Boiling Heat Transfer

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Introduction

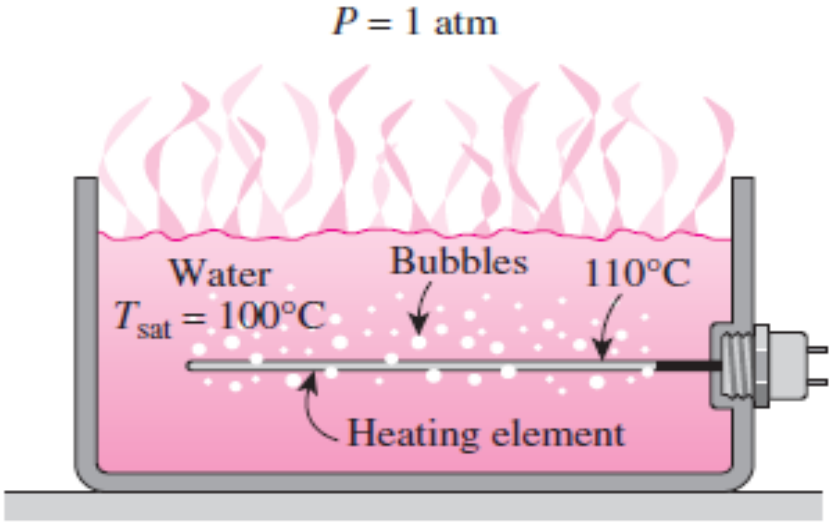
- In LWRs, boiling is the mechanism of carrying away heat to be converted into mechanical work in the steam turbine.
- Good boiling characteristics has to be maintained.
- However, boiling crisis must be avoided to prevent catastrophe.
- If thermal crisis occurs, the cladding will fail and fission products will be released.

Objectives

- To introduce the importance of boiling heat transfer.
- To introduce terms used in boiling heat transfer.
- To understand the classification and phenomena of boiling.
- To understand the boiling curve
- To introduce some correlations applicable to boiling.
- To understand the importance of boiling crisis in LWR.
- To introduce some elements of two phase flow.

Boiling

- Occurs at the *solid–liquid interface* when a liquid is brought into contact with a surface maintained at a temperature sufficiently above the saturation temperature of the liquid.



Boiling heat flux from a solid surface to the fluid

Newton's Law of Cooling

$$q''_{boiling} = h(T_s - T_{sat}) = h\Delta T_{excess}$$

$\Delta T_{excess} = T_s - T_{sat}$ = Excess temperature

T_s = Temperature of heating surface

T_{sat} = Saturation temp of liquid

h = convective heat transfer coefficient.

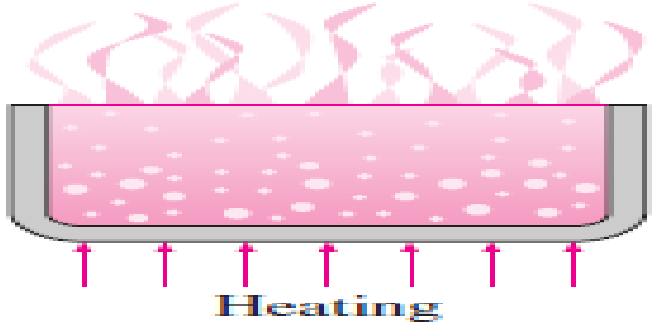
Classification of Boiling

1) Based on Bulk Fluid Motion
   a. Pool Boiling
   b. Flow Boiling

2) Based on Bulk liquid temperature
   a. Sub-cooled Boiling
   b. Saturated Boiling

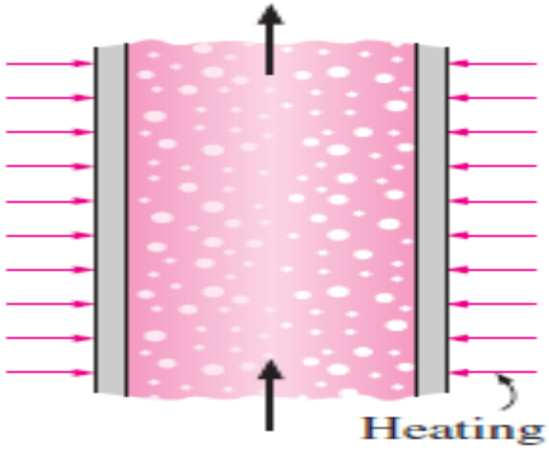
Pool Boiling

- Boiling in absence of bulk fluid flow
- Fluid body is stationary
- Any possible fluid motion will be due to natural convection currents
- E.g. boiling of water in a pan on stove



Flow Boiling/Forced Convection Boiling

- Boiling in presence of bulk fluid flow
- Fluid is forced to flow in a heated pipe or over a surface by pump etc
- Convection effects will be present

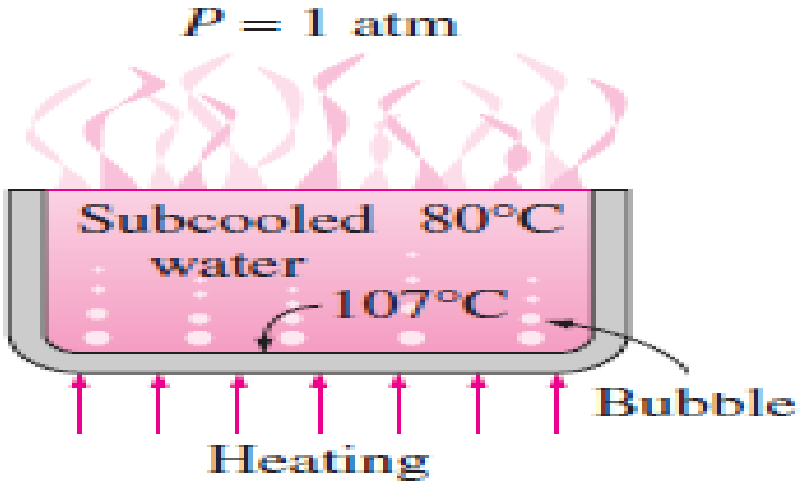


Sub-cooled Boiling

- Boiling is sub-cooled if temperature of main body of fluid is below the saturation temp T_{sat} (i.e. bulk of liquid is sub-cooled)
- It occurs at early stages of boiling
- Bubbles formation and disappearance near hot surface
- Bubbles disappear as they transfer heat to surrounding sub-cooled liquid
- Boiling is confined to locality of hot surface so also called local boiling

Contd…

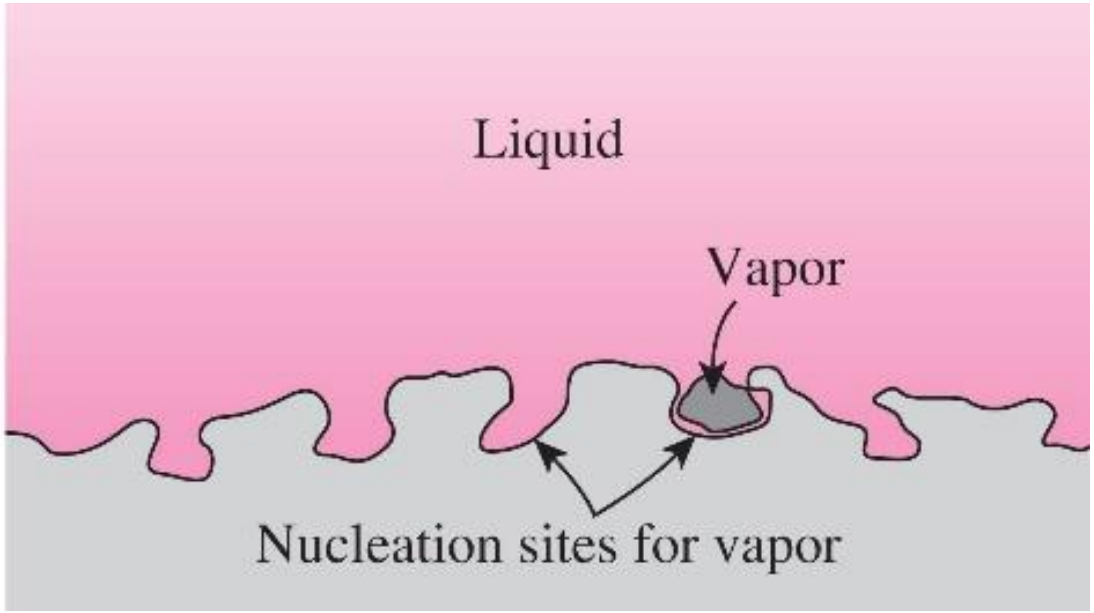
- Bubbles serve as energy movers and transfer heat to fluid by condensing

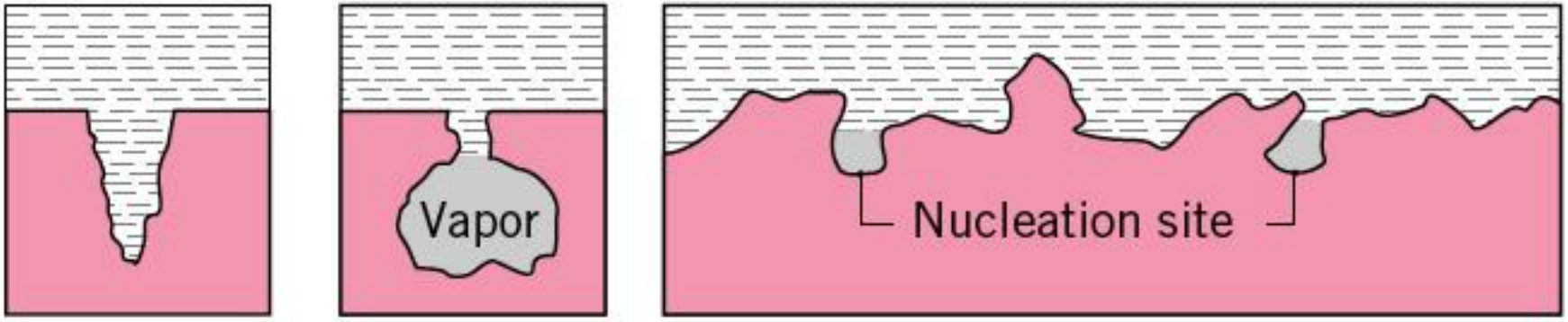


Inception of Boiling

- Boiling starts with
  - Temperature > Tsat
  - Nucleation sites
- Without nucleation sites, liquid can be superheated beyond Tsat (metastable state)

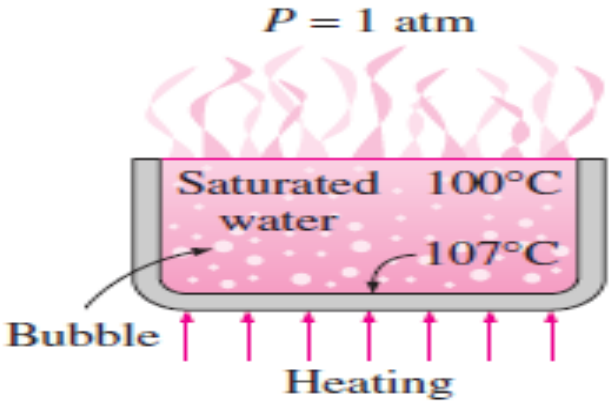
Nucleation Sites





Saturated/Bulk Boiling

- Boiling is saturated if temperature of main body of fluid is equal to the saturation temp T_{sat} (i.e. bulk of liquid is saturated)
- It occurs when entire liquid body reaches saturation temperature
- Bubbles rise to the top



Boiling Curve for Pool Boiling

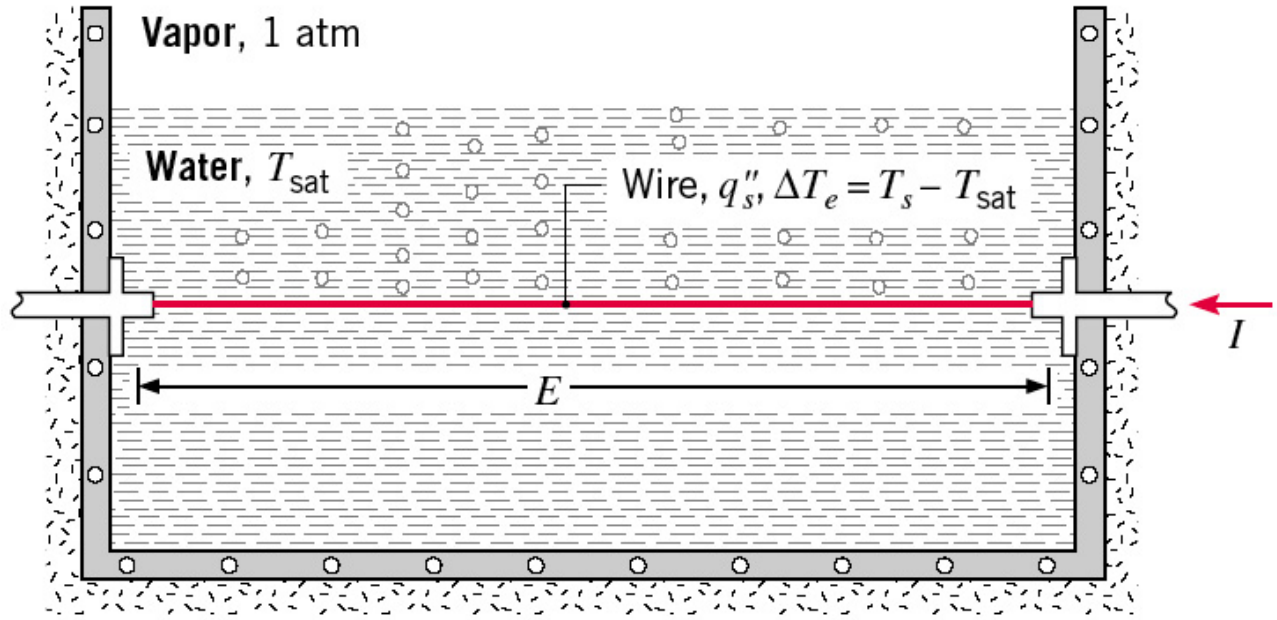
Four regimes/phases of pool boiling with change in excess temperature :

1. Natural Convection Boiling
2. Nucleate Boiling
3. Transition Boiling
4. Film Boiling

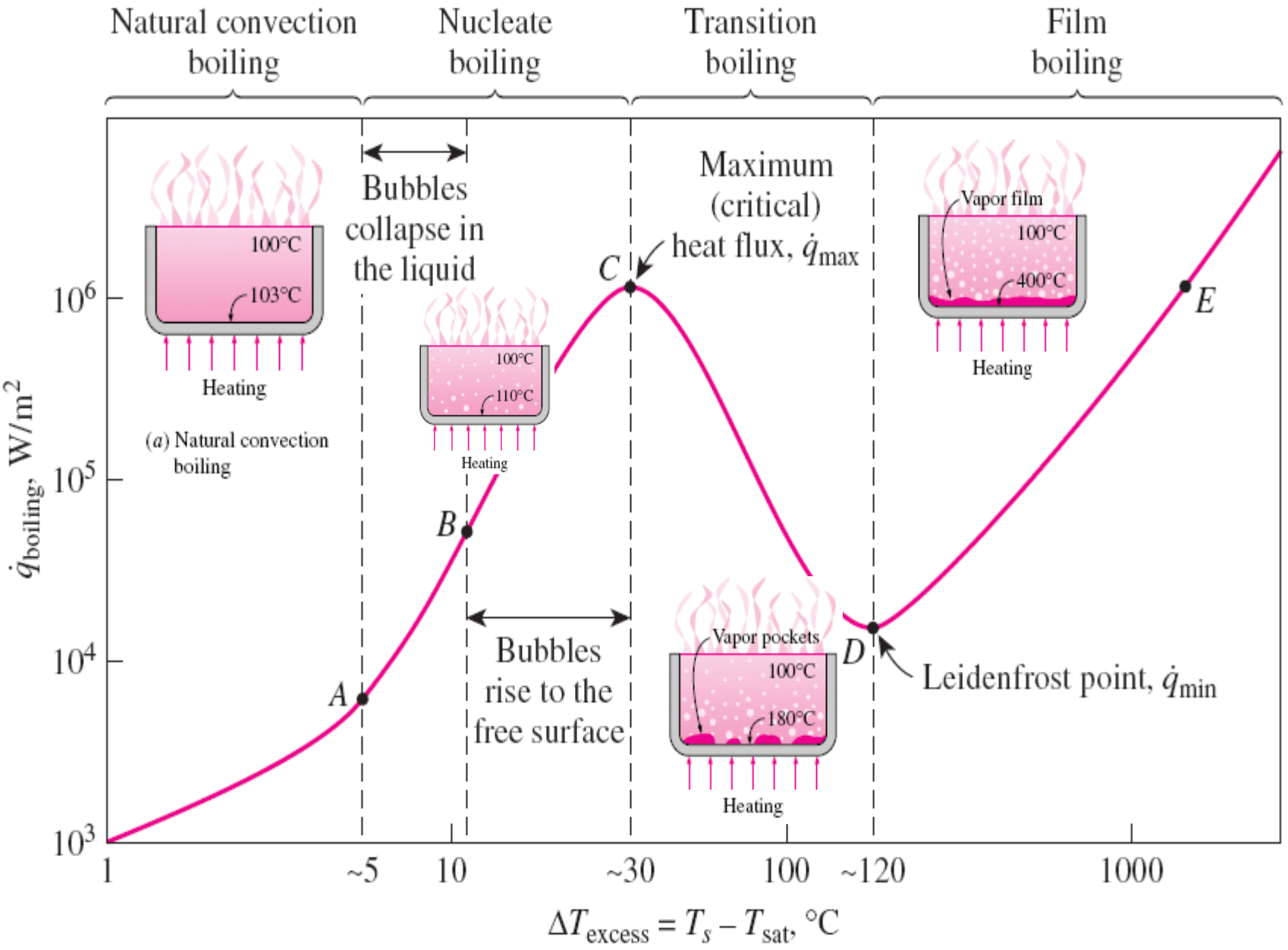
Boiling Curve

Nukiyama's Experiment (1934)

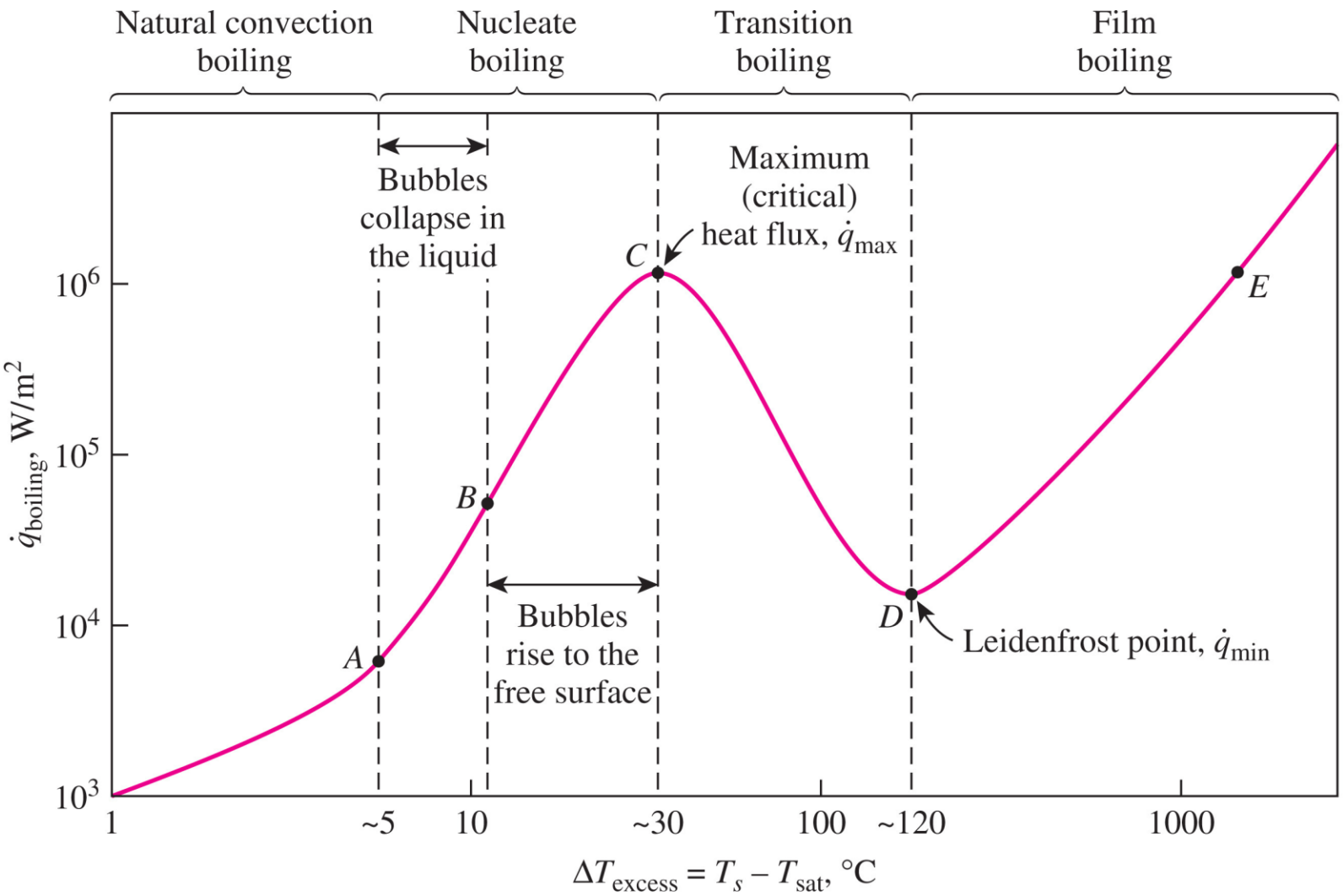
Used electrically heated nichrome and platinum wires immersed in liquids in his experiments. Nukiyama noticed that boiling takes different forms, depending on the value of the excess temperature Δ*Texcess*



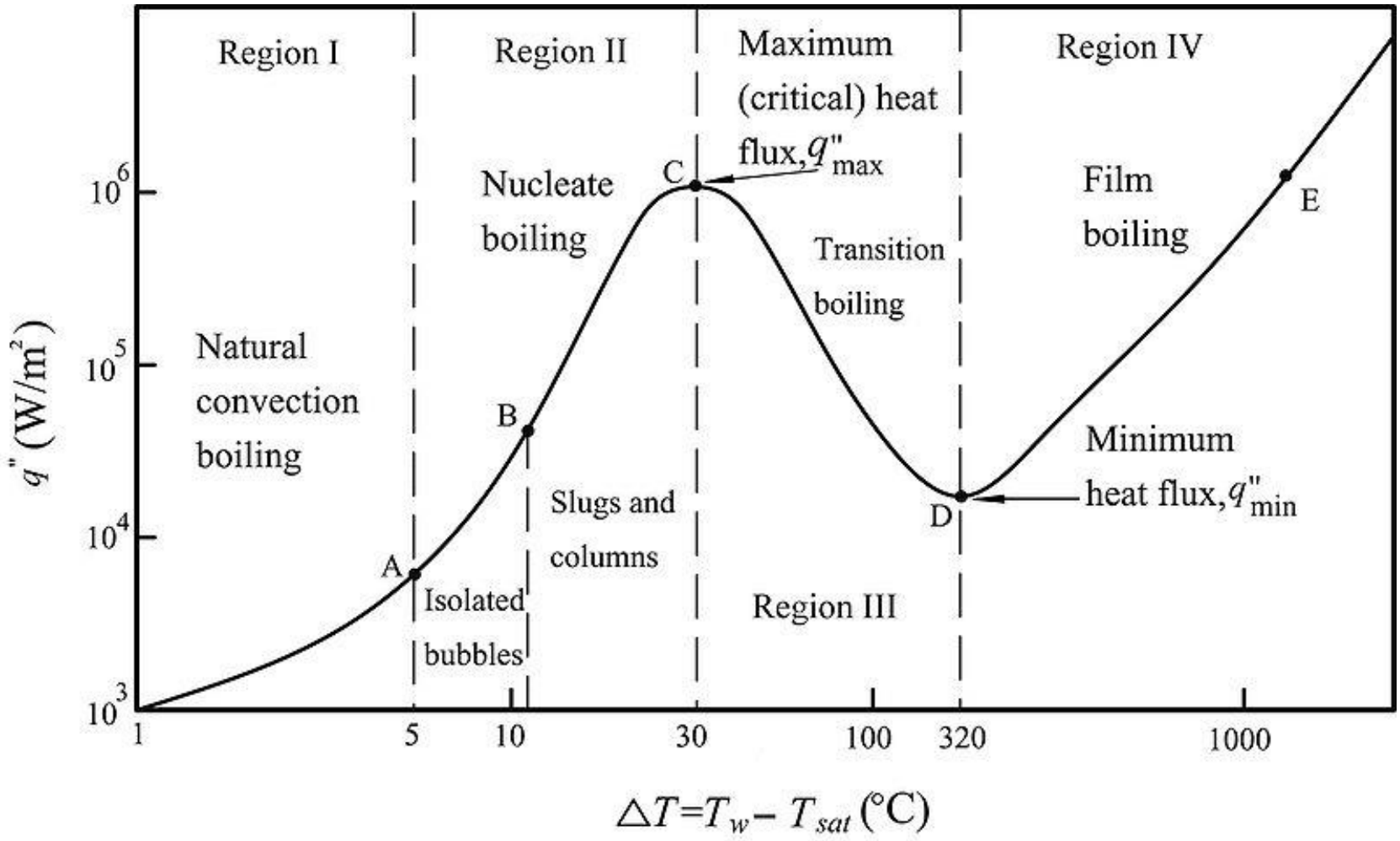
Boiling curve



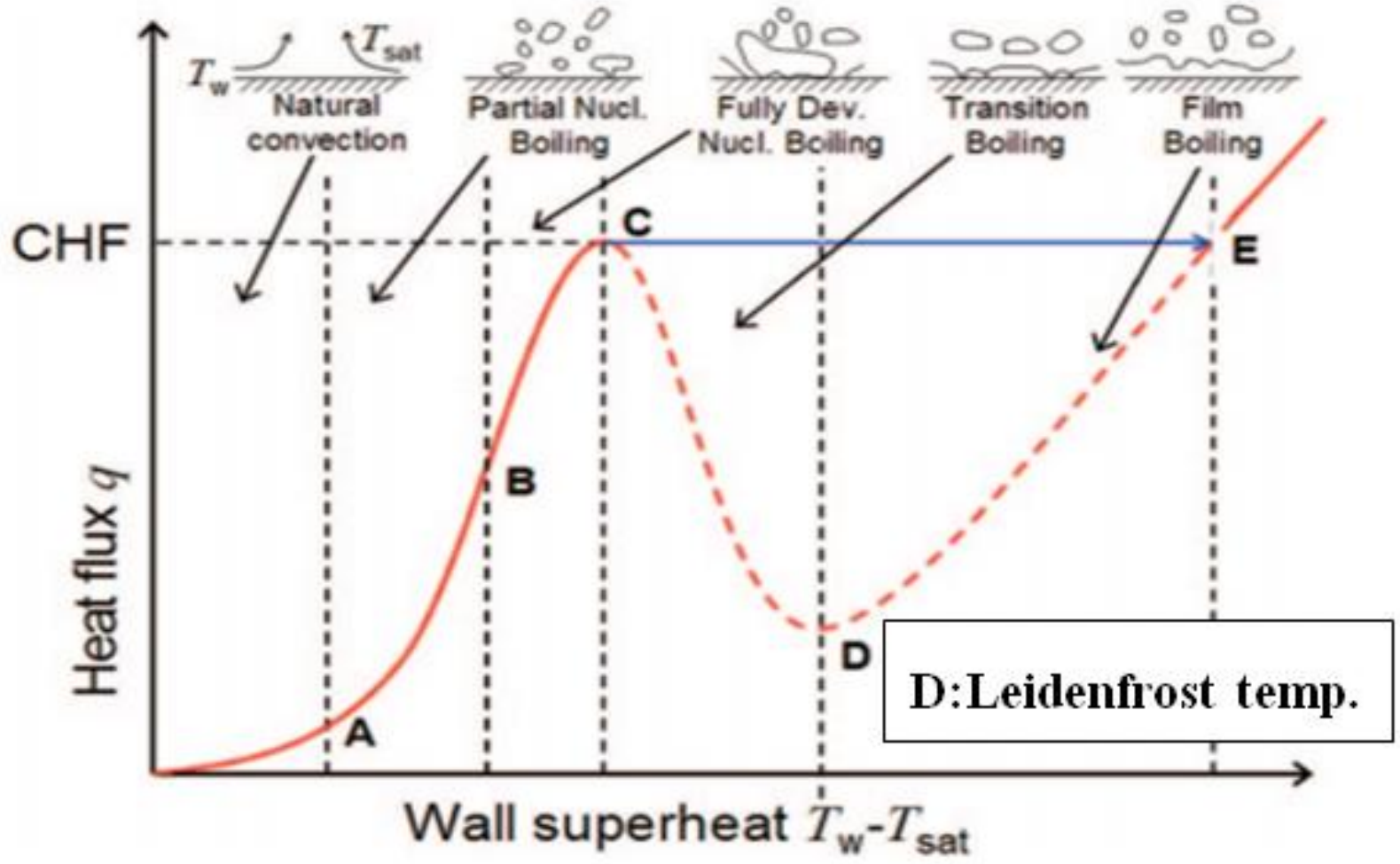
Boiling Curve



Boiling Curve



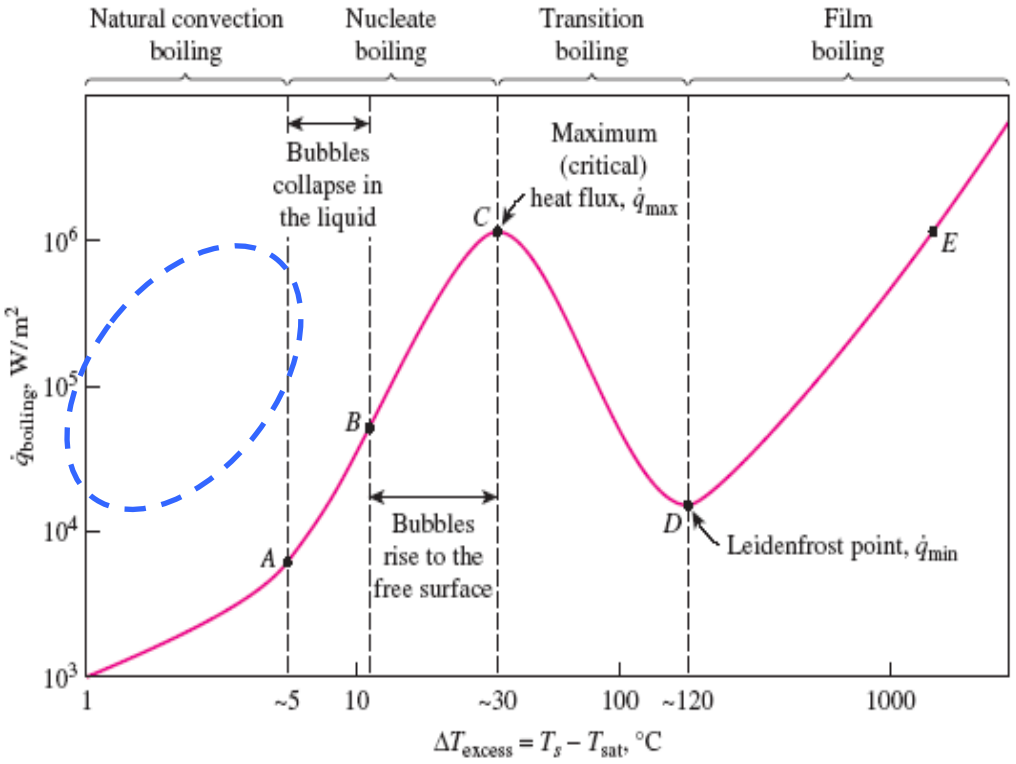
Boiling Curve



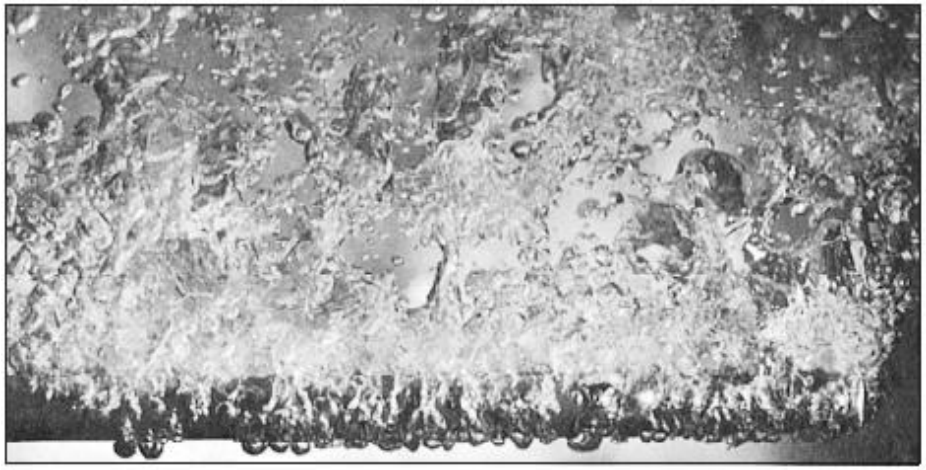
Natural Convection Boiling
(to Point *A* on the Boiling Curve)

- Bubbles do not form on the heating surface until the liquid is heated a few degrees above the saturation temperature (about 2 to 6°C for water)
- The liquid is slightly *superheated* in this case (*metastable* state).
- The fluid motion in this mode of boiling is governed by natural convection currents.

- Heat transfer from the heating surface to the fluid is by natural convection.
- The natural convection boiling ends at an excess temperature of about 5°C.



Nucleate Boiling (between Points A and C)



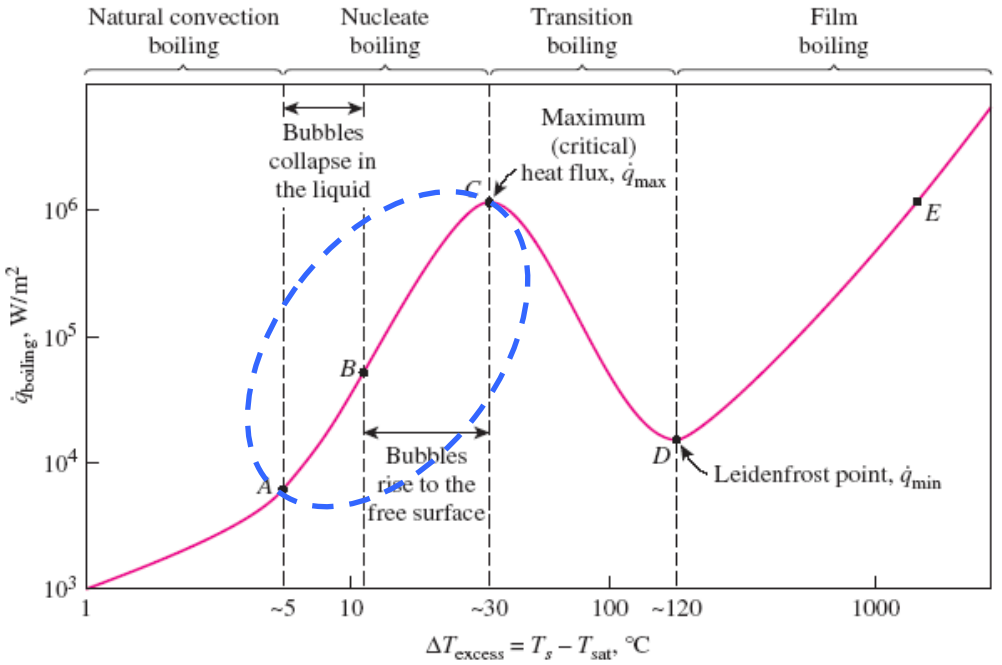
- The bubbles form at an increasing rate at an increasing number of nucleation sites as we move along the boiling curve toward point *C*.

- Region *A–B – isolated bubbles.*

$$(5°C \leq \Delta T_{excess} \leq 10°C)$$

- Region *B–C* – numerous *continuous columns of vapor* in the liquid.

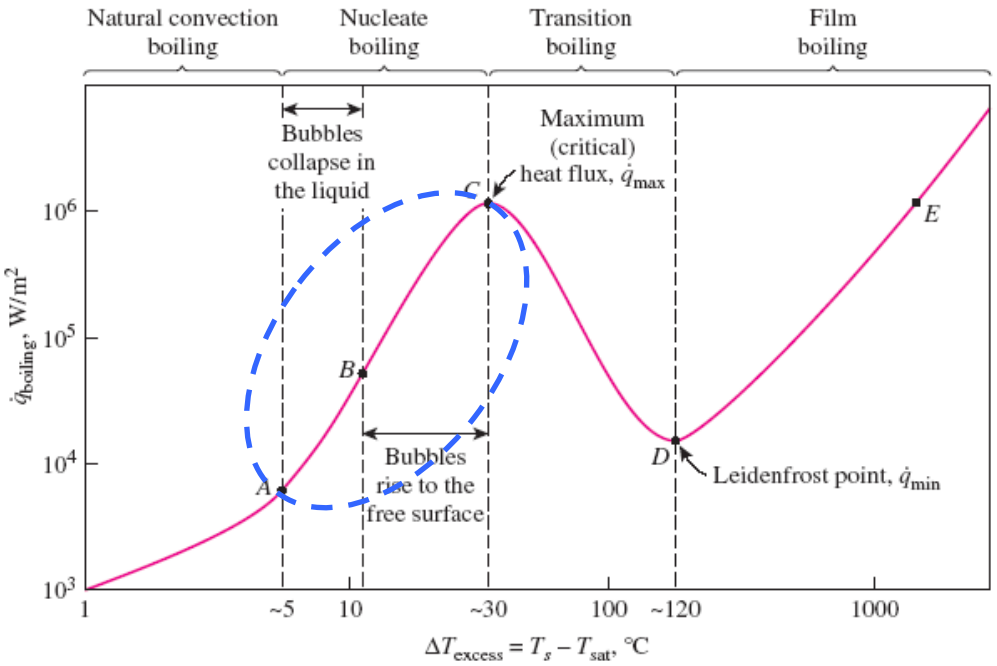
$$(10°C \leq \Delta T_{excess} \leq 30°C)$$



Point *A* is referred to as the *onset of nucleate boiling (ONB)*.

- In region *A–B* the stirring and agitation caused by the entrainment of the liquid to the heater surface is primarily responsible for the increased heat transfer coefficient.
- In region *A–B* the large heat fluxes obtainable in this region are caused by the combined effect of liquid entrainment and evaporation.
- For the entire nucleate boiling range, the heat transfer coefficient ranges from about 2000 to 30,000 W/m^2·K.

- After point *B* the heat flux increases at a lower rate with increasing ΔT_{excess}, and reaches a maximum at point *C*.
- The heat flux at this point is called the critical (or maximum) heat flux, and is of prime engineering importance.

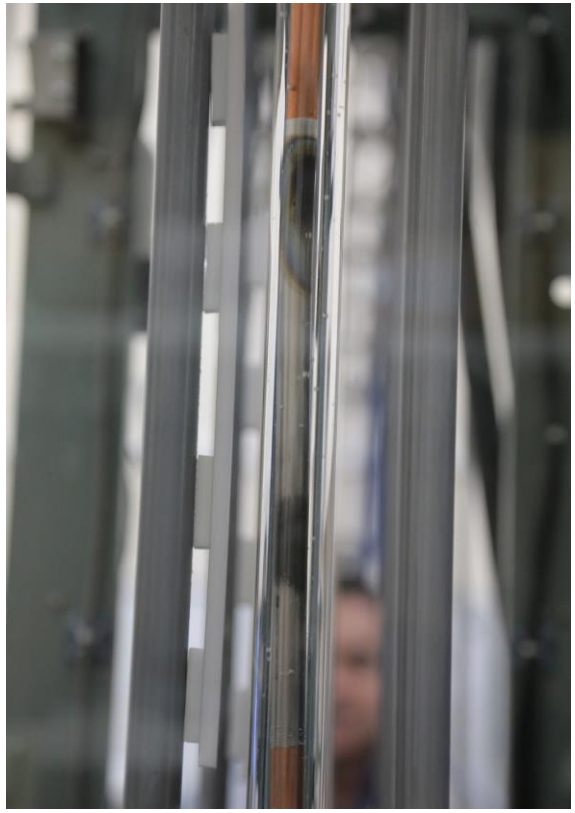


Boiling Crisis

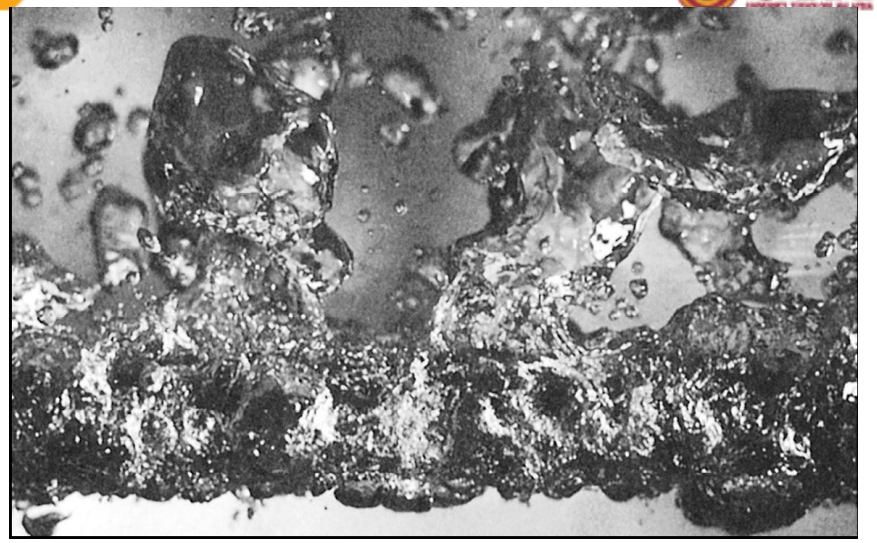
A variety of names for Point C

- Burnout point
- Peak heat flux
- Boiling crisis (Russian)
- DNB — Departure from Nucleate Boiling
- CHF — Critical Heat Flux
- Boiling Transition (BT)

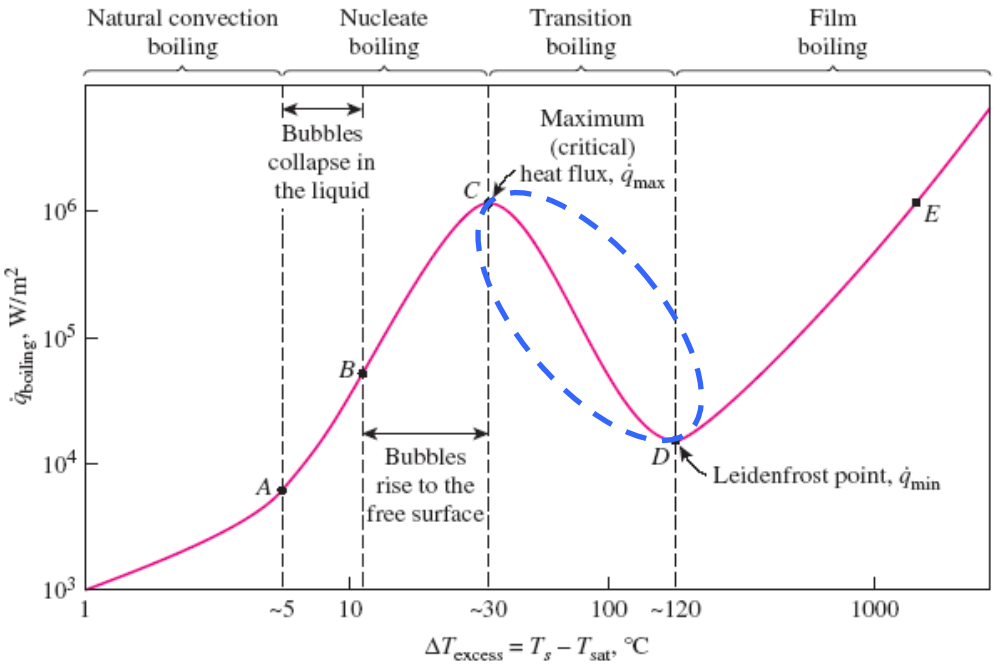
Burnout Phenomenon



Transition Boiling (between Points C and D)

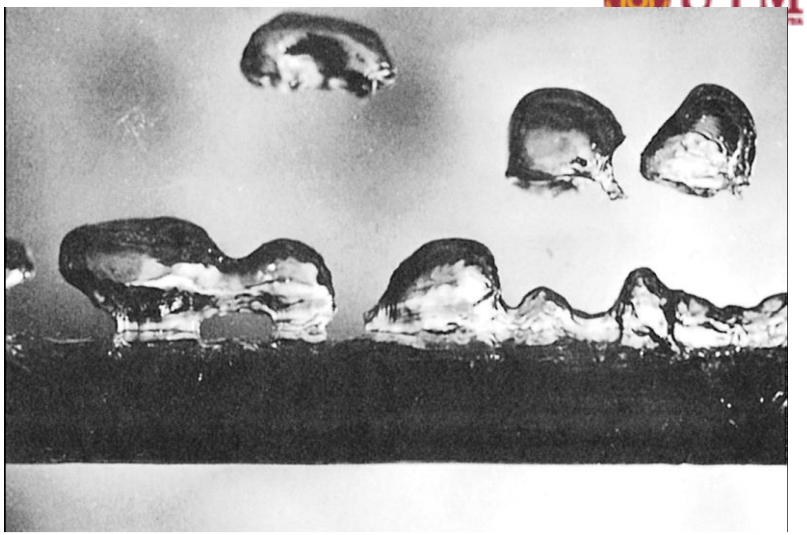


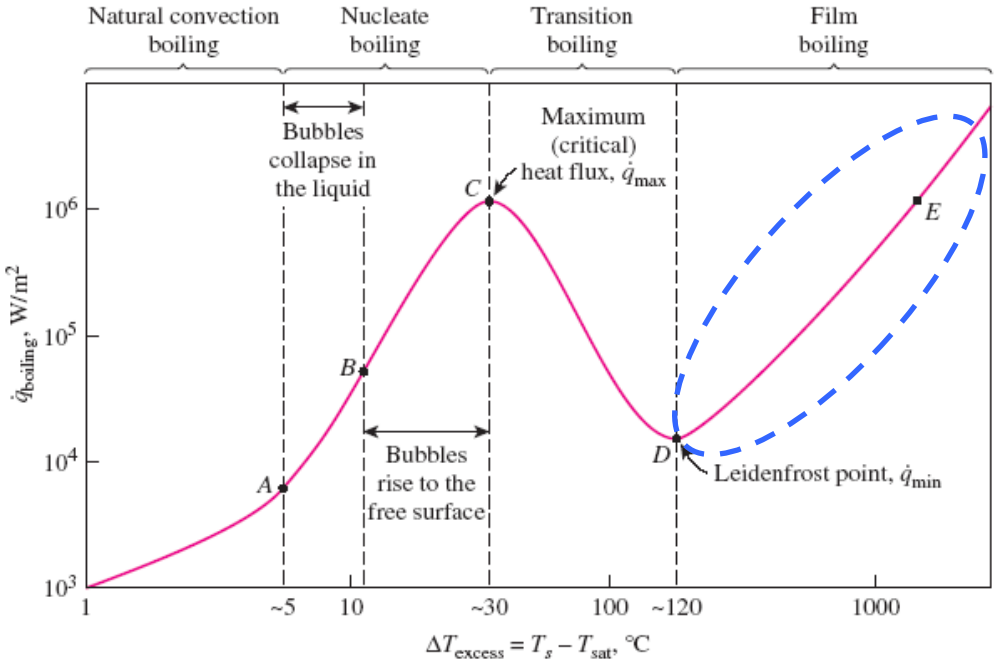
- When ΔT_{excess} is increased past point *C*, the heat flux decreases.
- This is because a large fraction of the heater surface is covered by a vapor film, which acts as an insulation.
- In the transition boiling regime, both nucleate and film boiling partially occur.
- Operation in the transition boiling regime, which is also called the *unstable film boiling regime,* is avoided in practice.
- For water, transition boiling occurs over the excess temperature range from about 30°C to about 120°C.



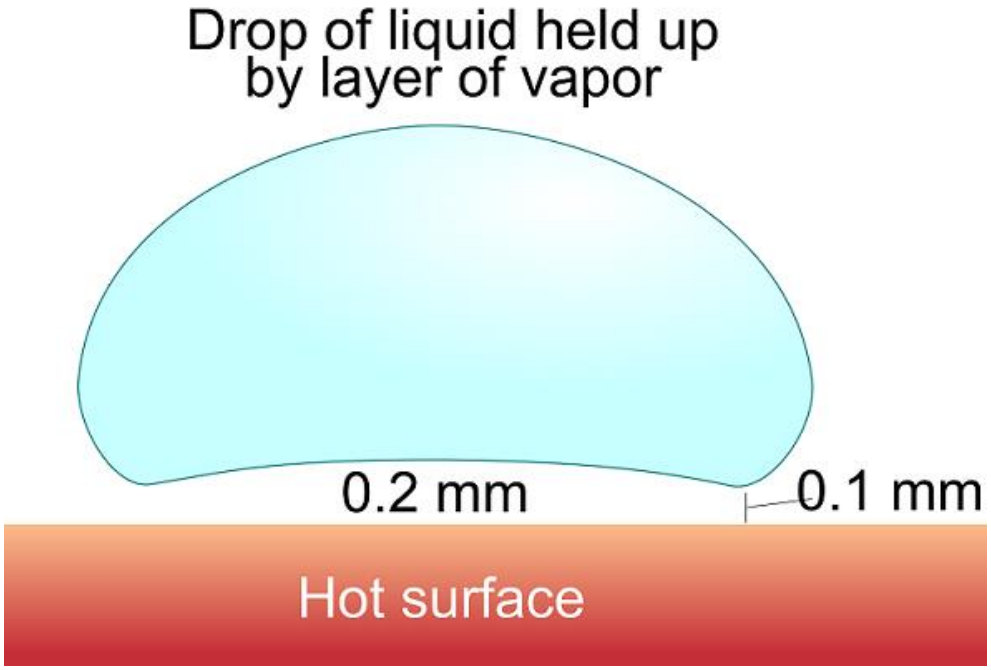
Film Boiling (beyond Point *D*)

- Beyond point *D* the heater surface is completely covered by a continuous stable vapor film.
- Point *D*, where the heat flux reaches a minimum is called the **Leidenfrost point**.
- The presence of a vapor film between the heater surface and the liquid is responsible for the low heat transfer rates in the film boiling region.
- The heat transfer rate increases with increasing excess temperature due to radiation to the liquid.

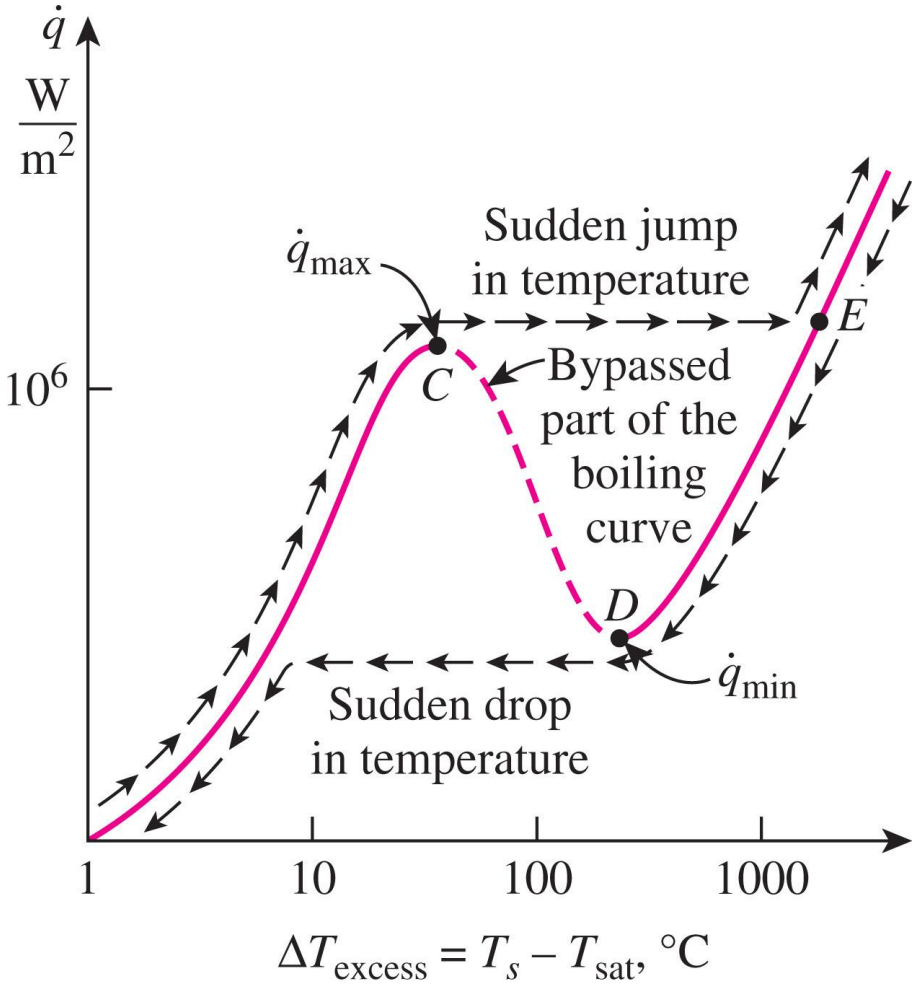




Leidenfrost Effect

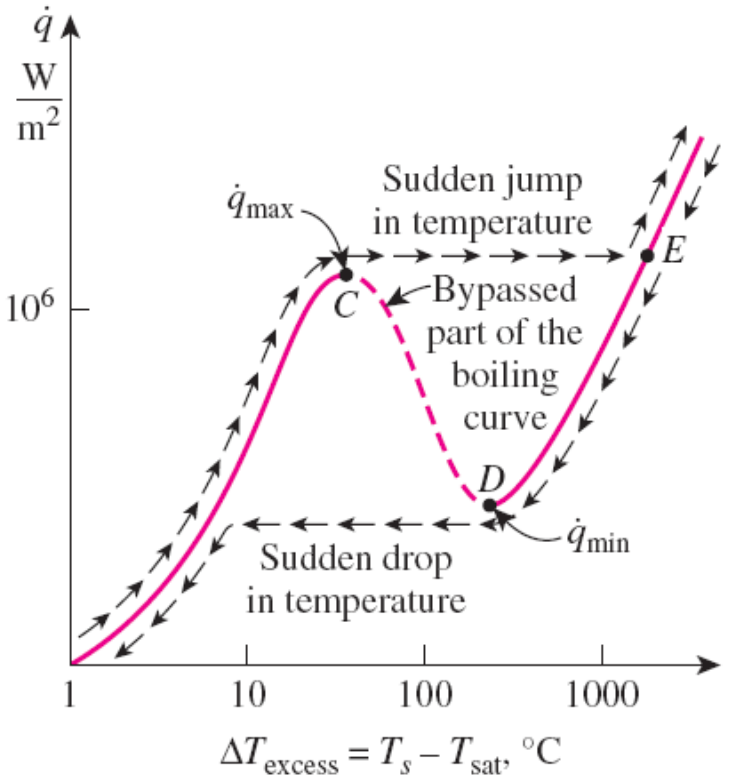


Boiling Curve Hysteresis



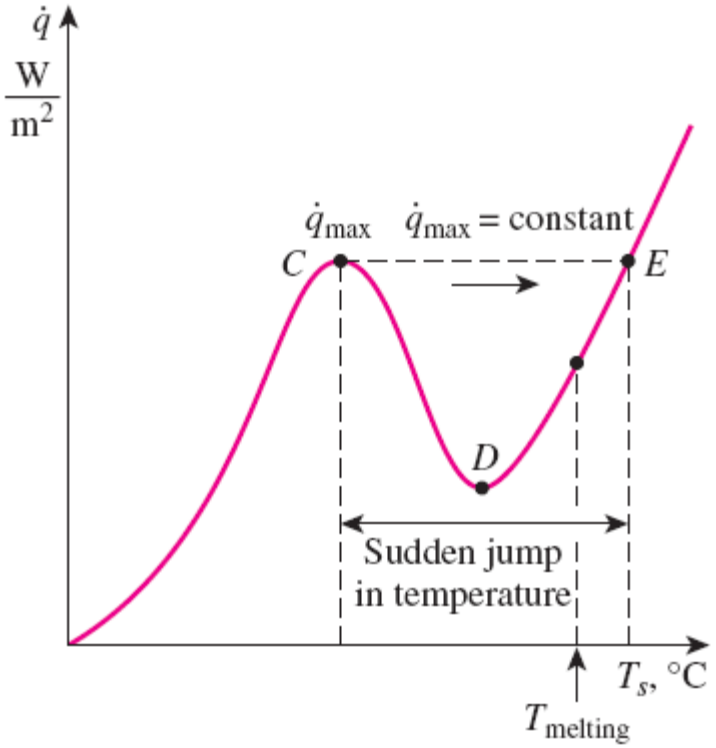
Burnout Phenomenon

- A typical boiling process does not follow the boiling curve beyond point *C*.
- When the power applied to the heated surface exceeded the value at point *C* even slightly, the surface temperature increased suddenly to point *E*.
- When the power is reduced gradually starting from point *E* the cooling curve follows with a sudden drop in excess temperature when point *D* is reached.



Hysteresis of boiling curve

- Any attempt to increase the heat flux beyond q_{max} will cause the operation point on the boiling curve to jump suddenly from point *C* to point *E.*
- However, surface temperature that corresponds to point *E* is beyond the melting point of most heater materials, and *burnout* occurs.
- Therefore, point *C* on the boiling curve is also called the burnout point, and the heat flux at this point the burnout heat flux.
- Most boiling heat transfer equipment in practice operate slightly below q_{max} to avoid any disastrous burnout.

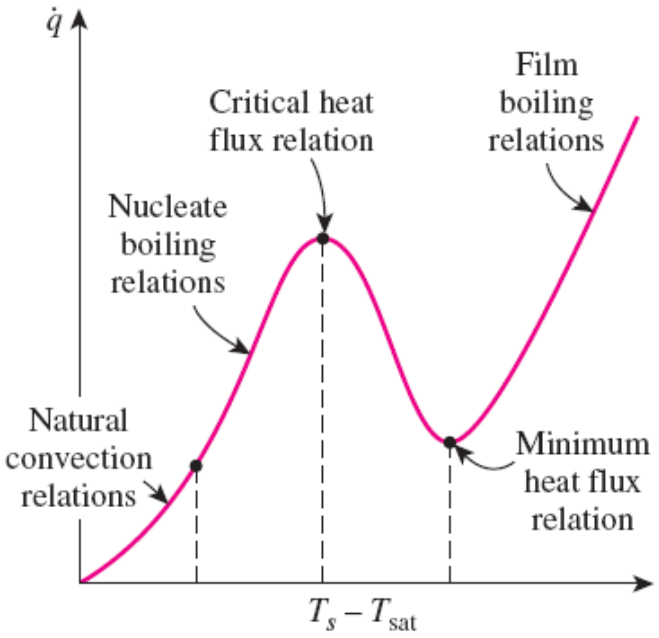


Heat Transfer Correlations in Pool Boiling

- Boiling regimes differ considerably in their character.
- Different heat transfer relations need to be used for different boiling regimes.
- In the *natural convection boiling* regime heat transfer rates can be accurately determined using natural convection relations (e.g. Dittus-Boelter relation).

Nucleate Boiling

- No general theoretical relations for heat transfer in the nucleate boiling regime is available.
- Experimental based correlations are used.
- The rate of heat transfer strongly depends on the nature of nucleation and the type and the condition of the heated surface.



Rohsenow Correlation for Nucleate Boiling

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

q_s'' = nucleate boiling heat flux, W/m^2
μ_l = viscosity of the liquid, kg/m·s
h_{fg} = enthalpy of vaporization, J/kg
g = gravitational acceleration, m/s^2
ρ_l = density of the liquid, kg/m^3
ρ_v = density of the vapor, kg/m^3
σ = surface tension of liquid–vapor interface, N/m
c_{pl} = specific heat of the liquid, J/kg·°C
T_s = surface temperature of the heater, °C
T_{sat} = saturation temperature of the fluid, °C
C_{sf} = experimental constant that depends on surface–fluid combination
Pr_l = Prandtl number of the liquid
n = experimental constant that depends on the fluid

Constants for Rohsenow

TABLE 10–1

Surface tension of liquid–vapor interface for water

T, °C	σ, N/m*
0	0.0757
20	0.0727
40	0.0696
60	0.0662
80	0.0627
100	0.0589
120	0.0550
140	0.0509
160	0.0466
180	0.0422
200	0,0377
220	0.0331
240	0.0284
260	0.0237
280	0.0190
300	0.0144
320	0.0099
340	0.0056
360	0.0019
374	0.0

*Multiply by 0.06852 to convert to lbf/ft or by 2.2046 to convert to lbm/s².

TABLE 10-2

Surface tension of some fluids (from Suryanarayana, originally based on data from Jasper)

Substance and Temp. Range	Surface Tension, σ, N/m* (T in °C)
Ammonia, –75 to –40°C:	$0.0264 + 0.000223T$
Benzene, 10 to 80°C:	$0.0315 - 0.000129T$
Butane, –70 to –20°C:	$0.0149 - 0.000121T$
Carbon dioxide, –30 to –20°C:	$0.0043 - 0.000160T$
Ethyl alcohol, 10 to 70°C:	$0.0241 - 0.000083T$
Mercury, 5 to 200°C:	$0.4906 - 0.000205T$
Methyl alcohol, 10 to 60°C:	$0.0240 - 0.000077T$
Pentane, 10 to 30°C:	$0.0183 - 0.000110T$
Propane, –90 to –10°C:	$0.0092 - 0.000087T$

*Multiply by 0.06852 to convert to lbf/ft or by 2.2046 to convert to lbm/s².

TABLE 10–3

Values of the coefficient C_{sf} and n for various fluid–surface combinations

Fluid–Heating Surface Combination	C_{sf}	n
Water–copper (polished)	0.0130	1.0
Water–copper (scored)	0.0068	1.0
Water–stainless steel (mechanically polished)	0.0130	1.0
Water–stainless steel (ground and polished)	0.0060	1.0
Water–stainless steel (teflon pitted)	0.0058	1.0
Water–stainless steel (chemically etched)	0.0130	1.0
Water–brass	0.0060	1.0
Water–nickel	0.0060	1.0
Water–platinum	0.0130	1.0
n-Pentane–copper (polished)	0.0154	1.7
n-Pentane–chromium	0.0150	1.7
Benzene–chromium	0.1010	1.7
Ethyl alcohol–chromium	0.0027	1.7
Carbon tetrachloride–copper	0.0130	1.7
Isopropanol–copper	0.0025	1.7

Nucleate Boiling, High Pressures

Jens-Lottes correlation
(commonly used in LWR calculations)

$$q'' \left[\mathrm{W/m^2}\right] = \left[\frac{\Delta T_{sat}[\mathrm{K}]}{0.791 exp(-p[\mathrm{MPa}]/6.2)}\right]^4$$

Critical Heat Flux for Nucleate Boiling

Kutateladze, Zuber correlation

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

TABLE 10–4

Values of the coefficient C_{cr} for use in Eq. 10–3 for maximum heat flux (dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

Heater Geometry	C_{cr}	Charac. Dimension of Heater, L	Range of L^*
Large horizontal flat heater	0.149	Width or diameter	$L^* > 27$
Small horizontal flat heater[1]	$18.9K_1$	Width or diameter	$9 < L^* < 20$
Large horizontal cylinder	0.12	Radius	$L^* > 1.2$
Small horizontal cylinder	$0.12L^{*-0.25}$	Radius	$0.15 < L^* < 1.2$
Large sphere	0.11	Radius	$L^* > 4.26$
Small sphere	$0.227L^{*-0.5}$	Radius	$0.15 < L^* < 4.26$

[1] $K_1 = \sigma/[g(\rho_l - \rho_v)A_{heater}]$

Minimum Heat Flux

Zuber correlation

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

Film Boiling

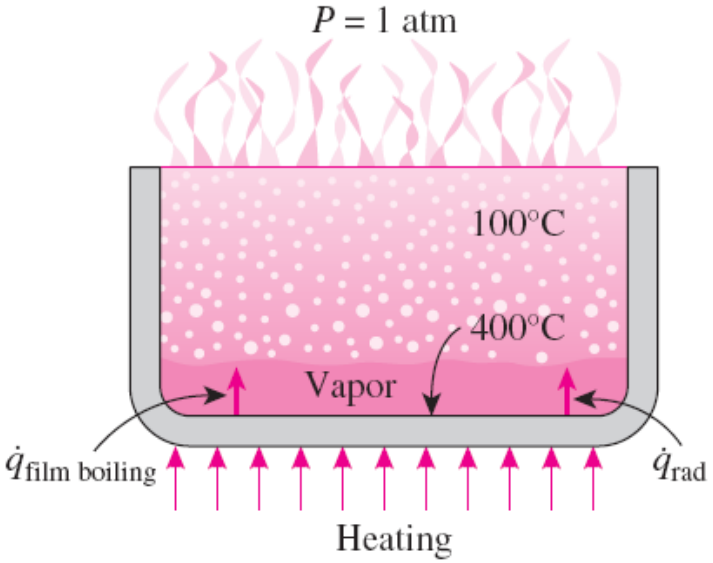
- Berenson Correlation (film boiling on a horizontal surface)

$$q'' = 0.425 \frac{\Delta T_{sat} k_v}{l_L} \left[\frac{g l_L^3}{\nu_v^3} \frac{(\rho_l - \rho_v)}{\rho_v} \right]^{1/4} \left[\frac{\Delta h_{fg}}{C_{pv} \Delta T_{sat}} \right]^{1/4} Pr_v^{1/4}$$

$$l_L = \sqrt{\frac{\sigma}{g(\rho_l - \rho_v)}} = \text{Laplace length}$$

Film Boiling (Radiation Heat Transfer)

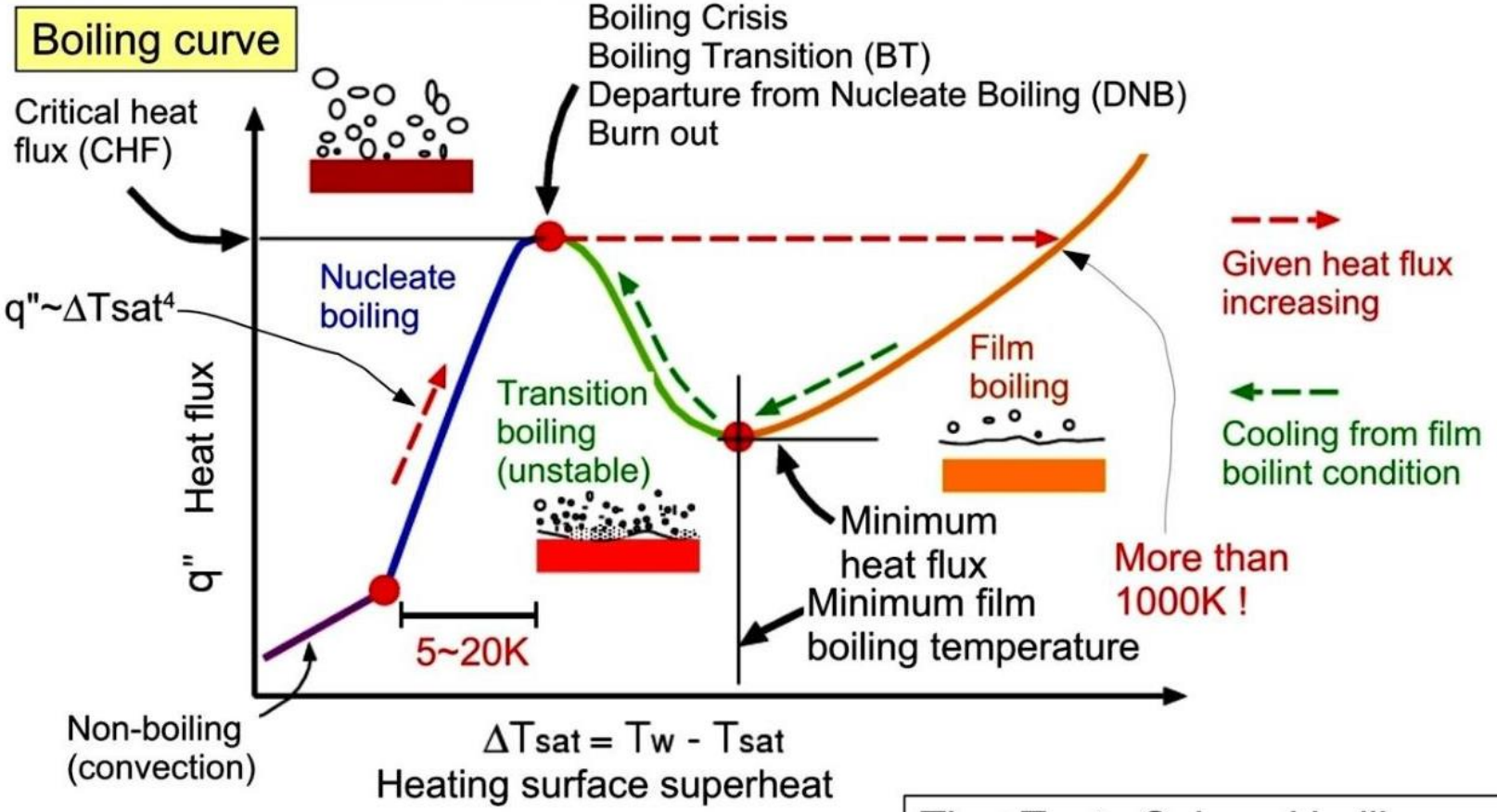
- At high surface temperatures (typically above 300°C), heat transfer across the vapor film by *radiation* becomes significant and needs to be considered.



$$\dot{q}_{\text{rad}} = \varepsilon\sigma\,(T_s^4 - T_{\text{sat}}^4) \quad \text{For } \dot{q}_{\text{rad}} < \dot{q}_{\text{film}},$$

$$\dot{q}_{\text{total}} = \dot{q}_{\text{film}} + \frac{3}{4}\,\dot{q}_{\text{rad}}$$

Boiling curve



$$q'' \ [\mathrm{W/m^2}] = \left[\frac{\Delta T_{sat}[\mathrm{K}]}{0.791 \exp(-p[\mathrm{MPa}]/6.2)} \right]^4$$

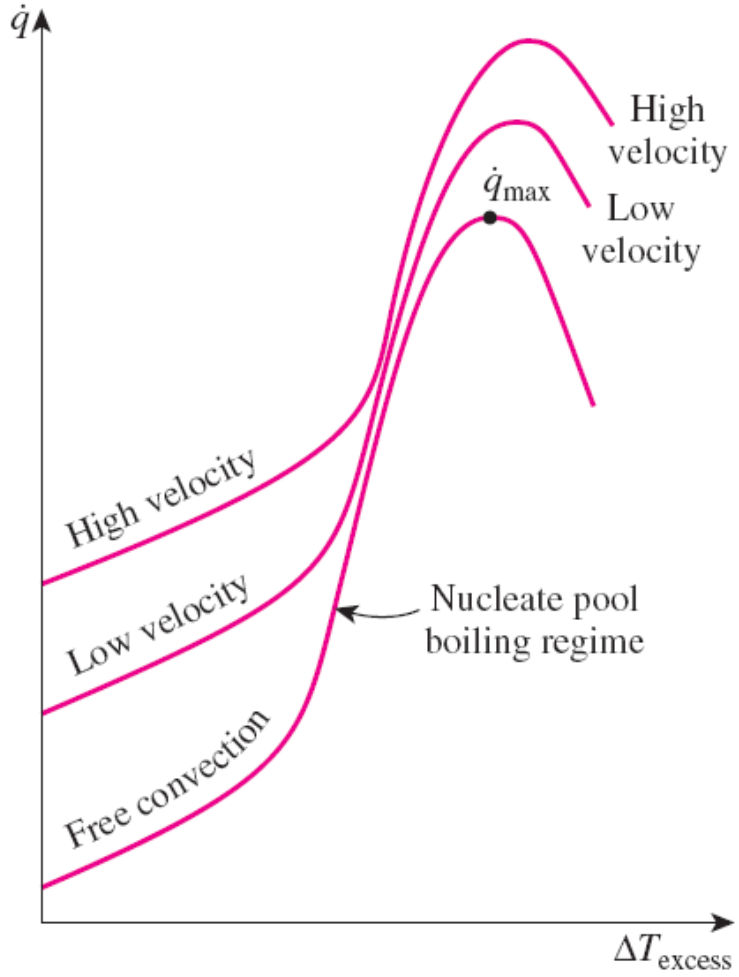
Jens-Lottes' correlation
(Empirical correlation for nucleate boiling, used for light water reactor design)

Tb < Tsat : Subcool boiling
Tb = Tsat : Saturation boiling

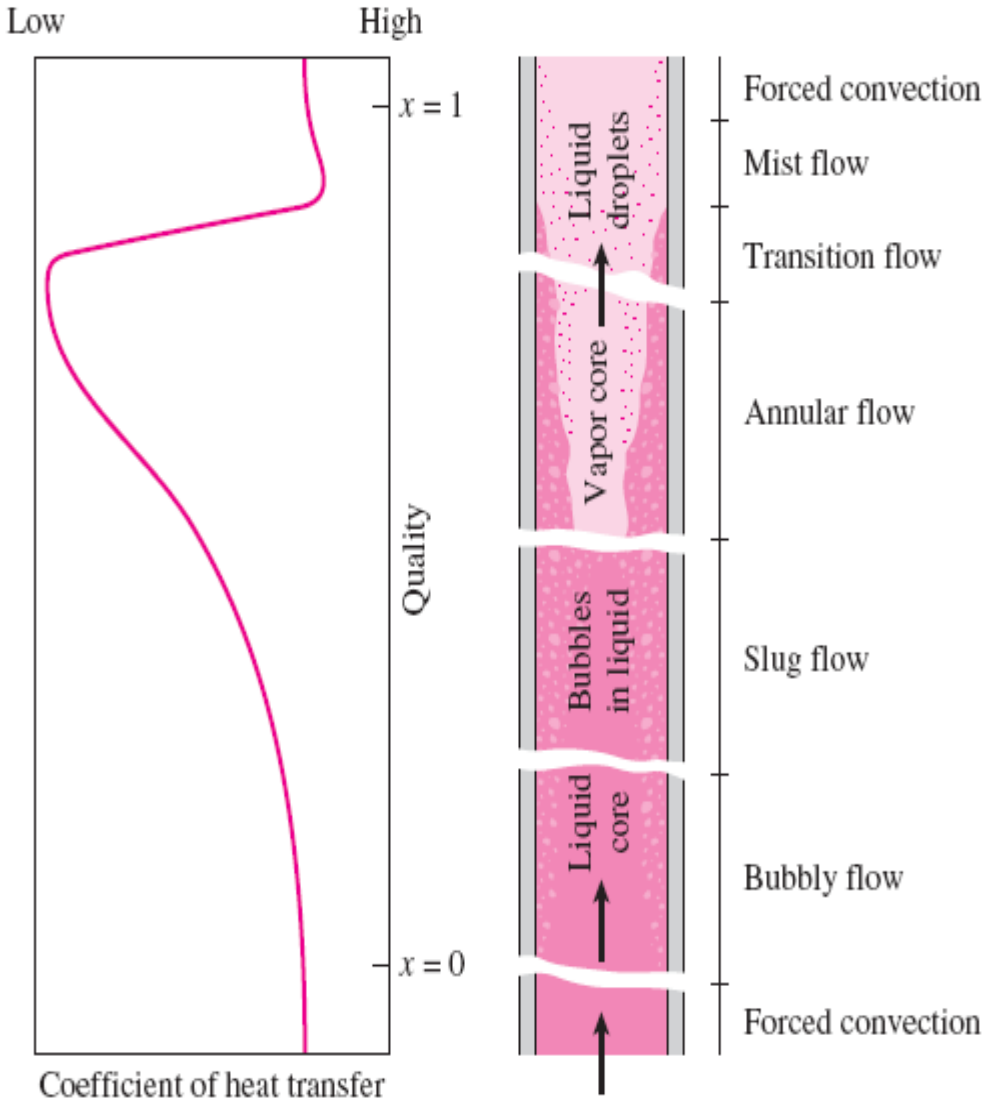
Without flow: Pool boiling
With flow: Forced convection boiling

Flow Boiling – of Interest in Nuclear Reactors

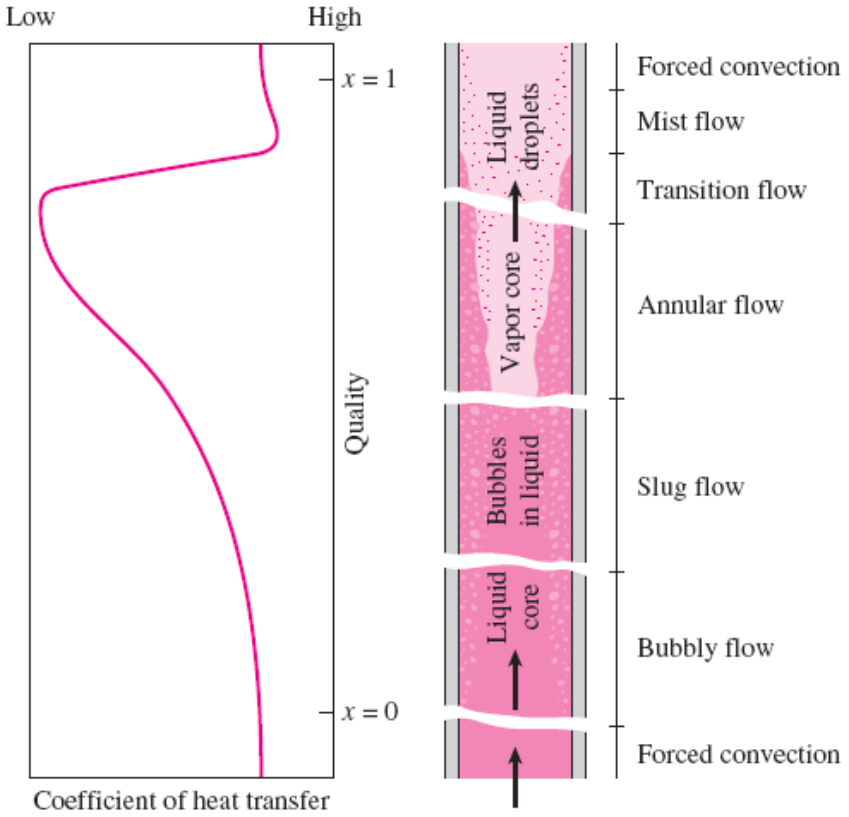
- In **flow boiling**, the fluid is forced to move by an external source such as a pump as it undergoes a phase-change process.
- It exhibits the combined effects of convection and pool boiling.
- *External flow boiling* over a plate or cylinder is similar to pool boiling, but the added motion increases both the nucleate boiling heat flux and the maximum heat flux considerably.
- The higher the velocity, the higher the nucleate boiling heat flux and the critical heat flux.
- *Internal flow boiling*, commonly referred to as *two-phase flow*, is much more complicated in nature because there is no free surface for the vapor to escape, and thus both the liquid and the vapor are forced to flow together.



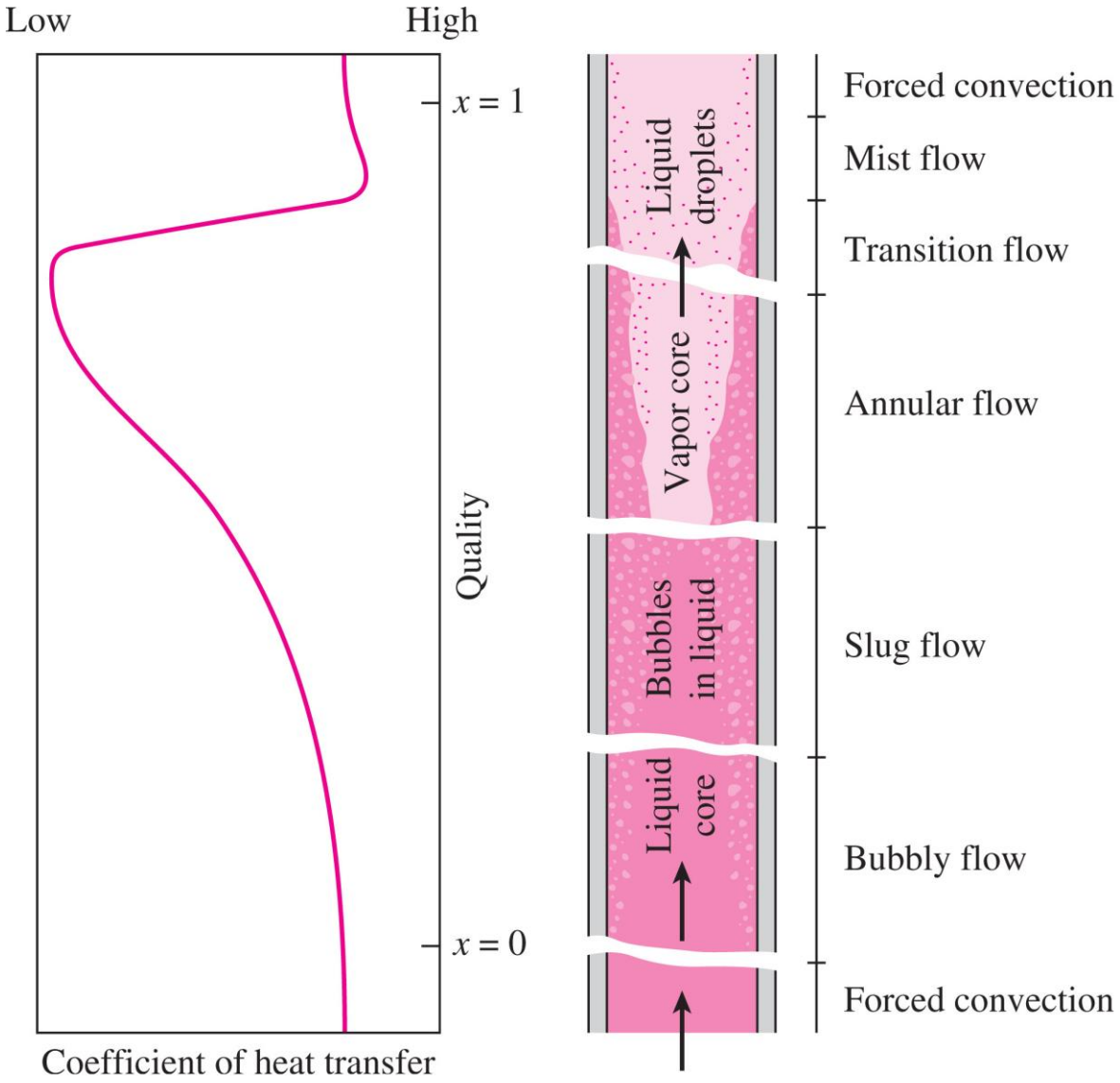
- The two-phase flow in a tube exhibits different flow boiling regimes, depending on the relative amounts of the liquid and the vapor phases.
- Note that the tube contains a liquid before the bubbly flow regime and a vapor after the mist-flow regime.
- Heat transfer in those two cases can be determined using the appropriate relations for single-phase convection heat transfer.

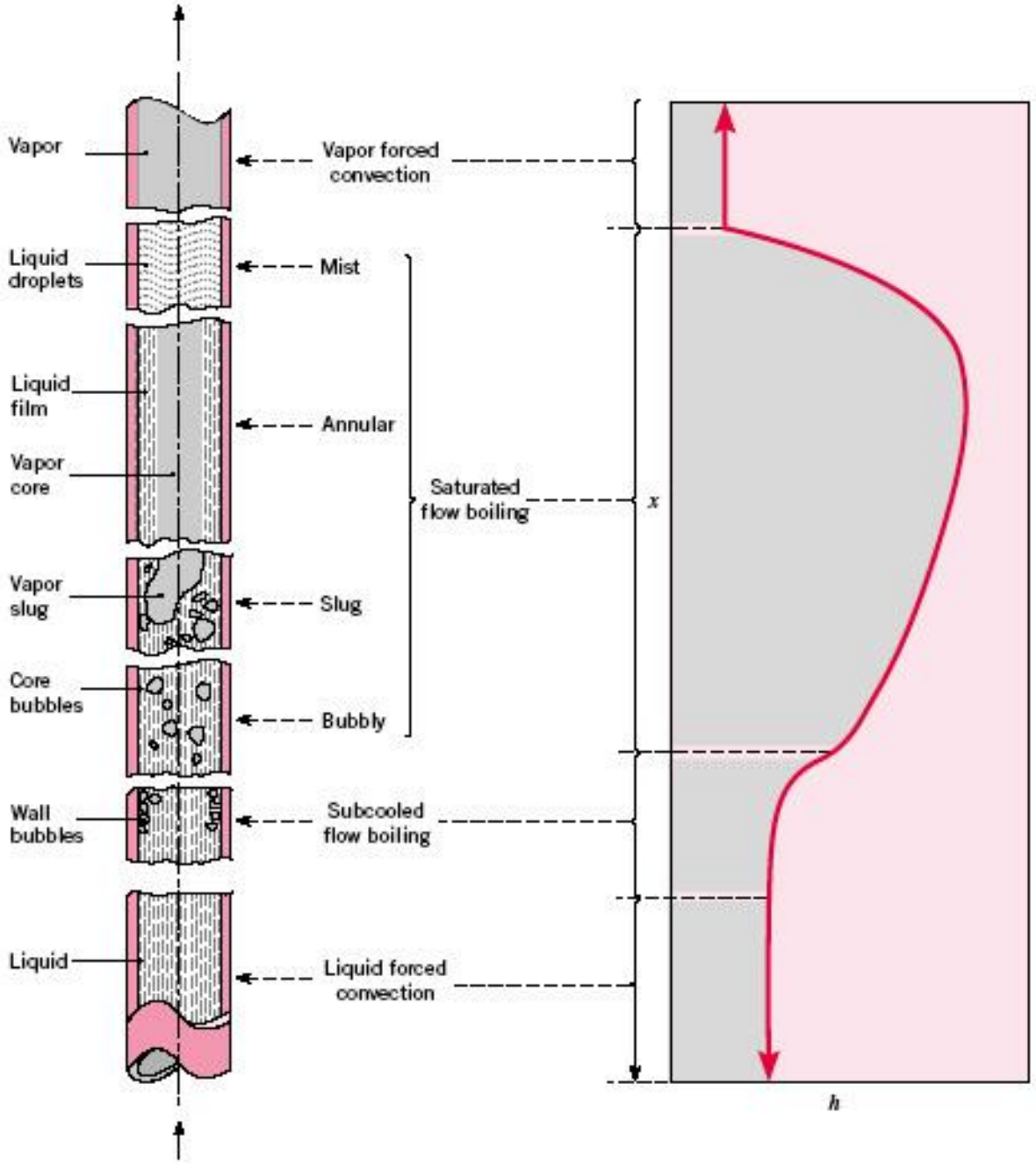


- Liquid single-phase flow
  - ✓ In the inlet region the liquid is subcooled and heat transfer to the liquid is by *forced convection* (assuming no subcooled boiling).
- Bubbly flow
  - ✓ Individual bubbles
  - ✓ Low mass qualities
- Slug flow
  - – Bubbles coalesce into slugs of vapor.
  - – Moderate mass qualities
- Annular flow
  - – Core of the flow consists of vapor only, and liquid adjacent to the walls.
  - – Very high heat transfer coefficients
- Mist flow
  - – A sharp decrease in the heat transfer coefficient
- Vapor single-phase flow
  - – The liquid phase is completely evaporated and vapor is superheated.



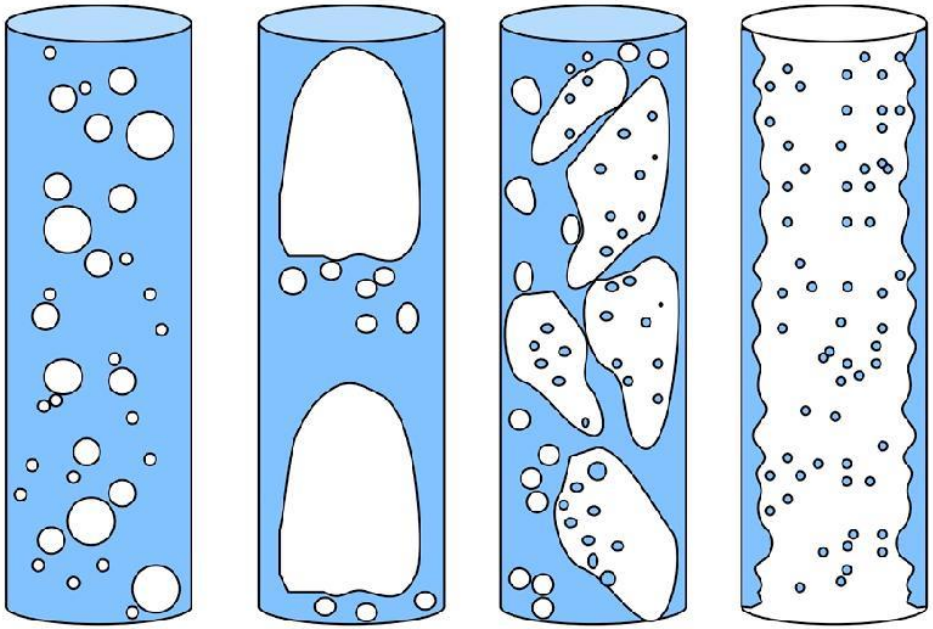
Flow Regime

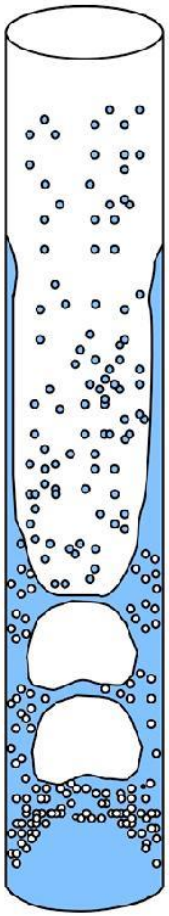

Low
High
x = 1
x = 0
Quality
Coefficient of heat transfer
Liquid droplets
Vapor core
Bubbles in liquid
Liquid core
Forced convection
Mist flow
Transition flow
Annular flow
Slug flow
Bubbly flow
Forced convection


Vapor
Vapor forced convection
Liquid droplets
Mist
Liquid film
Annular
Vapor core
Saturated flow boiling
Vapor slug
Slug
Core bubbles
Bubbly
Wall bubbles
Subcooled flow boiling
Liquid
Liquid forced convection
x
h

Flow Regime

Flow Patterns (Flow Regimes)

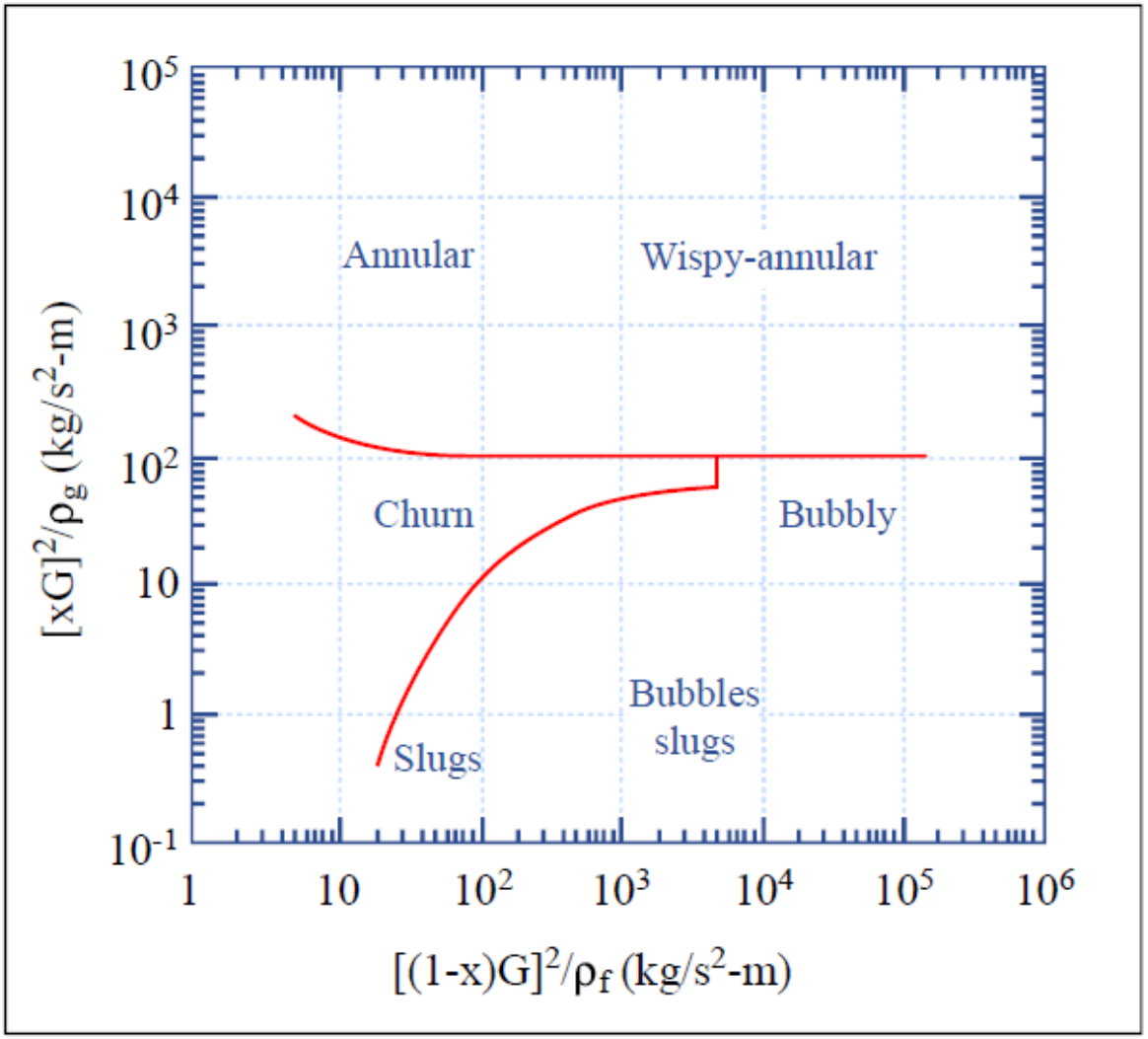




Flow pattern depends on
- gas/liquid flow rates
- physical properties (density, surface tension, viscosity, etc.)
- heating condition

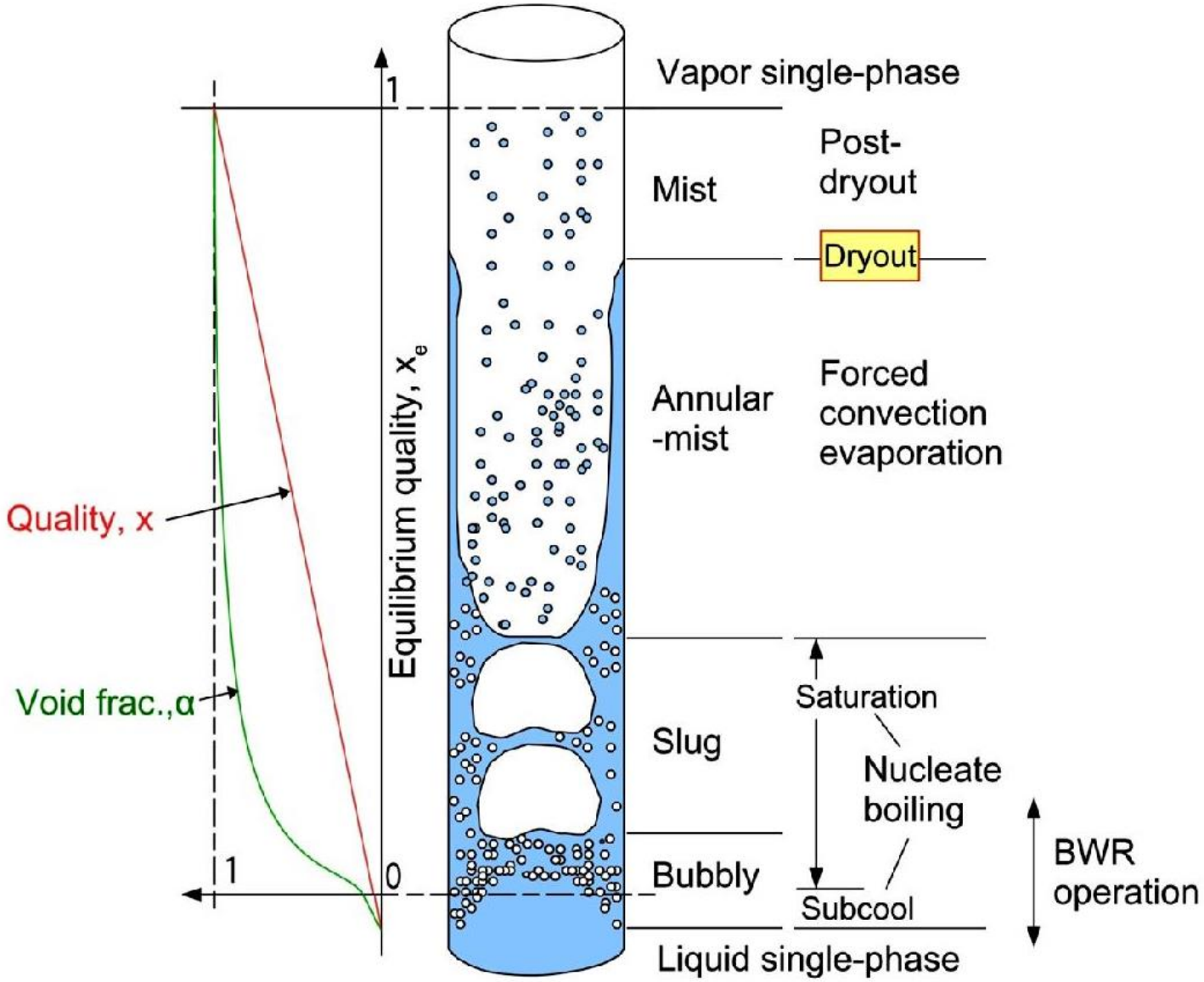
Flow in a boiling channel (boiling two-phase flow)

Flow Map



Hewitt and Roberts 1969

Two Phase Flow Heat Transfer



Heat Transfer Correlation

- Single phase liquid region:
  - Use a single phase heat transfer correlation appropriate for the geometry, fluid and flow regime (turbulent vs laminar) present in the channel. (e.g. Dittus Boelter correlation)
- Two phase region:
  - For this region (from the onset of nucleate boiling to the point of dryout), we can use Klimenko's correlation.
  - Klimenko's correlation distinguishes between two subregions:
    - Nucleate boiling dominated subregion (roughly corresponding to bubbly and plug flow)
    - Forced evaporation dominated subregion (roughly corresponding to annular flow).

Klimenko Correlation

Along with Newton's Law of Cooling $q'' = h(T_w - T_b)$

Klimenko correlation for Nucleate Boiling Dominated Subregion

$$\frac{hL_c}{k_f} = 4.9 \times 10^{-3} Pe_m^{0.6} \mathrm{Pr}_f^{-0.33} \left(\frac{PL_c}{\sigma} \right)^{0.54}$$

Klimenko correlation for Forced Evaporation Subregion

$$\frac{hL_c}{k_f} = 0.087 \mathrm{Re}_m^{0.6} \mathrm{Pr}_f^{1/6} \left(\frac{\rho_g}{\rho_f} \right)^{0.2}$$

Klimenko Correlation

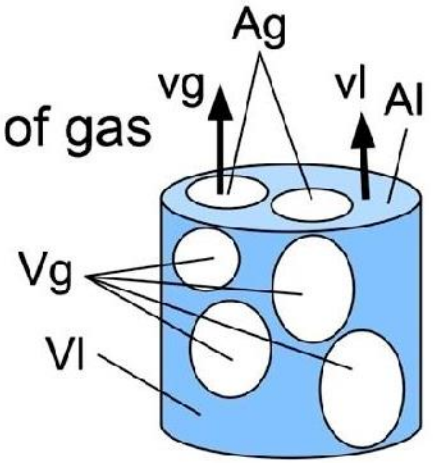
Where the parameters Pe_m, Re_m, L_c are

$$Pe_m \equiv \frac{q'' L_c \rho_f c_{p,f}}{h_{fg} \rho_g k_f}$$

$$\mathrm{Re}_m \equiv G\left[1 + x\left(\frac{\rho_f}{\rho_g} - 1\right)\right]\frac{L_c}{\mu_f}$$

$$L_c \equiv \sqrt{\frac{\sigma}{g(\rho_f - \rho_g)}}$$

Two Phase Flow Important Parameters



- Void fraction, α : volume (cross section) fraction of gas

$$\alpha = \frac{V_g}{V_g + V_l} = \frac{A_g}{A_g + A_l}$$

- Quality, x : mass flow rate fraction of gas

$$x = \frac{W_g}{W_g + W_l} = \frac{G_g}{G_g + G_l} = \frac{\alpha \rho_g v_g}{\alpha \rho_g v_g + (1-\alpha)\rho_l v_l}$$

v : velocity [m/s]
G : mass flux [kg/m²s]
W=GA : mass flow rate [kg/s]

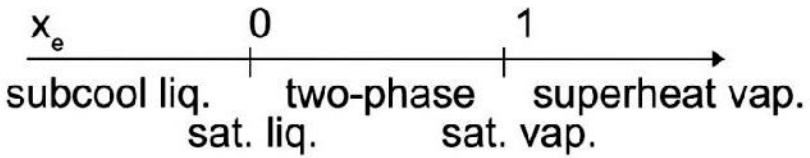
- Equilibrium quality, x_e : enthalpy level of two-phase mixture

$$x_e = \frac{h - h_{ls}}{h_{gs} - h_{ls}} = \frac{\alpha \rho_g}{\rho}$$

h : enthalpy of two-phase medium [J/kg]
h_{ls} : enthalpy of saturation liquid [J/kg]
h_{gs} : enthalpy of saturation gas [J/kg]

($x = x_e$ at thermal equilibrium)

the static mass fraction of gas



$$h = \frac{\alpha \rho_g h_{gs} + (1-\alpha)\rho_l h_{ls}}{\alpha \rho_g + (1-\alpha)\rho_l}, \quad \rho = \alpha \rho_g + (1-\alpha)\rho_l$$

Continued

- Relation of the mass flux, void fraction and the quality

$$G = G_g + G_l = \alpha\rho_g v_g + (1-\alpha)\rho_l v_l$$
$$G_g = xG = \alpha\rho_g v_g,\ G_l = (1-x)G = (1-\alpha)\rho_l v_l$$

$$\Rightarrow G = \frac{\alpha\rho_g v_g}{x} = \frac{(1-\alpha)\rho_l v_l}{1-x}$$

$$\Rightarrow \frac{1}{x} = 1 + \frac{(1-\alpha)\rho_l}{\alpha\rho_g}\frac{v_l}{v_g},\ \frac{1}{\alpha} = 1 + \frac{(1-x)\rho_g}{x\rho_l}\frac{v_g}{v_l}$$

the velocities appear as a ratio

- Slip ratio

$$s = \frac{v_g}{v_l} = \frac{1-\alpha}{\alpha}\frac{x}{1-x}\frac{\rho_l}{\rho_g}$$

- In general, the gas and liquid have different velocities in the two-phase flow.
- They may have very close velocities. In that case, vg=vl can be assumed. (homogeneous two-phase flow, s=1)

The two-phase density of homogeneous flow :

$$\frac{1}{\rho} = \frac{x}{\rho_g} + \frac{1-x}{\rho_l}$$

Two-Phase Flow Pressure Drop

$$-\frac{dp}{dz} = \frac{1}{A}\frac{d}{dz}\left[\left\{\alpha\rho_g v_g^2 + (1-\alpha)\rho_l v_l^2\right\} A\right] + \rho g \cos\theta + \frac{l_w}{A}\tau_w$$

Acceleration due to evaporation
Change of cross section

Gravity
(static head)

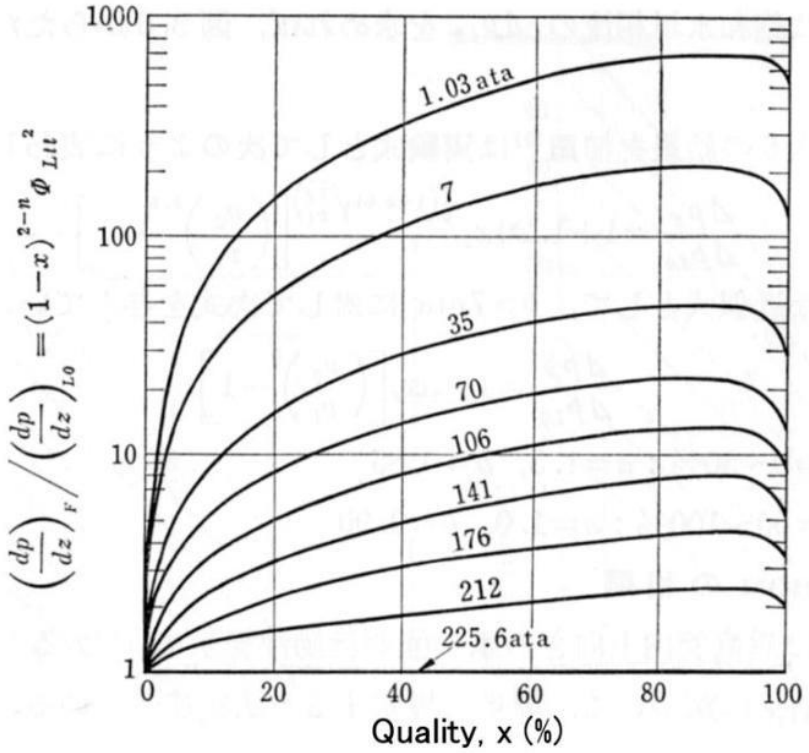
Friction

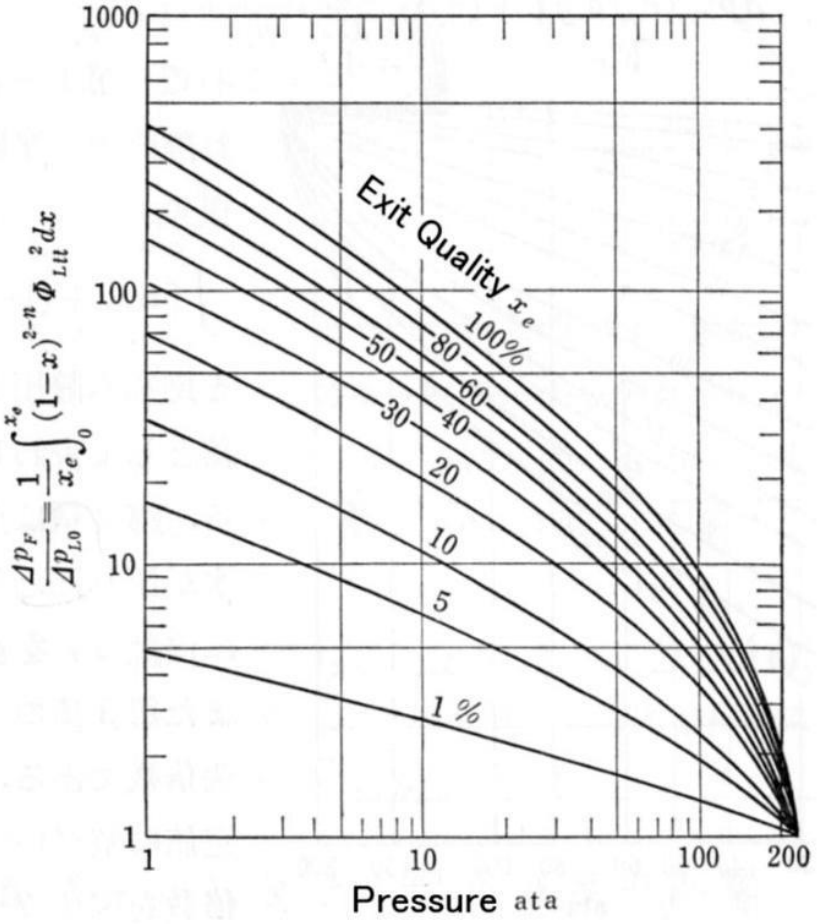
- Acceleration pressure drop
  - Evaporation during the flow causes significant change of the average momentum along the channel => the acceleration pressure drop becomes important
- Friction pressure drop
  - Addition of gas flow and complexed structure gives special characteristics
- Static head
  - The average density ~ liquid volume fraction
  - The static head strongly depends on the void fraction

Two Phase Pressure Drop Correlations

- Martinelli – Lockhart
- Nelson – Martinelli
- Chisholm – Laird
- Ueda

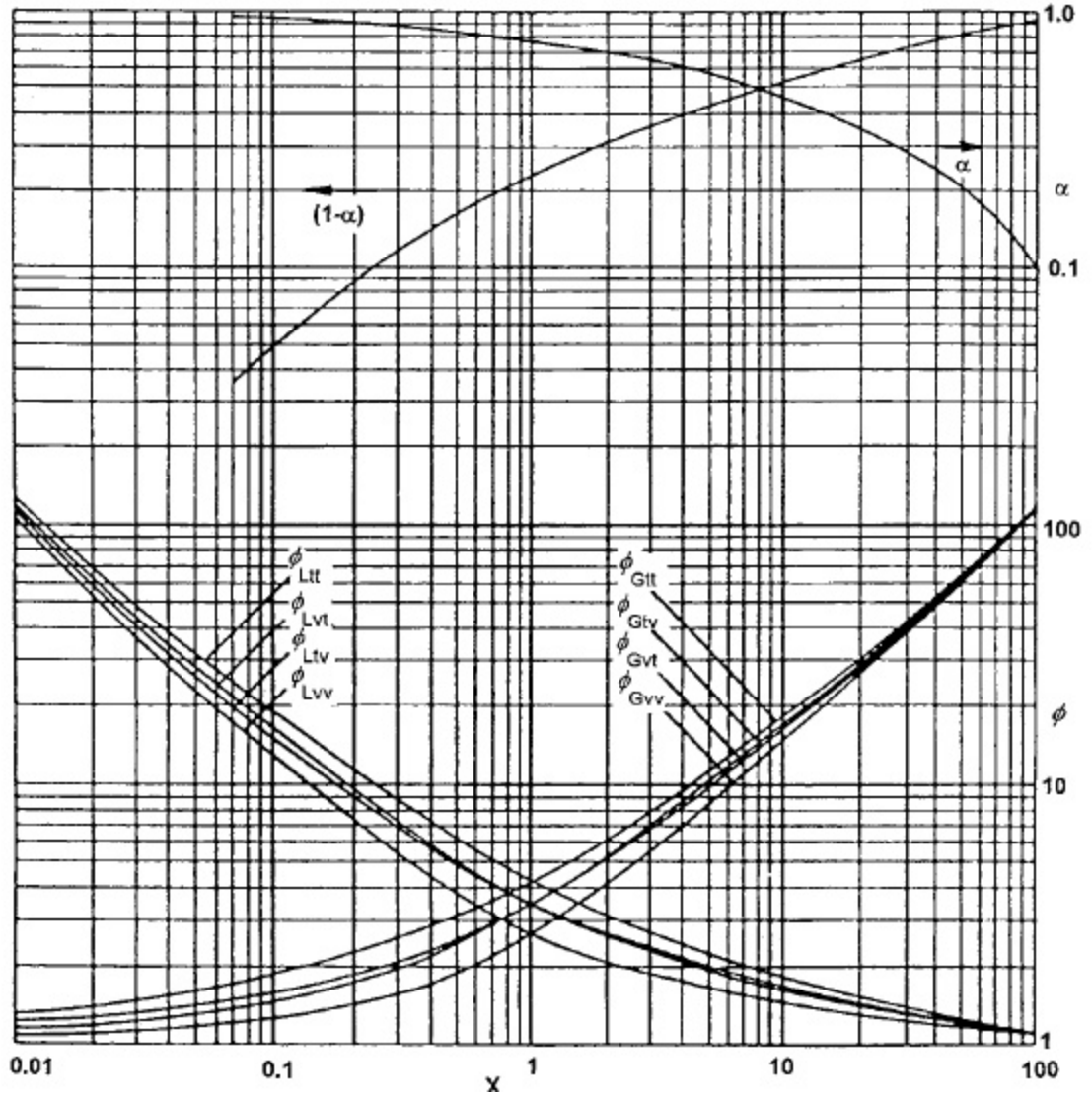
Martinelli-Nelson correlation for two-phase friction multiplier





Given for water at wide pressure range
Left: local pressure gradient multiplier
Right: overall pressure drop multiplier for x=0--x_e

Lockhart-Martinelli Variation Curve



Boiling Crisis for LWR

- LWR core design limitation: Boiling transition must not happen in the core.
- Different terminologies of BT for PWR and BWR depending on the mechanism.

PWR: subcooled boiling, high heat flux; DNB (severe)

BWR: saturation boiling, low heat flux; liquid film dryout (moderate)

(1) Evaluation by local heat flux

DNBR = DNB heat flux / local heat flux > limit value : current PWR

(2) Evaluation by total power (not determined by local condition)

-> Considering that the liquid film dryout depends on the total power input in the upstream

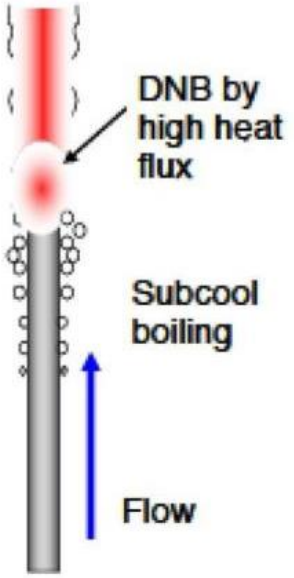
CPR = assembly critical power / assembly power > limit value : current BWR

+ (DNBR=Departure from Nucleate Boiling (Heat Flux) Ratio)

Evaluation by Local Heat Flux (PWR)

$$DNBR = \frac{q''_{DNB}}{q''}, \text{ Minimum DNBR (MDNBR)} > 1.17$$

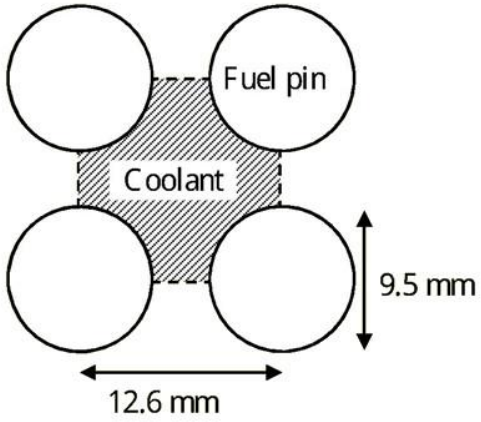
- MDNBR: minimum value of DNBR in the whole core (DNBR at the thermally most severe location) must always keep the limitation even in the anticipated operational occurrence (AOO).
- DNB criteria q''_{DNB} correlation: MIRC or NFI correlation (current PWR, not publicly open)



+ (AOO: abnormal events encountered more than once through a plant life.)

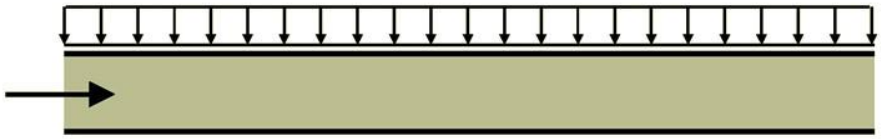
Thermal-hydraulics of PWR Core

Channel geometry

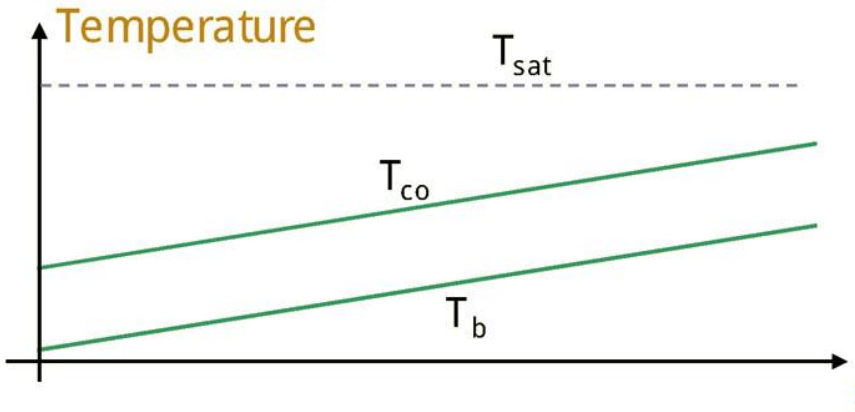


Assumed axially uniform for simplicity

Average channel

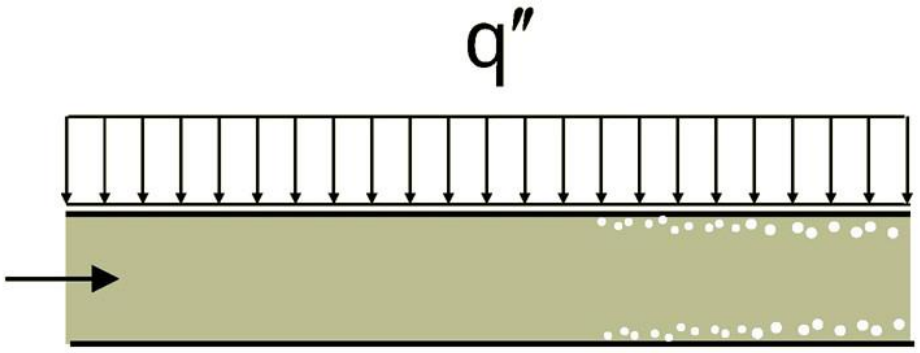


No boiling in the average channel

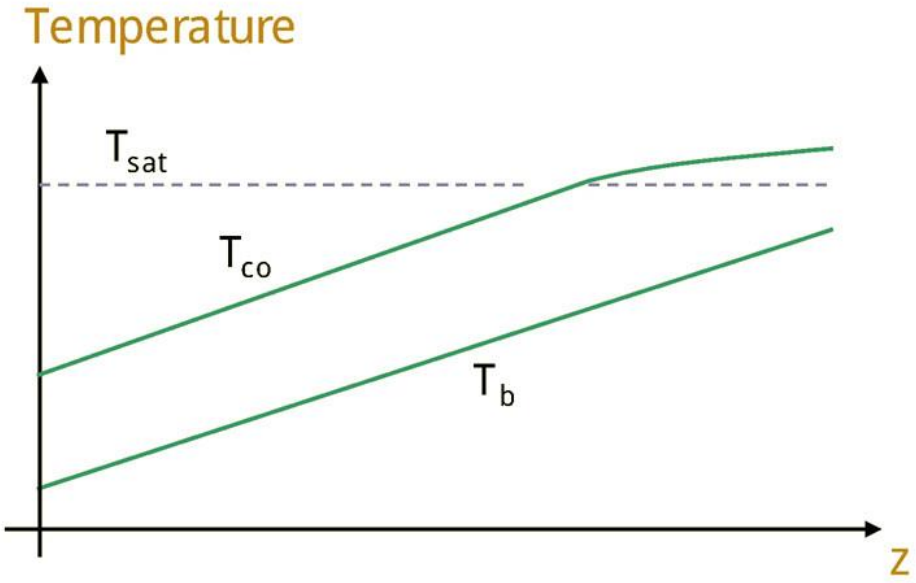


Thermal-hydraulics of PWR Core (2)

Hot channel

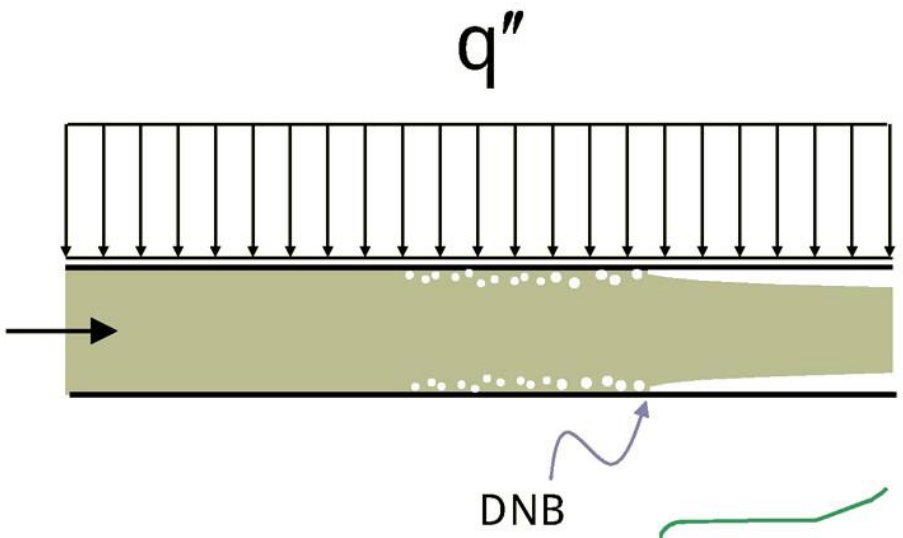


Subcooled boiling in the hot channel

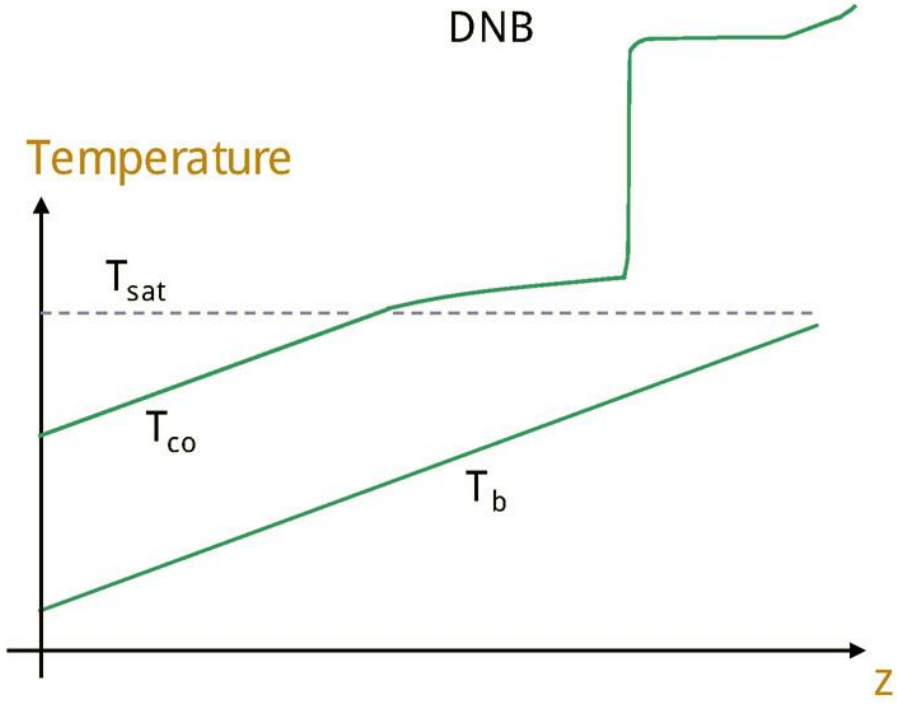


Thermal-hydraulics of PWR Core (3)

DNB (thermal crisis) in hot channel

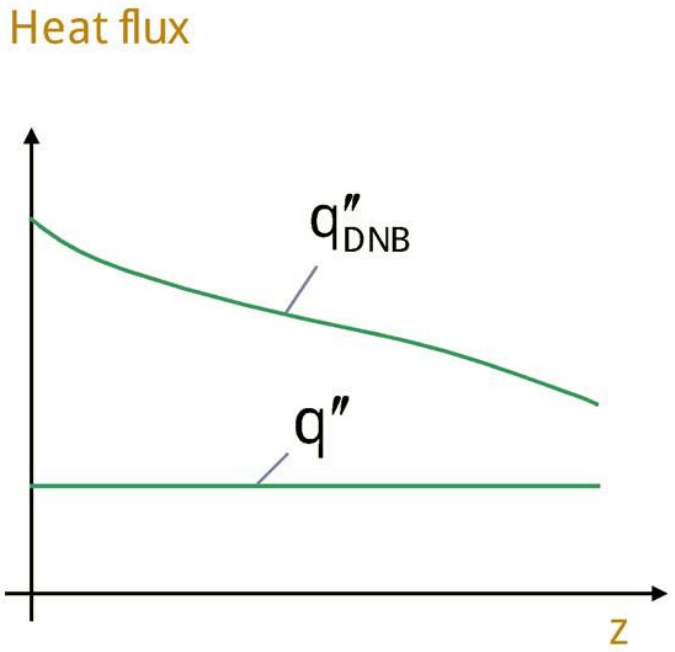


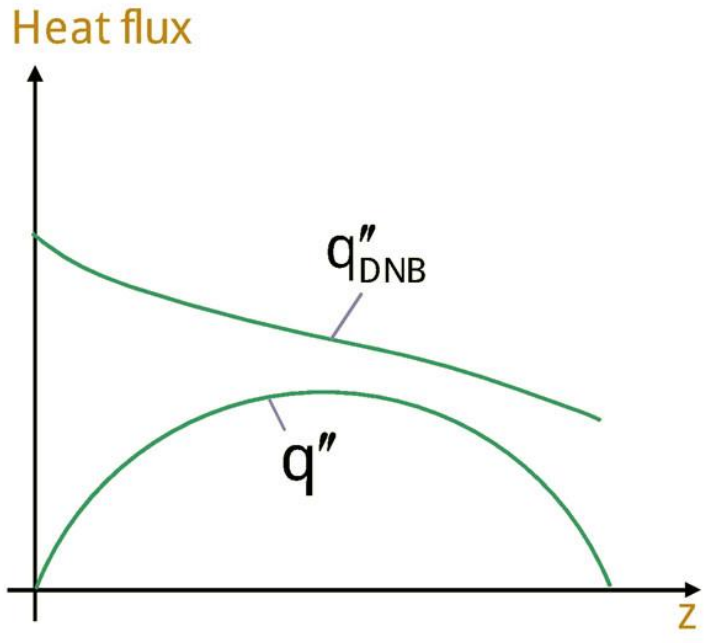
Clad temperature skyrockets when DNB occurs



Thermal-hydraulics of PWR Core (4)

Heat flux to cause DNB depends on T_b, G and P $\Rightarrow$ $q''_{DNB}(T_b, G, P)$



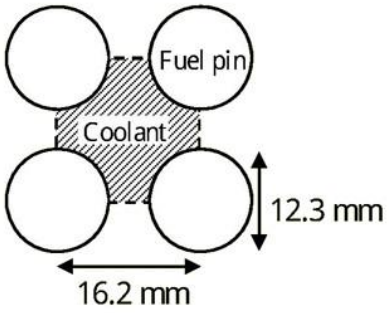


$$DNBR(z) \equiv \frac{q''_{DNB}}{q''}$$

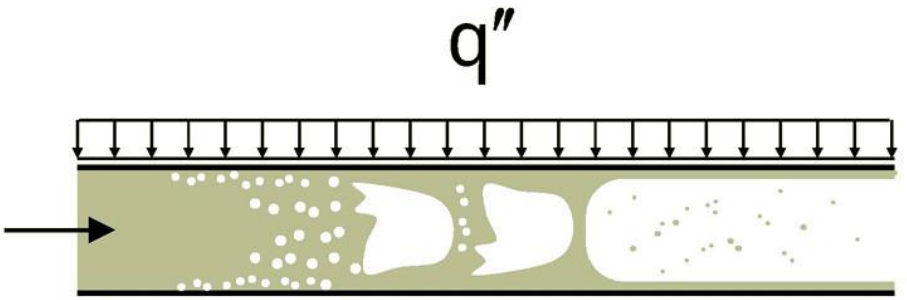
MDNBR $\equiv$ min. DNBR > 1.3 in the US

Thermal-hydraulics of BWR Core

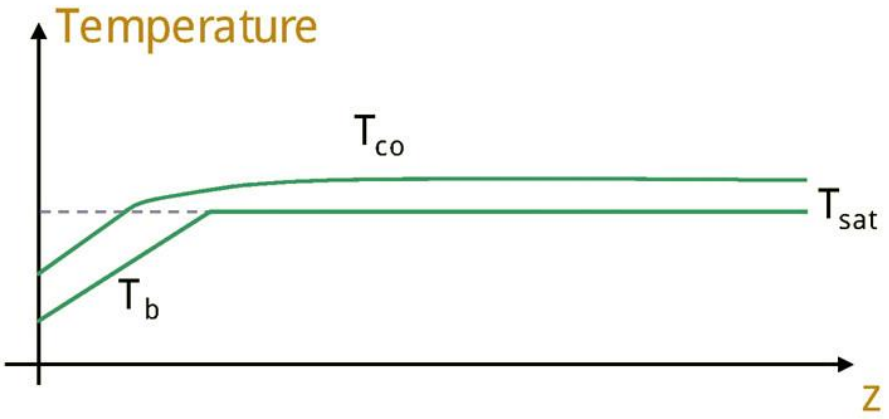
Channel geometry



Average or hot channel

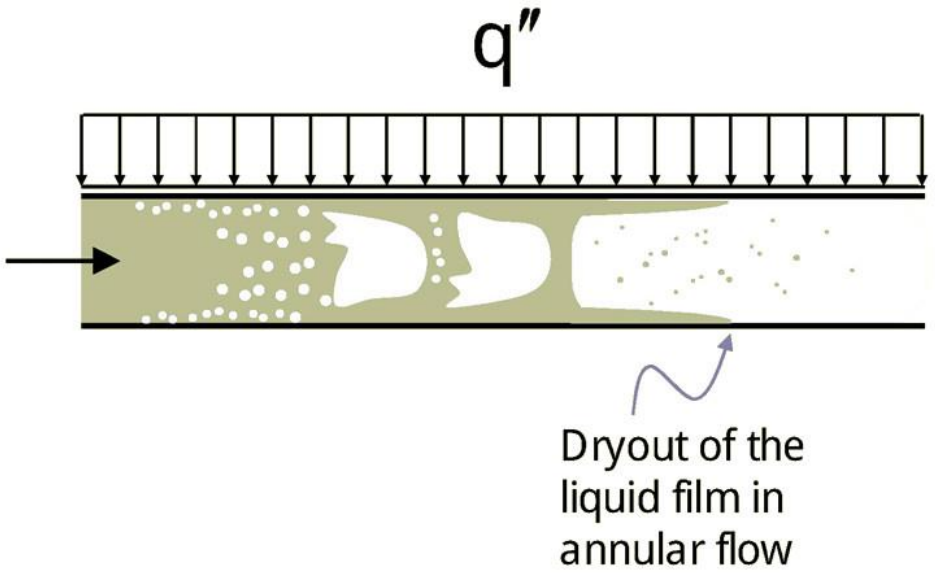


Saturated boiling in most of the channel

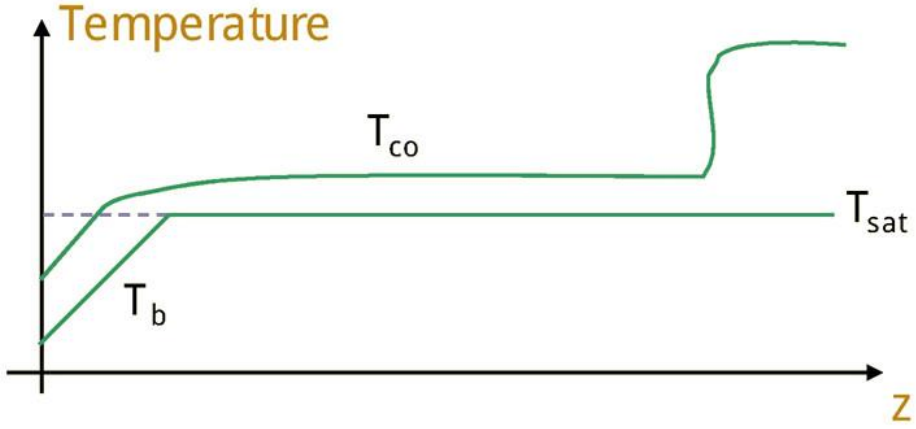


Thermal-hydraulics of BWR Core (2)

Dryout (thermal crisis) in hot channel



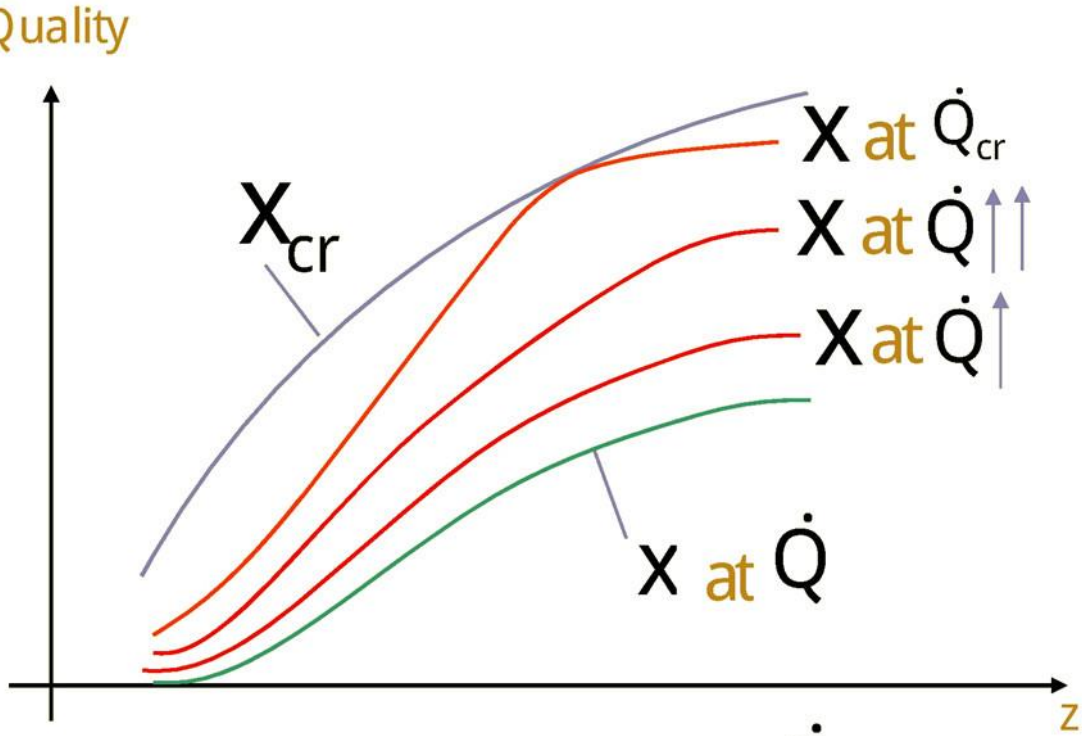
Clad temperature increases sharply when dryout occurs



Thermal-hydraulics of BWR Core (3)

Steam quality at which dryout occurs depends on $\dot{m}$, P and z

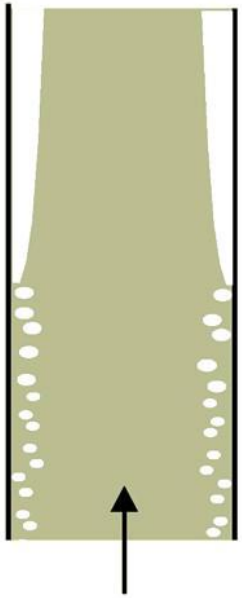
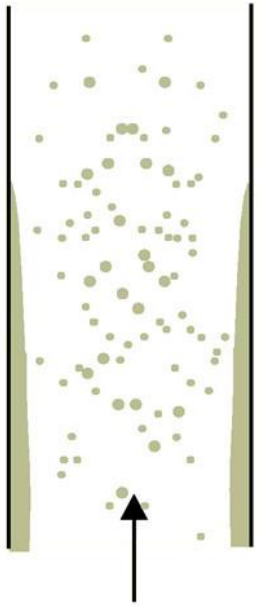
$\Rightarrow x_{cr}(\dot{m}, P, z)$



$$\text{Critical Power Ratio (CPR)} \equiv \frac{\dot{Q}_{cr}}{\dot{Q}}$$

CPR > 1.2 in the US

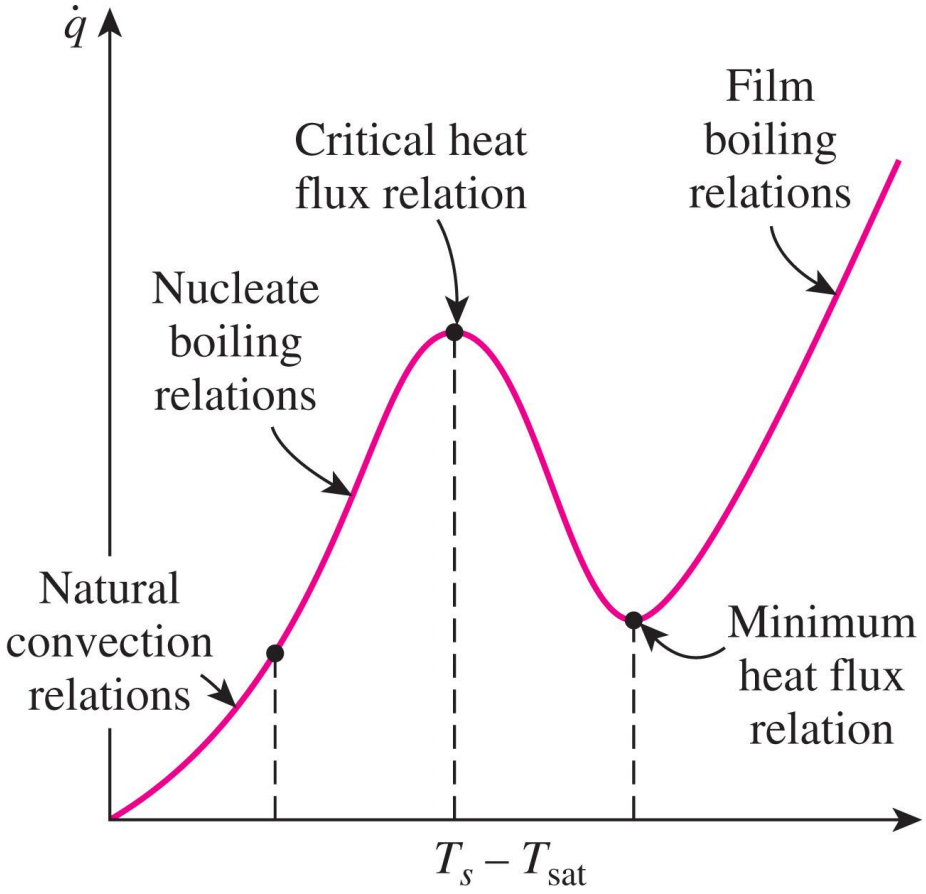
Thermal Crisis Summary

Reactor	PWR	BWR
Thermal crisis type	Departure from Nucleate Boiling (DNB)	Dryout
Phenomenon		
Design limit	MDNBR > 1.3	CPR > 1.2

MDNBR > 1.17 (Japan)

Summary

- Nucleation Sites
- Pool, Flow Boiling
- Excess Temperature
- Boiling Curve
- Boiling Crisis (CHF)
- DNB
- DNBR, CPR
- Two-phase flow
- Flow Regime
- Heat Flux, Pressure Drop
- Correlations



References

- Cengel, Heat Transfer, A Practical Approach, McGraw Hill
- Incropera, DeWitt, Foundations of Heat Transfer, Wiley
- Buongiorno, Notes on Two Phase Flow, Boiling Heat Transfer, and Boiling Crises in PWRs and BWRs, MIT
- Buongiorno, Boiling Crisis in LWRs, MIT
- Reactor Thermal Engineering IIb, ITP @ JAEA, August 2010