# Heat Transfer Boiling

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Boiling is the transition from liquid to vapor via formation (or nucleation) of bubbles. It typically requires heat addition. The heat required to vaporize a unit mass of liquid is latent heat of vaporization.

- 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.
- Conventionally, based on the relative bulk motion of the body of a liquid to the heating surface, the boiling is divided into two categories:
  - pool boiling, and
  - convective boiling



Pool boiling is a process in which the heating surface is submerged in a large body of stagnant liquid. The relative motion of the vapor produced and the surrounding liquid near the heating surface is due primarily to the buoyancy effect of the vapor. Nevertheless, the body of the liquid as a whole is essentially at rest.



# Pool Boiling (contd..)

By force balance, it can be shown that the vapor pressure within the bubble must be somewhat higher than the pressure of the surrounding liquid. It follows that the vapor (and liquid) temperature must be somewhat higher than the saturation temperature,  $T_{sat}$ , corresponding to the liquid (or system) pressure. Using the Clausius-Clapeyron equation to relate saturation temperatures and pressures, it can then be shown that the magnitude of the superheat ( $T_{nucleation} - T_{sat}$ ) required to sustain the bubble is inversely proportional to the radius of the bubbles,  $r_{bubble}$ :

$$T_{
m nucleation} - T_{
m sat} \propto rac{1}{r_{
m bubble}}$$

This shows that the smaller the bubble, the higher is the superheat required for nucleation



# Pool Boiling (contd..)

The boiling process consists of the following steps:

- 1. Nucleation
- 2. Bubble growth
- 3. Bubble departure from the surface
- 4. Collapse or further growth depending upon whether the bubble liquid is sub-cooled or super heated





Typical boiling curve for water at 1 atm. Note: the *x*-scale is logarithmic!



Though the study on the boiling process can be traced back to as early as the eighteen century (the observation of the vapor film in the boiling of liquid over the heating surface by Leiden in 1756), the extensive study on the effect of the very large difference in the temperature of the heating surface and the liquid,  $\Delta T$ , was first done by Nukiyama (1934). However, it was the experiment by Farber and Scorah (1948) that gave the complete picture of the heat transfer rate in the pool boiling process as a function of  $\Delta T$ . Applying the Newton's law of cooling,  $q = h\Delta T$ , the heat transfer coefficient, h, was used to characterize the pool boiling process over a range of  $\Delta T$  by Farber and Scorah as illustrated by the boiling curve in the following figure.





Experimental Observations of Farber and Scorah



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Farber and Scorah conducted their experiments by heating the water at various pressures with a heated cylindrical wire submerged horizontally under the water level. From the results, they divided the boiling curve into 6 regions based on the observable patterns of vapor production.

**Region I**:  $\Delta T$  is so small that the vapor is produced by the evaporation of the liquid into gas nuclei on the exposed surface of the liquid.

**Region II**:  $\Delta T$  is large enough that additional small bubbles are produced along the heating surface but later condense in the region above the superheated liquid.

**Region III**:  $\Delta T$  is enough to sustain "nucleate boiling", with the creation of the bubbles such that they depart and rise through the liquid regardless of the condensation rate.

**Region IV**: an unstable film of vapor was formed over the heating surface, and oscillates due to the variable presence of the film. In this region, the heat transfer rate decreases due to the increased presence of the vapor film.

**Region V**: the film becomes stable and the heat transfer rate reaches a minimum point.

**Region VI**: Here,  $\Delta T$  is very large, and "film boiling" is stable such that the radiation through the film becomes significant and thus increases the heat transfer rate with the increasing  $\Delta T$ .







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The Rosenhow correlation is a popular tool to predict nucleate boiling heat transfer:

$$h = \mu_l \lambda \left[ \frac{g(\rho_l - \rho_g)}{\sigma} \right]^{0.5} \left[ \frac{C_{Pl}}{C_{sf} \lambda Pr_l} \right]^3 (T_w - T_{sat})^2$$

In this correlation  $\Pr_I$  is the Prandtl number for the liquid and  $C_{sf}$  is an empirical coefficient which depends on the fluid/surface combination. For example, for water on polished stainless steel the recommended value for  $C_{sf}$  is 0.013.  $C_{sf}$  is meant to capture the effect of surface (micro-cavities) on nucleate boiling.  $\sigma$  - surface tension of liquid vapor interface. The subscripts *I*-refer to liquid; *g* refer to vapor.



The critical (and hence the maximum) heat flux is given by

$$q_{\sf max} = 0.18 
ho_g \lambda \left[ rac{g \sigma(
ho_l - 
ho_g)}{
ho_g^2} 
ight]^{1/4}$$

It is very desirable to be able to operate heat exchange equipment in upper end of nucleate boiling regime. Here the temperature difference is low while the heat flux is very high. Heat transfer coefficients in this range are enormous. However, it is very dangerous to run equipment near  $q_{max}$  in systems for which q is the independent variable (as in nuclear reactors).



If *q* is raised beyond the upper limit of the nucleate boiling regime, such a system will suffer a sudden and damaging increase of temperature. This transition is known by a variety of names: the burnout point (although a complete burning up or melting away does not always accompany it); the peak heat flux (a modest descriptive term); the boiling crisis (a Russian term); the DNB, or departure from nucleate boiling, and the CHF, or critical heat flux (terms more often used in flow boiling); and the first boiling transition (which term ignores previous transitions).



# Flow Boiling





Consider a vertical channel of arbitrary cross-sectional shape (i.e., not necessarily circular) uniformly heated (axially as well as circumferentially) by a heat flux q. At axial locations below the onset of nucleate boiling, the flow regime is single-phase liquid. As the fluid marches up the channel, more and more vapor is generated because of heat addition. As a result, the flow regime goes from bubbly flow (for relatively low values of flow quality) to plug (intermediate quality) and annular (high quality). Eventually, the liquid film in contact with the wall dries out. In the region beyond the point of dryout, the flow regime is mist flow and finally, when all droplets have evaporated, single-phase vapor flow.



**Example 1**: Critical Heat Flux and Critical Temperature Difference

For water boiling at 1 atm at  $100^{\circ}$ C determine the value of excess temperature in the film nucleate boiling region for a heat flux equal to the critical heat flux for this condition. (AU-Apr-2017)

#### Solution:

Heat transfer correlations and data from: Heat and Mass Transfer Data Book (7th ed.) – C. P. Kothandaraman & S. Subramanyan From page no. 143: Critical heat flux  $(q_c)$  is given by

$$q_c = 0.18\lambda \,\rho_{\nu} \left[ \frac{\sigma g(\rho_l - \rho_{\nu})}{\rho_{\nu}^2} \right]^{0.25} \tag{1}$$

where, the properties are evaluated at  $(T_w + T_{sat})/2$ . Given:  $T_{sat} = 100^{\circ}$ C. Since, we don't know  $T_w$ , we shall assume that  $T_w = 150^{\circ}$ C, and proceed with. Hence, we need to get the fluid properties at  $(150 + 100)/2 = 125^{\circ}$ C. From the data book, (page no. 147)

 $\sigma = \text{surface tension of water with its vapor} = \frac{0.0589 + 0.0487}{2}$ 

= 0.0538 N/m

From Steam Tables, at  $125^{\circ}\mathrm{C}$ 

 $ho_{
m v}=$  density of water vapor (i.e., steam) = 1.299 kg/m<sup>3</sup>

 $\rho_I = \text{density of liquid water} = 939 \text{ kg/m}^3$ 

 $\lambda = {\rm latent}$  heat of vaporization of water = 2188000  $\rm J/kg$ 

Substituting these in Eqn.(1), we get

$$q_c = 0.18 imes 2188000 imes 1.299 imes \left[ rac{0.0538 imes 9.812 imes (939 - 1.299)}{1.299^2} 
ight]^{0.25}$$

= **2117266** W/m<sup>2</sup>

## Solved Problem (contd..)

From the data book, (page no: 143), for the nucleate pool boiling,

$$q = \mu_l \lambda \left[ g \frac{(\rho_l - \rho_v)}{\sigma} \right]^{0.5} \left[ \frac{C_{Pl}}{C_{sf} \lambda \operatorname{Pr}} \right]^3 (\Delta T)^3$$
(2)

From page no. 22, of data book, we get

 $\nu_{\rm I} = {\rm kinematic \ viscosity \ of \ liquid \ water} = 0.23 \times 10^{-6} \ {\rm m}^2/{\rm s}$  From which,

$$\mu_I = \nu_I \rho_I = 0.23 \times 10^{-6} \times 939 = 2.2 \times 10^{-4} \text{ kg/m.s}$$

Data for liquid water from data book: (page no. 22):

 $C_{Pl} = 4266.5 \text{ J/kg.K}$  and  $Pr_l = 1.3435$ 

From page no. 144 of data book,

 $C_{sf} = 0.013$ r. M. Subramanian Boiling

## Solved Problem (contd..)

Substituting the data in Eqn.(2), we get

$$q = 2.2 \times 10^{-4} \times 2188000 \times \left[9.812 \times \frac{(939 - 1.299)}{0.0538}\right]^{0.5} \times \left[\frac{4266.5}{0.013 \times 2188000 \times 1.3435}\right]^3 \times (\Delta T)^3$$
  
= 481.36 × 413.5 × 1.392 × 10<sup>-3</sup> × ( $\Delta T$ )<sup>3</sup> = 277.1( $\Delta T$ )<sup>3</sup>  
Equating q to q<sub>c</sub>, we get

 $2117300 = 277.1 (\Delta T_c)^3 \implies \Delta T_c = 19.7^{\circ} C$ 

Therefore, the excess temperature =  $\Delta T = T_w - T_{sat} = 19.7^{\circ}C$ 

