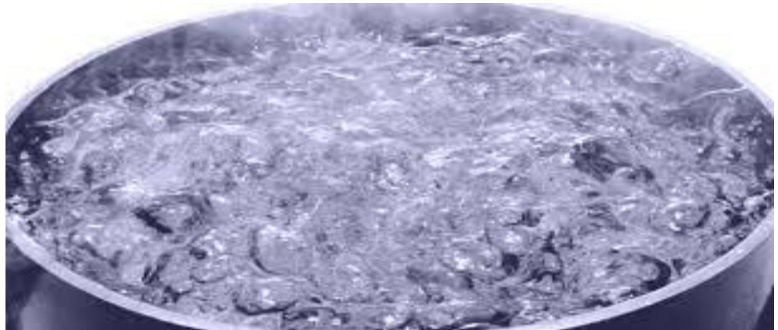
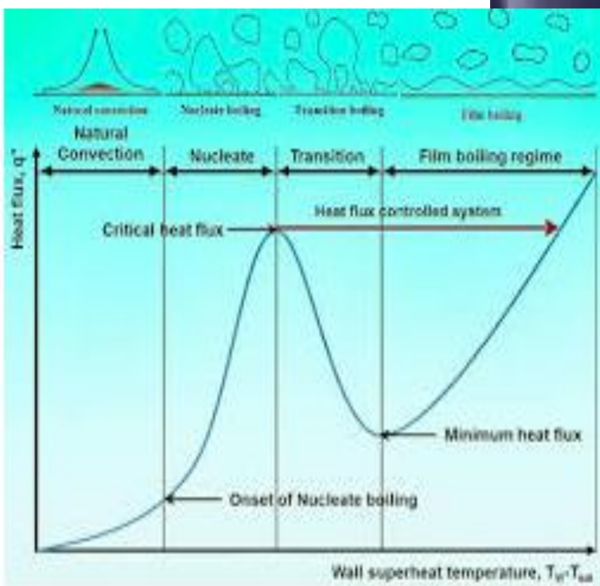




Boiling

Prof. Dr. Majid

Boiling

- **pool boiling** is the boiling of stationary fluids. In pool boiling, the fluid is not forced to flow by a mover such as a pump, and any motion of the fluid is due to natural convection currents and the motion of the bubbles under the influence of buoyancy. As a familiar example of pool boiling, consider the boiling of tap water in a pan on top of a stove. The water is initially at about 15°C, far below the saturation temperature of 100°C at standard atmospheric pressure

- Boiling Regimes and the Boiling Curve

-A natural convection until boiling

A-C nucleate boiling

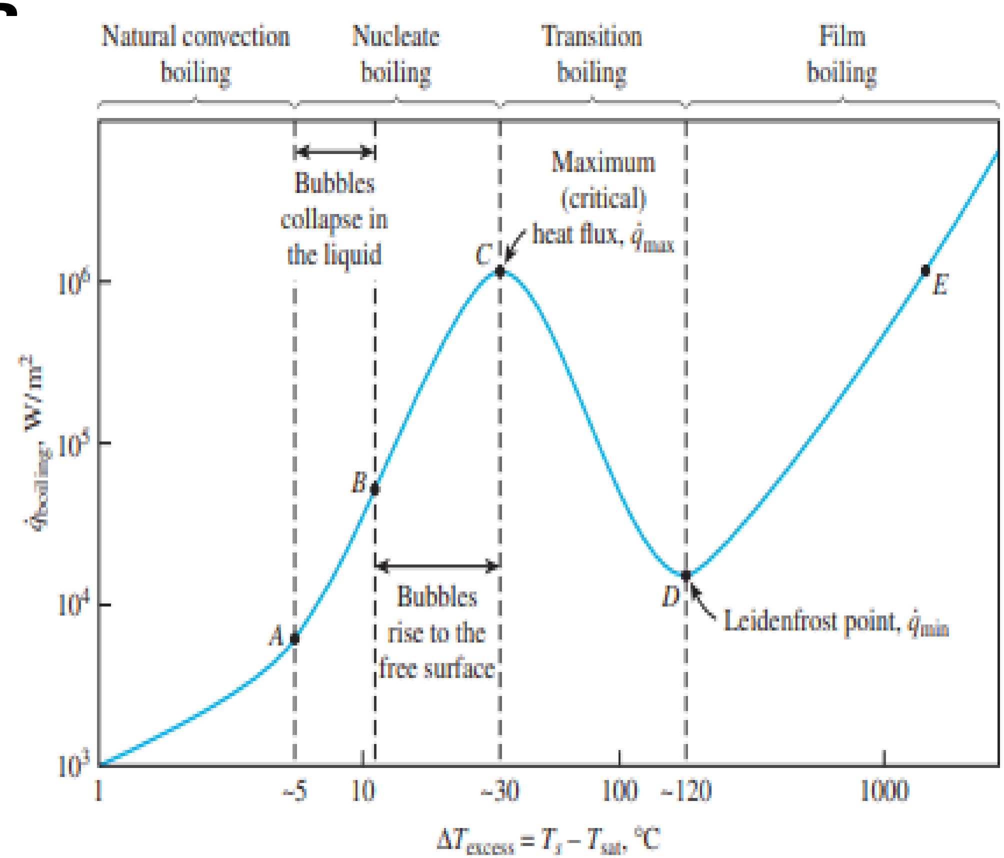
Transition Boiling

(between Points C

and D)

Film Boiling

(beyond Point D)



Heat Transfer Correlations in Pool Boiling

For Nucleate Boiling

Nucleate boiling regime is between $(5^o C \leq \Delta T_{excess} \leq 30^o C)$

$$\dot{q}_{nucleate} = \mu_f h_{fg} \left[\frac{g(\rho_f - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{Cp_f (T_w - T_{sat})}{C_{sf} h_{fg} Pr_f^n}\right]^3$$

Where $\dot{q}_{nucleate} = nucleate\ boiling\ heat\ flux$ W/m^2

μ_f = viscosity of liquid kg/m.sec, h_{fg} =enthalpy of evaporation J/kg

$\rho_f, \rho_v = density\ of\ liquid\ and\ vapor\ respectively\ in\ kg/m^3$

σ= surface tension of liquid-vapor interface N/m

cp_f =specific heat of liquid J/kg.$^o C$, T_w =surface temperature of heater .$^o C$

T_{sat}=saturation temperature of fluid .$^o C$, Pr_f = Prandtl Number of liquid

C_{sf} = experimental constant that depends on surface-fluid compensation

n= experimental constant that depends on the fluid, n=1 for water and 1.7 for other liquids.

- ## Peak Heat Flux

- The maximum (or critical) heat flux in nucleate pool boiling was determined theoretically by S. S. Kutateladze in Russia in 1948 and N. Zuber in the United States in 1958 using quite different approaches, and is expressed as

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

- Where $C_{cr} = constant$ whose value depend on heater geometry
- $C_{cr} = 0.131$ for large horizontal cylinders and sphere
- $C_{cr} = 0.149$ for large horizontal plate

- ## Minimum Heat Flux

- Zuber [10] used stability theory to derive the following expression for the minimum heat flux .

- $$\dot{q}_{min} = 0.09 \rho_v h_{fg} \left[\frac{\sigma g(\rho_f - \rho_v)}{(\rho_f + \rho_v)^2}\right]^{1/4} \qquad (3)$$

Film Boiling TheNusult number for film boiling on a horizontal cylinder or sphere of diameter D is given by

$$\overline{Nu}_D = \frac{\bar{h}D}{k_v} = C\left[\frac{g\rho_v(\rho_f-\rho_v)h'_{fg}}{\mu_f}\right]^{1/4} \qquad (4)$$

Where $k_v$is the thermal conductivity of the vapor in W/m.K and

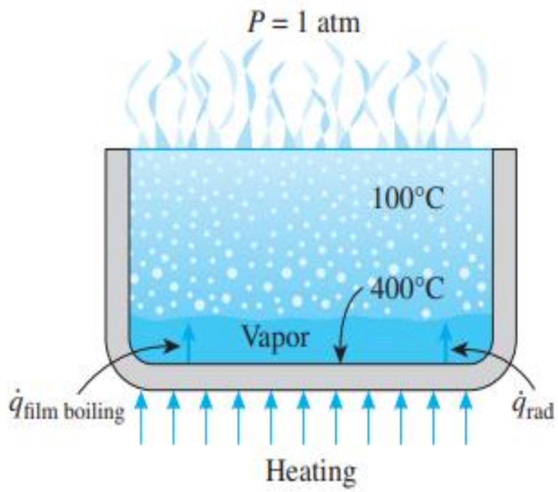
$$C = \begin{Bmatrix} 0.62\ for\ horizontal\ cylinder \\ 0.67\ for\ spheres \end{Bmatrix}$$

In film boiling the heat transfer by radiation

Is be considered

$$q_{film} = \bar{h}(T_w - T_{sat}) \qquad (5)$$

$$\dot{q}_{rad} = \varepsilon\sigma(T_w^4 - T_{sat}^4) \qquad (6)$$



Where ε is emissivity of the heating surface

And $\sigma = 5.67 \times 10^{-8} W/m^2K^4$

And temperature here in K not .$^o C$

$$\dot{q}_{tot} = \dot{q}_{film} + \frac{3}{4}\dot{q}_{rad} \qquad (7)$$

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

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

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

Surface tension of some fluids (from Suryanarayana, 1995, originally based on data from Jasper, 1972)

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:	$0.0092 - 0.000087T$

Example.1 The bottom of a copper pan, 150 mm in diameter, is maintained at 115°C by the heating element of an electric range. Estimate the power required to boil the water in this pan. Determine the evaporation rate. What is the ratio of the surface heat flux to the critical heat flux? What pan temperature is required to achieve the critical heat flux?

Solution: D=150mm=0.15m copper pan T_w=115°C, T_{sat}=100°C at 1atm

Requirements: 1-Power required to boil the water, 2- evaporating rate, 3- ratio of surface heat flux to the critical heat flux. 4- the temperature required to achieve the critical heat flux.

- **Properties:** the properties of water at 100°C, ρ_f=957.9kg/m^3, ρ_v=0.5978kg/m^3, h_{fg}=2257kJ/kg, cp_f=4217J/kg.K, k_f=0.679W/m.K, μ_f=0.282x10^{-3}kg/m.sec, Pr=1.75, C_{sf}=0.0128, n=1.0, σ=0.0589N/m.
- **Analysis:** The heat flux for boiling is
- $\dot{q}_{nucleate} = \mu_f h_{fg}\left[\frac{g(\rho_f - \rho_v)}{\sigma}\right]^{1/2}\left[\frac{cp_f(T_w - T_{sat})}{C_{sf} h_{fg} Pr_f^n}\right]^3$
- $\dot{q}_{nucleate} = 0.282 \times 10^{-3} \times 2257$ $\times 10^3 \left[\frac{9.81(957.9 - 0.5978)}{0.0587}\right]^{1/2}\left[\frac{4217(115 - 100)}{0.0128 \times 2257 \times 10^3 1.75^{1.0}}\right]^3$ $= 498616 W/\text{m}^2$

- The heat of nucleation
- $\dot{Q} = \frac{\pi}{4} D^2 \dot{q}_{nucleate} = \frac{\pi}{4}(0.15)^2 \times 498616$ $= 8811.28W$
- Mass of water evaporation
- $\dot{m}_s = \frac{\dot{Q}}{h_{fg}} = \frac{8811.28}{2257\times10^3} \times 3600 = 14.0kg/hr$
- The maximum heat flux:
- $\dot{q}_{max} = Ch_{fg}\rho_v \left[\frac{\sigma g(\rho_f - \rho_v)}{\rho_v^2}\right]^{1/4}$
- $\dot{q}_{max} = 0.149 \times 2257 \times 10^3$ $\times 0.5978 \left[\frac{0.0589\times9.81(957.9-0.5978)}{(0.5978)^2}\right]^{1/4} = 1260.968kW$ /m²
- $\frac{\dot{q}_{nucleate}}{\dot{q}_{max}} = \frac{498616}{1260968.1} = 0.395$

- For maximum heat flux $\dot{q}_{max}$

$$= \mu_f h_{fg} \left[\frac{g(\rho_f - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{cp_f (T_w - T_{sat})}{C_{sf} h_{fg} Pr_f^n}\right]^3$$

- $\dot{q}_{nucleate} = 0.282 \times 10^{-3} \times 2257$

$$\times 10^3 \left[\frac{9.81(957.9 - 0.5978)}{0.0587}\right]^{1/2} \left[\frac{4217(T_w - T_{sat})}{0.0128 \times 2257 \times 10^3 1.75^{1.0}}\right]^3$$

$$= 1260968.1$$

- $\Delta T_e = 20.43^o C$