.2 \le C_1 \le 0.9$ yield the following variations of T_s and T_o with q''_o.



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

$$q''_{o,max} = 11.3 \times 10^4 \, W/m^2$$ <

which is 73% of CHF ($q''_{max} = 15.5 \times 10^4$ W/m^2).

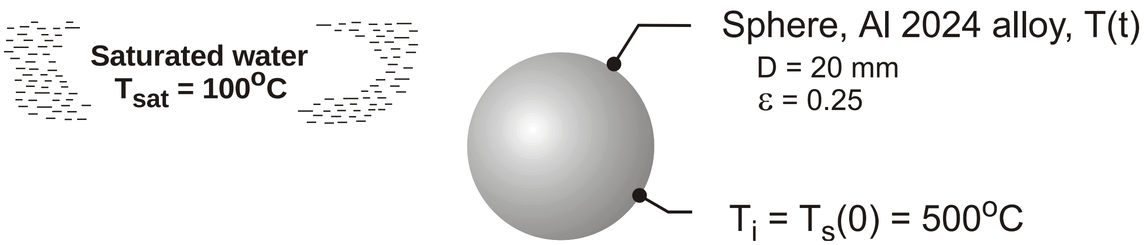
COMMENTS: Many of today's VLSI chip designs involve heat fluxes well in excess of 15 W/cm^2, in which case pool boiling in a fluorocarbon would not be an appropriate means of heat dissipation.

Problem 10.26: Initial heat transfer coefficient for immersion of an aluminum sphere in a saturated water bath at atmospheric pressure and its temperature after immersion for 30 seconds.

KNOWN: A sphere (aluminum alloy 2024) with a uniform temperature of 500°C and emissivity of 0.25 is suddenly immersed in a saturated water bath maintained at atmospheric pressure.

FIND: (a) The total heat transfer coefficient for the initial condition; fraction of the total coefficient contributed by radiation; and (b) Estimate the temperature of the sphere 30 s after it has been immersed in the bath.

SCHEMATIC



ASSUMPTIONS: (1) Water is at atmospheric pressure and uniform temperature, T_{sat}, and (2) Lumped capacitance method is valid.

PROPERTIES:

Vapor Blanket $\left(T_{f,i} = 573K\right)$: $h_{fg} = 1.41 \text{ x } 10^6$ J/kg, $k_v = 0.0767$ W/m·K, $c_{p,v} = 5889$ J/kg·K, $Pr_v = 1.617$, $\rho_v = 46.0\,\text{kg/m}^3$, $\nu_v = 4.33 \text{ x } 10^{-7}\,\text{m}^2/\text{s}$, $\rho_l = 712\,\text{kg/m}^3$.

Aluminum Alloy: $\rho_s = 2700\,\text{kg/m}^3$, $c_{p,s} = 875$ J/kg·K, $k_s = 186$ W/m·K.

ANALYSIS: (a) For the initial condition with T_s = 500°C, *film boiling* will occur and the coefficients due to convection and radiation are estimated using Eqs. 10.9 and 10.11, respectively,

$$\overline{Nu}_D = \frac{\bar{h}_{conv}D}{k_v} = C\left[\frac{g\left(\rho_\ell - \rho_v\right)h'_{fg}D^3}{\nu_v k_v\left(T_s - T_{sat}\right)}\right]^{1/4} \quad (1)$$

$$\bar{h}_{rad} = \frac{\varepsilon\sigma\left(T_s^4 - T_{sat}^4\right)}{T_s - T_{sat}} \quad (2)$$

where C = 0.67 for spheres and $\sigma = 5.67 \times 10^{-8}$ W/m²·K⁴. The corrected latent heat is

$$h'_{fg} = h_{fg} + 0.8\,c_{p,v}\left(T_s - T_{sat}\right) \quad (3)$$

The total heat transfer coefficient is given by Eq. 10.10a as

$$\bar{h}^{4/3} = \bar{h}_{conv}^{4/3} + \bar{h}_{rad} \cdot \bar{h}^{1/3} \qquad (4)$$

Using the foregoing relations, the following results are obtained.

$\overline{Nu}_D$	$\bar{h}_{cnv}\left(W/m^2 \cdot K\right)$	$\bar{h}_{rad}\left(W/m^2 \cdot K\right)$	$\bar{h}\left(W/m^2 \cdot K\right)$
226	867	12.0	876

(b) For the lumped-capacitance method, from Section 5.3, the energy balance is

$$-\bar{h}A_s\left(T_s - T_{sat}\right) = \rho_s V c_s \frac{dT_s}{dt} \qquad (5)$$

where ρ_s and c_s are properties of the sphere. Numerically integrating Eq. (5) and evaluating $\bar{h}$ as a function of T_s, the following result is obtained for the sphere temperature after 30s.

$$T_s(30s) = 333°C.$$

COMMENTS: (1) The Biot number associated with the aluminum alloy sphere cooling process for the initial condition is Bi = 0.09. Hence, the lumped-capacitance method is valid.

(2) Radiation makes a negligible contribution to the heat rate throughout the process.