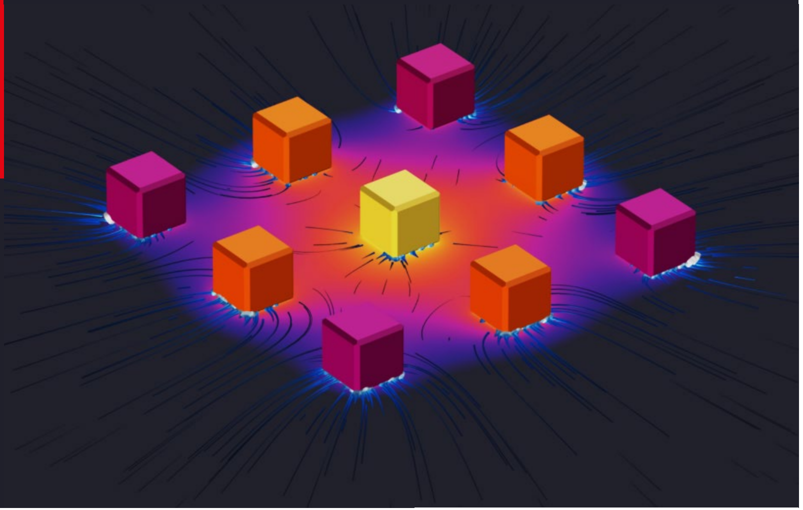
Heat and Mass Transfer
ME-341

Instructor: Giulia Tagliabue



École
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de Lausanne

Spring Semester

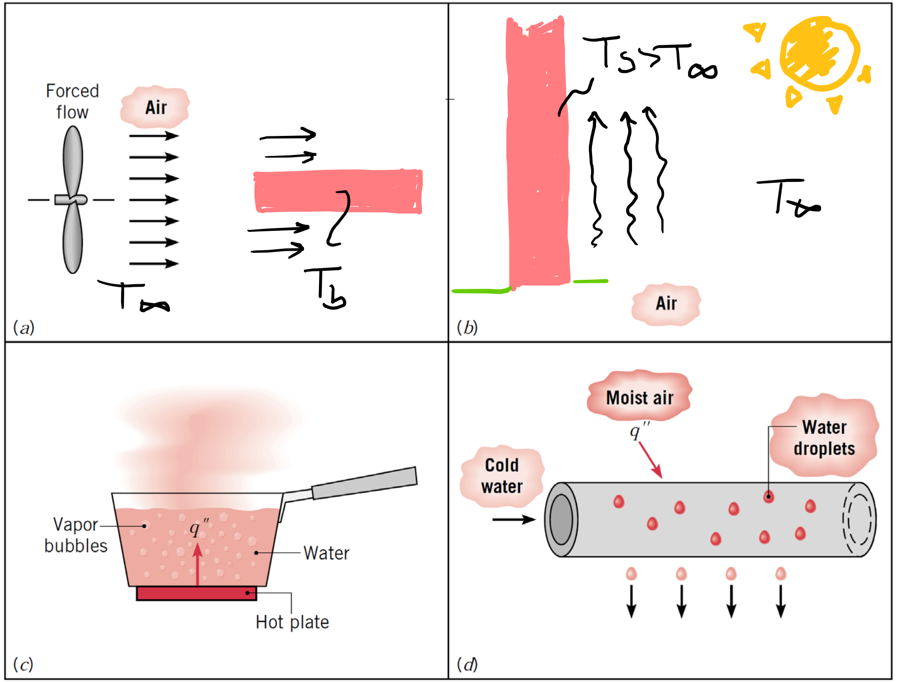
This Week

1. Forced Convection

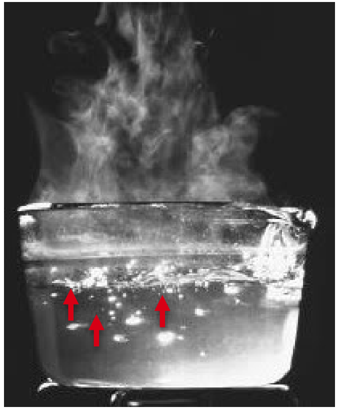
2. Natural (Free) Convection

3. Boiling

4. Condensation



Introduction to Boiling and Condensation



Boiling: heat transfer from the wall to the fluid

Condensation: heat transfer from the fluid to the wall

Fluid motion controlled by:

- Surface tension σ at the liquid-vapor interface
- Density difference (buoyancy) between liquid/vapor phases

Phase Transition = Isothermal Process

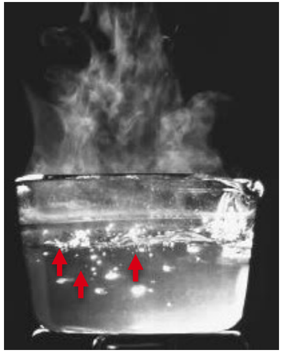
Latent heat (h_{fg}) is exchanged between solid and fluid

Small solid/fluid ΔT

Introduction to Boiling

Boiling occurs when the surface temperature exceeds the saturation temperature at that pressure.

$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e \qquad \Delta T_e \text{ excess temperature}$$



Fluid Dynamics

Pool boiling
the liquid is initially quiescent and only free convection occurs

Forced boiling
the fluid is moving while it boils (e.g. inside a pipe)

Heat Transfer

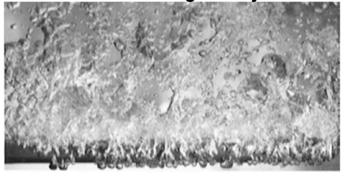
Saturated Boiling
$T_s > T_{sat}$, the bubble must rise

Subcooled Boiling
$T_s < T_{sat}$, the bubbles can re-condense in the liquid

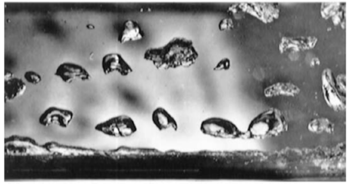
Saturated Pool Boiling

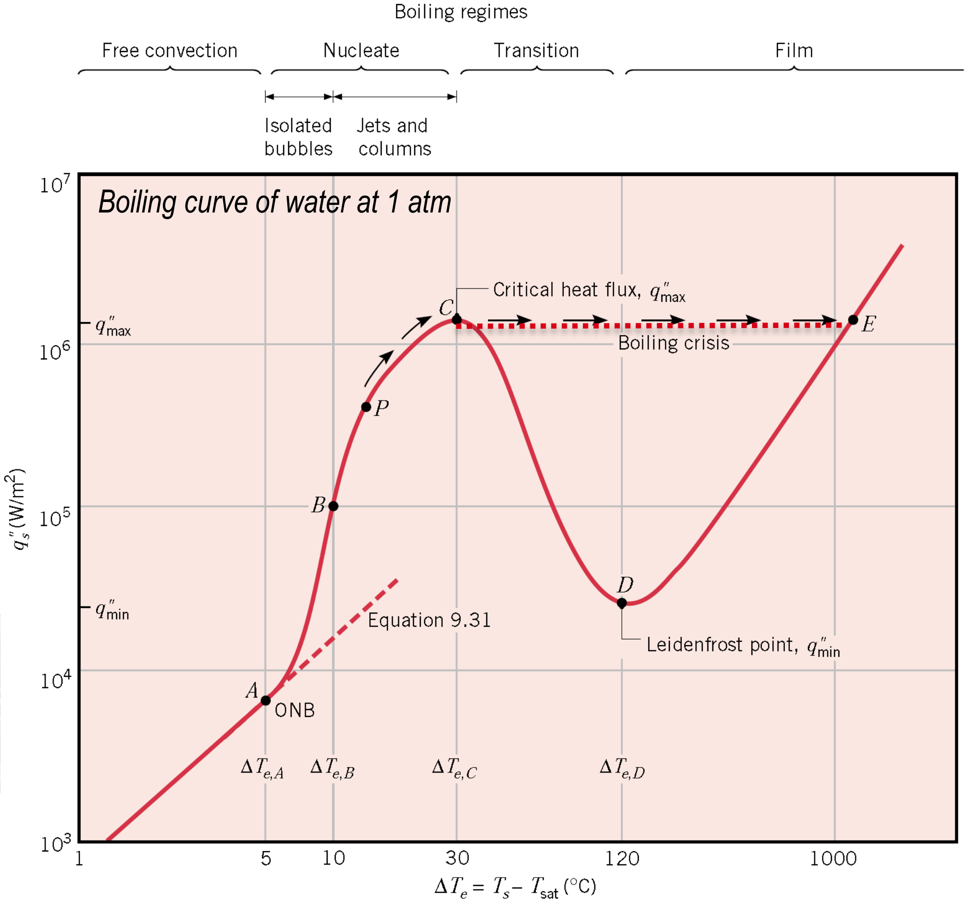
$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e$$

Nucleate boiling with jets



Film boiling





The solid curve is followed when we control ΔT_e. However in most applications we control q_s''. In such a case (as in the previous experiment) we observe:

C->E : boiling crisis - past the critical heat flux a film of vapor rapidly replaces isolated bubbles. The thermal conductivity of the vapor film is much less than that of the liquid and the surface temperature suddenly increases to much higher values

This can cause the failure of the component. Hence, when designing a heat exchanger we must be sure not to surpass the critical heat flux condition.

This Lecture

- ❑ Correlations for Nucleate and Film Pool Boiling

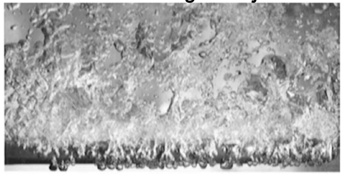
Learning Objectives:

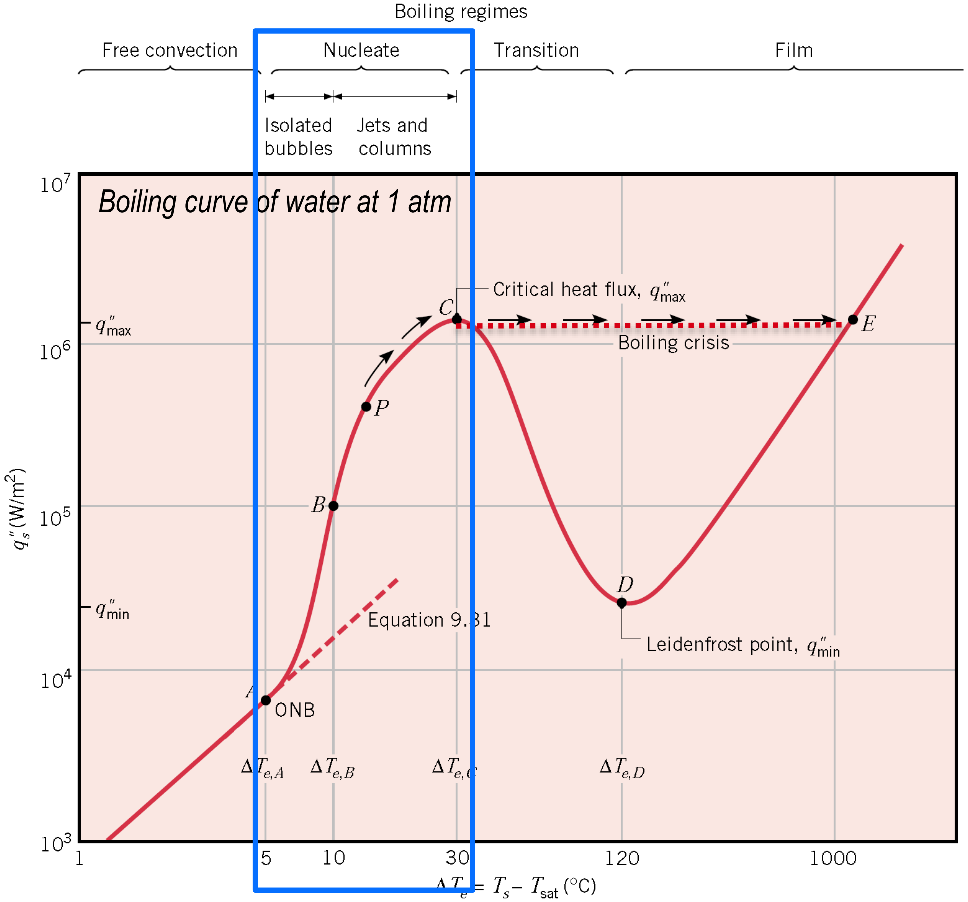
- ❑ Calculate heat flux and temperature difference during boiling

Saturated Pool Boiling

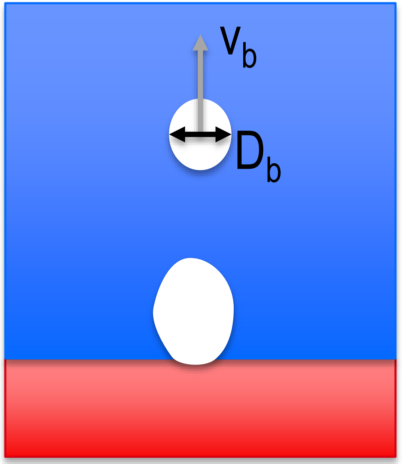
$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e$$

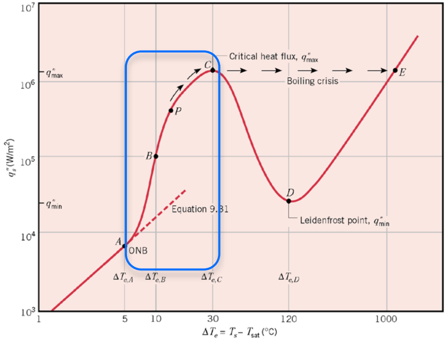
Nucleate boiling with jets





Nucleate Pool Boiling Correlations





Bubbles can be considered to cause forced convection

Define a characteristic length and velocity to calculate Re and Nu for boiling

Characteristic length: $D_b \propto \sqrt{\dfrac{\sigma}{g(\rho_l - \rho_v)}}$ Ratio of surface tension and buoyancy

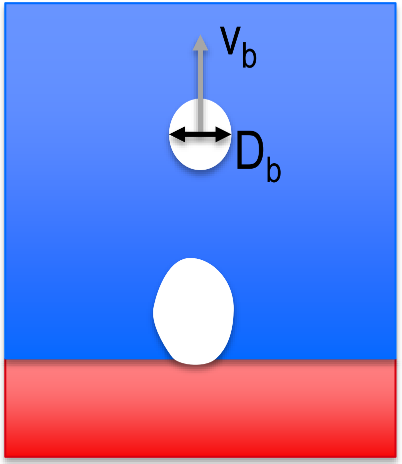
Characteristic velocity: $V \propto \dfrac{D_b}{t_b}$ Distance travelled by the liquid to fill the void of a bubble / Time interval between bubble detachment

$$V \propto \frac{D_b}{\left(\dfrac{\rho_l h_{fg} D_b^3}{q_s'' D_b^2}\right)}$$

Energy it takes to form a bubble / Heat transferred from the solid to the vapor

$$V \propto \frac{q_s''}{\rho_l h_{fg}}$$

Nucleate Pool Boiling Correlations



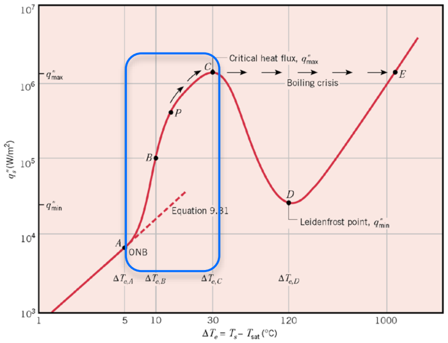
$$q''_s = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left(\frac{c_{p,l} \Delta T_e}{C_{s,f} h_{fg} Pr_l^n} \right)^3$$

h_{fg} = (latent) heat of vaporization (Table A6)

!!Units in tables are [kJ/kg] !!

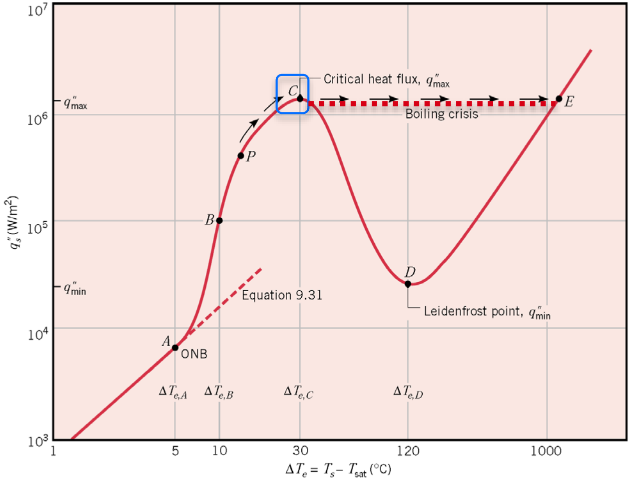
TABLE 10.1 Values of $C_{s,f}$ for various surface–fluid combinations [5–7]

Surface–Fluid Combination	$C_{s,f}$	n
Water–copper		
Scored	0.0068	1.0
Polished	0.0128	1.0
Water–stainless steel		
Chemically etched	0.0133	1.0
Mechanically polished	0.0132	1.0
Ground and polished	0.0080	1.0
Water–brass	0.0060	1.0
Water–nickel	0.006	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper		
Polished	0.0154	1.7
Lapped	0.0049	1.7
Benzene–chromium	0.0101	1.7
Ethyl alcohol–chromium	0.0027	1.7



The Rohsenow correlation applies only for clean surfaces. When it is used to estimate the heat flux, errors can amount to ±100%. However, since $\Delta T_e \propto (q''_s)^{1/3}$, this error is reduced by a factor of 3 when the expression is used to estimate ΔT_e from knowledge of q''_s. Also, since $q''_s \propto h_{fg}^{-2}$ and h_{fg} decreases with increasing saturation pressure (temperature), the nucleate boiling heat flux will increase as the liquid is pressurized.

Pool Boiling Critical Heat Flux



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

$C = \pi/24$ for large horizontal cylinders, spheres, and finite heated surfaces

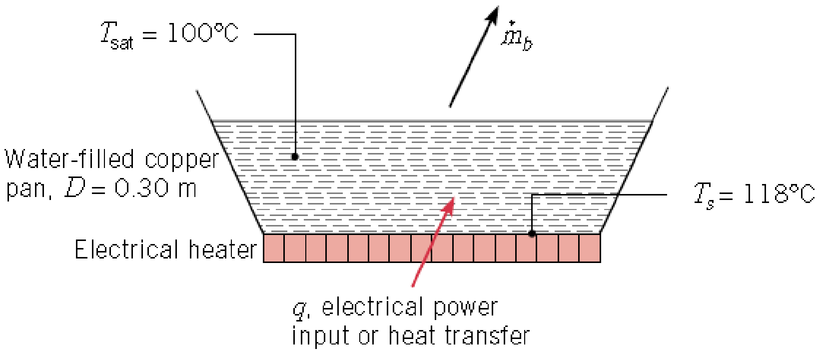
$C = 0.149$ for large horizontal plates

The properties are evaluated at the saturation temperature

Note that the critical heat flux depends on pressure.

Nucleate Pool Boiling – Example

The bottom of a copper pan, 0.3 m in diameter, is maintained at 118°C by an electric heater. Estimate the power required to boil water in this pan. What is the evaporation rate? Estimate the critical heat flux.



1. Steady-state conditions.
2. Water exposed to standard atmospheric pressure, 1.01 bar.
3. Water at uniform temperature $T_{sat} = 100°C$.
4. Large pan bottom surface of polished copper.
5. Negligible losses from heater to surroundings.

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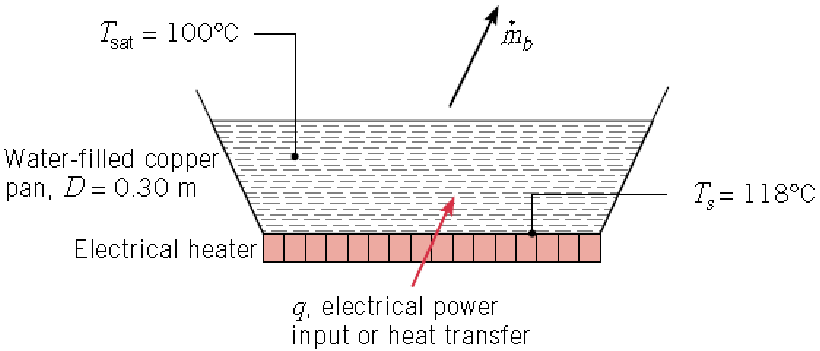

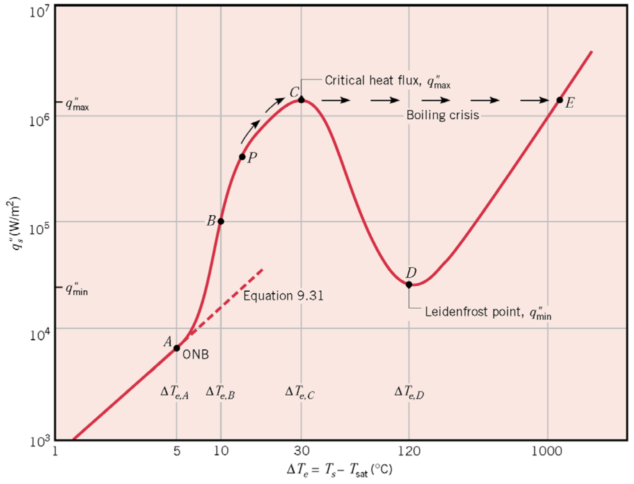

Properties: Table A.6, saturated water, liquid (100°C): $\rho_l = 1/v_f = 957.9$ kg/m^3, $c_{p,l} = c_{p,f} = 4.217$ kJ/kg · K, $\mu_l = \mu_f = 279 \times 10^{-6}$ N · s/m^2, $Pr_l = Pr_f = 1.76$, $h_{fg} = 2257$ kJ/kg, $\sigma = 58.9 \times 10^{-3}$ N/m. Table A.6, saturated water, vapor (100°C): $\rho_v = 1/v_g = 0.5956$ kg/m^3.

$$\Delta T_e \equiv T_s - T_{sat} = 118°C - 100°C = 18°C$$

Nucleate Pool Boiling – Example

The bottom of a copper pan, 0.3 m in diameter, is maintained at 118°C by an electric heater. Estimate the power required to boil water in this pan. What is the evaporation rate? Estimate the critical heat flux.

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

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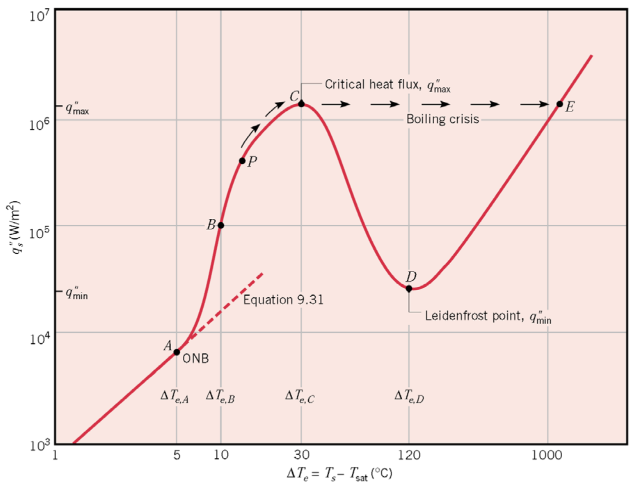
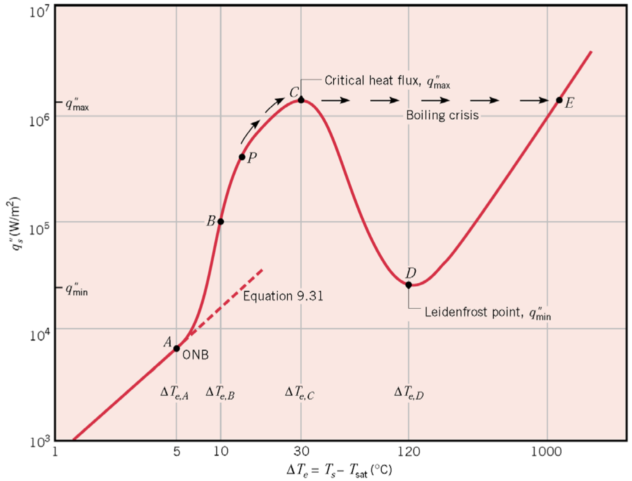


$$\Delta T_e \equiv T_s - T_{sat} = 118°C - 100°C = 18°C$$

Nucleate Pool Boiling – Example

The bottom of a copper pan, 0.3 m in diameter, is maintained at 118°C by an electric heater. Estimate the power required to boil water in this pan. What is the evaporation rate? Estimate the critical heat flux.

$$q_s'' = 279 \times 10^{-6}\ \mathrm{N \cdot s/m^2} \times 2257 \times 10^3\ \mathrm{J/kg} \times \left[\frac{9.8\ \mathrm{m/s^2}\,(957.9 - 0.5956)\ \mathrm{kg/m^3}}{58.9 \times 10^{-3}\ \mathrm{N/m}}\right]^{1/2} \times \left(\frac{4.217 \times 10^3\ \mathrm{J/kg \cdot K} \times 18^\circ\mathrm{C}}{0.0128 \times 2257 \times 10^3\ \mathrm{J/kg} \times 1.76}\right)^3 = 836\ \mathrm{kW/m^2}$$



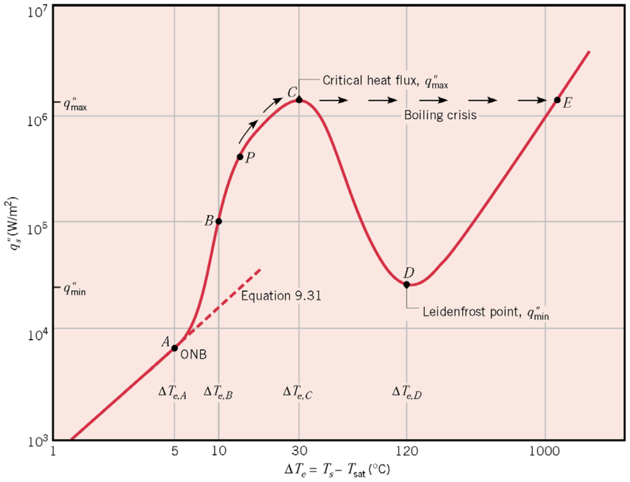
$$\Delta T_e \equiv T_s - T_{sat} = 118^\circ\mathrm{C} - 100^\circ\mathrm{C} = 18^\circ\mathrm{C}$$

$$q_s = q_s'' \times A = q_s'' \times \frac{\pi D^2}{4}$$

$$q_s = 8.36 \times 10^5\ \mathrm{W/m^2} \times \frac{\pi (0.30\ \mathrm{m})^2}{4} = 59.1\ \mathrm{kW}$$

Nucleate Pool Boiling – Example

The bottom of a copper pan, 0.3 m in diameter, is maintained at 118°C by an electric heater. Estimate the power required to boil water in this pan. What is the evaporation rate? Estimate the critical heat flux.



Under steady-state conditions all heat addition to the pan will result in water evaporation from the pan. Hence

$$q_s = \dot{m}_b h_{fg}$$

where $\dot{m}_b$ is the rate at which water evaporates from the free surface to the room. It follows that

$$\dot{m}_b = \frac{q_s}{h_{fg}} = \frac{5.91 \times 10^4 \text{ W}}{2257 \times 10^3 \text{ J/kg}} = 0.0262 \text{ kg/s} = 94 \text{ kg/h} \quad \triangleleft$$

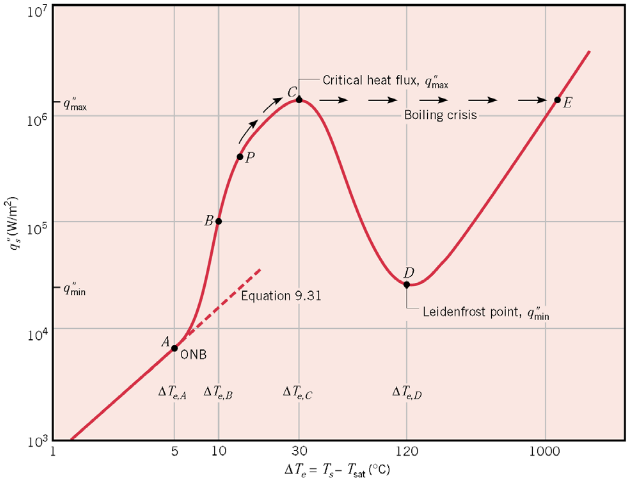
$$\Delta T_e \equiv T_s - T_{sat} = 118°\text{C} - 100°\text{C} = 18°\text{C}$$

Nucleate Pool Boiling – Example

The bottom of a copper pan, 0.3 m in diameter, is maintained at 118°C by an electric heater. Estimate the power required to boil water in this pan. What is the evaporation rate? Estimate the critical heat flux.

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

$C = 0.149$ for large horizontal plates



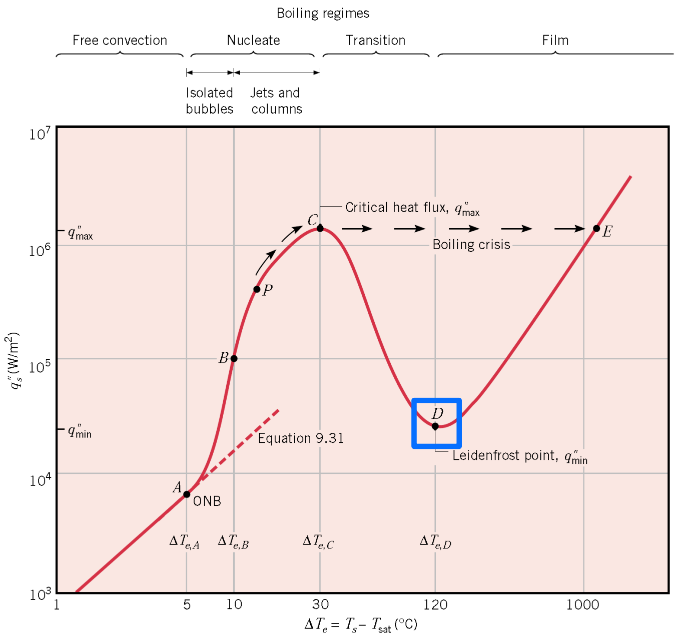
$$q''_{max} = 0.149 h_{fg} \rho_v \left[\frac{\sigma g(\rho_l - \rho_v)}{\rho_v^2} \right]^{1/4}$$

$$\Delta T_e \equiv T_s - T_{sat} = 118°C - 100°C = 18°C$$

$$q''_{max} = 0.149 \times 2257 \times 10^3 \text{ J/kg} \times 0.5956 \text{ kg/m}^3 \times \left[\frac{58.9 \times 10^{-3} \text{ N/m} \times 9.8 \text{ m/s}^2 (957.9 - 0.5956) \text{ kg/m}^3}{(0.5956)^2 (\text{kg/m}^3)^2} \right]^{1/4}$$

$$q''_{max} = 1.26 \text{ MW/m}^2$$

Minimum Heat Flux



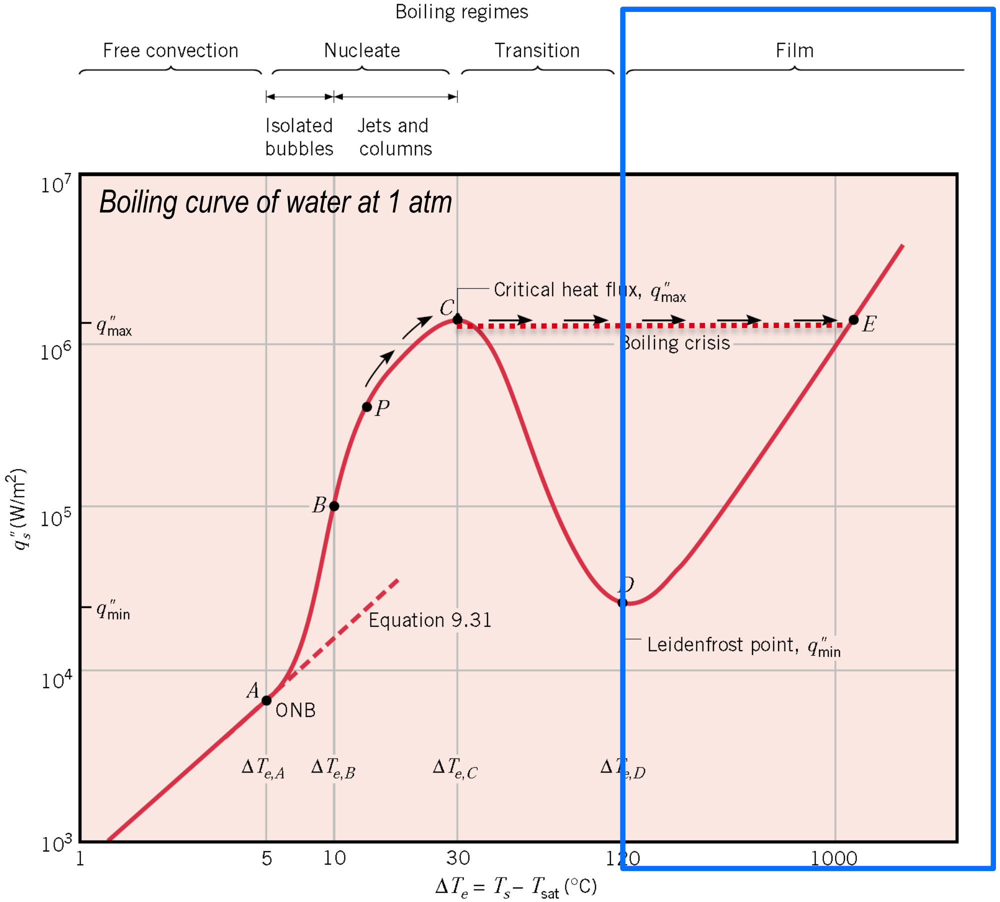
Zuber [10] used stability theory to derive the following expression for the minimum heat flux, $q''_{s,D} = q''_{min}$, from a large horizontal plate.

$$q''_{min} = C\rho_v h_{fg}\left[\frac{g\sigma(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2}\right]^{1/4} \tag{10.7}$$

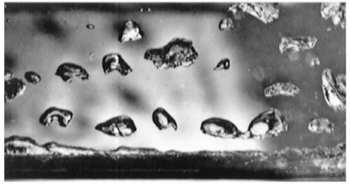
where the properties are evaluated at the saturation temperature. The constant, $C = 0.09$, has been experimentally determined by Berenson [14]. This result is accurate to approximately 50% for most fluids at moderate pressures but provides poorer estimates at higher pressures [15]. A similar result has been obtained for horizontal cylinders [16].

Film Pool Boiling

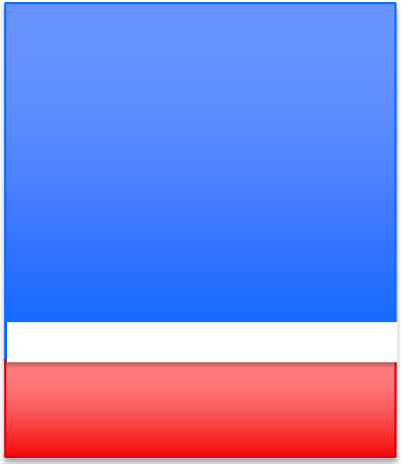
$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e$$



Film boiling



Film Pool Boiling



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

Where $h'_{fg} = h_{fg} + 0.8c_{p.v}(T_s - T_{sat})$

$C = 0.62$ *for horizontal cylinders*

$C = 0.67$ *for spheres*

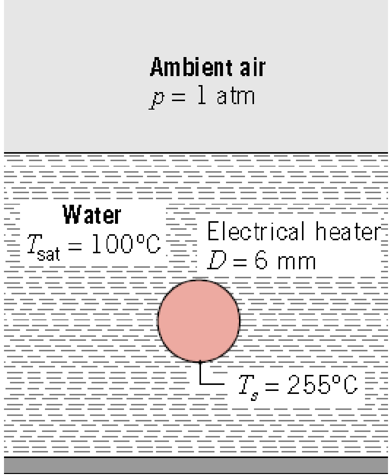
With properties estimated at $T_f = \frac{(T_s + T_{sat})}{2}$

If $T_s > 300C$, radiation is also present. We estimate the total convection coefficient as:

$$\bar{h} = \overline{h_{conv}} + \frac{3}{4}\overline{h_{rad}}$$

where $\overline{h_{conv}}$ has to be estimated with the previous correlation and $\overline{h_{rad}} = [\varepsilon\sigma(T_s^4 - T_{sat}^4)]/(T_s - T_{sat})$

Film Pool Boiling – Example

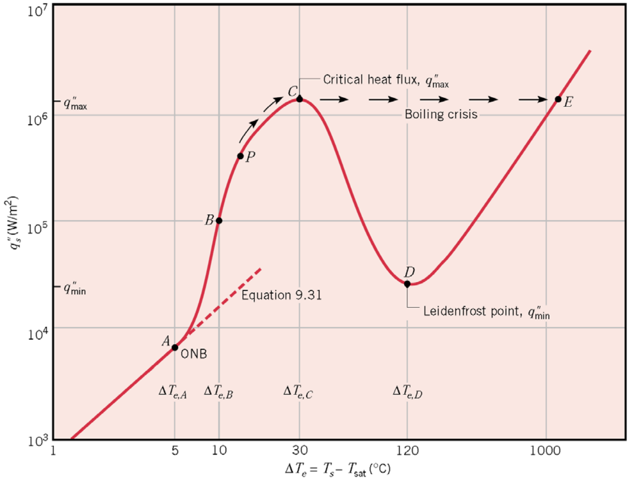


A metal-clad heating element of 6-mm diameter and emissivity $\varepsilon = 1$ is horizontally immersed in a water bath. The surface temperature of the metal is 255°C under steady-state boiling conditions. Estimate the power dissipation per unit length of the heater.

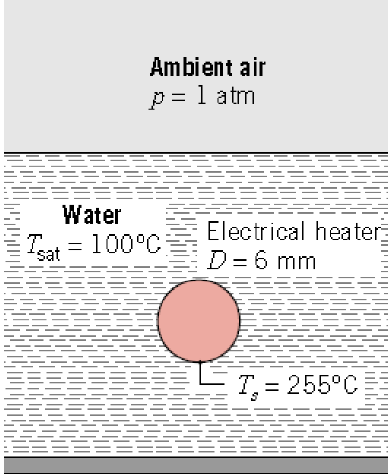
Properties: Table A.6, saturated water, liquid (100°C): $\rho_l = 1/v_f = 957.9\ \text{kg/m}^3$, $h_{fg} = 2257\ \text{kJ/kg}$. Table A.4, water vapor at atmospheric pressure ($T_f \approx 450\ \text{K}$): $\rho_v = 0.4902\ \text{kg/m}^3$, $c_{p,v} = 1.980\ \text{kJ/kg}\cdot\text{K}$, $k_v = 0.0299\ \text{W/m}\cdot\text{K}$, $\mu_v = 15.25 \times 10^{-6}\ \text{N}\cdot\text{s/m}^2$.

The excess temperature is

$$\Delta T_e = T_s - T_{sat} = 255°\text{C} - 100°\text{C} = 155°\text{C}$$



Film Pool Boiling – Example



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$$q_s' = q_s'' \pi D = \bar{h} \pi D \Delta T_e$$

$$\bar{h}^{4/3} = \bar{h}_{\text{conv}}^{4/3} + \bar{h}_{\text{rad}} \bar{h}^{1/3}$$

$$\bar{h}_{\text{conv}} = 0.62 \left[\frac{k_v^3 \rho_v (\rho_l - \rho_v) g (h_{fg} + 0.8 c_{p,v} \Delta T_e)}{\mu_v D \Delta T_e} \right]^{1/4}$$

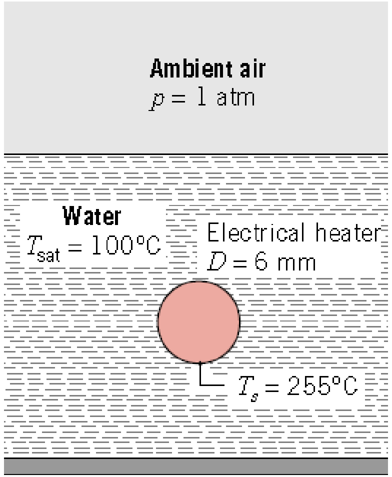
$$= 0.62$$

$$\times \left[\frac{(0.0299)^3 (\text{W/m} \cdot \text{K})^3 \times 0.4902\ \text{kg/m}^3\ (957.9 - 0.4902)\ \text{kg/m}^3 \times 9.8\ \text{m/s}^2}{1} \right.$$

$$\left. \times \frac{(2257 \times 10^3\ \text{J/kg} + 0.8 \times 1.98 \times 10^3\ \text{J/kg} \cdot \text{K} \times 155°\text{C})}{15.25 \times 10^{-6}\ \text{N} \cdot \text{s/m}^2 \times 6 \times 10^{-3}\ \text{m} \times 155°\text{C}} \right]^{1/4}$$

$$= 238\ \text{W/m}^2 \cdot \text{K}$$

Film Pool Boiling – Example



A metal-clad heating element of 6-mm diameter and emissivity $\varepsilon = 1$ is horizontally immersed in a water bath. The surface temperature of the metal is 255°C under steady-state boiling conditions. Estimate the power dissipation per unit length of the heater.

Properties: Table A.6, saturated water, liquid (100°C): $\rho_l = 1/v_f = 957.9\ \mathrm{kg/m^3}$, $h_{fg} = 2257\ \mathrm{kJ/kg}$. Table A.4, water vapor at atmospheric pressure ($T_f \approx 450$ K): $\rho_v = 0.4902\ \mathrm{kg/m^3}$, $c_{p,v} = 1.980\ \mathrm{kJ/kg \cdot K}$, $k_v = 0.0299\ \mathrm{W/m \cdot K}$, $\mu_v = 15.25 \times 10^{-6}\ \mathrm{N \cdot s/m^2}$.

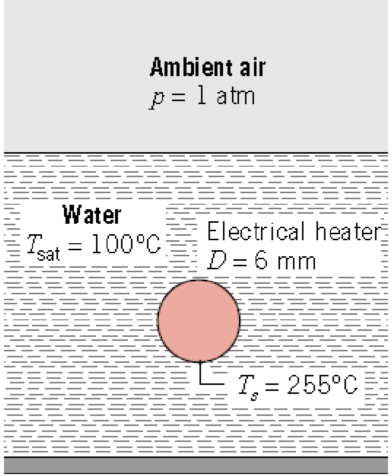
$$q'_s = q''_s \pi D = \bar{h} \pi D \Delta T_e$$

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

$$\bar{h}^{4/3} = \bar{h}_{\text{conv}}^{4/3} + \bar{h}_{\text{rad}}\bar{h}^{1/3}$$

$$= \frac{5.67 \times 10^{-8}\ \mathrm{W/m^2 \cdot K^4}\ (528^4 - 373^4)\ \mathrm{K^4}}{(528 - 373)\ \mathrm{K}} = 21.3\ \mathrm{W/m^2 \cdot K}$$

Film Pool Boiling – Example



A metal-clad heating element of 6-mm diameter and emissivity $\varepsilon = 1$ is horizontally immersed in a water bath. The surface temperature of the metal is 255°C under steady-state boiling conditions. Estimate the power dissipation per unit length of the heater.

Properties: Table A.6, saturated water, liquid (100°C): $\rho_l = 1/v_f = 957.9\ \text{kg/m}^3$, $h_{fg} = 2257\ \text{kJ/kg}$. Table A.4, water vapor at atmospheric pressure ($T_f \approx 450$ K): $\rho_v = 0.4902\ \text{kg/m}^3$, $c_{p,v} = 1.980\ \text{kJ/kg} \cdot \text{K}$, $k_v = 0.0299\ \text{W/m} \cdot \text{K}$, $\mu_v = 15.25 \times 10^{-6}\ \text{N} \cdot \text{s/m}^2$.

$$q_s' = q_s'' \pi D = \bar{h} \pi D \Delta T_e$$

$$\bar{h}^{4/3} = \bar{h}_{conv}^{4/3} + \bar{h}_{rad} \bar{h}^{1/3} \Rightarrow \bar{h}^{4/3} = 238^{4/3} + 21.3 \bar{h}^{1/3} \Rightarrow \bar{h} = 254.1\ \text{W/m}^2 \cdot \text{K}$$

$$q_s' = 254.1\ \text{W/m}^2 \cdot \text{K} \times \pi \times 6 \times 10^{-3}\ \text{m} \times 155°\text{C} = 742\ \text{W/m}$$

This Lecture

☑ Correlations for Nucleate and Film Pool Boiling

Learning Objectives:

☑ Calculate heat flux and temperature difference during boiling

Next Lecture

- Forced Convection Boiling
  - External
  - Internal

Learning Objectives:

- Calculate heat flux and convection coefficient in forced convection