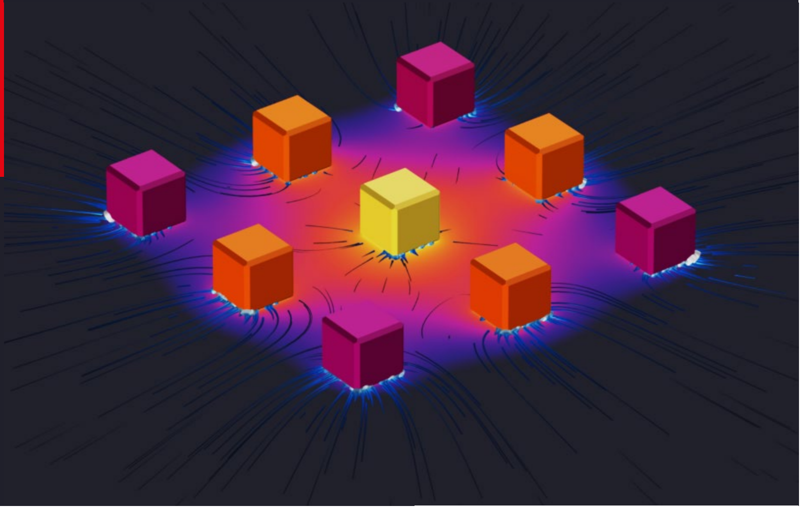
Heat and Mass Transfer
ME-341

Instructor: Giulia Tagliabue



École
polytechnique
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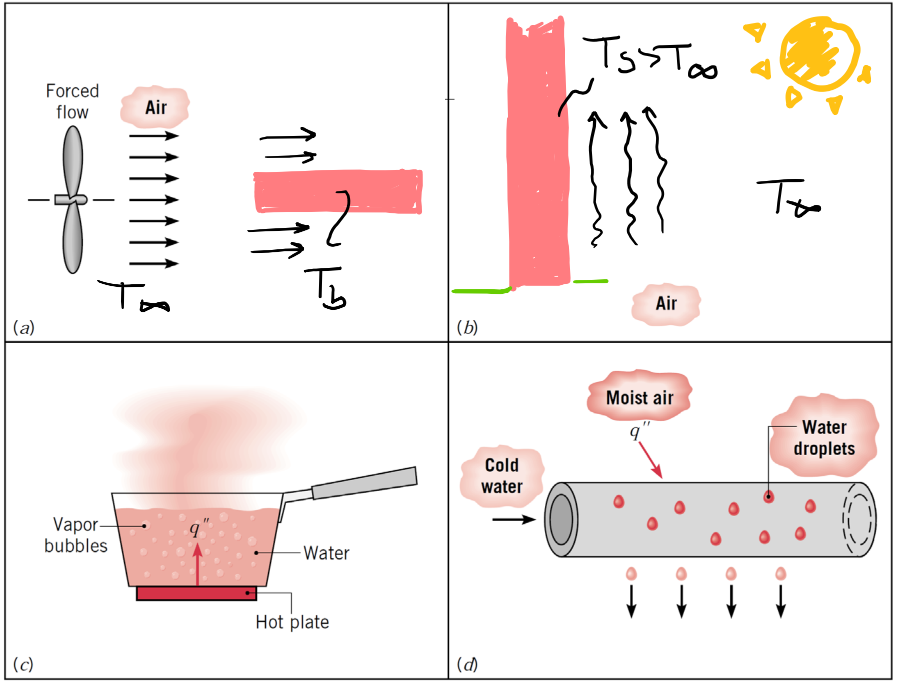
de Lausanne

Spring Semester

Previously

1. Forced Convection

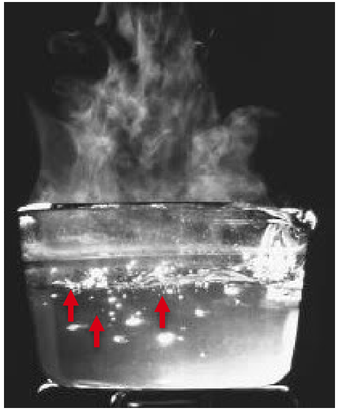
2. Natural (Free) Convection



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

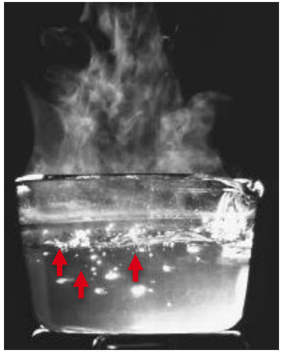
Latent heat (h_{fg}) is exchanged between solid and fluid

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

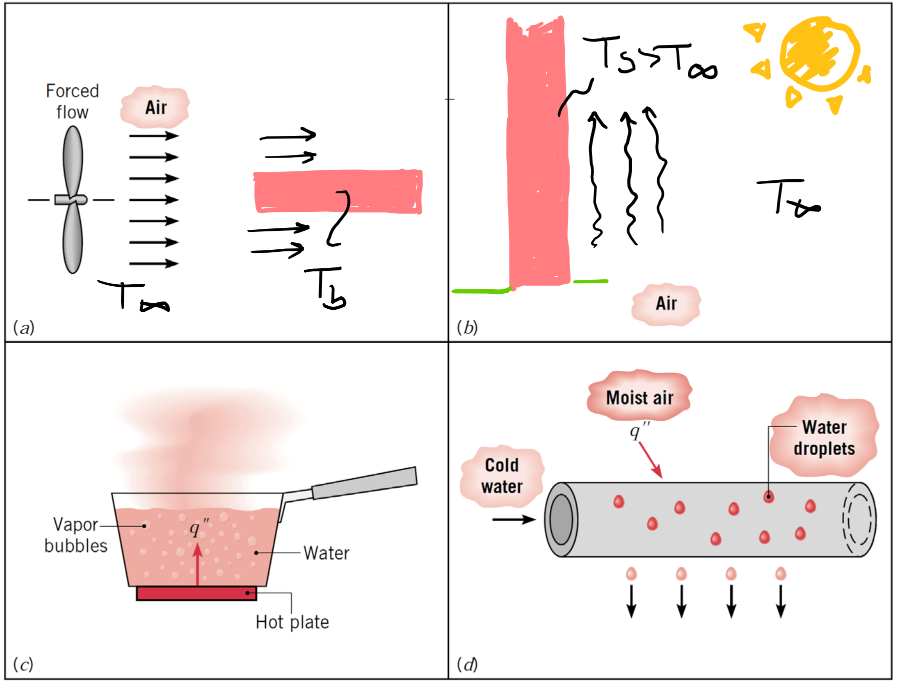
Saturated Boiling
$T_s > T_{sat}$, the bubble must rise

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

Next Lecture

1. Forced Convection

2. Natural (Free) Convection



3. Boiling

4. Condensation

This Lecture

- Condensation
  - Laminar Film Condensation on a Vertical Plate

Learning Objectives:

- Understand condensation

Condensation

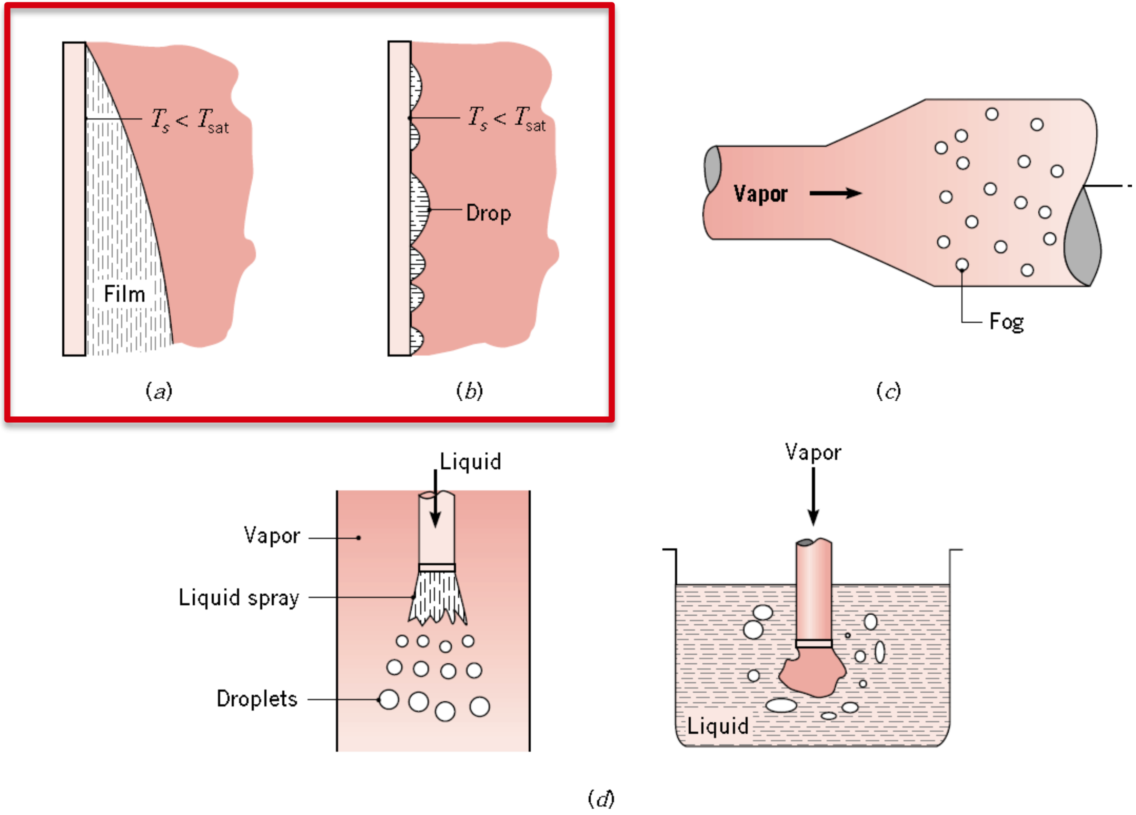
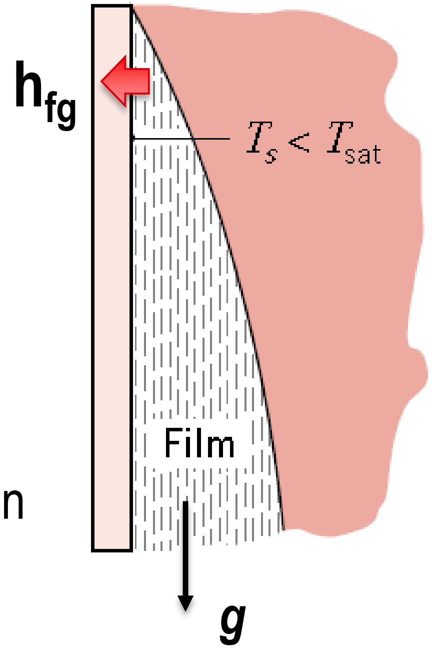
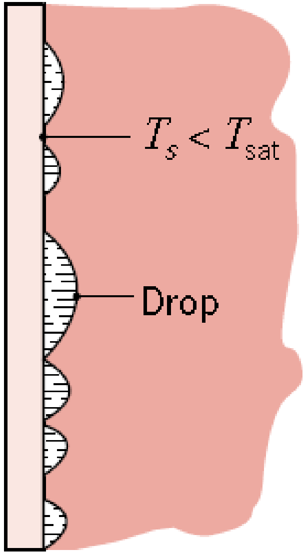


FIGURE 10.9 Modes of condensation. (*a*) Film. (*b*) Dropwise condensation on a surface. (*c*) Homogeneous condensation or fog formation resulting from increased pressure due to expansion. (*d*) Direct contact condensation.

Condensation



Film condensation

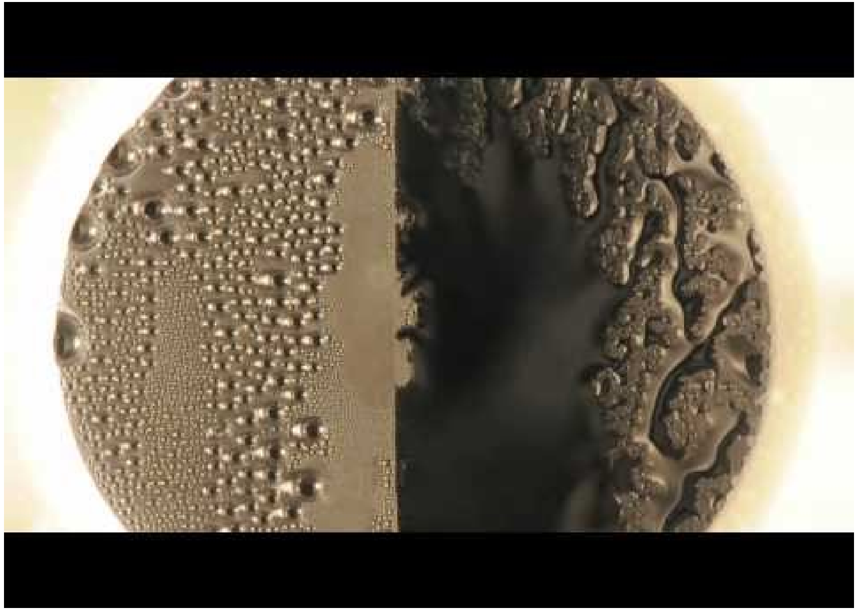


Dropwise condensation

The conditions of the surface (wettability) determine the mode of condensation

Which one is most desirable?

Condensation



Credit: Varanasi group (MIT)

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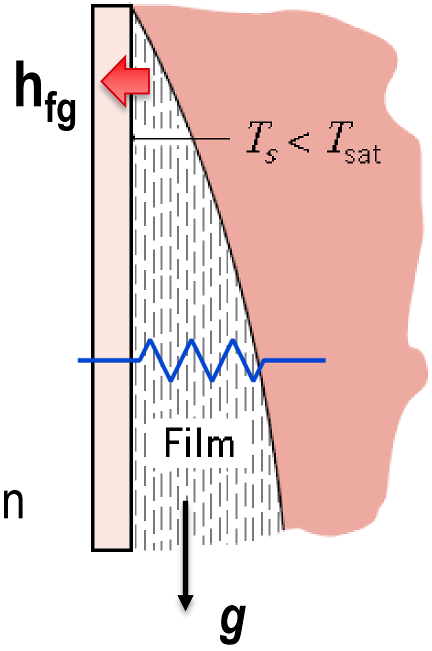
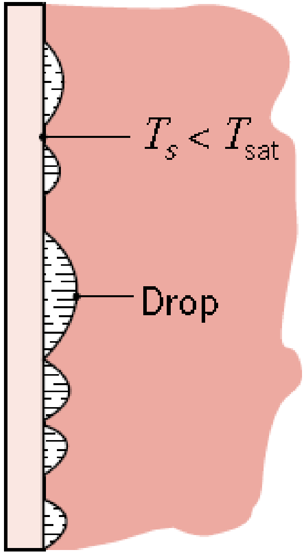
Condensation



Film condensation



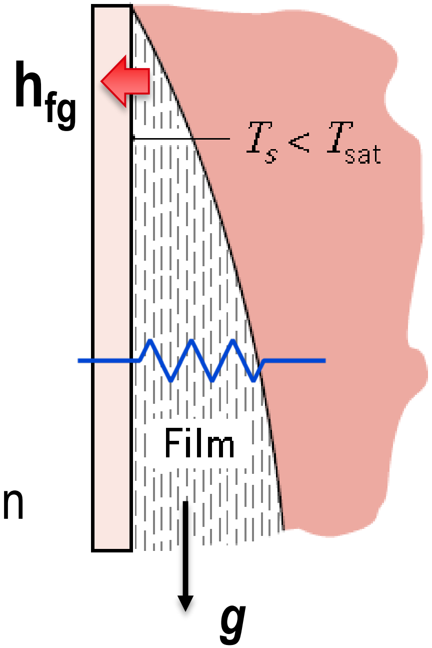
Degradation of the surface properties can reverse the condensation to film mode (lower heat transfer rate)

Dropwise condensation

The conditions of the surface (wettability) determine the mode of condensation

Which one is most desirable?

Condensation

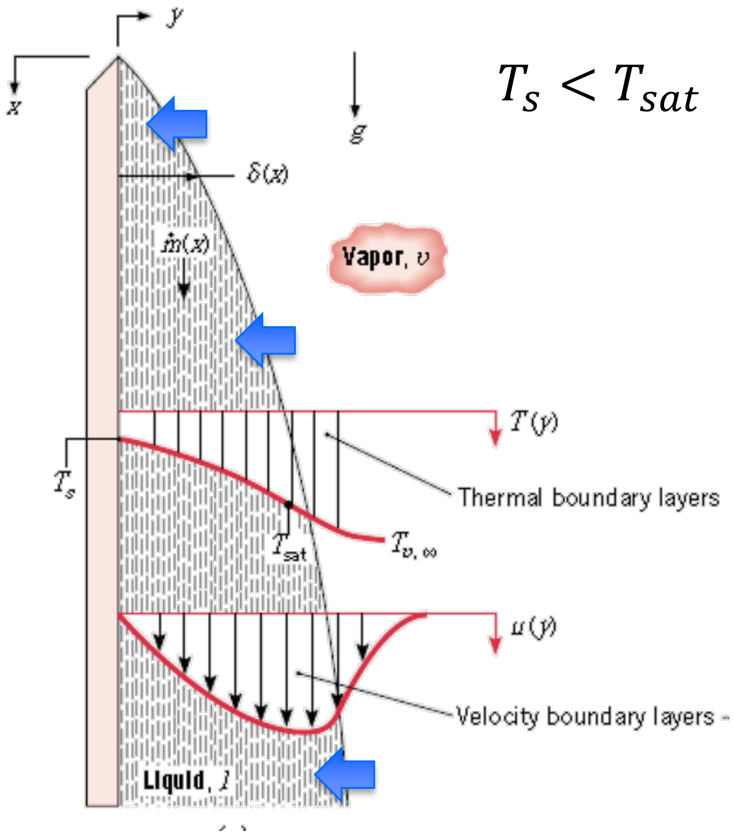


Film condensation

Minimize the thickness of the condensate film

- Short plates
- Horizontal tubes

Condensation: Laminar Film on a Vertical Plate

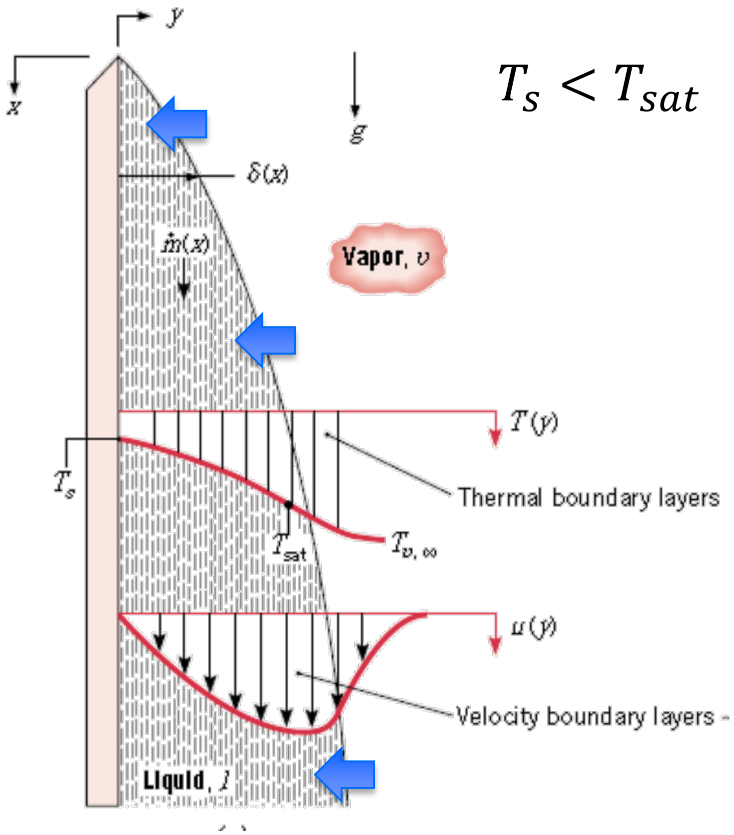


$$T_s < T_{sat}$$

As the condensate moves downwards, more vapor condenses onto the film:

- The thickness of the film increases with x
- The mass flow rate of the condensate increases with x
- Stresses are present at the liquid-vapor film (a velocity gradient is present in the vapor near the interface with the liquid)

Condensation: Laminar Film on a Vertical Plate



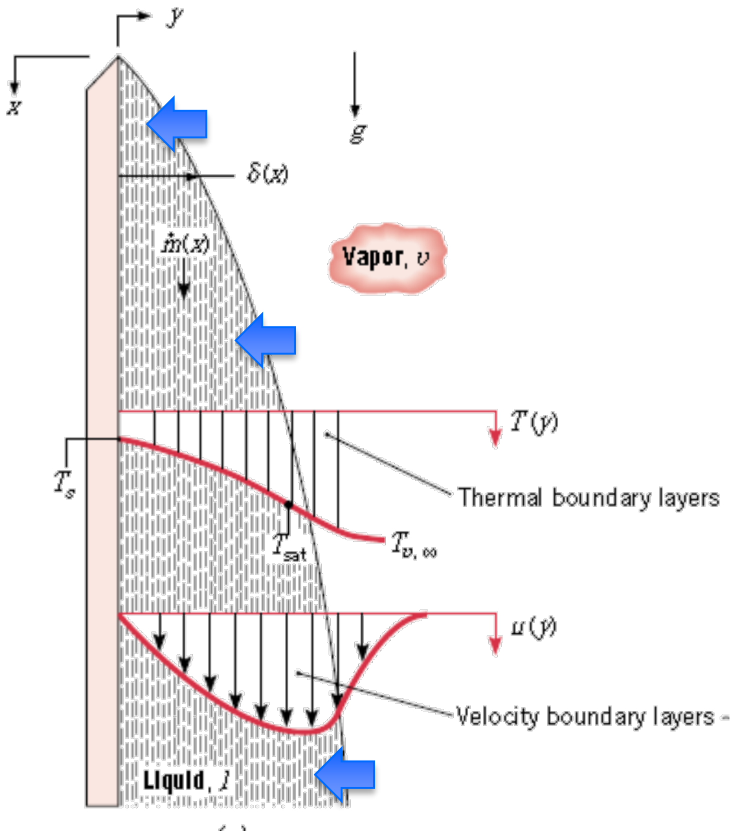
$$T_s < T_{sat}$$

We want to obtain a solution for the convection coefficient during film condensation on a vertical plate. Similarly to what we did for natural convection we can write:

- Momentum conservation (including gravity term)
- Energy conservation

However, an analytical solution is available only with significant simplifications.

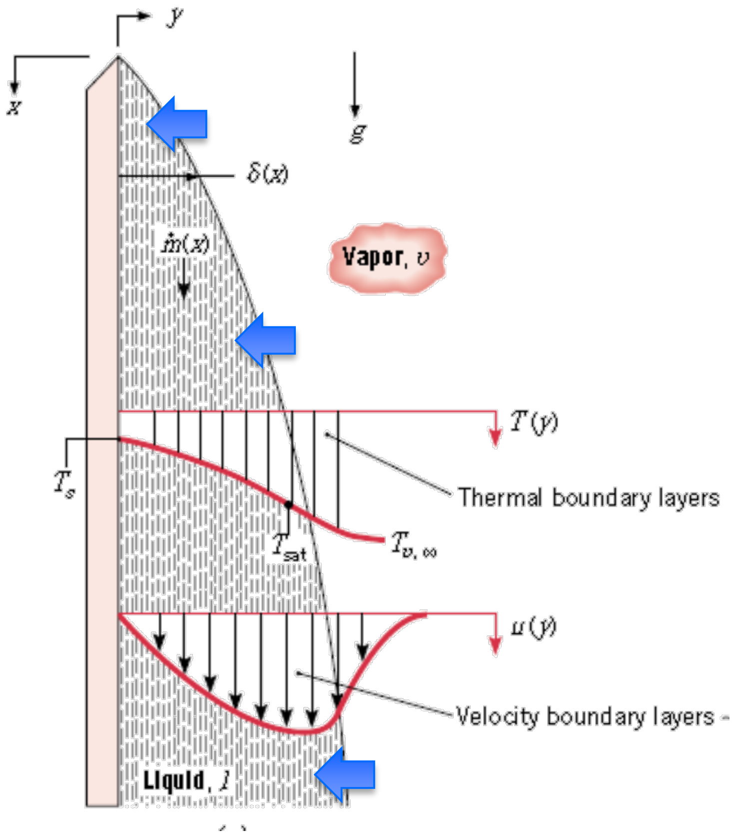
Condensation: Laminar Film on a Vertical Plate

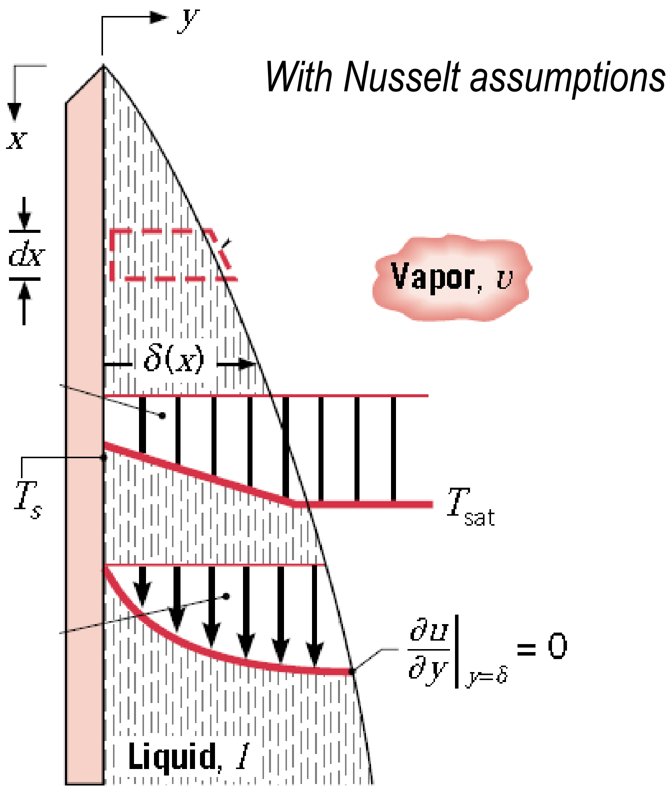


Simplifying assumptions from Nusselt:

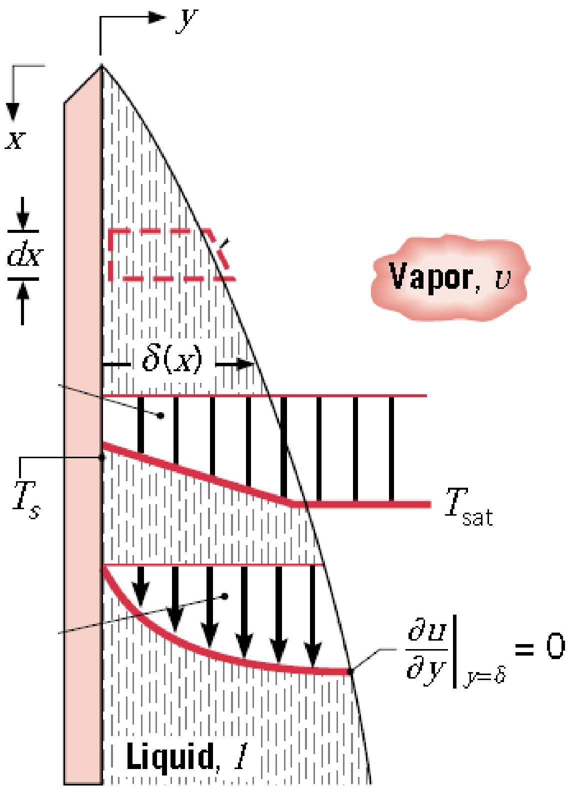
1. Laminar flow and constant properties in the film
2. Gas is pure vapor at uniform T_{sat}, no conduction heat transfer at the vapor-liquid interface (only condensation)
3. The shear stress at the vapor-liquid interface is negligible ($\partial u/\partial y|_{y=\delta} = 0$)
4. Negligible momentum transfer (advection) in the liquid film, i.e. only heat conduction across the film → linear T profile

Condensation: Laminar Film on a Vertical Plate





Condensation: Laminar Film on a Vertical Plate



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

Only conduction through the film

Fourier law of heat transfer

Linear temperature profile

$$q_s'' = \frac{k_l(T_{sat} - T_s)}{\boldsymbol{\delta}}$$

$\boldsymbol{\delta = condensate\ film\ thickness}$

➡ Find the condensate-film thickness

Condensation: Laminar Film on a Vertical Plate

During condensation, gravity forces the liquid to move along the solid.

FLUID DYNAMICS

Mass conservation → Continuity equation
Momentum conservation → Navier-Stokes equations

Flow condition (Laminar/turbulent) → $\boldsymbol{Re}$

Velocity profile: $\vec{\boldsymbol{u}}(\boldsymbol{x},\boldsymbol{y})$

- Shear stress τ_w
- Friction coefficient C_f
- Friction factor f

Condensate-film Thickness δ

HEAT TRANSFER

Energy conservation → 1st Law of Thermodynamics
Nusselt assumption = NO ADVECTION TERMS

Boundary Conditions (Temperature)
$\boldsymbol{Pr}$

Temperature profile: $\boldsymbol{T}(\boldsymbol{x},\boldsymbol{y})$

No slip condition $u(x,0) = 0$

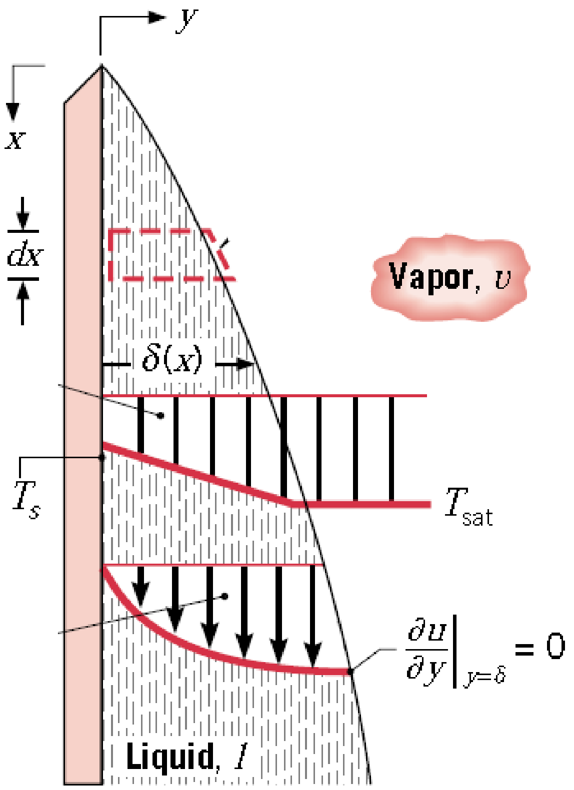
$Q_{convection} = Q_{cond,film}$

Transport Laws (Newton/Fourier)

$$h(T_{sat} - T_s) = -\frac{k_l(T_{sat} - T_s)}{\boldsymbol{\delta}}$$

$\boldsymbol{Nu}$

Condensation: Laminar Film on a Vertical Plate



FLUID DYNAMICS (momentum conservation)

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -\frac{1}{\rho}\frac{dp_\infty}{dx} + g + \nu\frac{\partial^2 u}{\partial y^2}$$

$\boldsymbol{\rho, \nu}$ **= liquid**

Away from the wall, $u = 0$ and $v = 0$ ➡ $\frac{dp_\infty}{dx} = +\rho_v g$ ρ_v = vapor

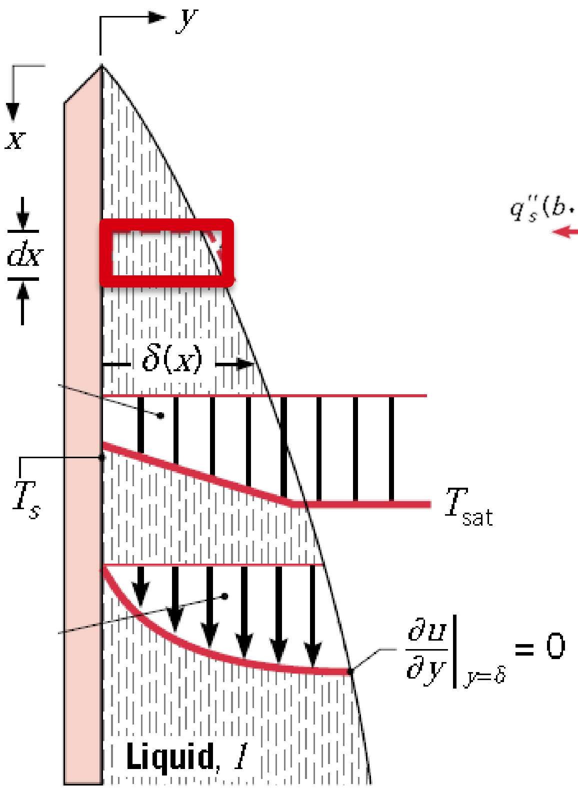
From <u>Nusselt assumption #4 advection can be neglected</u> (i.e. left-hand-side = 0) :

$$\frac{\partial^2 u}{\partial y^2} = \frac{1}{\mu_l}\frac{dp_\infty}{dx} - \frac{g\rho_l}{\mu_l} \quad ➡ \quad \frac{\partial^2 u}{\partial y^2} = -\frac{g}{\mu_l}(\rho_l - \rho_v)$$

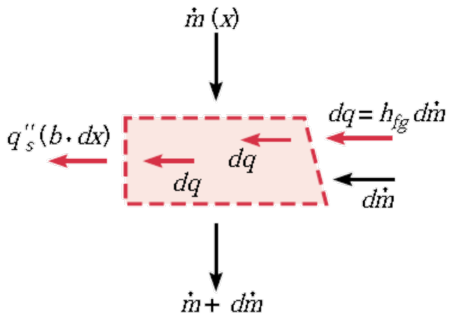
$$\begin{cases} u(0) = 0 \\ \left.\frac{\partial u}{\partial y}\right|_{y=\delta} = 0 \end{cases} \quad ➡ \quad u(y) = \frac{g(\rho_l - \rho_v)\delta^2}{\mu_l}\left[\frac{y}{\delta} - \frac{1}{2}\left(\frac{y}{\delta}\right)^2\right]$$

We still need the condensate-film thickness

Condensation: Laminar Film on a Vertical Plate



HEAT TRANSFER (energy balance)



$$0 = \dot{m}\,h_{in} - (\dot{m} + d\dot{m})h_{out} + dq_{condens} - q_s''(b \cdot dx)$$

From Nusselt assumption #4 advection can be neglected:

$$dq_{condens} = h_{fg} d\dot{m} = q_s''(b \cdot dx)$$

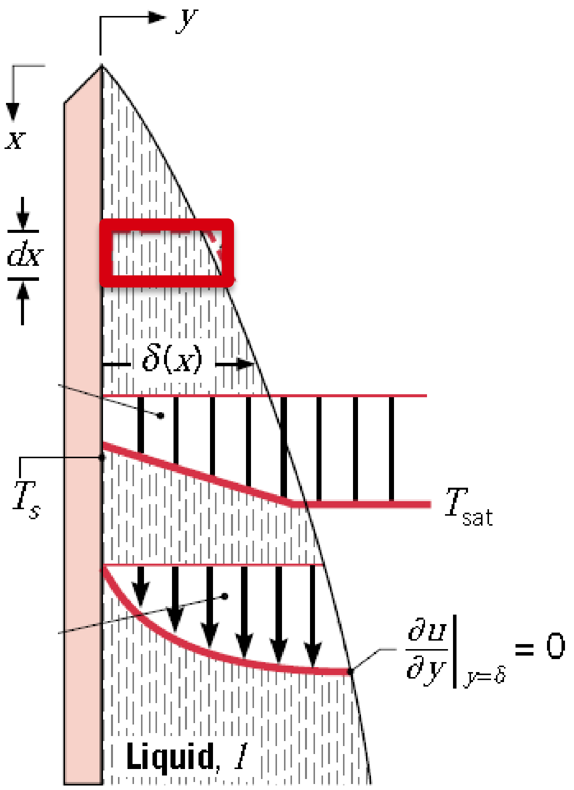
From Nusselt assumption #4, only conduction through the liquid film:

$$q_s'' = \frac{k_l(T_{sat} - T_s)}{\boldsymbol{\delta}} = \frac{h_{fg}}{dx}\frac{\boldsymbol{d\dot{m}}}{\boldsymbol{b}}$$

We define the condensate mass flow rate per unit width of the plate:

$$\Gamma(x) = \frac{\dot{m}(x)}{b} = \int_0^{\delta(x)} \rho_l u(y) dy = \frac{g\rho_l(\rho_l - \rho_v)\boldsymbol{\delta}^3}{3\mu_l}$$

Condensation: Laminar Film on a Vertical Plate



HEAT TRANSFER (energy balance)

$$q_s'' = \frac{k_l(T_{sat} - T_s)}{\delta} = h_{fg}\frac{d\Gamma}{dx}$$

Where: $$\frac{d\Gamma}{dx} = \frac{g\rho_l(\rho_l - \rho_v)\delta^2}{\mu_l}\frac{d\delta}{dx}$$

Therefore: $$\delta^3 d\delta = \frac{k_l\mu_l(T_{sat} - T_s)}{g\rho_l(\rho_l - \rho_v)h_{fg}}\mathrm{dx}$$

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

$$h'_{fg} = h_{fg} + 0.68c_{p,l}(T_{sat} - T_s)$$

Includes the effect of advection in an approximate way!

Condensation: Laminar Film on a Vertical Plate

During condensation, gravity forces the liquid to move along the solid.

FLUID DYNAMICS

Mass conservation → Continuity equation
Momentum conservation → Navier-Stokes equations

Flow condition (Laminar/turbulent) → Re

Velocity profile: $\vec{u}(x, y)$

- Shear stress τ_w
- Friction coefficient C_f
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Condensate-film Thickness δ

No slip condition $u(x, 0) = 0$

$$Q_{convection} = Q_{cond,film}$$

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Energy conservation → 1st Law of Thermodynamics
Nusselt assumption = NO ADVECTION TERMS

Boundary Conditions (Temperature)
Pr

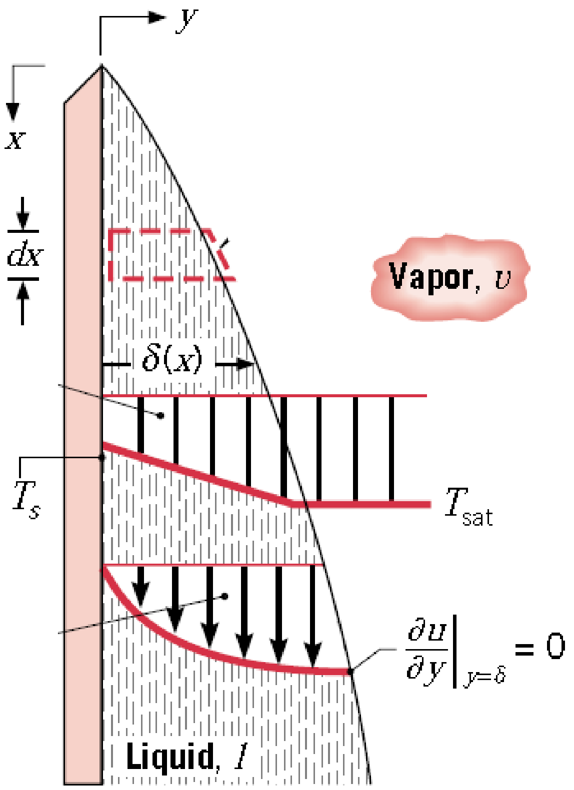
Temperature profile: $T(x, y)$

Transport Laws (Newton/Fourier)

$$h(T_{sat} - T_s) = -\frac{k_l(T_{sat} - T_s)}{\delta}$$

Nu

Condensation: Laminar Film on a Vertical Plate



To obtain the local convection coefficient:

$$q_s'' = \frac{k_l(T_{sat} - T_s)}{\delta} = h_x(T_{sat} - T_s) \quad \Rightarrow \quad h_x = \frac{k_l}{\delta}$$

$$\Rightarrow \quad h(x) = \left[\frac{g\rho_l(\rho_l - \rho_v)k_l^3 h'_{fg}}{4\mu_l(T_{sat} - T_s)x}\right]^{1/4}$$

$$h'_{fg} = h_{fg} + 0.68c_{p,l}(T_{sat} - T_s)$$

With liquid properties estimated at $T_f = \frac{(T_s + T_{sat})}{2}$
and ρ_v, h_{fg} estimated at T_{sat}

This Lecture

- ❑ Condensation
  - ☑ Laminar Film Condensation on a Vertical Plate

Learning Objectives:

- ☑ Understand condensation

Next Lecture

- ❑ Film Condensation on a Vertical Plate: Correlations
- ❑ Film Condensation on Radial Systems
  - ❑ Correlations for Laminar Flow
  - ❑ Overall Heat Transfer Coefficient

Learning Objectives:

- ❑ Calculate convection coefficient in selected condensation cases