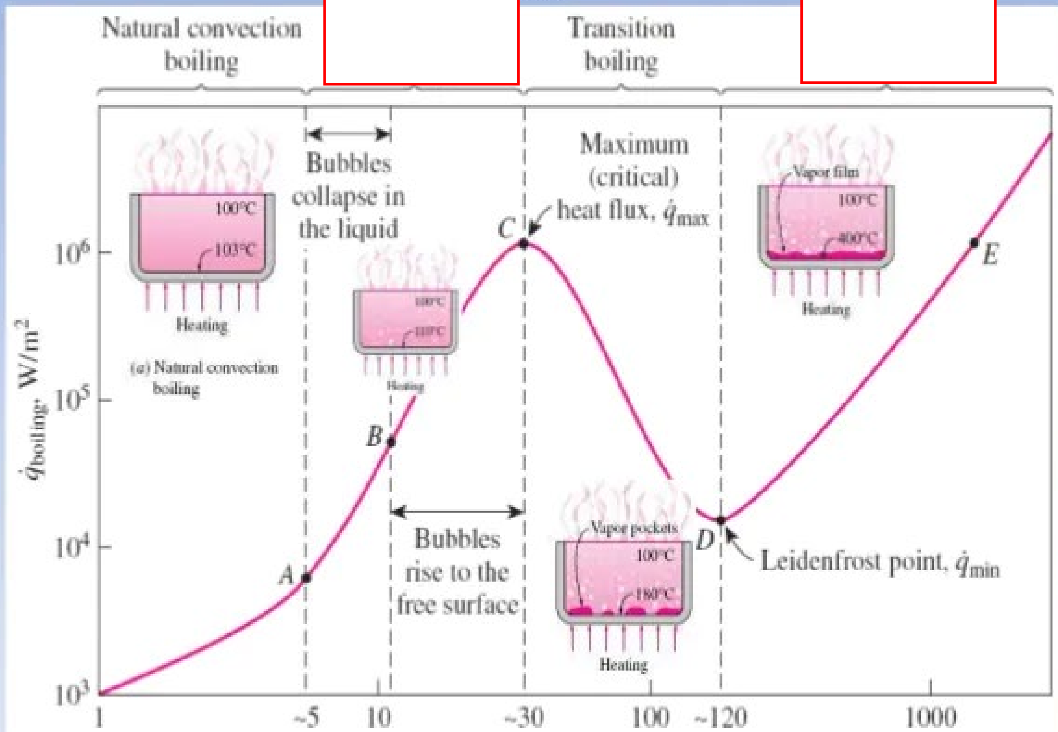
Boiling curve



ΔT_{sat} =

Rohsenow's Nucleate Boiling Correlation

- For nucleate boiling a widely used correlation proposed in 1952 by Rohsenow:

$$\dot{q}_{nucleate} = \mu_l h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[\frac{c_{pl}(T_s - T_{sat})}{C_{sf} h_{fg} \mathrm{Pr}_l^n} \right]^3$$

$$\dot{q} = \left(\frac{\mathrm{kg}}{\mathrm{m \cdot s}}\right)\left(\frac{\mathrm{J}}{\mathrm{kg}}\right) \times \left(\frac{\frac{\mathrm{m}}{\mathrm{s^2}}\frac{\mathrm{kg}}{\mathrm{m^3}}}{\frac{\mathrm{N}}{\mathrm{m}}}\right)^{1/2} \left(\frac{\frac{\mathrm{J}}{\mathrm{kg \cdot {}^\circ C}}{}^\circ\mathrm{C}}{\frac{\mathrm{J}}{\mathrm{kg}}}\right)^3 = \frac{\mathrm{W}}{\mathrm{m}}\left(\frac{1}{\mathrm{m^2}}\right)^{1/2}(1)^3 = \mathrm{W/m^2}$$

$\dot{q}_{nucleate}$ = nucleate boiling heat flux, W/m²
μ_l = viscosity of the liquid, kg/m·s
h_{fg} = enthalpy of vaporization, J/kg
g = gravitational acceleration, m/s²
ρ_l = density of the liquid, kg/m³
ρ_v = density of the vapor, kg/m³
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

Surface Tension of Water and C_{sf} Value

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.

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.

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

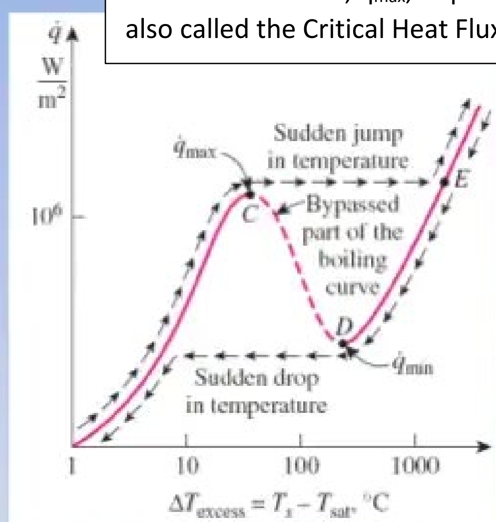
Fluid–Heating Surface Combination	C_{sf}	n
Water–copper (polished)	0.0130	1.0
Water–copper (scored)	0.0068	1.0
Water–stainless steel (mechanically polished)	0.0130	1.0
Water–stainless steel (ground and polished)	0.0060	1.0
Water–stainless steel (teflon pitted)	0.0058	1.0
Water–stainless steel (chemically 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

Burnout and Critical Heat Flux (CHF)

Burnout Phenomenon

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

The max. heat flux, q_{max}, at point C is also called the Critical Heat Flux or CHF.



In such as nuclear reactors, heat flux varies with wall superheat as shown by dark arrows, with a sudden jump from C to E.

In such as steam generators, a red boiling curve applies without any jump from C to E.

Critical Heat Flux in Nucleate or Pool Boiling

C_{cr} is a constant whose value depends on the heater geometry, but generally is about 0.15.

- The CHF is independent of the fluid–heating surface combination, as well as the
- The CHF increases with up to about one-third of the critical pressure, and then starts to decrease and becomes zero at the critical pressure.
- The CHF is proportional to h_{fg}, and large maximum heat fluxes can be obtained using fluids with a large such as

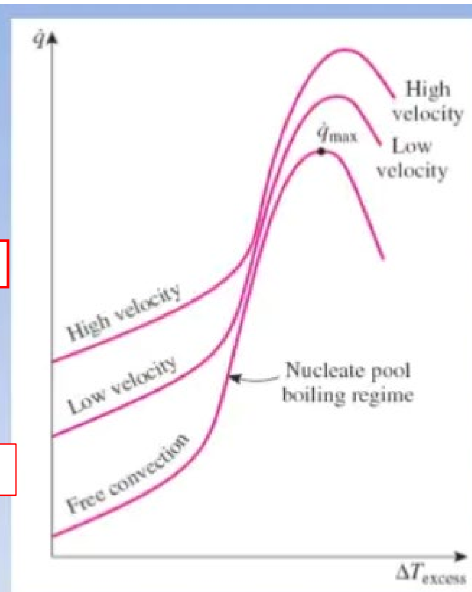
Values of the coefficient C_{cr} for use in Eq. 10–3 for maximum heat flux (dimensionless parameter $L^* = L[g(\rho_l - \rho_v)/\sigma]^{1/2}$)

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

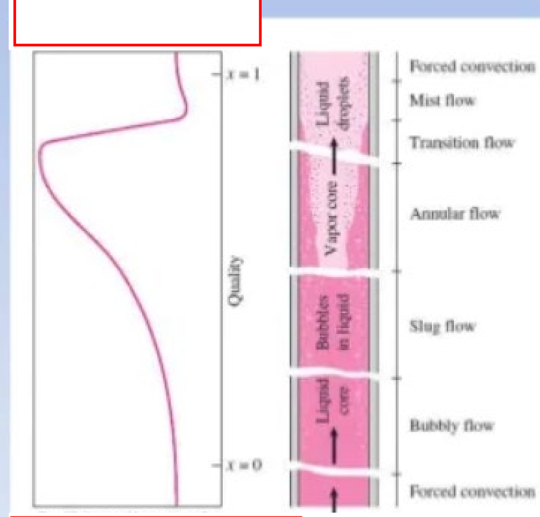
FLOW BOILING

- 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
  and
- *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 or lower? nucleate boiling heat flux and the critical heat flux.
- *Internal flow boiling*, commonly referred to as , 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.



Flow Boiling and Two-Phase Flow in a Heated Tube

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



water

Flow Boiling and Two-Phase Flow