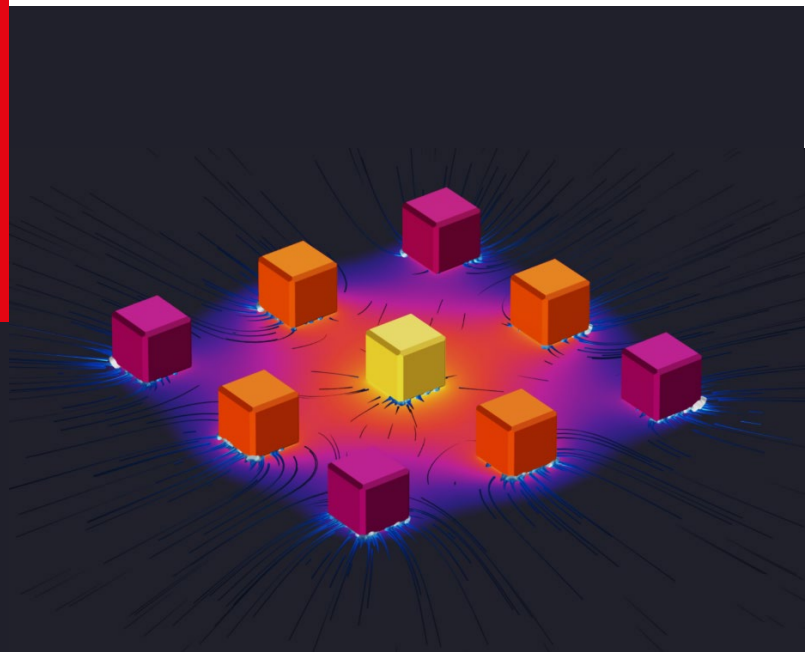
Heat and Mass Transfer
ME-341



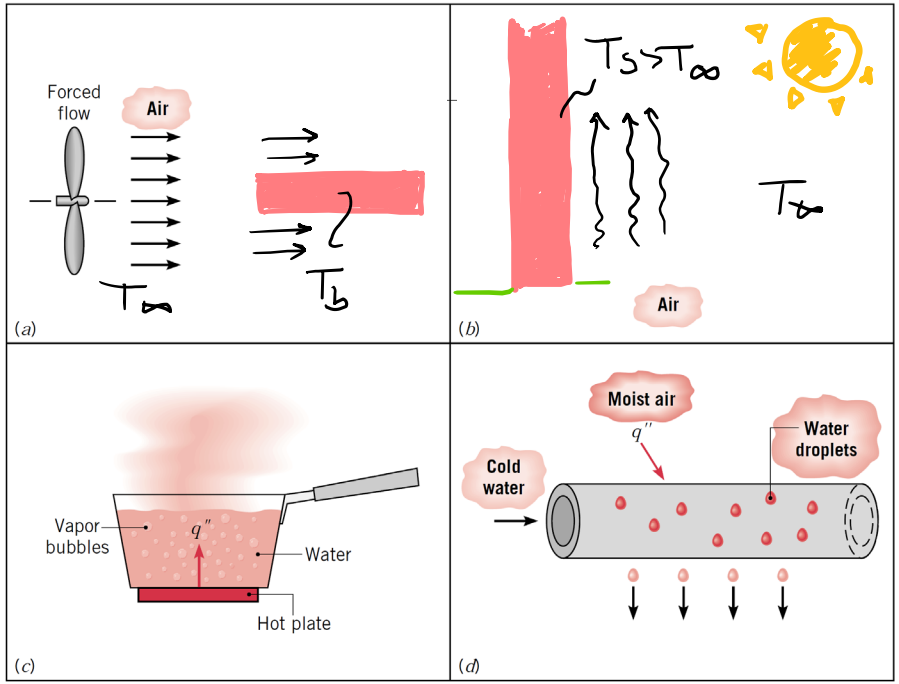
Instructor: Giulia Tagliabue

École
polytechnique
fédérale
de Lausanne

Spring Semester

Previously

1. Forced Convection



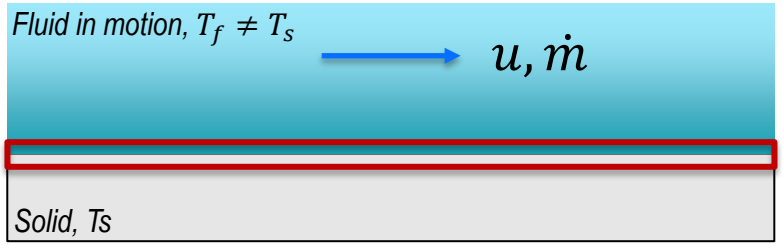
2. Natural (Free) Convection

3. Boiling

4. Condensation

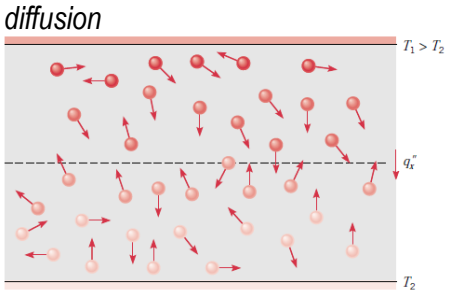
Introduction to Convection

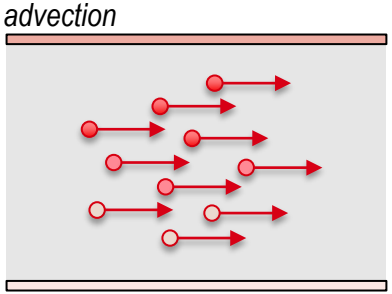
Convection refers to the heat transfer between a **solid** and a **fluid in motion** when they are at **different temperatures**.



Energy transfer at the solid-fluid interface !! (Boundary layer)

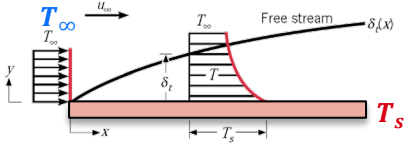
During convection heat is transferred through both **diffusion** (**random** molecular motion) and **advection** (**net** macroscopic mass transport)



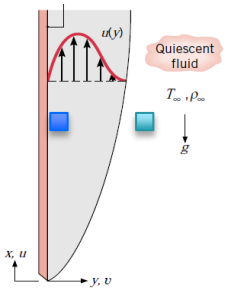


Governing Equations of Forced and Free Convection

Forced Convection



Free Convection



- Conservation of mass

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0$$

- Conservation of momentum

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\frac{\partial^2 u}{\partial y^2}$$

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=g\beta(T-T_\infty)+\nu\frac{\partial^2 u}{\partial y^2}$$

- Conservation of energy

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}$$

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}=\alpha\frac{\partial^2 T}{\partial y^2}$$

Heat transfer includes advection!

Temperature-driven fluid-motion!

Heat transfer includes advection!

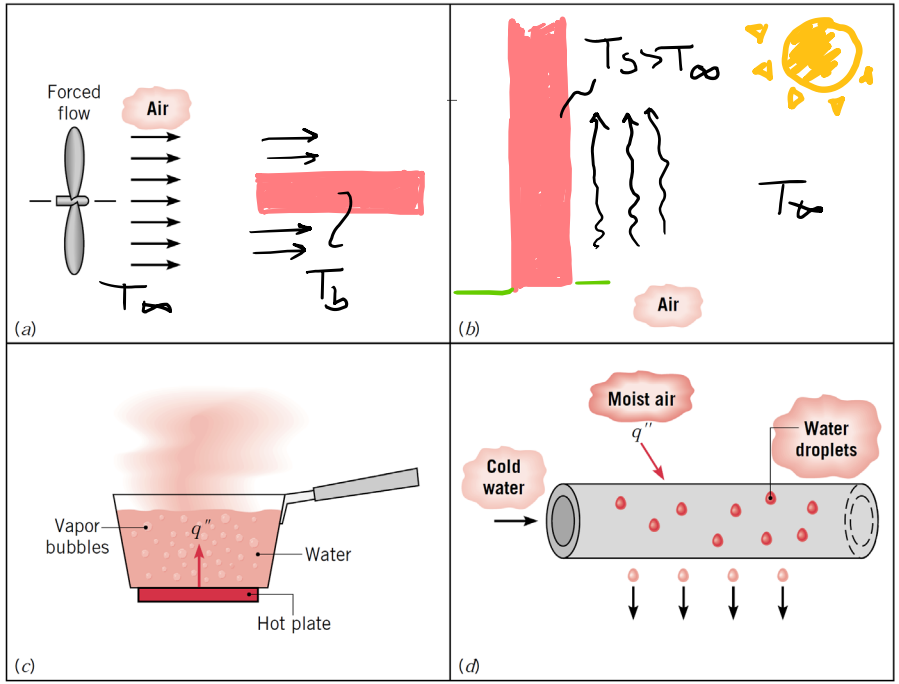
This Week

1. Forced Convection

2. Natural (Free) Convection

3. Boiling

4. Condensation



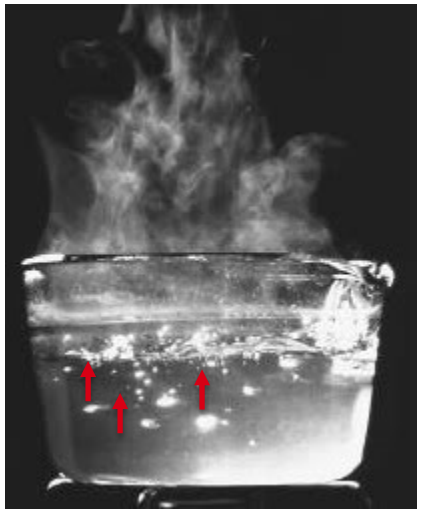
This Lecture

- ❑ Introduction to Boiling and Condensation
- ❑ Boiling Modes and Boiling Curves for Saturated Pool Boiling

Learning Objectives:

- ❑ Understand the fundamentals of boiling

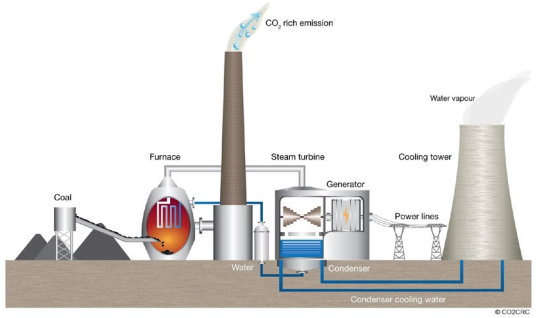
Introduction to Boiling and Condensation

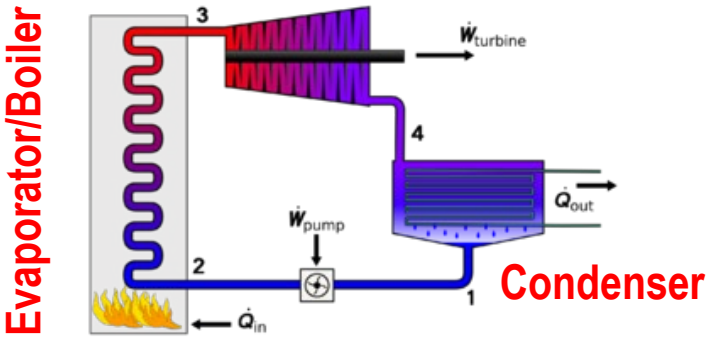


Boiling: heat transfer from the wall to the fluid

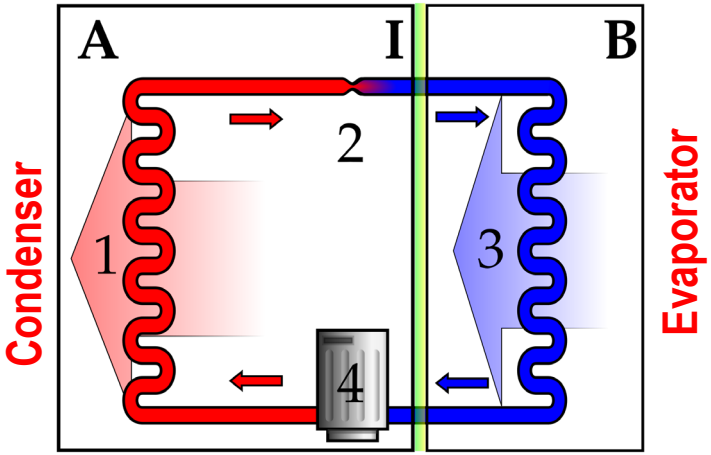
Condensation: heat transfer from the fluid to the wall

Introduction to Boiling and Condensation



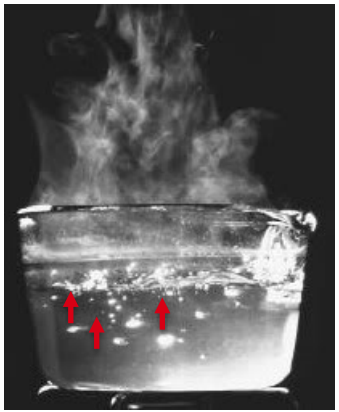


Closed-loop power cycles



Refrigeration Cycle

Introduction to Boiling and Condensation



Boiling: heat transfer from the wall to the fluid

Condensation: heat transfer from the fluid to the wall

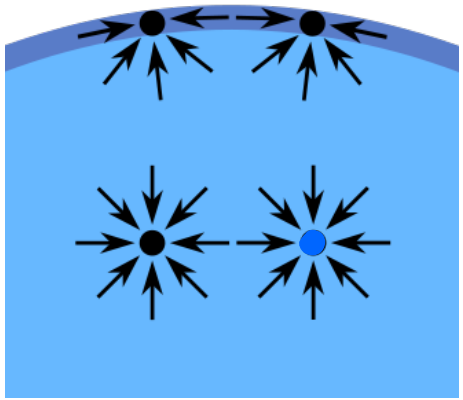
Phase Transition = Isothermal Process

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

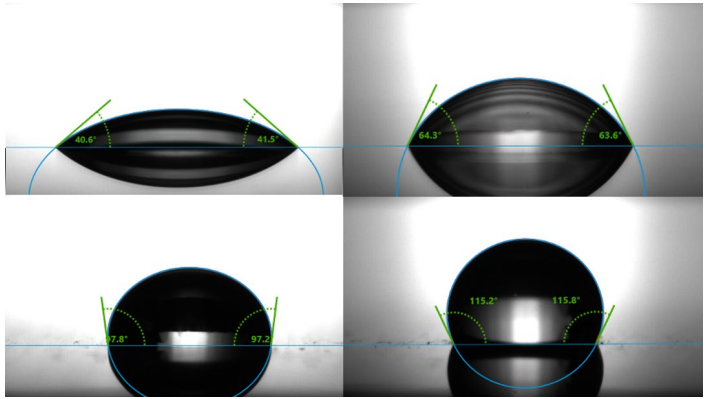
Small solid/fluid ΔT

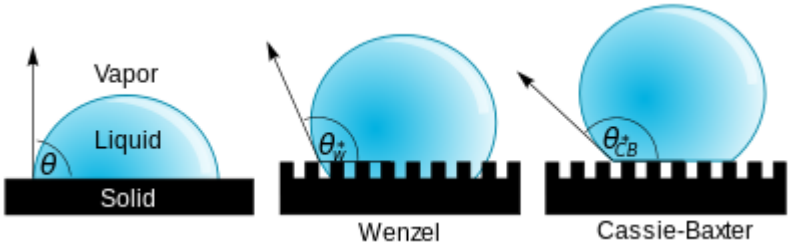
Introduction to Boiling and Condensation

Surface Tension

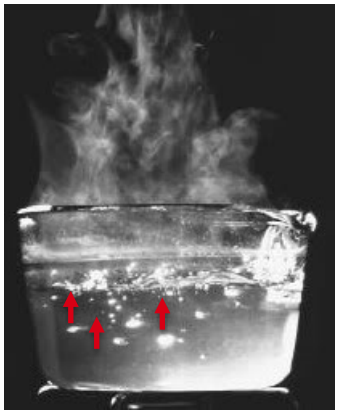


Hydrophobic and Hydrophilic surfaces





Introduction to Boiling and Condensation



Boiling: heat transfer from the wall to the fluid

Condensation: heat transfer from the fluid to the wall

Phase Transition = Isothermal Process

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

Small solid/fluid ΔT

This Lecture

Introduction to Boiling and Condensation

❑ Boiling Modes and Boiling Curves for Saturated Pool Boiling

Learning Objectives:

❑ Understand the fundamentals of boiling

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

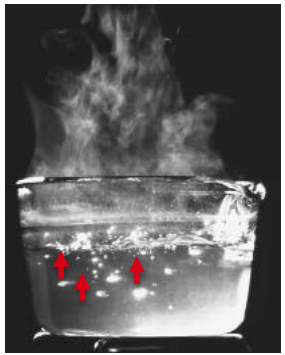
Forced boiling
the fluid is moving while it boils (e.g. inside a pipe)

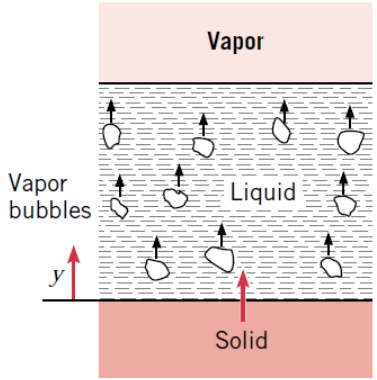
Heat Transfer

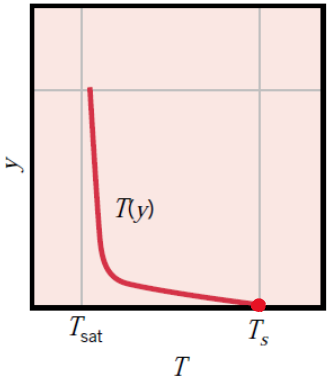
Saturated Boiling
$T_s > T_{sat}$, the bubble must rise

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

Saturated Pool Boiling







Bubbles rise to the surface

High liquid temperature only locally, close to the wall

Fluid Dynamics

What "flow" conditions do we encounter?

Going beyond laminar/turbulent

Heat Transfer

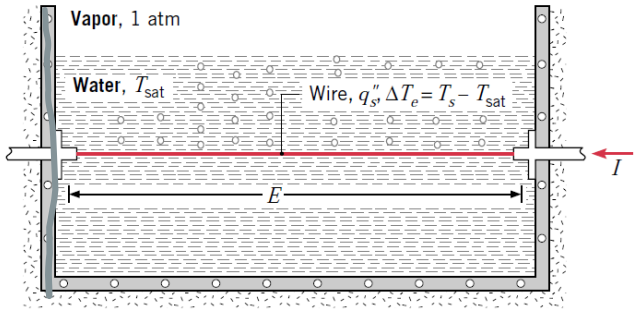
What is the wall/fluid temperature difference?

How much heat flux do we have?

What is the convection coefficient?

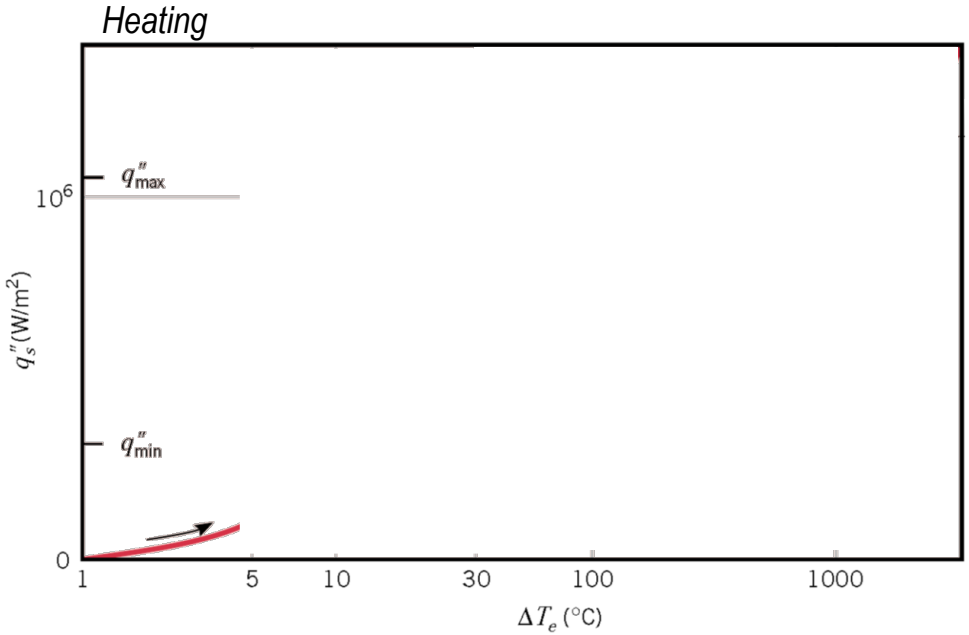
Saturated Pool Boiling

The complexity of the boiling phenomenon is shown by the boiling curve.



Power-controlled heating

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



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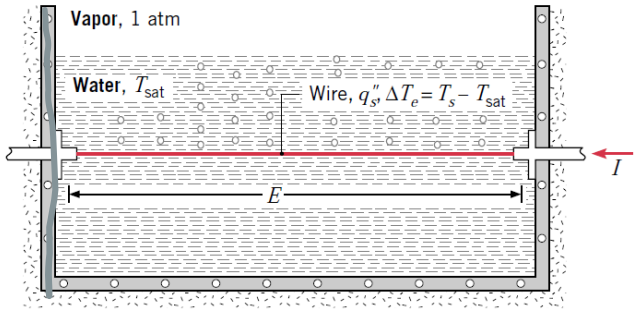

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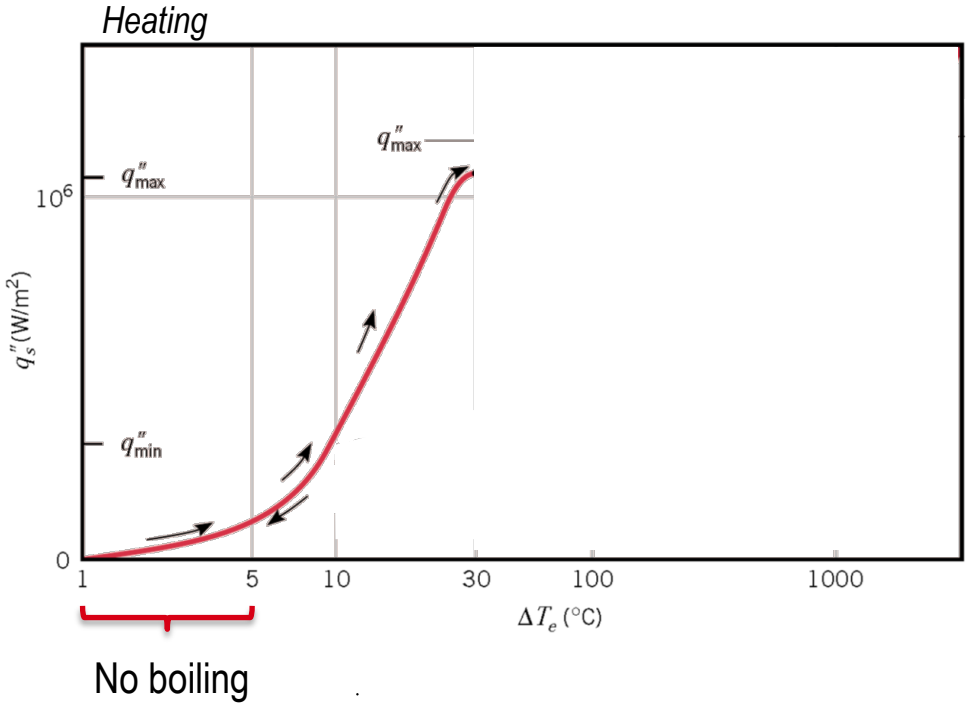

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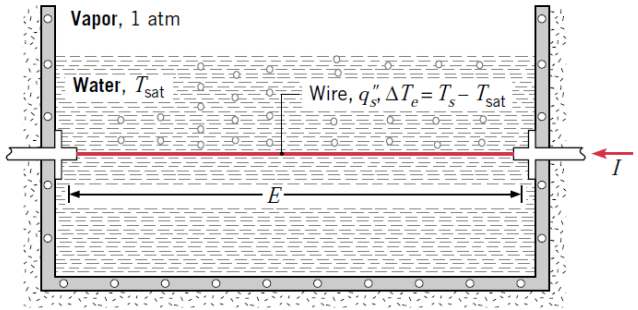

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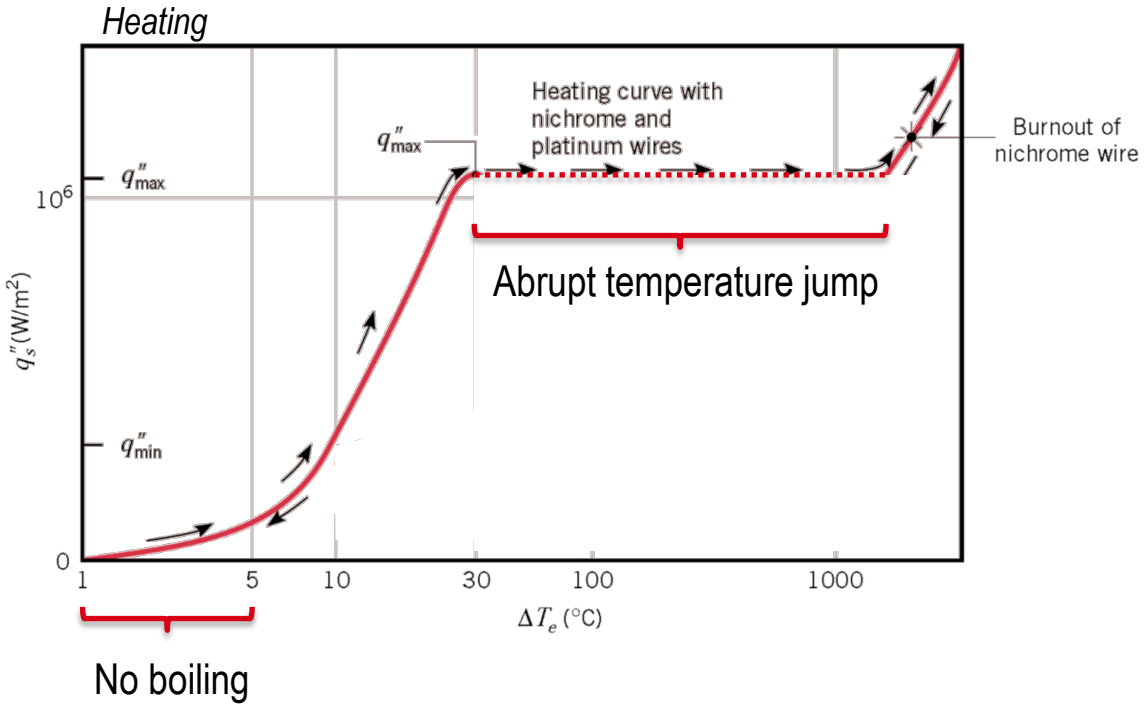

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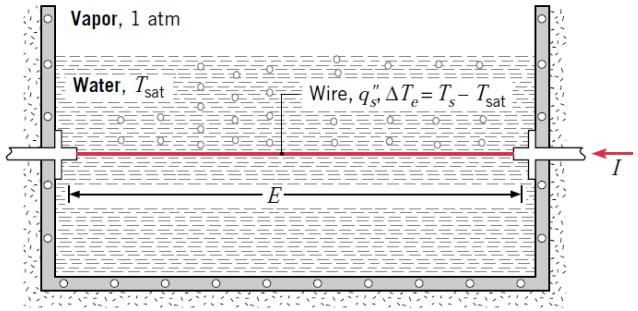

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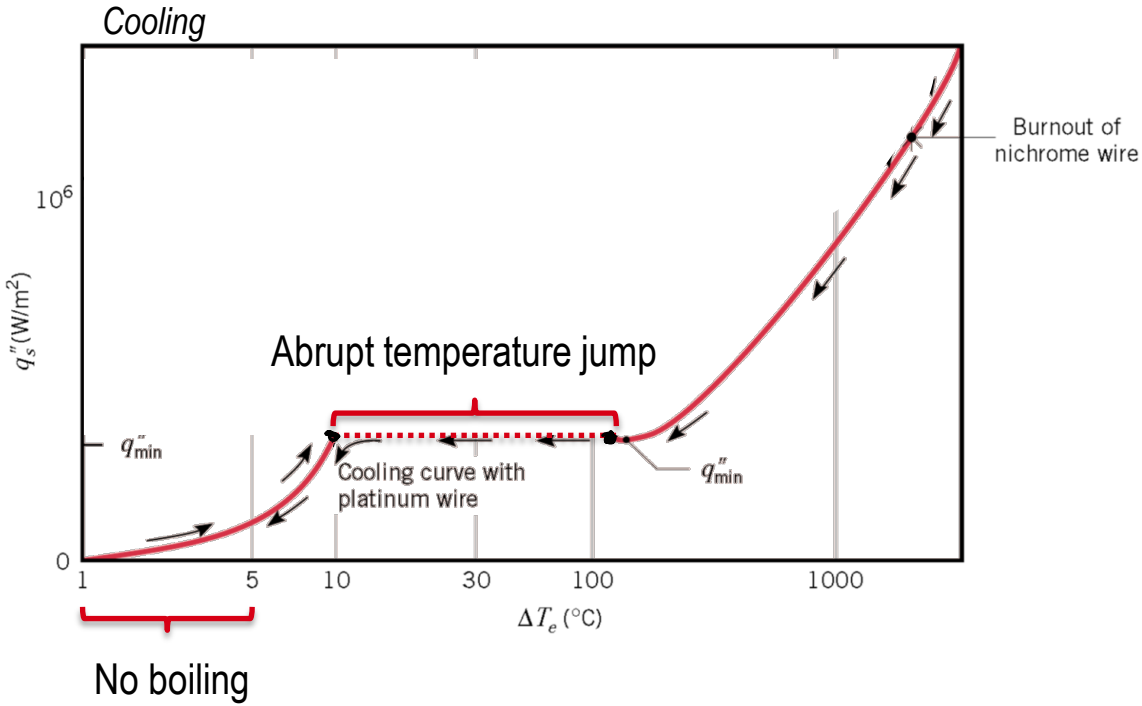

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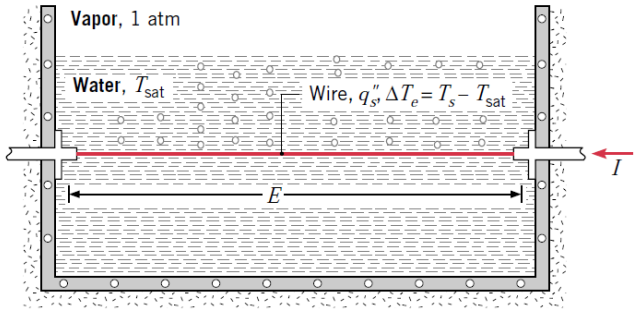
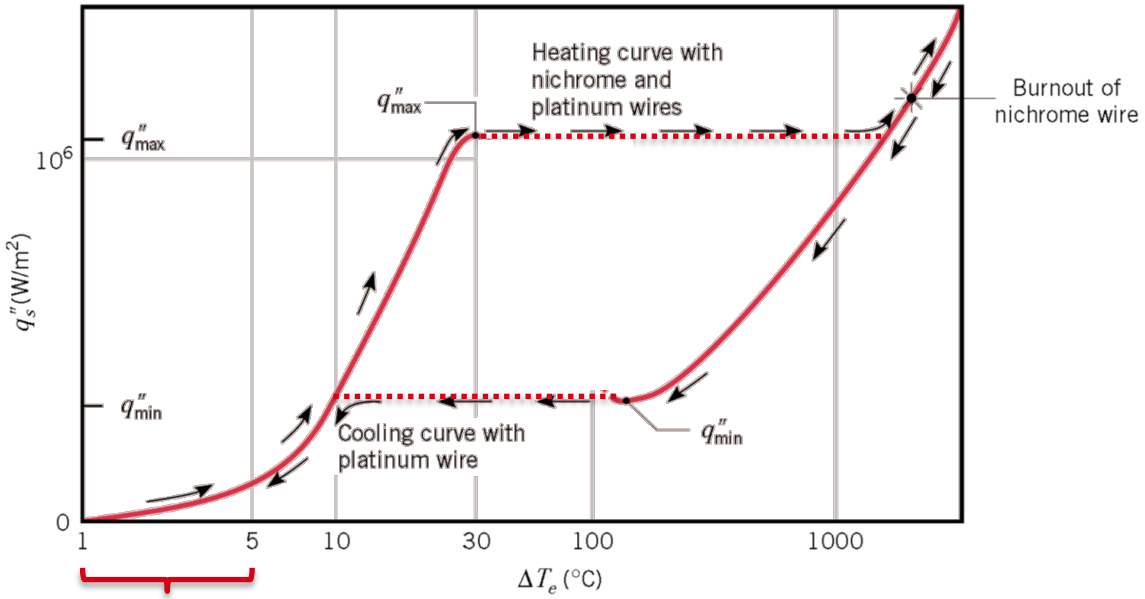


Power-controlled heating

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

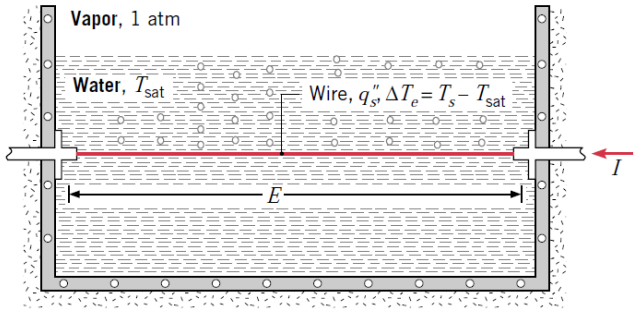
Boiling curve under power-controlled heating/cooling



No boiling

Saturated Pool Boiling

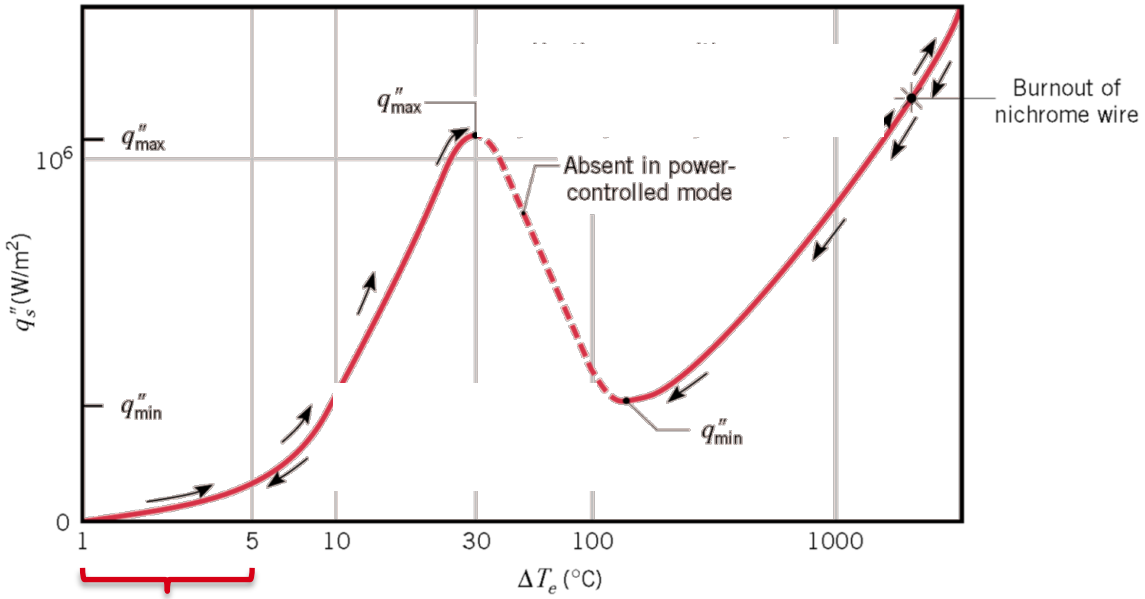
The complexity of the boiling phenomenon is shown by the boiling curve.



Temperature-controlled heating

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

Boiling curve under temperature-controlled heating/cooling

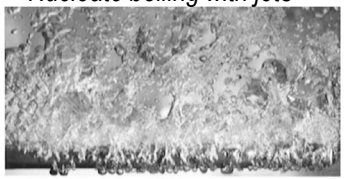


No boiling

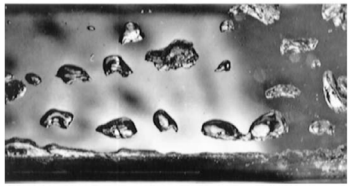
Saturated Pool Boiling

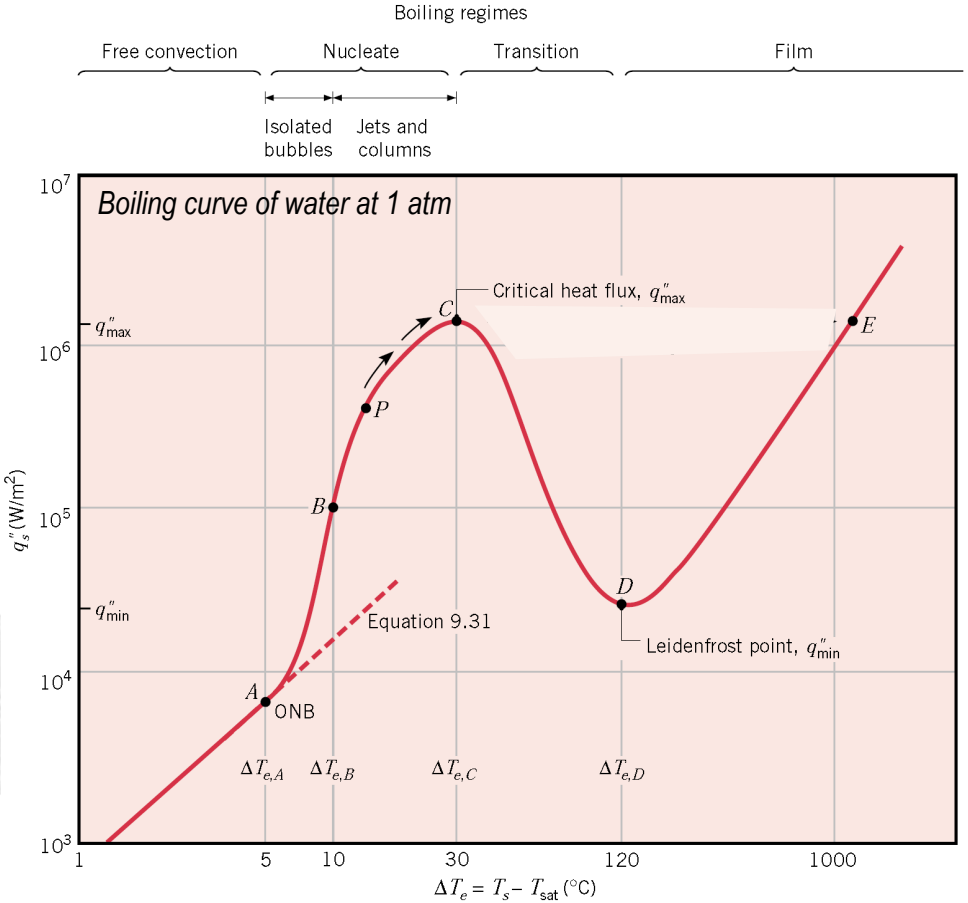
$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e$$

Nucleate boiling with jets



Film boiling





A: Onset Nucleate Boiling

A->B : Isolated bubble nucleate on the surface

B->C : more and more nucleation sites become active and jet pattern emerge

P : maximum convection coefficient point

B->P both h and ΔT_e increase

P->C ΔT_e increase but h decreases

C : maximum (critical) heat flux

C->D : large areas are covered by a film and h drops significantly due to the lower thermal conductivity of vapor compared to liquid.

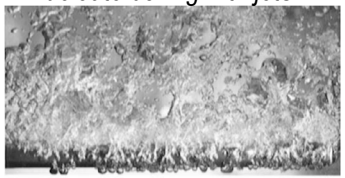
D: minimum heat flux – a complete film of vapor covers the surface

Past D: increase in surface temperature drives an increase in the heat flux across the vapor film.

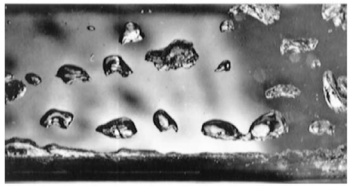
Saturated Pool Boiling

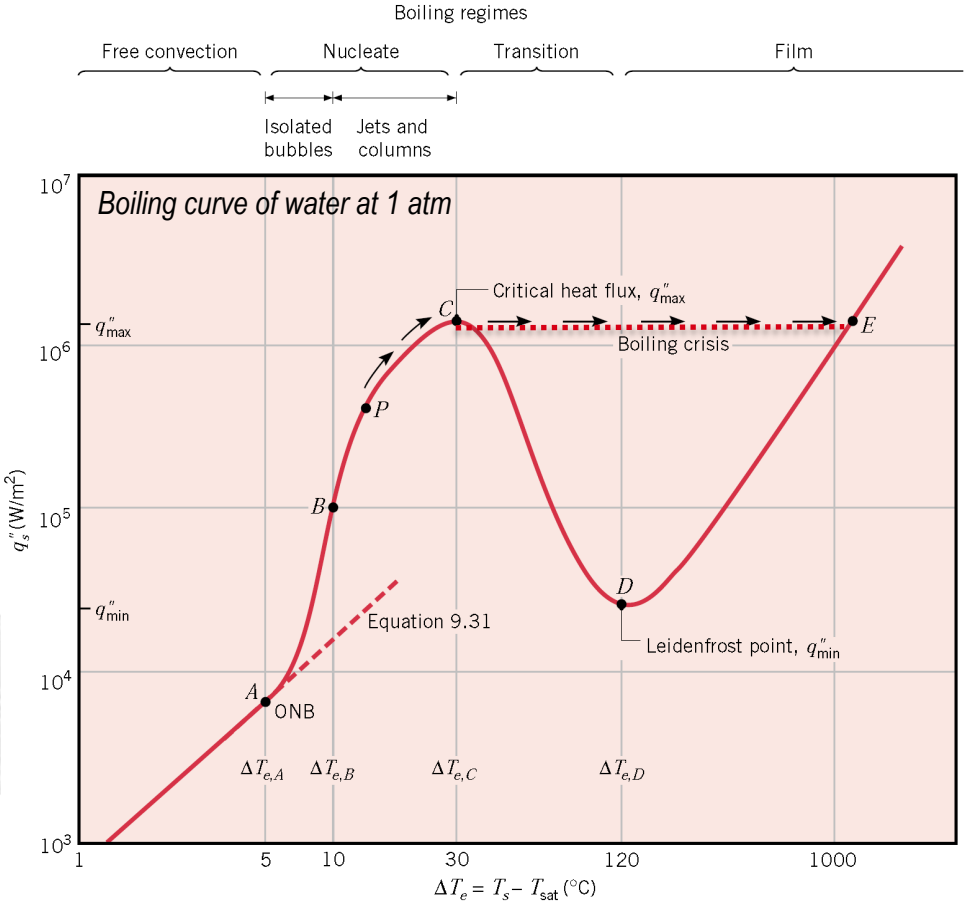
$$q_s'' = h(T_s - T_{sat}) = h\Delta T_e$$

Nucleate boiling with jets



Film boiling



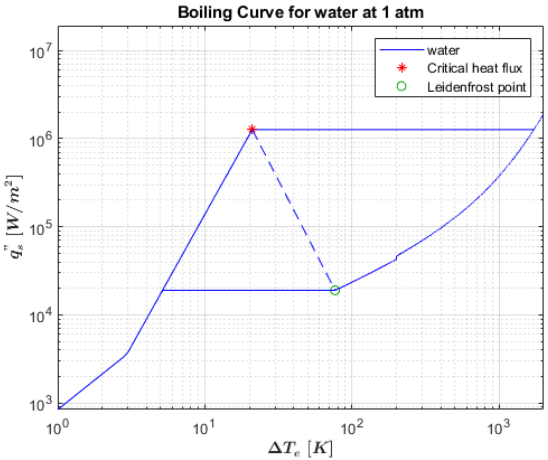


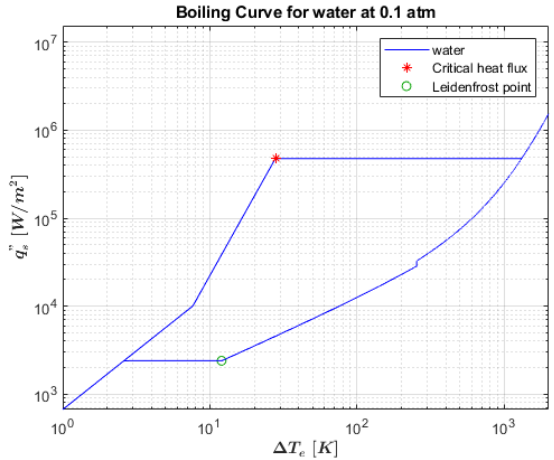
The solid curve is followed when we control ΔT_e. However in most applications we control q_s''. In such a case (as in the previous experiment) we observe:

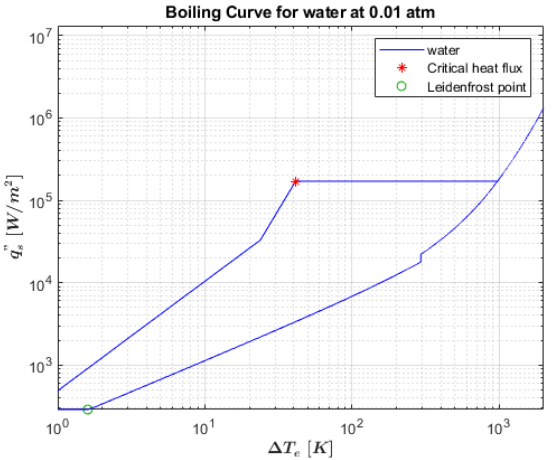
C->E : boiling crisis - past the critical heat flux a film of vapor rapidly replaces isolated bubbles. The thermal conductivity of the vapor film is much less than that of the liquid and the surface temperature suddenly increases to much higher values

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.

A Few Saturated Boiling Curves







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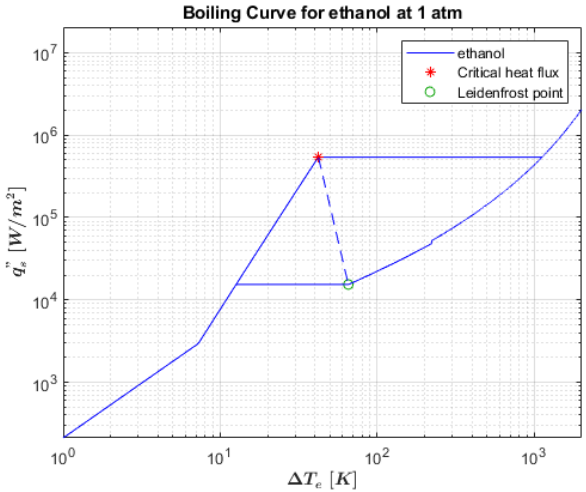
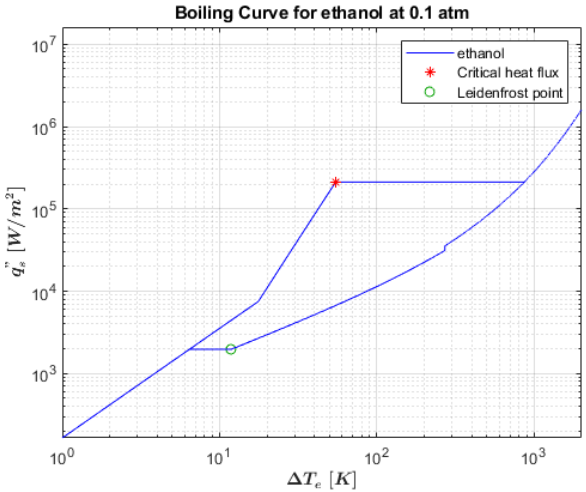
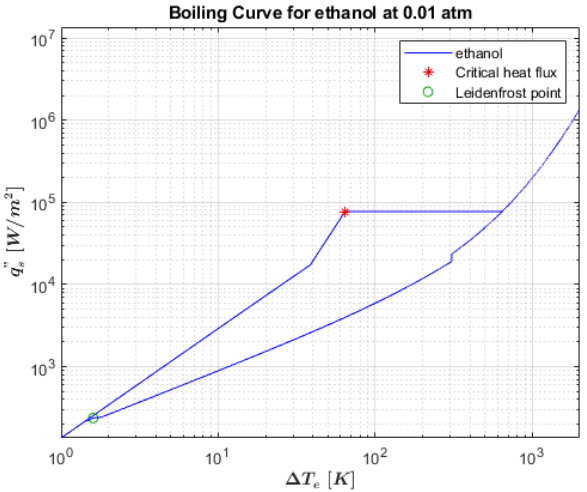
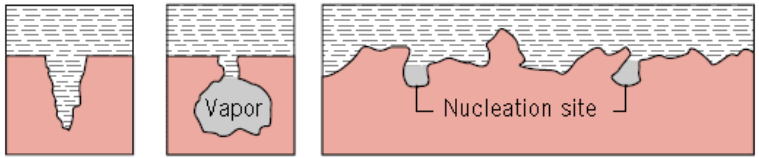
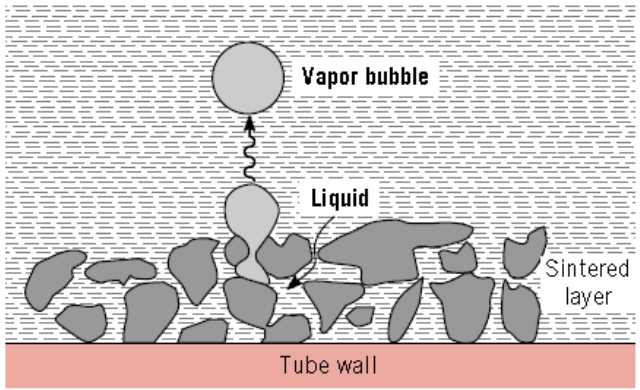


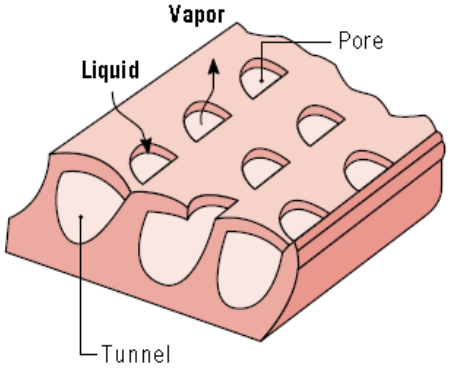




Saturated Pool Boiling – Some Observations







This Lecture

- ☑ Introduction to Boiling and Condensation
- ☑ Boiling Modes and Boiling Curves for Saturated Pool Boiling

Learning Objectives:

- ☑ Understand the fundamentals of boiling

Next Lecture

- Correlations for Nucleate and Film Pool Boiling

Learning Objectives:

- Calculate heat flux and temperature difference during boiling