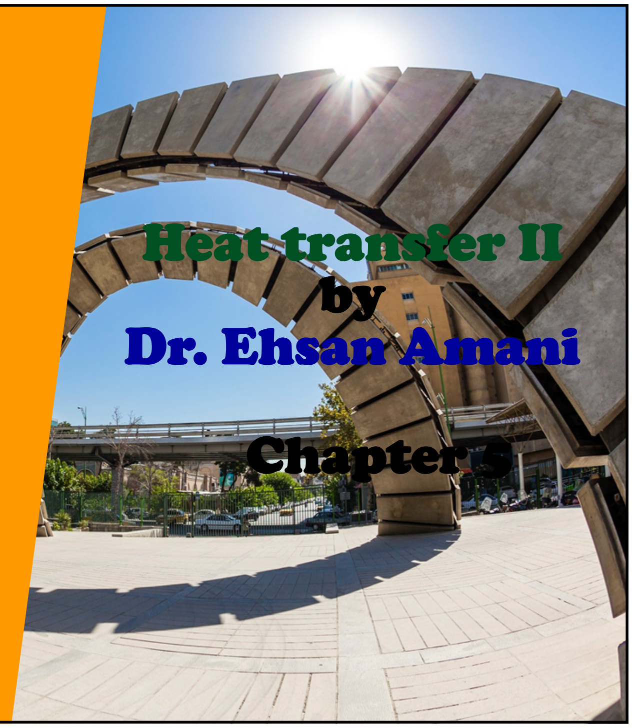
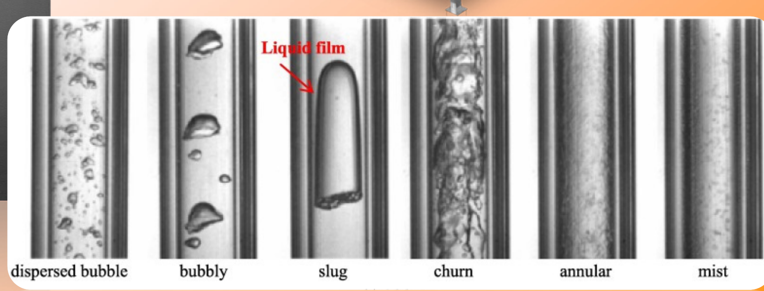


Heat transfer II
by
Dr. Ehsan Amani

Chapter 5

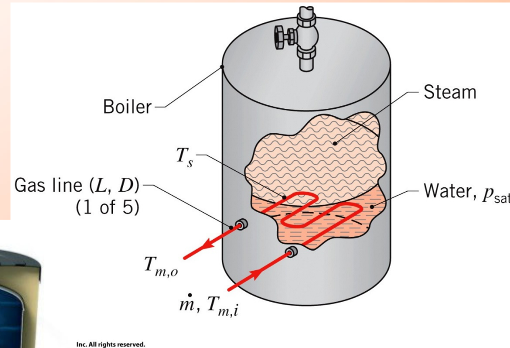
Condensation: Applications

- **Condenser**



Boiling: Applications

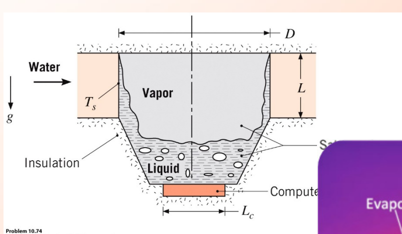
- **Boilers**

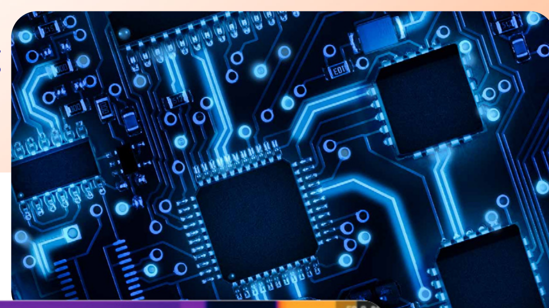


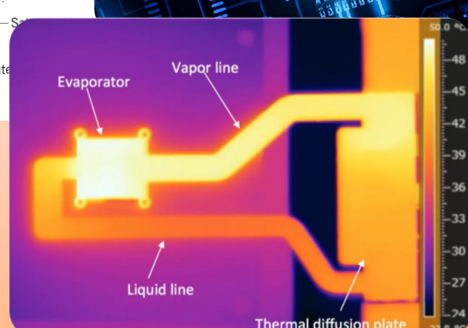
Chapter 5 By E. Amani

Boiling: Applications

- **Electronic cooling**



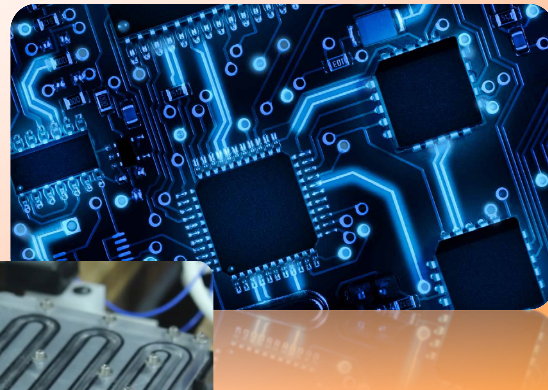


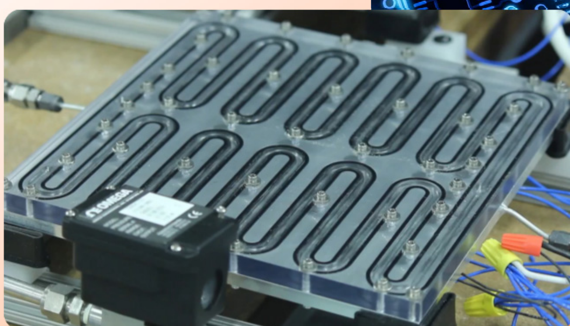


Chapter 5 By E. Amani

Boiling: Applications

- **Electronic cooling**





Chapter 5 By E. Amani

Dimensional analysis

- **Phase-change convection**

$$h \equiv \frac{q_s''}{\Delta T_e} = \frac{q_s''}{T_s - T_{\text{sat}}} \qquad (0.5)$$

Excess temperature

Saturation temperature

$$\bar{h} \equiv \frac{q_s}{A\Delta \bar{T}_e} = \frac{q_s}{A(\bar{T}_s - T_{\text{sat}})} \qquad (0.5)'$$

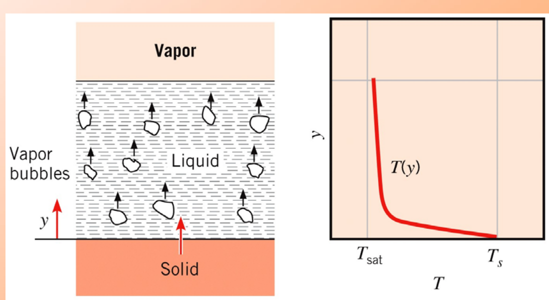


Figure 10.1

Chapter 5 By E. Amani

Dimensional analysis

- **Phase-change convection**
  - **Free convection (pool boiling/condensation):**

$$\bar{h} = h(\underbrace{h_{fg}}_{\text{Latent heat}}, \underbrace{c_{pl}\Delta T}_{\text{Sensible enthalpy difference}}, \underbrace{g(\rho_l - \rho_v)}_{\text{Buoyancy force per unit volume}}, L, \sigma, \rho_l, c_{pl}, k_l, \mu_l, \rho_g, c_{pg}, k_g, \mu_g) \qquad (1.5)$$

$$\Delta T = |T_s - T_{\text{sat}}| = |\Delta T_e| \qquad (2.5)$$

  - **Exercise: By dimensional analysis of Eq. (1.5), show that:**

$$\overline{\text{Nu}}_L = f(\text{Gr}_L^{\text{pc}}, \text{Ja}, \text{Pr}, \text{Bo}, \frac{\rho_g}{\rho_l}, \frac{c_{pg}}{c_{pl}}, \frac{k_g}{k_l}, \frac{\mu_g}{\mu_l}) \qquad (3.5)$$

Nusselt number

$$\overline{\text{Nu}}_L = \frac{\bar{h}L}{k_l} \sim \frac{\text{convection heat transfer rate}}{\text{pure conduction heat rate}} \qquad (4.5)$$

Grashof number

$$\text{Gr}_L^{\text{pc}} = \frac{\rho_l g(\rho_l - \rho_v)L^3}{\mu_l^2} \sim \frac{\text{Buoyancy force}}{\text{viscous force}} \qquad (5.5)$$

Jakob number

$$\text{Ja} = \frac{c_{pl}\Delta T}{h_{fg}} \sim \frac{\text{maximum sensible energy}}{\text{Latent energy}} \qquad (6.5)$$

Chapter 5 By E. Amani

Dimensional analysis

- **Phase-change convection**
  - **Free convection (pool boiling/condensation):**
  - **Exercise: By dimensional analysis of Eq. (1.5), show that:**

$$\overline{\text{Nu}}_L = f(\text{Gr}_L^{\text{pc}}, \text{Ja}, \text{Pr}, \text{Bo}, \frac{\rho_g}{\rho_l}, \frac{c_{pg}}{c_{pl}}, \frac{k_g}{k_l}, \frac{\mu_g}{\mu_l}) \qquad (3.5)$$

Nusselt number

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Grashof number

$$\text{Gr}_L^{\text{pc}} = \frac{\rho_l g(\rho_l - \rho_v)L^3}{\mu_l^2} \sim \frac{\text{Buoyancy force}}{\text{Viscous force}} \qquad (5.5)$$

Jakob number

$$\text{Ja} = \frac{c_{pl}\Delta T}{h_{fg}} \sim \frac{\text{maximum sensible energy}}{\text{Latent energy}} \qquad (6.5)$$

Prandtl number

$$\text{Pr} = \frac{\mu_l c_{pl}}{k_l} \sim \frac{\text{momentum diffusion}}{\text{heat diffusion}} \qquad (7.5)$$

Bond number

$$\text{Bo} = \frac{g(\rho_l - \rho_v)L^2}{\sigma} \sim \frac{\text{Buoyancy force}}{\text{surface tension force}} \qquad (8.5)$$

Chapter 5 By E. Amani

Dimensional analysis

- **Phase-change convection**
  - **Forced convection (flow boiling/condensation):**

$$\bar{h} = h(h_{fg}, c_{pl}\Delta T, g(\rho_l - \rho_v), L, \sigma, U, \rho_l, c_{pl}, k_l, \mu_l, \rho_g, c_{pg}, k_g, \mu_g) \qquad (1.5)'$$

Characteristic velocity

$$\overline{\mathrm{Nu}}_L = \frac{\bar{h}L}{k_l} = f(\mathrm{Gr}_L^{\mathrm{pc}}, \mathrm{Ja}, \mathrm{Pr}, \mathrm{Bo}, \mathrm{Re}, \frac{\rho_g}{\rho_l}, \frac{c_{pg}}{c_{pl}}, \frac{k_g}{k_l}, \frac{\mu_g}{\mu_l}) \qquad (3.5)'$$

Reynolds number $\mathrm{Re} = \frac{\rho_l U L}{\mu_l}$

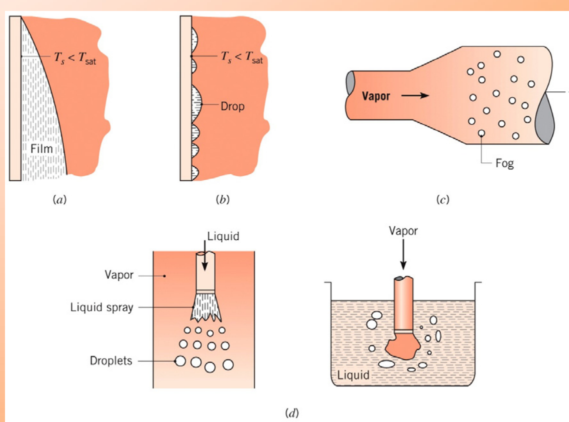
  - **For mini/micro-channels, buoyancy forces are negligible**

$$\overline{\mathrm{Nu}}_L = \frac{\bar{h}L}{k_l} = f(\mathrm{Ja}, \mathrm{Pr}, \mathrm{Bo}, \mathrm{Re}, \frac{\rho_g}{\rho_l}, \frac{c_{pg}}{c_{pl}}, \frac{k_g}{k_l}, \frac{\mu_g}{\mu_l}) \qquad (3.5)''$$

Chapter 5 **By E. Amani**

Condensation

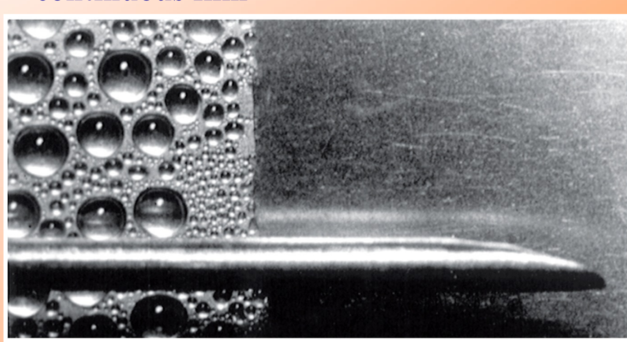
- **When the surface temperature is less than the saturation temperature of an adjoining vapor**
- **Modes:**
  - **Film**
  - **Dropwise**
  - **Homogeneous**
  - **Direct contact**



Chapter 5 **By E. Amani**

Condensation

- Dropwise vs. film
  - ✓ Film condensation on clean, uncontaminated surfaces.
  - ✓ Surface coatings can inhibit wetting and stimulate dropwise condensation
  - ✓ Reduced thermal resistance in the absence of a continuous film



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Film condensation

- Why is film condensation only considered here?
  - Simpler to study and existence of a variety of correlations
  - Design for worst condition
  - The dominant resistance is not the condensation resistance

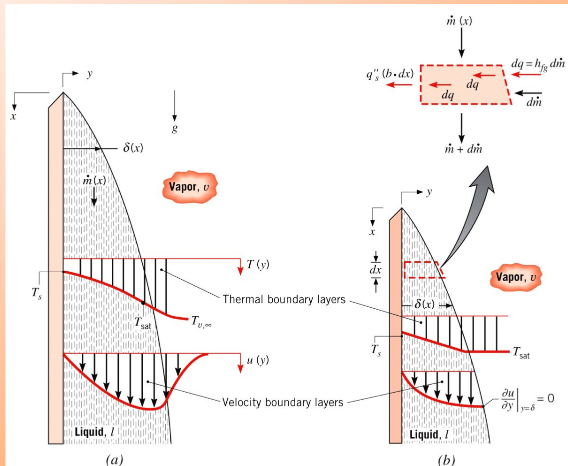
Chapter 5 By E. Amani

Film condensation

- **Laminar film condensation on a vertical plate**
  - **Nusselt's Semi-analytical solution assuming**

1. **Constant physical properties**
2. **Vapor at T_{sat}**
3. **Negligible shear stress in vapor**
4. **Boundary layer approximation**
5. **Neglecting advection (!!? to be relaxed)**

Lecture Notes: V.2.1



Chapter 5 **By E. Amani**

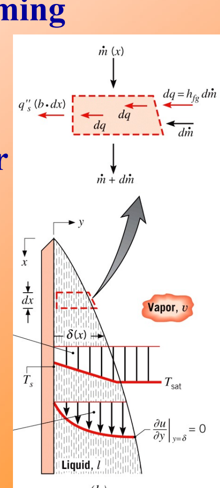
Film condensation

- **Laminar film condensation on a vertical plate**
  - **Nusselt's Semi-analytical solution assuming**

$$\delta(x)=\left[\frac{4k_l\mu_l\left(T_{sat}-T_s\right)x}{g\rho_l\left(\rho_l-\rho_v\right)h_{fg}}\right]^{1/4} \qquad (14.5)$$

  - **Rohsenow's modification to account for advection:**

$$h'_{fg}=h_{fg}\left(1+0.68\ Ja\right) \qquad (15.5)$$



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Film condensation

- **Laminar film condensation on a vertical plate**
  - **Therefore,**

$$\delta(x)=\left[\frac{4k_l\mu_l(T_{\text{sat}}-T_s)x}{g\rho_l(\rho_l-\rho_v)h'_{fg}}\right]^{1/4} \qquad (14.5)$$

$$h'_{fg}=h_{fg}(1+0.68\,Ja) \qquad (15.5)$$

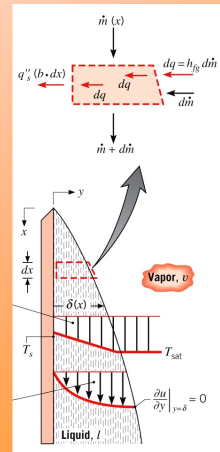
$$h=\frac{q''_s}{T_{\text{sat}}-T_s}=\frac{k_l}{\delta(x)} \qquad (17.5)$$

$$\xrightarrow[T_s=cte]{(14.5)} \quad \bar{h}_L=\frac{1}{L}\int_0^L h(x)dx=\frac{4}{3}h(x=L) \qquad (18.5)$$

$$\xrightarrow[T_s=cte]{(0.5)'} \quad q_s=\bar{h}_L A(T_s-T_{\text{sat}}) \quad (19.5) \qquad \xrightarrow{(12.5)} \dot{m}=\frac{q_s}{h'_{fg}} \quad (20.5)$$

$$\overline{Nu}_L=\frac{\bar{h}_L L}{k_l}=0.943\left[\frac{\rho_l g(\rho_l-\rho_v)h'_{fg}L^3}{\mu_l k_l(T_{sat}-T_s)}\right]^{1/4} \qquad (21.5)$$

$$\overline{Nu}_L=0.943\left[Gr_L^{pc}\,Ja'\,\text{Pr}\right]^{1/4}$$



(b)

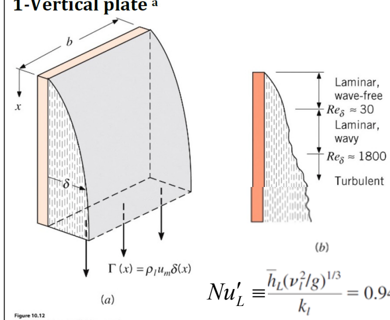
Chapter 5 **By E. Amani**

Film condensation

- **Empirical correlations: Table 1 in "chap5-summary.pdf"**

Table 1: Film condensation

Geometry	Recommended Correlation	Restrictions
1-Vertical plate [a]	$h'_{fg}=h_{fg}+0.68c_{p,l}(T_{\text{sat}}-T_s)$	
	Vertical (10.32) or (21.5)	Laminar, Ja < 0.1, $1 \lesssim Pr \lesssim 100$, $\rho_l \gg \rho_v$
	(10.42)-(10.45)	$\rho_l \gg \rho_v$
2-Spheres & cylinders		



$$P=\frac{k_l L(T_{\text{sat}}-T_s)}{\mu_l h'_{fg}(\nu_l^2/g)^{1/3}}=\frac{Ja'}{\text{Pr}}\left[Gr_L^{pc}\frac{1}{1-\frac{\rho_v}{\rho_l}}\right]^{1/3}$$

$$Nu'_L \equiv \frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l}=0.943\,P^{-1/4} \qquad P \lesssim 15.8$$

$$Nu'_L \equiv \frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l}=\frac{1}{P}(0.68\,P+0.89)^{0.82} \qquad 15.8 \lesssim P \lesssim 2530$$

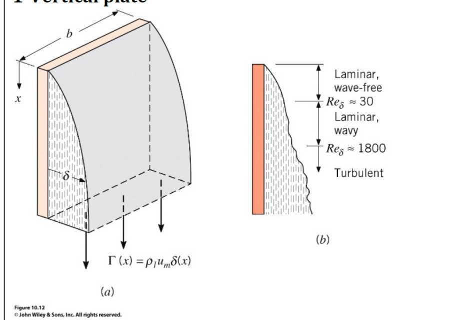
$$Nu'_L \equiv \frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l}=\frac{1}{P}[(0.024\,P-53)Pr_l^{1/2}+89]^{4/3} \qquad P \gtrsim 2530,\ Pr_l \ge 1$$

Chapter 5 **By E. Amani**

Film condensation

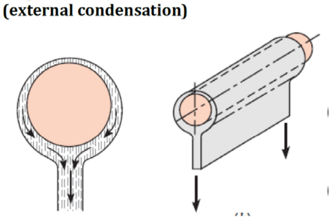
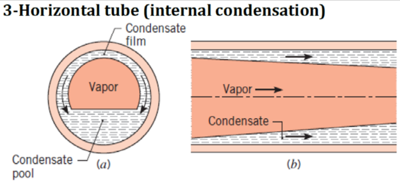
- **Empirical correlations: Table 1 in "chap5-summary.pdf"**

Table 1: Film condensation

Geometry	Recommended Correlation	Restrictions
1-Vertical plate [a] 	$h'_{fg} = h_{fg} + 0.68c_{p,l}(T_{sat} - T_s)$ **Vertical** (10.32) (10.42)-(10.45) **Inclined** above + ($g \rightarrow g \cos\theta$)	Laminar, Ja < 0.1, $1 \leq Pr \leq 100$ $\rho_l \gg \rho_v$.
2-Spheres & cylinders	(10.46)	

Film condensation

- **Empirical correlations: Table 1 in "chap5-summary.pdf"**

2-Spheres & cylinders (external condensation) 	(10.46) $h'_{fg} = h_{fg} + 0.68c_{p,l}(T_{sat} - T_s)$ Sphere: C = 0.826 Cylinder: C = 0.729 **vertical tier of N horizontal unfinned tubes** (10.49), n = -1/6 **Inclined** above + ($g \rightarrow g \cos\theta$) **Finned tube** (10.48)	($L/D > 1.8 \tan\theta$)
3-Horizontal tube (internal condensation) 	(10.50) **a) low vapor velocity** (10.46), C = 0.555 $h'_{fg} = h_{fg} + 0.375c_{p,l}(T_{sat} - T_s)$ **b) high vapor velocity** (10.51)	$Re_{v,i} < 35000$ $\dot{m}/A > 500 kg/s.m^2$

Boiling

- When the surface temperature is greater than the saturation temperature of an adjoining liquid
- Classification:
  - Pool boiling: Natural convection + bubble-induced
  - Flow boiling: Forced convection + bubble-induced
- Classification:
  - Saturated boiling: Liquid temperature is slightly higher than saturation temperature
  - Subcooled Boiling: Liquid temperature is less than saturation temperature

Chapter 5 By E. Amani

Boiling

- When the surface temperature is greater than the saturation temperature of an adjoining liquid
- Classification:
  - Pool boiling: Natural convection + bubble-induced

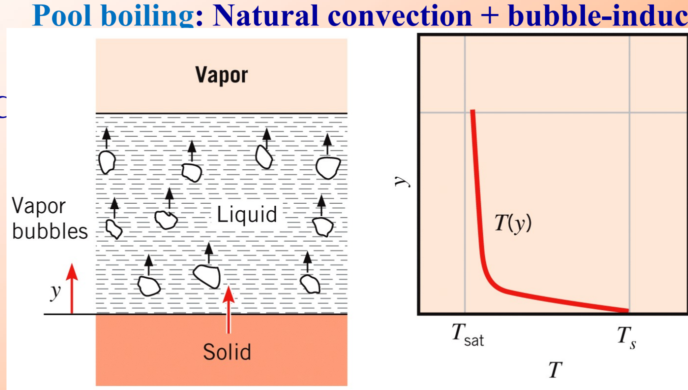


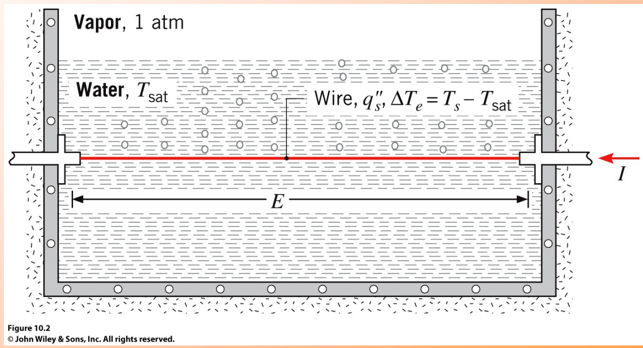
Figure 10.1

Saturated pool boiling

Chapter 5 By E. Amani

Pool boiling

- **The Boiling Curve**
  - **Saturated pool boiling on a $q_s'' - \Delta T_e$ plot**

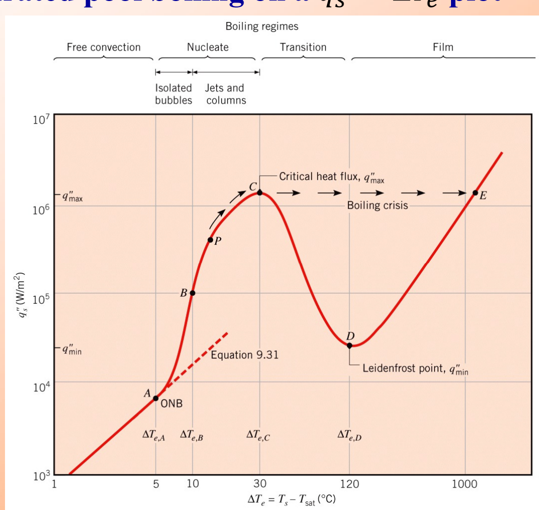


Saturated pool boiling

Chapter 5 **By E. Amani**

Pool boiling

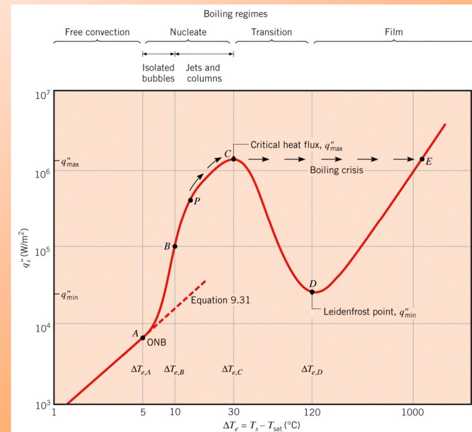
- **The Boiling Curve**
  - **Saturated pool boiling on a $q_s'' - \Delta T_e$ plot**



Chapter 5 **By E. Amani**

The boiling curve

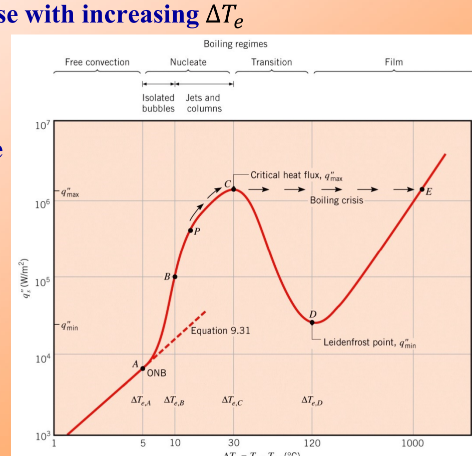
- **Free Convection Boiling ($\Delta T_e < 5°C$)**
  - **Little vapor formation**
  - **single-phase natural convection**

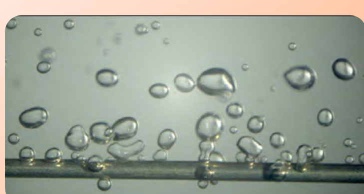


Chapter 5 **By E. Amani**

The boiling curve

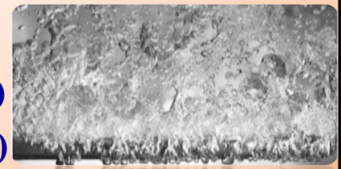
- **Nucleate Boiling ($5 < \Delta T_e < 30°C$)**
  - **Isolated Vapor Bubbles ($5 < \Delta T_e < 10°C$)**
    - ✓ q''_s **and** h **sharply increase with increasing** ΔT_e
    - ✓ **Heat transfer is principally due to contact of liquid with the surface (single-phase convection) and not to vaporization**





Chapter 5 **By E. Amani**

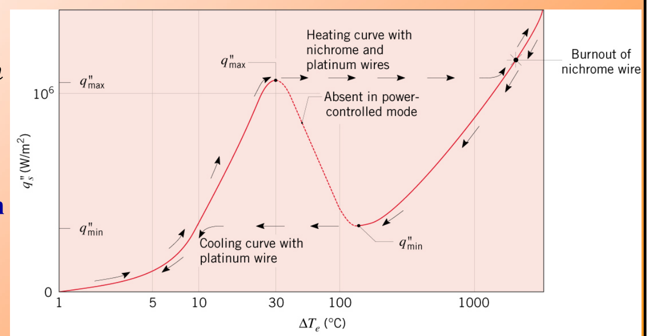
The boiling curve



- **Nucleate Boiling** ($5 < \Delta T_e < 30°C$)
  - **Jets and columns** ($10 < \Delta T_e < 30°C$)
    - ✓ **Increasing number of nucleation sites**
    - ✓ **Bubble interactions and coalescence into jets and slugs**
    - ✓ **Liquid/surface contact is impaired**

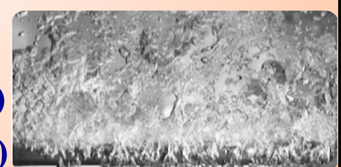
✓ q''_s **continues to increase with increasing** ΔT_e **while** h **begins to decrease**

✓ **Critical Heat Flux (CHF),** $q''_{\max}$ **(**$\Delta T_e \sim 30°C$**): Maximum attainable heat flux in nucleate boiling**



Chapter 5 $q''_{\max} \approx 1$ MW/m^2 for water at atmospheric pressure. **By E. Amani**

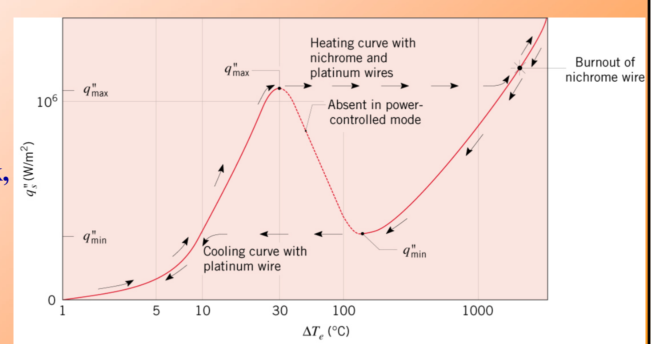
The boiling curve



- **Nucleate Boiling** ($5 < \Delta T_e < 30°C$)
  - **Jets and columns** ($10 < \Delta T_e < 30°C$)
    - ✓ **Potential Burnout for Power-Controlled Heating**
    - ✓ **An increase in** q''_s **beyond CHF causes the surface to be blanketed by vapor**

✓ **Surface temperature can spontaneously exceeds its melting point (**$T_s > 1000°C$**)**

✓ **If the surface survives the temperature shock, film boiling prevails**



Chapter 5 $q''_{\max} \approx 1$ MW/m^2 for water at atmospheric pressure. **By E. Amani**

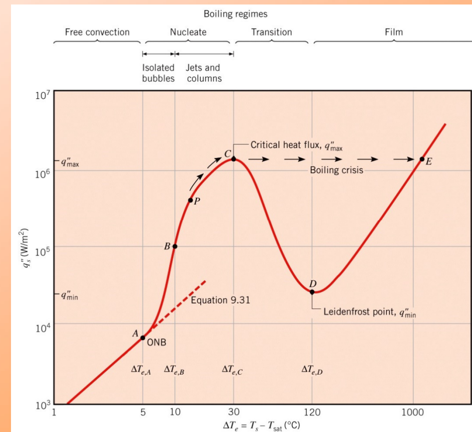
The boiling curve

- **Transition boiling for temperature-controlled heating ($30 < \Delta T_e < 120$°C)**

✓ **Characterized by a continuous decay of q''_s (from q''_{max} to q''_{min}) with increasing ΔT_e**

✓ **Oscillation between nucleate and film boiling, but portion of surface experiencing film boiling increases with ΔT_e**

✓ **Also termed unstable or partial film boiling**



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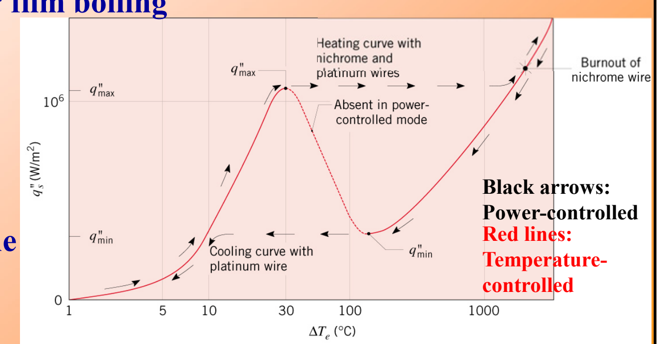
The boiling curve

- **Film Boiling ($\Delta T_e > 120$°C)**
  - **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**



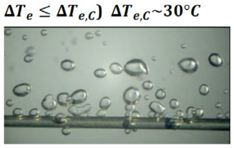
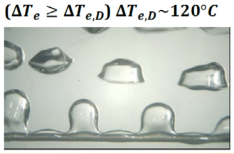
Chapter 5 $q''_{max} \approx 1$ MW/m² for water at atmospheric pressure. **By E. Amani**

Pool boiling correlations

- **Empirical correlations: Table 2 in "chap5-summary.pdf"**

Semi-empirical Rohsenow's correlation

Table 2: Pool boiling

Geometry	Recommended Correlation	Restrictions
1-Free convection boiling **($\Delta T_e \le \Delta T_{e,A}$) $\Delta T_{e,A} \sim 5°C$**	**Natural convection relations**	
2-Nucleate boiling [a] **($\Delta T_{e,A} \le \Delta T_e \le \Delta T_{e,C}$) $\Delta T_{e,C} \sim 30°C$** 	(10.5) and Table 10.1 **Critical heat flux** (10.6) Large horizontal plate: C = 0.149 Sphere, cylinder, and others: C = 0.131 **Minimum heat flux** (10.7) C = 0.09	Clean surface $Bo^{-1/2} > 0.2$ moderate pressures
3-Film boiling [b] **($\Delta T_e \ge \Delta T_{e,D}$) $\Delta T_{e,D} \sim 120°C$** 	(10.8) $h'_{fg} = h_{fg} + 0.80 c_{p,v}(T_s - T_{sat})$ Horizontal cylinder: C = 0.62 Sphere: C = 0.67 **Including Radiation ($T_s \ge 300°C$)** (10.9)-(10.11)	

Similar to film condensation

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Pool boiling correlations

- **Empirical correlations: Table 2 in "chap5-summary.pdf"**
- **Rohsenow's 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)

- The derivation: Appendix A
- Exercise: Show that Rohsenow's correlation can be recast as:

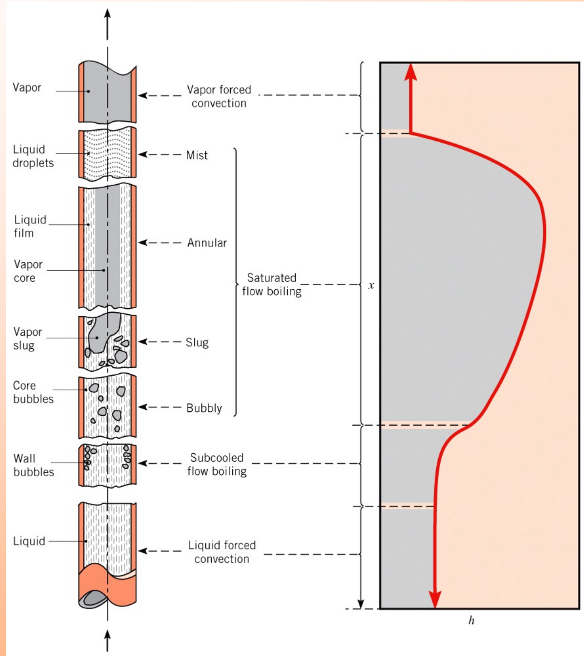
$$\overline{\mathrm{Nu}}_{D_b} \equiv \frac{\bar{h} D_b}{k_l} = \mathrm{Ja}^2 \mathrm{Pr}^{1-3n} \qquad (24.5)$$

- Exercise: Is Eq. (24.5) consistent with Eq. (3.5)? What are the assumptions of Rohsenow's correlation? Based on them, why does $\overline{\mathrm{Nu}}$ not depend on $\mathrm{Gr}_L^{\mathrm{pc}}$ and Bo?

Chapter 5 **By E. Amani**

Flow boiling

- **Flow boiling or forced convection boiling**
- **External and internal flow**

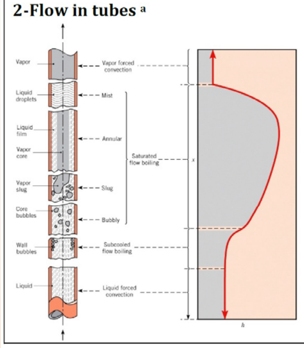


Chapter 5 By E. Amani

Flow boiling correlations

- **Empirical correlations: Table 3 in "chap5-summary.pdf"**

Table 3: Forced convection boiling

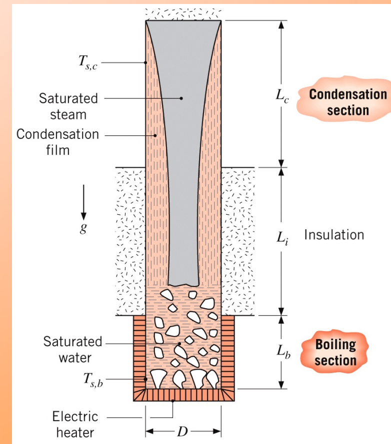
Geometry	Recommended Correlation	Restrictions
1- Flow over a cylinder in cross-flow	critical heat flux: (10.12)-(10.14)	
2-Flow in tubes [a] 	**single-phase forced convection region** (8.62) [a] **saturated flow boiling region** max (10.15a,10.15b), (10.16) and Table 10.2 $Fr \lesssim 0.04$, $f(Fr) = 2.63\,Fr^{0.3}$, and otherwise, $f(Fr) = 1$ $Fr = (\dot{m}''/\rho_l)^2/gD$ h_{sp} from (8.62) [a]	turbulent flow turbulent flow $Co = \sqrt{\sigma/(g[\rho_l - \rho_v])}/D_h \lesssim 1/2$ smooth tubes

[a] All properties at T_{sat}

Chapter 5 By E. Amani

Sample problem

- **Thermosyphon**

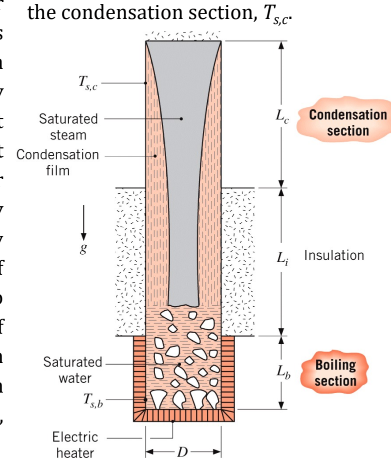


Sample problem

- **Thermosyphon**

10.73 A thermosyphon consists of a closed container that absorbs heat along its boiling section and rejects heat along its condensation section. Consider a thermosyphon made from a thin-walled mechanically polished stainless steel cylinder of diameter D. Heat supplied to the thermosyphon boils saturated water at atmospheric pressure on the surfaces of the lower boiling section of length L_b and is then rejected by condensing vapor into a thin film, which falls by gravity along the wall of the condensation section of length L_c back into the boiling section. The two sections are separated by an insulated section of length L_i. The top surface of the condensation section may be treated as being insulated. The thermosyphon dimensions are $D = 20\ mm$, $L_b = 20\ mm$, $L_c = 40\ mm$, and $L_i = 40\ mm$.

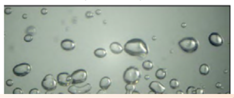
(a) Find the mean surface temperature, $T_{s,b}$, of the boiling surface if the nucleate boiling heat flux is to be maintained at 30% of the critical heat flux.
(b) Find the total condensation flow rate, $\dot{m}$, and the mean surface temperature of the condensation section, $T_{s,c}$.



Lecture Notes: V.4

Sample problem

Table 2: Pool boiling

Geometry	Recommended Correlation	Restrictions
1-Free convection boiling **($\Delta T_e \le \Delta T_{e,A}$) $\Delta T_{e,A} \sim 5°C$**	**Natural convection relations**	
2-Nucleate boiling [a] ($\Delta T_{e,A} \le \Delta T_e \le \Delta T_{e,C}$) $\Delta T_{e,C} \sim 30°C$ 	(10.5) and Table 10.1 **Critical heat flux** (10.6) Large horizontal plate: C = 0.149 Sphere, cylinder, and others: C = 0.131	Clean surface $Bo^{-1/2} > 0.2$

[a] All properties at T_{sat}

[b] Vapor properties at system pressure and film temperature ($T_f = (T_s + T_{sat})/2$), and ρ_l and h_{fg} at T_{sat}

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

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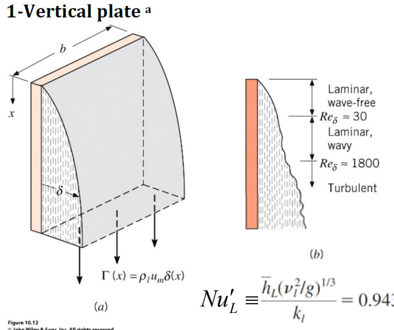
Sample problem

Table 1: Film condensation

Geometry	Recommended Correlation	Restrictions
1-Vertical plate [a]	$h'_{fg} = h_{fg} + 0.68 c_{p,l}(T_{sat} - T_s)$ **Vertical** (10.32) or (21.5) (10.42)-(10.45)	Laminar, Ja < 0.1, $1 \le Pr \le 100$ $\rho_l \gg \rho_v$ $\rho_l \gg \rho_v$
2-Spheres & cylinders		



$$P = \frac{k_l L (T_{sat} - T_s)}{\mu_l h'_{fg} (\nu_l^2/g)^{1/3}} = \frac{Ja'}{\text{Pr}}\left[Gr_L^{pc} \frac{1}{1 - \frac{\rho_v}{\rho_l}} \right]^{1/3}$$

$$\overline{Nu}'_L \equiv \frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l} = 0.943\, P^{-1/4} \qquad P \lesssim 15.8$$

$$\overline{Nu}'_L \equiv \frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l} = \frac{1}{P}(0.68\, P + 0.89)^{0.82} \qquad 15.8 \lesssim P \lesssim 2530$$

$$\overline{Nu}'_L \equiv \frac{\bar{h}_L(\nu_l^2/g)^{1/3}}{k_l} = \frac{1}{P}[(0.024\, P - 53)Pr_l^{1/2} + 89]^{4/3} \qquad P \gtrsim 2530,\ Pr_l \ge 1$$

[a] Fluid properties at film temperature ($T_f = (T_s + T_{sat})/2$), and h_{fg} and vapor properties (ρ_v) at T_{sat}

[b] May be used for condensation on the inner or outer surface of a vertical tube of radius $R \gg \delta$.

[c] All properties at T_{sat}

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The end of chapter 5