# Introduction to Flow Boiling

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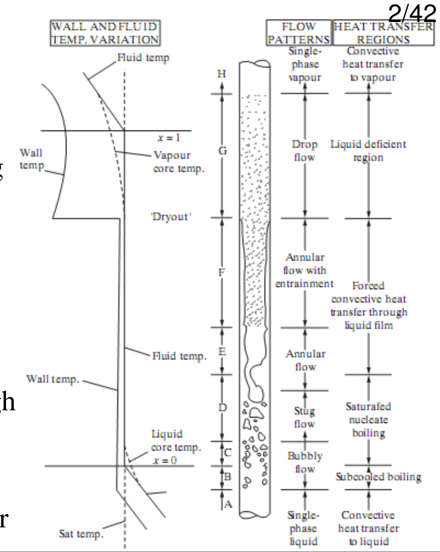
## Introduction-I

- We can classify the regimes of flow boiling under
  - Single-Phase liquid
  - Sub-Cooled Boiling
  - Saturated Boiling
  - Forced Convective Heat transfer through film
  - Mist flow
  - Single-phase Vapour






## Single-Phase Heat Transfer-I

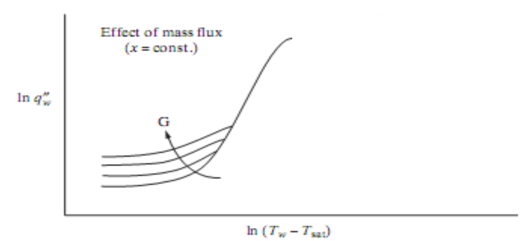
- Let us now proceed towards establishing methods to quantify the heat transfer coefficient
- In single-phase turbulent flow, the heat transfer coefficient can be estimated using the classical Dittus-Boelter Equation

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.33}$$

- The above equation signifies that higher the mass flux, higher shall be the heat transfer coefficient and hence higher heat flux for a given wall temperature or lower temperature for given wall heat flux
- This can be qualitatively represented as shown in the figure in next slide



## Single-Phase Heat Transfer-II




- We see from the above figure that once nucleate boiling develops, the heat flux is independent of mass flux for a given wall temperature
- In other words, Heat transfer coefficient is independent of mass flux,

15:53 5/42

## Boiling Incipience-I

- Let us now proceed towards establishing method to quantify the onset of nucleation
- For a constant heat flux system, we can write

$$q'' = h\left(T_W(z) - T_B(z)\right) \qquad \Rightarrow T_B(z) = T_W(z) - \frac{q''}{h} \qquad \boxed{1}$$

- From Energy Balance, we can write

$$q''Pdz = GAc_p dT_B \;\Rightarrow \frac{dT_B}{dz} = \frac{q''P}{GAc_p} = \frac{q''4}{Gd_h c_p}$$

- Separating the variable and integrating from entrance to any general point

$$\Rightarrow \int_{T_B(0)}^{T_B(z)} dT_B = \int_0^z \frac{q''4}{Gd_h c_p} dz$$

15:53 6/42

## Boiling Incipience-II

$$\Rightarrow T_B(z) - T_B(0) = \frac{q''4}{Gd_h c_p} z \qquad \boxed{2}$$

- Substituting for $T_B(z)$ from Eq. (2) in Eq. (1), we get

$$\Rightarrow T_W(z) - \frac{q''}{h} - T_B(0) = \frac{q''4}{Gd_h c_p} z$$

$$\Rightarrow T_W(z) = T_B(0) + q''\left(1/h + 4z/Gd_h c_p\right)$$

$$\Rightarrow T_W(z) - T_{sat} = q''\left(1/h + 4z/Gd_h c_p\right) - \left(T_{sat} - T_B(0)\right)$$

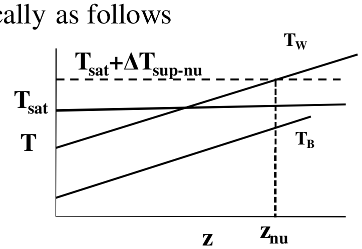
15:53 7/42

## Boiling Incipience-III

- We had shown the criterion for nucleation was

$$\left(T_W - T_{sat}\right) = \sqrt{\frac{8\sigma T_{sat} v_{fg}}{h_{fg}} \frac{q''}{k_l}} = \Delta T_{sup\text{-}nu}$$

- The position where nucleation will begin can be shown graphically as follows



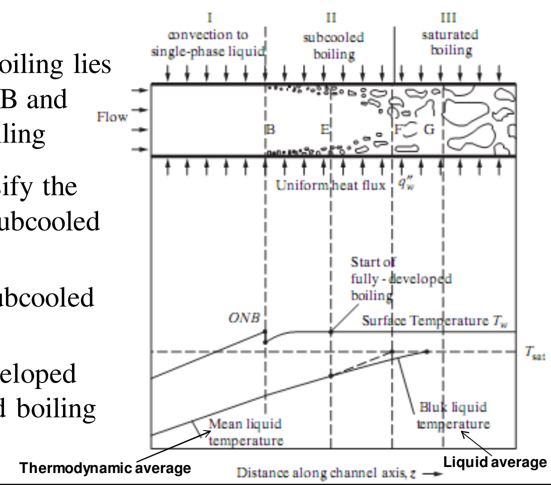

Note that nucleation initiates when bulk is subcooled

- We can obtain a similar condition for constant $T_W$ case

15:53 8/42

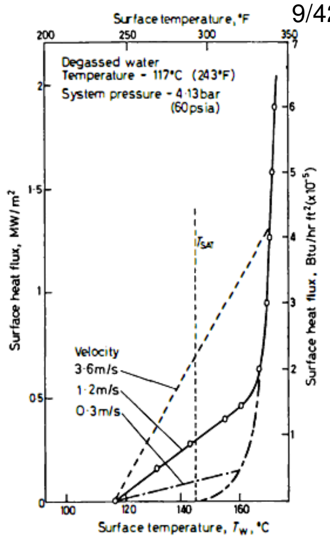
## Regimes in Subcooled Boiling-I

- Subcooled boiling lies between ONB and saturated boiling
- We can classify the regimes of subcooled boiling as
  - Partial Subcooled boiling.
  - Fully developed subcooled boiling

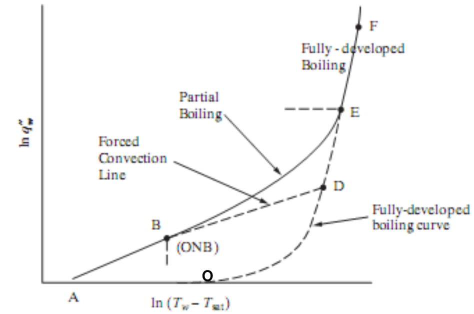


# Subcooled Boiling-II

- To appreciate the concepts, the data of Mcadams (1946) is shown.
- The near vertical line is the fully developed boiling curve
- The line with smaller slope is the single-phase line
- The merging curved line is the partial boiling line






- In the region near fully developed SCB, we can expand and understand the following
- ABEF actual experimental curve
- ABD Single-phase extrapolated
- FEDO fully developed SCB curve extrapolated



- Often the heat transfer coefficient is taken as the sum of two contributions, one due to single-phase and one due to nucleate boiling.
- First let us look at the correlations that are normally used in fully developed boiling.
- The more common ones are empirical
- McAdams Correlation

$$(T_W - T_{Sat})(K) = 22.62\left(q''(MW/m^2)\right)^{0.259}$$

- Valid for
  $0.3$ m/s < V < 11 m/s, 11 K < $\Delta T_{sub}$ < 83 K
  2 bar < p < 6 bar, 4.3 mm < d < 12.2 mm



**Jens and Lottes (1951) Correlation**

$$(T_W - T_{sat})(K) = 25\left(q''(MW/m^2)\right)^{0.25} e^{-p(bar)/62}$$

Valid for
11 kg/m$^2$-s < G < $10^4$ kg/m$^2$-s,
7 bar < p < 172 bar, 3.6 mm < d < 5.74 mm

**Thom et al. (1965) Correlation**

$$(T_W - T_{sat})(K) = 22.65\left(q''(MW/m^2)\right)^{0.5} e^{-p(bar)/87}$$

Valid for
51 bar < p < 136 bar

Kandlikar (1998) has a more complex and a recent correlation

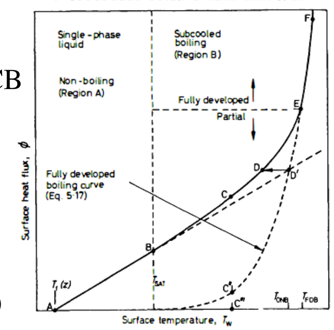
Kandlikar, S. G. (1998). Heat transfer and flow characteristics in partial boiling, fully developed boiling, and significant void flow regions of subcooled flow boiling. *J. Heat Transfer*, **120**, 395–401.

## 15:53 Models for Subcooled Boiling-I 13/42

- Bowring (1962) proposed a model for the entire range of partial subcooled boiling as

$$q''_{total} = q''_{SPL} + q''_{SCB}$$

- BCDEF is actual curve
- D' is the intersection of SPL curve with fully developed SCB
- This heat flux was considered the heat flux at ONB.
- The fully developed point (E) was defined such that q"(E) = 1.4 q"(D) for constant $T_W$ case (h is 1.4 times higher)




## 15:53 Models for Subcooled Boiling-II 14/42

- The points of location of ONB and FDSCB can be determined as follows
- If single-phase correlation is valid upto the point of ONB, at ONB we can write

$$q''_{ONB} = h_{fo}(T_{W\text{-}ONB} - T_B(z)) \Rightarrow (T_{W\text{-}ONB} - T_B(z)) = \frac{q''_{ONB}}{h_{fo}} \quad \text{a}$$

Also from the FDSCB correlation we can write,

$$(T_{W\text{-}ONB} - T_{sat}) = C(q''_{ONB})^n \quad \text{b}$$

Eq. (a)-Eq. (b) implies

$$(T_{sat} - T_B(z)) = \frac{q''_{ONB}}{h_{fo}} - C(q''_{ONB})^n$$

- Thus, for a constant heat flux case, we can determine $\Delta T_{sub}$ where the ONB will occur

## 15:53 Models for Subcooled Boiling-III 15/42

- For $q''$ is constant, the FDSCB point is determined using the condition that h is 1.4 times bigger;

$$(T_W(z) - T_B(z)) = \frac{q''}{1.4h_{fo}} \quad \text{c}$$

- Since at FDSCB,

$$(T_W(z) - T_{sat}) = C(q'')^n \quad \text{d}$$

- Eq. (c)-Eq. (d) implies

$$(T_{sat} - T_B(z)) = \frac{q''_{ONB}}{1.4h_{fo}} - C(q''_{ONB})^n \quad \text{e}$$

## 15:53 Models for Subcooled Boiling-IV 16/42

- The empirical method recommends the following
- Till ONB the treatment will be like single phase
- Between ONB and FDSCB, the local total heat flux shall be $q''_{total} = q''_{SPL} + q''_{SCB}$, where the second part is obtained by a suitable FDSCB correlation and the first part is obtained by $q''_{SPL} = h_{fo}(T_{sat} - T_B(z))$
- Beyond FDSCB, heat flux given by FDSCB will be the total heat flux.
- Because of the sudden change in the form of $q''_{SPL}$ discontinuities will be noticed at both ONB and FDSCB

## Models for Subcooled Boiling-V



- The methodology is straight forward for both heat flux specified and wall temperature specified cases. We shall look at the heat flux specified case
- The local bulk fluid temperature and wall temperature in the single phase regions are obtained by integrating the energy equation such as the one presented in slides 4-5
- The position of $z_{ONB}$ is obtained by equating the local subcooling for the bulk fluid to the value required for the ONB point.
- From this point onward, the partial SCB method has to be applied. The bulk coolant temperature will continue to be computed by energy balance.



## Models for Subcooled Boiling-VI

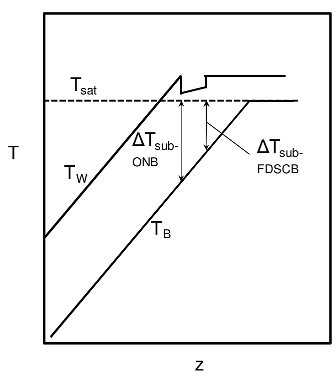


- $q''_{SPL}$ shall be computed using the formula given in previous slide
- The above value will be subtracted from the applied heat flux to get $q''_{FDSCB}$
- Using a suitable FDSCB correlation, we can obtain $T_W$.
- The position where FDSCB will occur can be obtained by equating the fluid subcooling to that required as required in Eq. (e) in slide 14.
- Beyond FDSCB pint, $T_W$ shall be constant
- The variation of wall and bulk coolant temperature for a case is shown in the next slide



## Models for Subcooled Boiling-VII



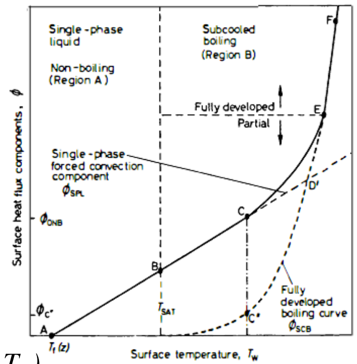





## Bergles-Rohsenow Model



- Bergles and Rohsenow (1963) presented an alternate model
- Heat flux prediction was done by a composite model



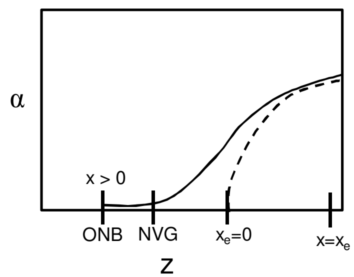

$$q'' = q''_{SPL}\left\langle 1+\left\langle \frac{q''_{SCB}}{q''_{SPL}}\left\langle 1-\frac{q''_{C'}}{q''_{SPL}}\right\rangle\right\rangle^{2}\right\rangle^{0.5}$$

$$q''_{C''} = q''_{SCB}(T_{W\ ONB}) \qquad q''_{SPL} = h_{fo}(T_W - T_B)$$

- ONB was predicted empirically but close to Davis-Anderson
- Note that at when $q''_{SCB}$ is very small then $q'' = q''_{SPL}$
- When $q''_{SCB}$ is very large, then $q'' = q''_{SCB}$

## Non-equilibrium effects

- 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
- Although the real quality shall be more than 0, equilibrium quality shall be –ve in the initial stages
- As quality builds up, the real quality and equilibrium quality merges






## Correlation for NVG-I

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

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

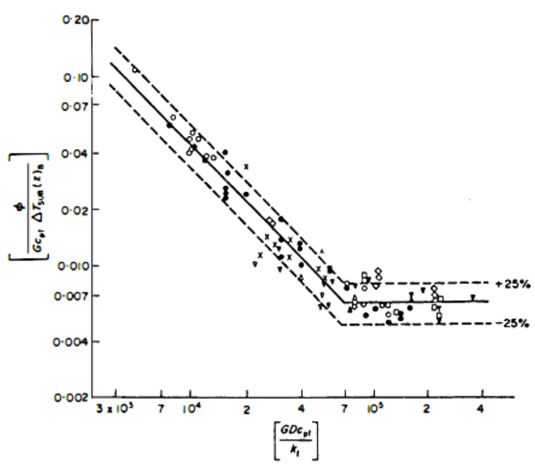
- Peclet Number, $Pe = Re\,Pr = \frac{c_p\mu}{k}\frac{GD}{\mu} = \frac{GDc_p}{k}$
- Saha and Zuber showed that at high Peclet Number, significant void occurs at constant St, while the same at lower Peclet occurs at constant Nu

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

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



## 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

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

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

## Models for Saturated Boiling-I



- For $x_{eq} > 0$ the region is called saturated boiling
- The most popular one for vertical tubes is Chen Correlation.
- There are several others, such as Shah and Kandlikar.
- The last one is a more recent one.
- We shall only discuss Chen Correlation
- Often the concepts are extended into the non-equilibrium region by using the actual quality



## Chen Correlation-I



$$h = h_{micro} + h_{macro}$$

$$h_{micro} = h_{ForsterZuber} S$$

$$h_{forster\text{-}Zuber} = 0.00122 \frac{\Delta T_{sat}^{0.24} \Delta p_{sat}^{0.75} c_{pl}^{0.45} \rho_l^{0.49} k_l^{0.79}}{\sigma^{0.5} h_{fg}^{0.24} \mu_l^{0.29} \rho_g^{0.24}}$$

$$h_{macro} = h_l F( X_{tt} ) pr_l^{0.296}$$

$$h_l = 0.023\, Re_l^{0.8}\, pr_l^{0.4} \frac{k_l}{d}$$

$$Re_l = \frac{G( 1 - x ) d}{\mu_l}$$



## Chen Correlation-II



$$X_{tt} = \left\langle \frac{( 1 - x )}{x} \right\rangle^{0.9} \left\langle \frac{\mu_l}{\mu_g} \right\rangle^{0.1} \left\langle \frac{\rho_g}{\rho_l} \right\rangle^{0.5}$$

$$F( X_{tt} ) = \frac{1}{X_{tt}} \quad \text{For } 1/X_{tt} < 0.1$$

$$F( X_{tt} ) = 2.35 \left( 0.213 + 1 / X_{tt} \right)^{0.736} \quad \text{For } 1/X_{tt} > 0.1$$

$$S(Re_{tp}) = \left( 1 + 2.56 X 10^{-6}\, Re_{tp}^{1.17} \right)^{-1}$$

$$Re_{tp} = Re_l \left( F( X_{tt} ) \right)^{1.25}$$



## 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 models exist, these are not universal. Most of the correlations are empirical

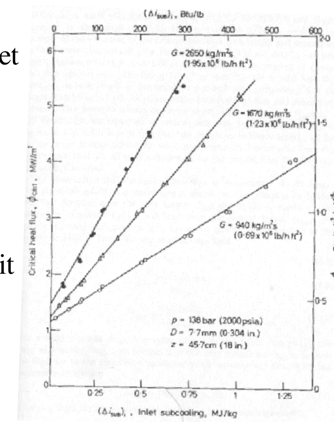
## Behaviour of CHF in Flow Boiling-II

- CHF is primarily dictated by 5 postulated variables, G, $\Delta T_{sub}$, 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

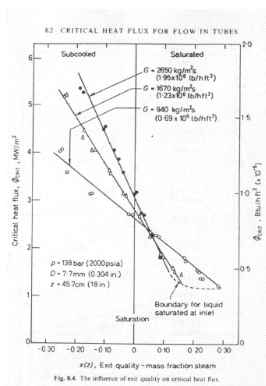
- Experiments indicate that CHF varies linearly with inlet sub-cooling
- Also at higher mass flux the CHF is higher
- However, the same data replotted as a function of exit quality reveals gives an altogether different conclusion





## CHF Plotted with Exit Quality

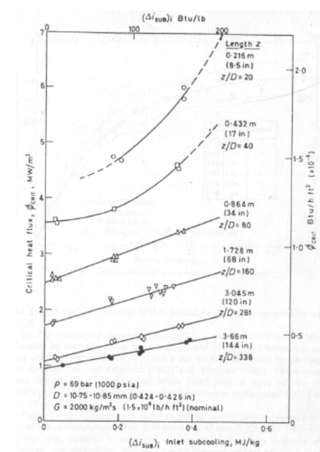
- The CHF varies linearly with exit quality
- There is a crossover of the constant G lines at some positive quality
- Thus, from the graph, the variation of trends of CHF with G at low quality is opposite to that at high quality





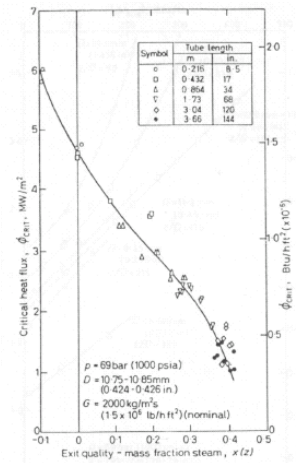
## Effect of Length

- 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

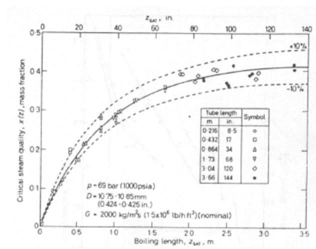
- An interesting conclusion can be arrived at if the data is replotted in terms of exit quality
- The entire data appears to line up indicating length has no effect (Some scatter is there)
- This suggests that the CHF is a local state phenomenon
- This point has been debated, but consensus is yet not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





## CHF Correlated with $Z_{SAT}$

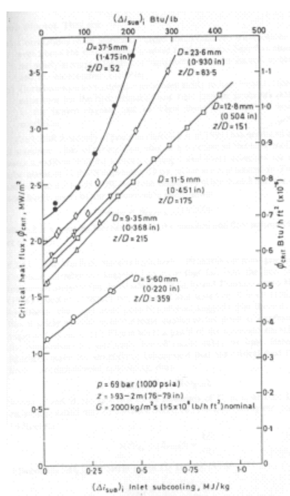
- The alternate argument has been to correlate the CHF to $Z_{sat}$, the boiling length and argue about global effects
- Arguments have been made on the fraction of fluid that is evaporated before CHF occurs
- The development of flow patterns seem to influence and hence strict local/global effect debate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





## Effect of Diameter

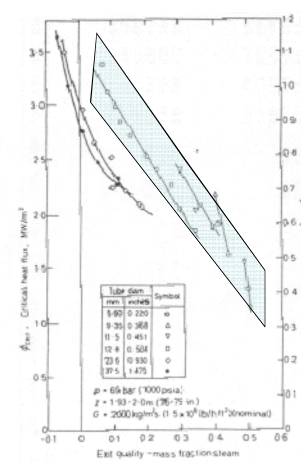
- The influence of diameter of the tube is as shown
- Smaller diameters have lower CHF for the same inlet sub-cooling
- Linear relationship between CHF and sub-cooling is respected by smaller tubes
- It breaks down with larger tubes





## 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



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## 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

15:53 — 38/42

## 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

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

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

15:53 — 39/42

## Bowring Correlation

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

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

- Rearranging Eq. (3) gives

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

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

15:53 — 40/42

## 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

$$A' = \frac{0.579 F_1 G D h_{fg}}{1 + 0.0143 F_2 D^{0.5} G} \qquad C' = \frac{0.077 F_3 G D}{1 + 0.347 F_4 \left(G/1356\right)^n}$$

$$n = 2.0 - 0.00725\,p$$

- 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 $\hat{p} < 1$

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

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

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

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

- 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