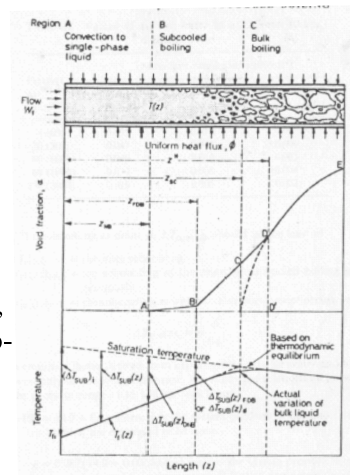
Introduction

- We have previously seen that wall superheat is required to nucleate vapour
- Davis and Anderson criterion was identified as the method to identify the location
- Depending on the heat flux, nucleation will occur in sub-cooled state
- Typical state of the system is as shown in the figure



Introduction

- The sub-cooled boiling heat transfer was divided into fully developed sub-cooled boiling, partial sub-cooled boiling.
- Correlations and methods were identified for computation of heat transfer as a sum of single-phase and two-phase contributions
- Correlations were also identified for saturated boiling, such as the method of Chen

Correlation for NVG-I

- Stanton Number, $St = Nu/(Re\,Pr)$

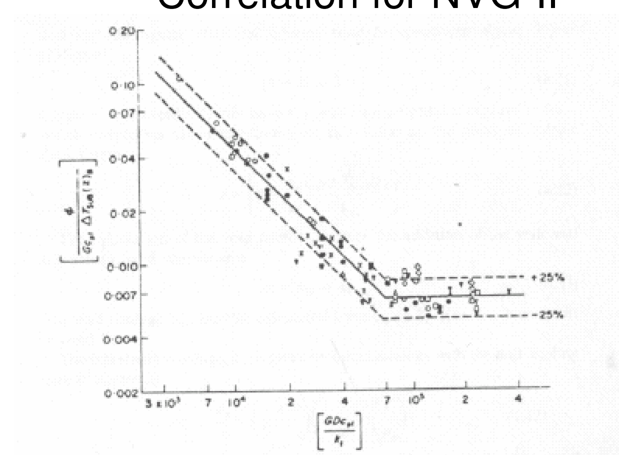
$$St = \frac{hD}{k}\frac{k}{c_p\mu}\frac{\mu}{GD} = \frac{h}{Gc_p} = \frac{q''}{\Delta T G c_p}$$

- Peclet Number, $Pe = Re\,Pr = \frac{c_p\mu}{k}\frac{GD}{\mu} = \frac{GDc_p}{k}$
- Saha and Zuber showed that at high Peclet Number, significant void occurs at Constant St, while the same at lower Peclet occurs at constant Nu

$$\frac{q''}{\Delta T_{sub-NVG} G c_p} = 0.0065 \Rightarrow \Delta T_{sub-NVG} = 153.8\frac{q''}{Gc_p} \qquad \text{Pe > 70000}$$

$$\frac{q'' D}{\Delta T_{sub-NVG} k_f} = 454 \Rightarrow \Delta T_{sub-NVG} = 0.0022\frac{q'' D}{k_f} \qquad \text{Pe < 70000}$$

Correlation for NVG-II



Variation of Non-Eqbm. Quality

- Having predicted the $\Delta T_{sub\ at}$ NVG, we can compute x at NVG using

$$x_{NVG} = \frac{c_p \Delta T_{sub-NVG}}{h_{fg}}$$

- This will be negative as we have assumed equilibrium. However, real quality will start from 0 at this point
- The relation between the real quality and equilibrium quality have been tried in many forms, the most common is the profile fit model

$$x(z) = x_e(z) - x_e(z_{NVG})\text{Exp}\left(\frac{x_e(z)}{x_e(z_{NVG})} - 1\right)$$

- Note that in the above expression $x(z_{NVG}) = 0$ and $x(z)$ will become equal to $x_e(z)$ as x increases to a high value

Behaviour of CHF in Flow Boiling-I

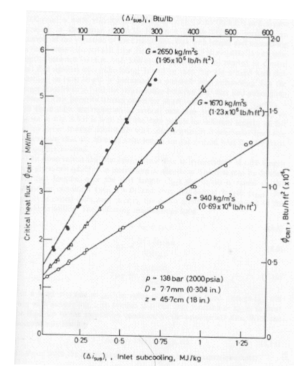
- We now move on to get a glimpse of the behaviour of CHF.
- We shall restrict the discussion to circular duct. Correction factors are available for rod bundles
- CHF will not occur if the wall temperature is below the saturation point
- Similarly, CHF value will be lower than that required to get an exit quality of 1.0
- While some theoretical model exists, these are not universal. Most of the correlations are empirical

Behaviour of CHF in Flow Boiling-II

- CHF is primarily dictated by 5 postulated variables, G, ΔT_{sub}, p, D, z (length)
- From common sense, the CHF would occur at exit for constant heat flux case. Hence exit variables should dictate CHF, i.e., CHF = f (G, h(z), p, D, z) or CHF = f (G, x(z), p, D, z)
- As energy balance will connect the exit state to the inlet state, one can use either of the set of variables
- Let us look at the general parametric trends

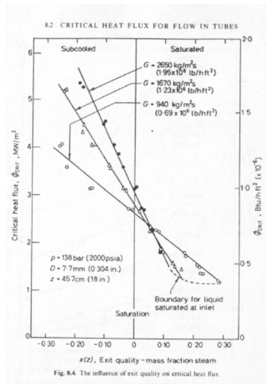
Effect of Inlet Sub-cooling

- Experiments indicate that CHF varies linearly with inlet suc-cooling
- Also at higher mass flux the CHF is higher
- However, the same data replotted as a function of exit quality reveals gives an altogether different conclusion



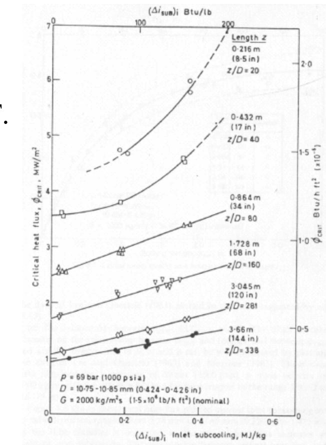
CHF Plotted with Exit Quality

- The CHF varies linearly with exit quality
- There is a crossover of the constant G lines at some positive quality
- Thus, from the graph, the variation of trends of CHF with G at low quality is opposite to that at high quality



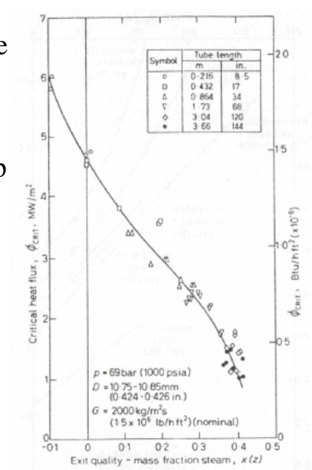
Effect of Length

- The effect of length is given by the data shown
- Higher lengths have lower CHF. This is expected as the power increases with length
- For larger lengths (larger z/D), the variation of CHF with inlet sub-cooling is linear
- This breaks down for lower lengths (lower z/D)
- Suggests global effect of the tube



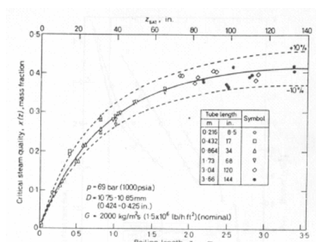
CHF Plotted with Exit Quality

- An interesting conclusion can be arrived at if the data is replotted in terms of exit quality
- The entire data appears to line up indicating length has no effect (Some scatter is there)
- This suggests that the CHF is a local state phenomenon
- This point has been debated, but consensus is yet not there



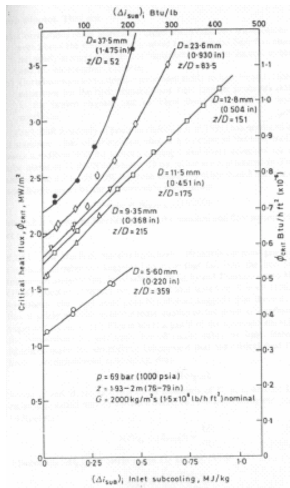
CHF Correlated with Z_{SAT}

- The alternate argument has been to correlate the CHF to Z_{sat}, the boiling length and argue about global effects
- Arguments have been made on the fraction of fluid that is evaporated before CHF occurs
- The development of flow patterns seem to influence and hence strict local/global effect debate cannot be resolved easily



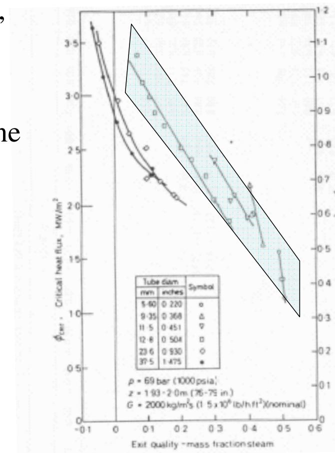
Effect of Diameter

- The influence of diameter of the tube is as shown
- Smaller diameters have lower CHF for the same inlet sub-cooling
- Linear relationship between CHF and sub-cooling is respected by smaller tubes
- It breaks down with larger tubes



CHF Plotted with Exit Quality

- When plotted with exit quality, smaller tube data line up, indicating no diameter effect
- Higher diameter data do not line up
- Most CHF predictions are through empirical correlations
- We shall see some of them



Correlations for CHF

- As stated earlier, several attempts have been made to correlate CHF through modelling, but most correlations that are used in computer codes are still the ones that are empirically derived.
- In the arena of empirical correlations, two types exist:
  - Functional Correlations
  - Look Up Tables
- The functional correlations exploit the observations of the experimental trends and arrive at fits
- Look Up Tables just provide experimental data in a tabular form and interpolate them

Bowring Correlation

- Bowring's correlation is one of the most common ones
- The functional form can be arrived at as follows
- From the experimental trends, we can assume that CHF varies linearly with x_{exit} as

$$q''_{CHF} = A - B\ x_{exit} \qquad 1$$

- Using energy balance, one can write

$$\dot{m}(h_{exit} - h_{in}) = q''_{CHF}\pi D z \qquad \Rightarrow (h_f + x_{exit}h_{fg} - h_{in}) = \frac{q''_{CHF}\pi D z}{G\,\pi D^2/4}$$

$$\Rightarrow x_{exit}h_{fg} + \Delta h_{in} = \frac{4q''_{CHF}z}{GD} \qquad \Rightarrow x_{exit} = \frac{4q''_{CHF}z}{GDh_{fg}} - \frac{\Delta h_{in}}{h_{fg}} \qquad 2$$

Bowring Correlation

- Substituting for x_{crit} from Eq. (2) in Eq. (1) gives

$$q''_{CHF} = A - B\left(\frac{4q''_{CHF}z}{GDh_{fg}} - \frac{\Delta h_{in}}{h_{fg}}\right) \quad (3)$$

- Rearranging Eq. (3) gives

$$q''_{CHF}\left(1 + \frac{4Bz}{GDh_{fg}}\right) = A + B\frac{\Delta h_{in}}{h_{fg}} \quad (4)$$

- Rearranging Eq. (4) gives $$q''_{CHF} = \frac{A + B\frac{\Delta h_{in}}{h_{fg}}}{\left(1 + \frac{4Bz}{GDh_{fg}}\right)} \quad (5)$$

Bowring Correlation

- Rearranging Eq. (5) gives

$$q''_{CHF} = \frac{A + B\frac{\Delta h_{in}}{h_{fg}}}{\frac{4B}{GDh_{fg}}\left(\frac{GDh_{fg}}{4B} + z\right)} = \frac{\frac{GDh_{fg}A}{4B} + \frac{GD\Delta h_{in}}{4}}{\left(\frac{GDh_{fg}}{4B} + z\right)}$$

$$q''_{CHF} = \frac{A' + \frac{GD\Delta h_{in}}{4}}{(C' + z)}$$

- Bowring Correlated A' and C' in terms of G, D and p

Bowring Correlation

- where

$$A' = \frac{0.579F_1GDh_{fg}}{1 + 0.0143F_2D^{0.5}G} \qquad C' = \frac{0.077F_3GD}{1 + 0.347F_4(G/1356)^n}$$

$$n = 2.0 - 0.00725p$$

- The units are: q" in W/cm^2, D and z in m,

  G in kg/m^2-s, h_{fg} in J/kg, h_{in} in J/kg, p in bar
- The four empirical constants F_1, F_2, F_3 and F_4 are functions of relative pressure $\hat{p}$ = p/69 and are given in next slide

- For $\hat{p} < 1$

$$F_1 = \frac{\left[\hat{p}^{18.942}Exp\{20.8(1-\hat{p})\}\right] + 0.917}{1.917}$$

$$F_2 = \frac{1.309F_1}{\left[\hat{p}^{1.316}Exp\{2.444(1-\hat{p})\}\right] + 0.309}$$

$$F_3 = \frac{\left[\hat{p}^{17.023}Exp\{16.658(1-\hat{p})\}\right] + 0.667}{1.667}$$

$$F_4 = F_3\hat{p}^{1.649}$$

- For $\hat{p} > 1$

$$F_1 = \hat{p}^{-0.368}Exp\{0.648(1-\hat{p})\}$$

$$F_1 = \hat{p}^{-0.448}Exp\{0.245(1-\hat{p})\}$$

$$F_3 = \hat{p}^{-0.219}$$

$$F_4 = F_3\hat{p}^{1.649}$$

- Range of Applicability: 0.15 < z < 3.7 m, 2 < D < 45 mm

  136 < G < 18600 kg/m^2-s, 2 < p < 190 bar

Scaling Relations in CHF

- It is expensive to conduct CHF Tests as powers and pressures are high
- In the literature, low h_{fg} fluids have been used as substitutes for water
- Ahmad has arrived at the scaling relations using dimensional analysis
- The parameter that have to be scaled are given in the next slide

Non-dimensional Numbers

$$\left.\frac{\rho_l}{\rho_g}\right|_{Water} = \left.\frac{\rho_l}{\rho_g}\right|_{Freon} \qquad (1)$$

$$\left.\frac{\Delta h_{sub}}{h_{fg}}\right|_{Water} = \left.\frac{\Delta h_{sub}}{h_{fg}}\right|_{Freon} \qquad (2)$$

$$\left.\frac{GD_{hyd}}{\mu_l}\left(\frac{\mu_l^2}{\sigma D_{hyd}\rho_l}\right)^{\frac{2}{3}}\left(\frac{\mu_l}{\mu_g}\right)^{\frac{1}{6}}\right|_{Water} = \left.\frac{GD_{hyd}}{\mu_l}\left(\frac{\mu_l^2}{\sigma D_{hyd}\rho_l}\right)^{\frac{2}{3}}\left(\frac{\mu_l}{\mu_g}\right)^{\frac{1}{6}}\right|_{Water} \qquad (3)$$

$$\left.\frac{q''}{Gh_{fg}}\right|_{water} = \left.\frac{q''}{Gh_{fg}}\right|_{freon} \qquad (4)$$

System parameters

- Let us assume that we need to get CHF for water at 70 bar, Δh_{in} 10 ^{o}C, G = 1500 kg/m^2-s
- Let Freon be the fluid. The pressure for freon experiments is found by matching Eq. (1), the inlet sub-cooling is found by matching Eq. (2) and the mass flux is found by matching Eq.(3),
- Geometry is assumed same. The Freon CHF is then experimentally obtained
- This value can then be extrapolated by using Eq. (4) to find water CHF