Pool Boiling Heat Transfer

by

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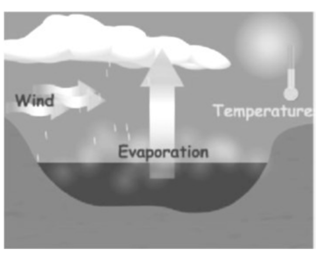
Evaporation and Boiling



- Evaporation: process of conversion of the liquid phase to vapor phase at an interface
- concentration difference between the liquid phase and its vapor;
- The overall system pressure may or may not not correspond to the saturation temperature. e.g., water evaporation into the atmosphere of a room where the relative humidity is less than 100 %.

- Boiling: liquid evaporates and forms vapor pockets or regions within the continuous liquid phase.
- The liquid-vapor system temperature corresponds to the existing saturation vapor pressure (The liquid is heated above the saturation temperature)

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Pool boiling – Basic characteristics

Boiling at the surface of a body immersed in an extensive pool of motionless liquid is generally referred to as pool boiling

Applications:

Metallurgical quenching
Shell side boiling in an heat exchanger (flooded type)
Electronics cooling
Making tea!!

The process is affected by:

Applied heat flux/ Degree of superheat

Thermophysical properties of the fluid

The surface material

and surface finish

The length scale of the heater

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Boiling and its classification

When a liquid is in contact with a surface maintained at a temperature above the saturation temperature of the liquid, boiling will eventually occur at that liquid-solid interface.

MECHANISM

- **Nucleate Boiling: vapor bubbles are formed – typically on solid surfaces**
- **Convective boiling: thin film evaporation – no bubbles**
- **Film boiling: blanket of vapor on the heated surface**

GEOMETRIES

- **Pool Boiling: boiling on a solid surface in a stagnant liquid**
- **Flow boiling: boiling in channels where liquid is pumped**

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Dimensionless parameters

$$h = f(\Delta T, g(\rho_l - \rho_g), h_{fg}, \sigma, L, \rho, c_p, k, \mu)$$

$$\frac{hL}{k} = f\left[\frac{\rho \cdot g(\rho_l - \rho_g)L^3}{\mu^2}, \frac{c_p \Delta T}{h_{fg}}, \frac{\mu c_p}{k}, \frac{g(\rho_l - \rho_g)L^2}{\sigma}\right]$$

$$Nu_{liquid} = f\left[\frac{\rho \cdot g(\rho_l - \rho_g)L^3}{\mu^2}, \ Ja, \ Pr, \ Bo\right]$$

Strong resemblance to Grashof number

Effect of buoyancy induced fluid motion

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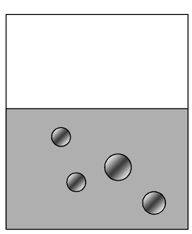
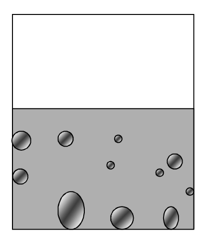
Type of nucleation



Homogeneous Nucleation

Heterogeneous Nucleation



Bubble nucleation completely within a superheated liquid

(OR droplet formation completely within supersaturated vapor)

Bubble nucleation at the interface of a solid in contact with a superheated liquid

(OR droplet formation at the solid - vapor interface)

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Nucleation sites and cavities

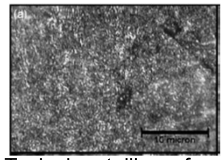
Cavities may be classified into the following categories:

(1) Cavities that trap only gas

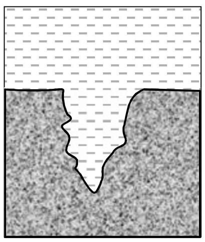
(2) Cavities that trap only liquid

(3) Cavities that trap both liquid and gas

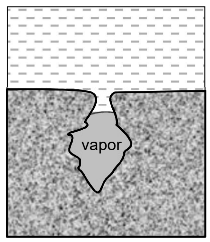
(4) Cavities that trap neither liquid nor vapor



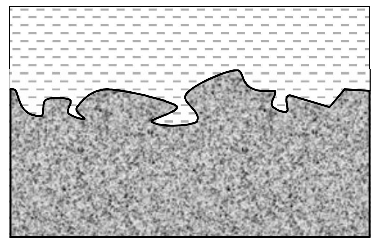
Typical metallic surface (copper)



Wetted cavity with no trapped vapor



Reentrant cavity with trapped vapor



Enlarged profile of a roughened surface

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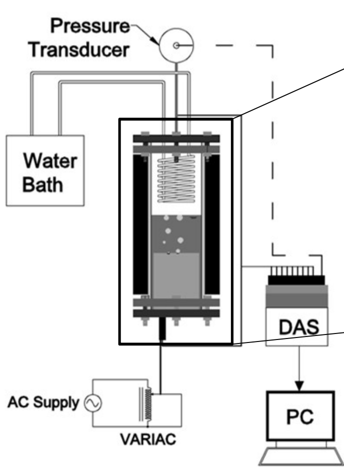
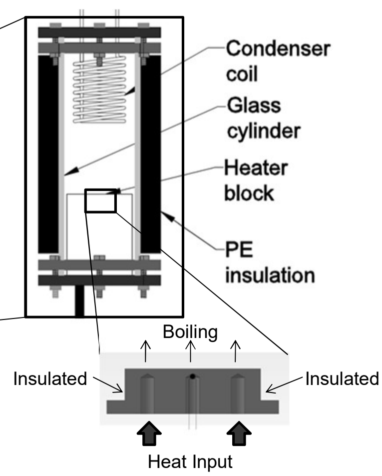
Experimental setup



Schematic diagram



Boiling surface (Al, φ30 mm)

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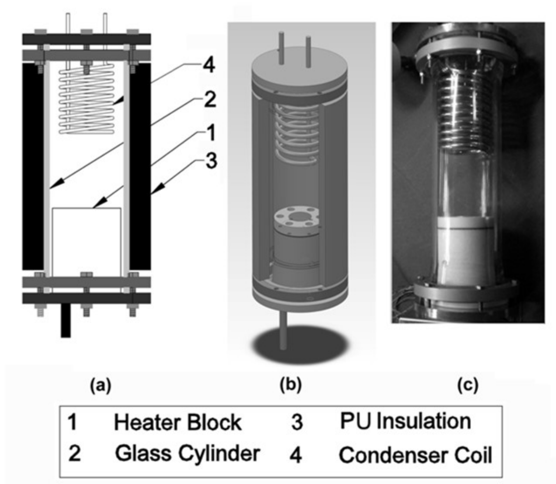
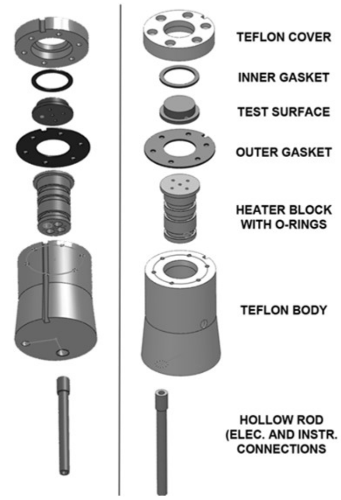


Boiling pressure vessel



Heater block design

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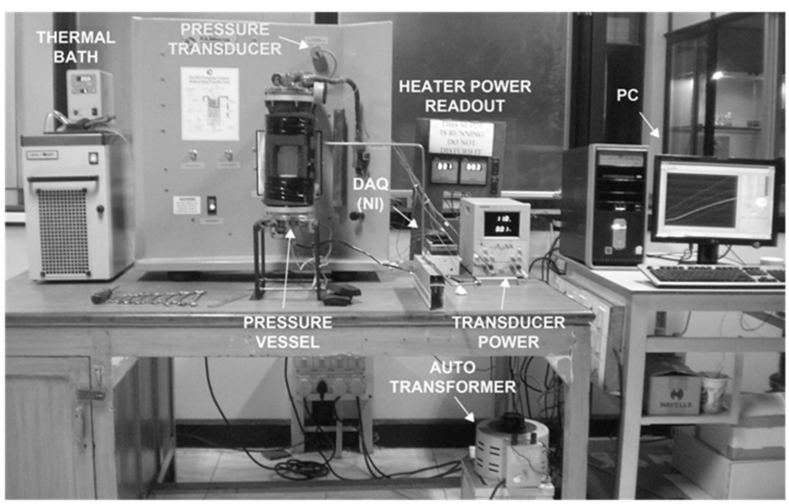
Experimental setup



Photograph of the actual setup

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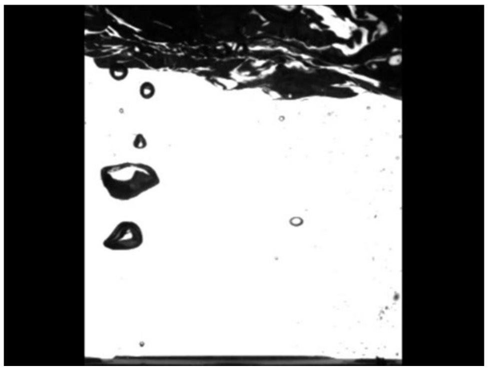
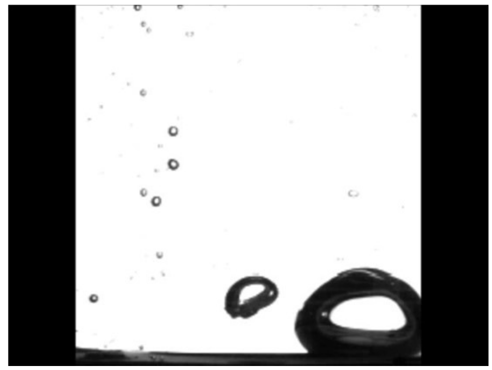
Bubble growth in pure water

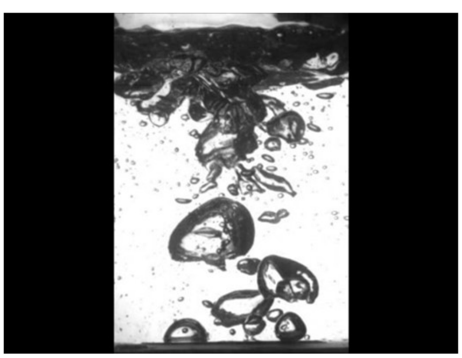


Bubble behaviour on smooth for pure water for T_{sat} = 50°C, q" = 0.046 MW/m^2



Bubble behaviour over smooth for pure water for T_{sat} = 30°C, q" = 0.055 MW/m^2

Bubble growth –Surface roughness



Ra = 0.8 µm

Ra = 20 µm

Bubble behaviour for 25.0% ethanol-water for T_{sat} = 60°C, q" = 0.098 MW/m^2

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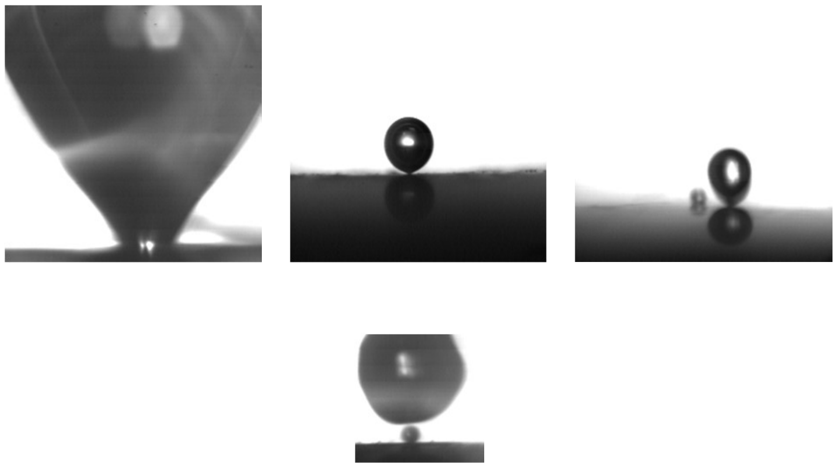
Bubble growth near heated surfaces



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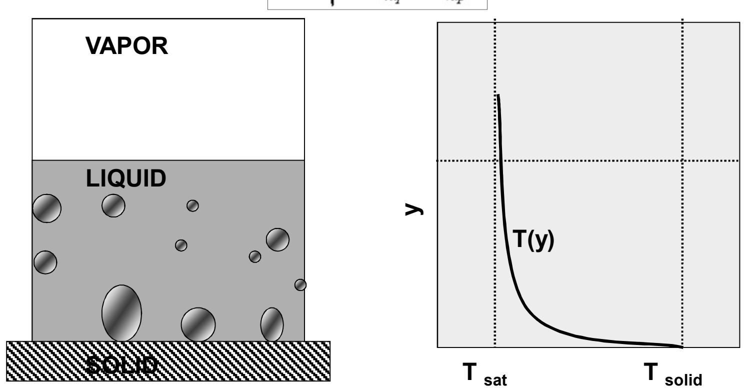
Temperature distribution in saturated pool boiling

We shall first restrict our attention to well wetted liquids and heaters having dimensions large as compared to the length scale defined by

$$L_b = \sqrt{\frac{\sigma}{g(\rho_{liq} - \rho_{vap})}}$$



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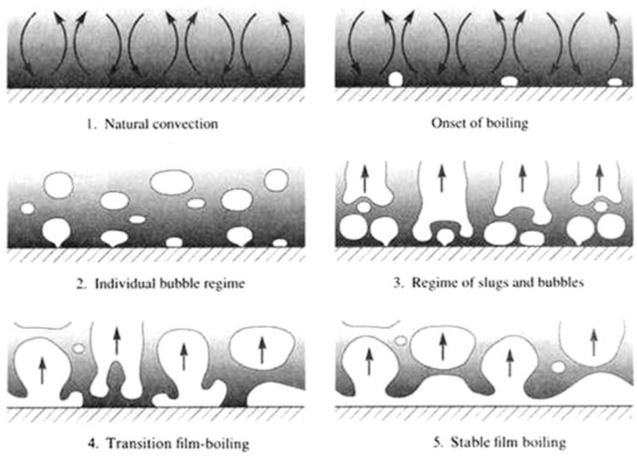
Regimes of pool boiling



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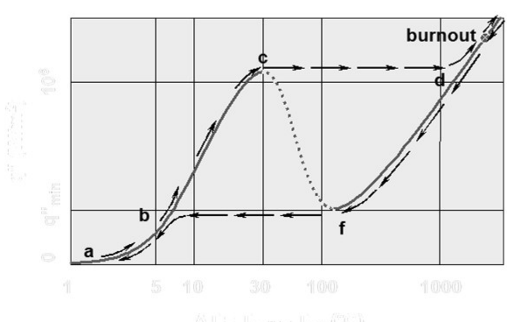

a-b: Natural convection – Single phase – no boiling

b-c: Nucleate boiling regime
c-f: Transition boiling
f-d-e: Film boiling

b: onset of nucleate boiling
c: burnout point
f: minimum film boiling point

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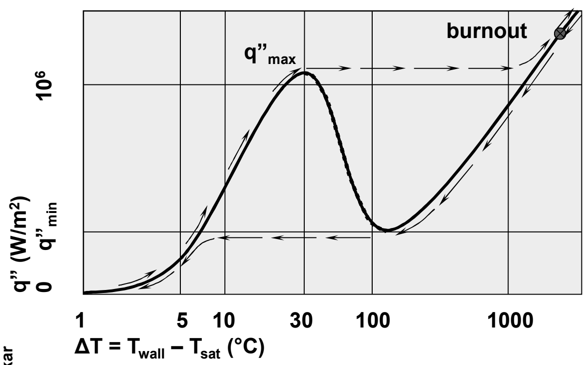
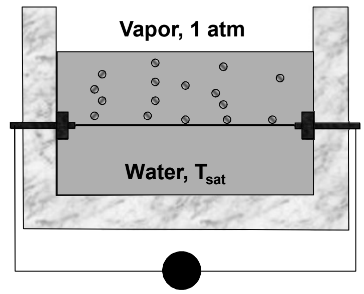
Nukiyama´s Boiling Curve





Two ways to do the experiment

- Constant heat flux
- Constant temperature

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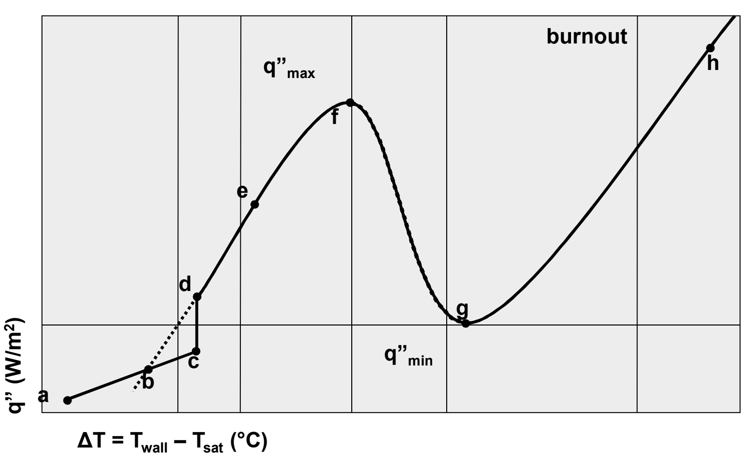
Constant temperature



a-b: natural convection; C:ONB; d-e: isolated bubble;
e-f: slugs and bubbles; f-g: transition boiling

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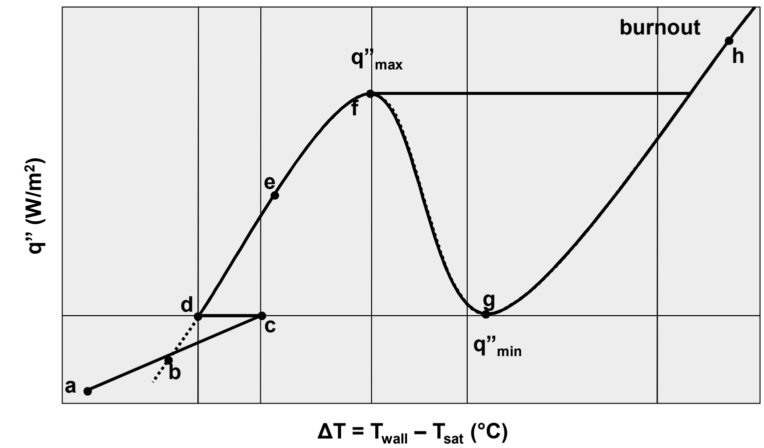
Constant heat flux



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Nucleate Pool Boiling

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Nucleation site density

Nucleation site density depends on:

- Surface morphology
- Thermophysical properties of the fluid
- Imposed pressure and flow conditions
- Wetting characteristics of the liquid-surface combination

In general

$$q'' \propto (\text{site density})^a (T_w - T_{sat})^b$$

$a \approx 0.3$ and 0.5

$b \approx 1$ to 1.8

$$q'' \propto (T_w - T_{sat})^c$$

where

c is around 3

! The values of a, b and c are still being debated !

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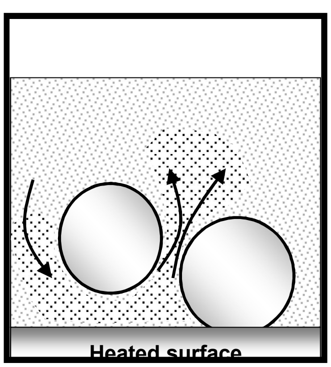
Mechanisms of Nucleate boiling heat transfer

The primary mechanisms of nucleate heat transfer boiling are identified as follows



(1) Bubble Agitation Model

- Systematic pumping action of growing and departing bubbles agitates the liquid
- Liquid gets pushed back and forth on the heater surface
- This transforms the otherwise natural convection which was going on into a forced convection process
- Sensible heat is transferred away in the form of superheated liquid

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Mechanisms of Nucleate boiling heat transfer

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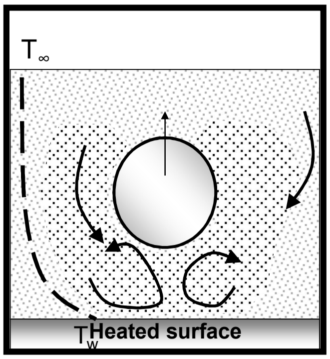
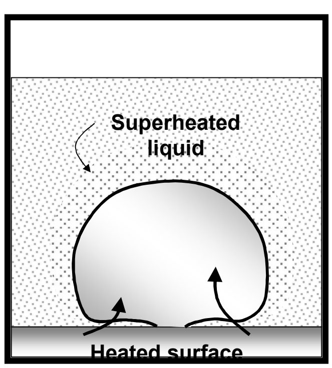


(2) Vapor Liquid Exchange Model

- Wake of the departing bubbles removes the thermal boundary layer from heated surface
- This creates the cyclic thermal boundary layer stripping process
- Sensible heat is transferred away in the form of superheated liquid
- Main parameters of interest are the thickness of the layer, mean temperature, area of boundary layer removed by the departing bubble, departure frequency and nucleation site density

Mechanisms of Nucleate boiling heat transfer

The primary mechanisms of nucleate boiling heat transfer are identified as follows



(3) Evaporative mechanism

- Heat is conducted to the thermal boundary layer and then to the bubble interface, where it is converted to latent heat
- Macro-evaporation occurs on the top interface of the bubble, while micro-layer evaporation occurs underneath the bubble across the trapped liquid layer trapped between the bubble and the heat surface
- Natural convection also occurs in the inactive areas of the bubble where no nucleation sites are active.

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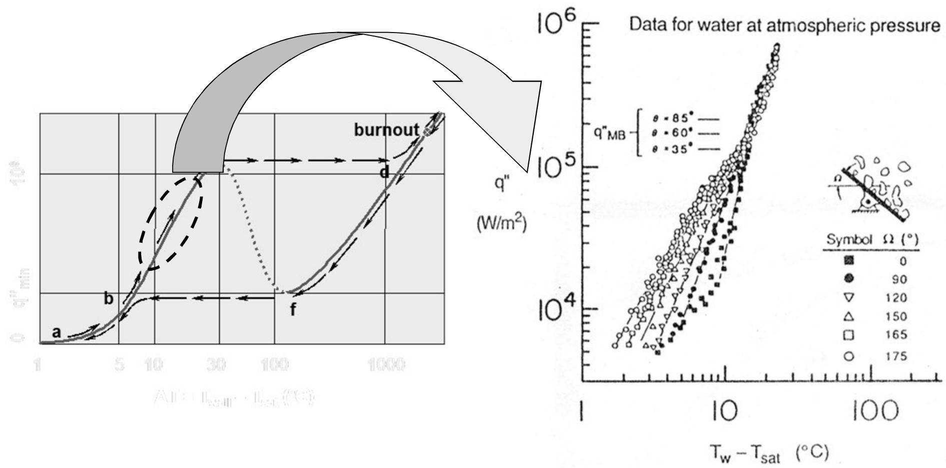
Typical data for the nucleate pool boiling of water



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General observations

It is evident that it will be difficult to obtain any general theoretical method of calculating heat transfer coefficients in nucleate boiling

The main reason is that boiling occurs in preferred nucleation sites which depend on:

- **Physical condition and preparation of the surface**
- **How well the liquid wets the surface**
- **How are cavities trapping gas/vapor**

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General observations

Most models suggest a power law dependence of nucleate boiling heat flux on the nucleation site density and the wall superheat

$$q'' \propto \left(n'_a\right)^x \left(T_w - T_{sat}\right)^y$$

Depending on the models

x = 0.2 to 0.8

y = 1 to 1.8

If we take a general engineering surface, then for most systems,

$$q'' \propto \left(T_w - T_{sat}\right)^a$$

where

$$a \approx 3.0 \text{ to } 3.33$$

Modeling is difficult because

- active nucleation site density

- bubble departure diameter/frequency

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General observations

Assuming

$$q'' \propto \left(T_w - T_{sat}\right)^a = \left(\Delta T\right)_{sat}^a$$

As we can also write
(assuming a linear model for heat transfer)

$$q'' = h \cdot \left(T_w - T_{sat}\right) = \left(\Delta T\right)_{sat}$$

Substituting from above, we get

$$h \propto \left(T_w - T_{sat}\right)^{a-1} = \left(\Delta T\right)_{sat}^{a-1}$$

or

$$h \propto \left(q''\right)^{\frac{a-1}{a}}$$

$$\Rightarrow$$

$$\left(\frac{a-1}{a}\right) = 0.666 \text{ if } a = 3.0$$

$$\left(\frac{a-1}{a}\right) = 0.7 \text{ if } a = 3.33$$

The ensuing heat transfer coefficient is quite high in nucleate boiling

How to estimate this heat transfer coefficient?

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General observations

Two practical approaches to the estimation of heat transfer coefficient are possible:

(**a**) Somehow include the effect of the surface texture and wettability details

(b) Ignore all surface effects and produce a method which predicts a value of heat transfer coefficient for a given applied heat flux

Usually a hybrid technique needs to be applied

Rohsenow Model (1962)

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Development of Rohsenow model

Main idea of the model goes back to Jakob and Linke (1935)

- **Nucleating bubbles induce motion to surrounding fluid**
- **This, in turn, increases the convective heat transfer**

So, taking basic idea from a convective transport theory

$$\mathrm{Nu} = \frac{hL_b}{k_l} = C \cdot \mathrm{Re}_b^n \cdot \mathrm{Pr}^m$$

where L_b is an appropriate bubble length scale, and

$$\mathrm{Re}_b = \frac{\rho_v U_b L_b}{\mu_l}$$

Now we must find a suitable length scale and a velocity scale for the problems and the correlation can be cast

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Development of Rohsenow model

Rohsenow adopted the length scale to be bubble departure diameter and the velocity scale to be the vapor superficial velocity

$$L_b = D_d = \left[\sqrt{2} \cdot (C_b \theta)\right] \cdot \left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2} \quad \text{and} \quad U_b = \left(\frac{q''}{\rho_v h_{fg}}\right)$$

If we define the heat transfer coefficient as,

$$h = \left(\frac{q''}{T_w - T_{sat}(P_l)}\right)$$

Then substituting these equations in the Nusselt Number Equation, we get the final form of the Rohsenow correlation

$$\mathrm{Nu} = \frac{hL_b}{k_l} = C \cdot \mathrm{Re}_b^n \cdot \mathrm{Pr}^m \quad \text{where } \mathrm{Re}_b = \frac{\rho_v U_b L_b}{\mu_l}$$

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Development of Rohsenow model

$$\left(\frac{q''}{\rho_v h_{fg}}\right)\left[\frac{\sigma}{g(\rho_l - \rho_v)}\right]^{1/2} = \left(\frac{1}{C_{surface}}\right)^{1/r}\left(\frac{C_{pl}\left[T_w - T_{sat}(P_l)\right]}{h_{fg}}\right)^{1/r} Pr_l^{-s/r}$$

The above equation requires the knowledge of the liquid-solid surface dependent constant $C_{surface}$

Original suggested values

r = 0.33 and s = 1.7

(for water s = 1.0)

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Value of Surface constant for Rohsenow Correlation

Liquid –surface combination	C_{sf}
Water on Teflon pitted stainless steel	0.0058
Water on scored copper	0.0068
Water on ground and polished stainless steel	0.0080
Water on polished copper	0.0128
Water on chemically etched stainless steel	0.0133
Water on mechanically polished stainless steel	0.0132
Water on emery polished , paraffin treated copper	0.0147
$_{n-}$pentane on lapped copper	0.0049
$_{n-}$pentane on emery polished nickel	0.0127
$_{n-}$pentane on emery polished copper	0.0154
Carbon tetrachloride on emery polished copper	0.0070

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End of Lecture

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