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A Numerical Approach for Prediction of Critical Heat Flux (CHF) utilizing Local Condition Hypotheses

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Content

1. Background and Objective (1/4)

- Critical Heat Flux (CHF)

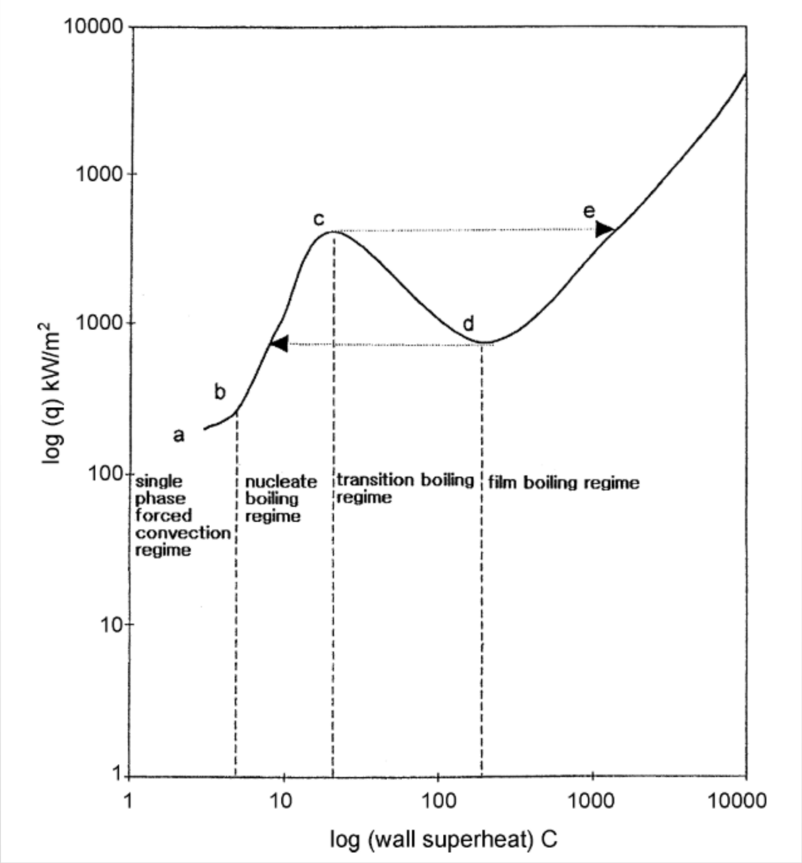

Fig. 1. Boiling curve of a heat flux controlled surface in forced flow boiling water (Shim and Park, 2004)

- ✓ "Critical Heat Flux (CHF), which is also known as burnout, dry-out, and boiling crisis, represents a heat transfer phenomenon in which there is a sudden decrease in the value of the heat transfer coefficient, or abrupt increase in the surface temperature" (Shim and Park, 2004)
- ✓ CHF reaches the point where the liquid film on the wall is depleted owing to vapor entrainment and evaporation.

- ✓ Local Condition Hypothesis
  - ✓ the CHF is determined only by the local variables at the local location; the system pressure (P), tube diameter (D), mass flux (G), and 'True mass quality' of Steam (X_t).
  - ✓ Thus, a LCC consists of $f(P, D, G, X_t)$ and it is usually calculated by Heat Balance Method (HBM).

$$q_{CHF} = f(P, D, G, X_t)$$

1. Background and Objective (2/4)

- True Steam Quality

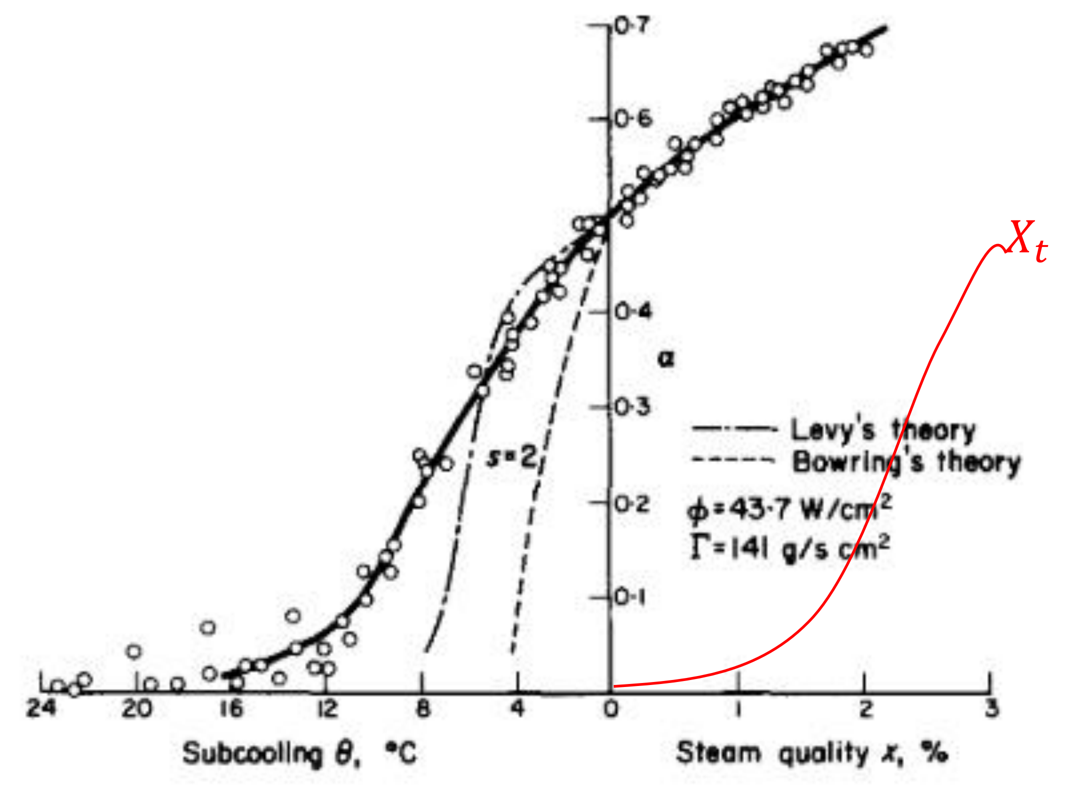

Fig. 2. Example of void fraction vs. Steam quality (%) (Evangelisti and Lupoli, 1969)

✓ The ratio of the ‘true’ mass flow rate of steam to the total mass flow rate of the steam-water two-phase mixture.

✓ it can describe the behavior of vapor generation quantitatively, it captures more of the physical meanings than the thermodynamic equilibrium quality (X_{eq}), especially in the subcooled boiling regime.

$$X_t = \frac{\rho_g v_g A_g}{(\rho_g v_g A_g + \rho_l v_l A_l)} \qquad 0.0 \le X_t \le 1.0$$

1. Background and Objective (3/4)

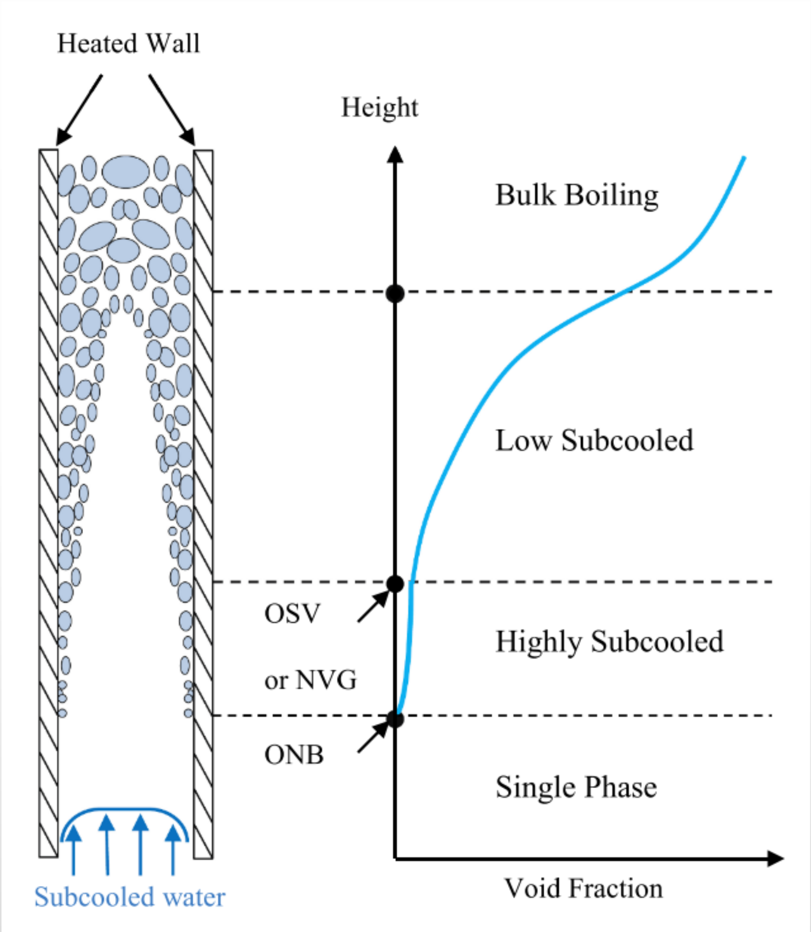

Fig. 3. Axial void development in a vertical pipe (Ha et al., 2020)

✓Relationship between X_t and The Onset of Significant Vaporization or Void (OSV)

- ➢ OSV
  - ✓ As the average cross-sectional bulk temperature of the subcooled liquid increases gradually, the condensation rate of bubbles decreases and the generation rate of bubbles increase, and then the event at which the generation rate is overwhelming the condensation rate occurs downstream. Here, the event that void fraction increase rapidly in the heated channel.

- Levy (1967)

$$X_t = X_e - X_{OSV} \exp(\frac{X_e}{X_{OSV}} - 1)$$

- Kroeger and Zuber (1968)

$$X_t = \frac{X_e - X_{OSV} \exp\left(\frac{X_e}{X_{OSV}} - 1\right)}{1 - X_{OSV} \exp(\frac{X_e}{X_{OSV}} - 1)}$$

$$at\ X_e = X_{OSV}, X_t = 0$$
$$at\ X_e = 1, X_t = 1$$

1. Background and Objective (4/4)

- ✓ Based on a non-equilibrium homogeneous fluid flow model, Jafri (1993) suggests the correlation that construct the local true mass fraction of vapor. And Deng proposed the correlation for CHF using HBM.

✓ Differential form

$$\frac{dX_t}{dX} = \frac{X_t - X}{X_{OSV}(1 - X_t)}$$

Initial condition

$$\begin{cases} \boldsymbol{X_t} = 0, & at\ X = \boldsymbol{X_{OSV}} \quad if\ \boldsymbol{X_i} < \boldsymbol{X_{OSV}} \\ \boldsymbol{X_t} = 0, & at\ X = \boldsymbol{X_i}\ \ if\ \boldsymbol{X_{OSV}} < \boldsymbol{X_i} < 0 \\ \boldsymbol{X_t} = \boldsymbol{X_i}, & at\ X = \boldsymbol{X_i} \quad if\ 0 < \boldsymbol{X_i} \end{cases}$$

✓ Integration form

$$X_{OSV} \ln\left(\frac{X_e - X_t}{X_b}\right) + \ln\left(\frac{1 - X_e + X_{OSV} - X_{OSV}X_t}{1 - X_b + X_{OSV}}\right) = 0 \qquad where, \qquad X_b = argmax(X_{in}, X_{OSV})$$

- ✓ **Objective**
  - ✓ Suggestion for predicting CHF using Heat Balance Method (HBM) based on local condition hypothesis.

2. A Numerical Approach using Heat Balance Method (1/2)

- ✓ Based on a non-equilibrium homogeneous fluid flow model, Jafri (1993) suggests the correlation that construct the local true mass fraction of vapor. And Deng proposed the correlation for CHF using HBM.

$$q_{CHF} = m\left(1 - n\sqrt{GX_t}\right) \qquad where,\, m = f\left(\frac{1}{\sqrt{D_h}}\right)\ at\ fixed\ pressure$$

- Deng correlation (1998) based on Jafri investigation

$$q_{CHF} = \frac{\alpha}{\sqrt{D_h}} \exp\left(-\gamma\sqrt{Z(X_t)GX_t}\right) \qquad \alpha = 1.669 - 6.544\left(\frac{P}{P_c} - 0.448\right)^2$$

$$\gamma = 0.06523 + \frac{0.1045}{\sqrt{2\pi\left(\ln\frac{P}{P_c}\right)^2}} \exp\left\{-5.413\,\frac{\left(\ln\left(\frac{P}{P_c}\right)+0.4537\right)^2}{\left(\ln\left(\frac{P}{P_c}\right)\right)^2}\right\}$$

$Z(X_t) = (1 + X_t^2)^3$ where, $Z(X_t)$ = slip factor

2. A Numerical Approach using Heat Balance Method (2/2)

✓DKU-PDL Algorithm

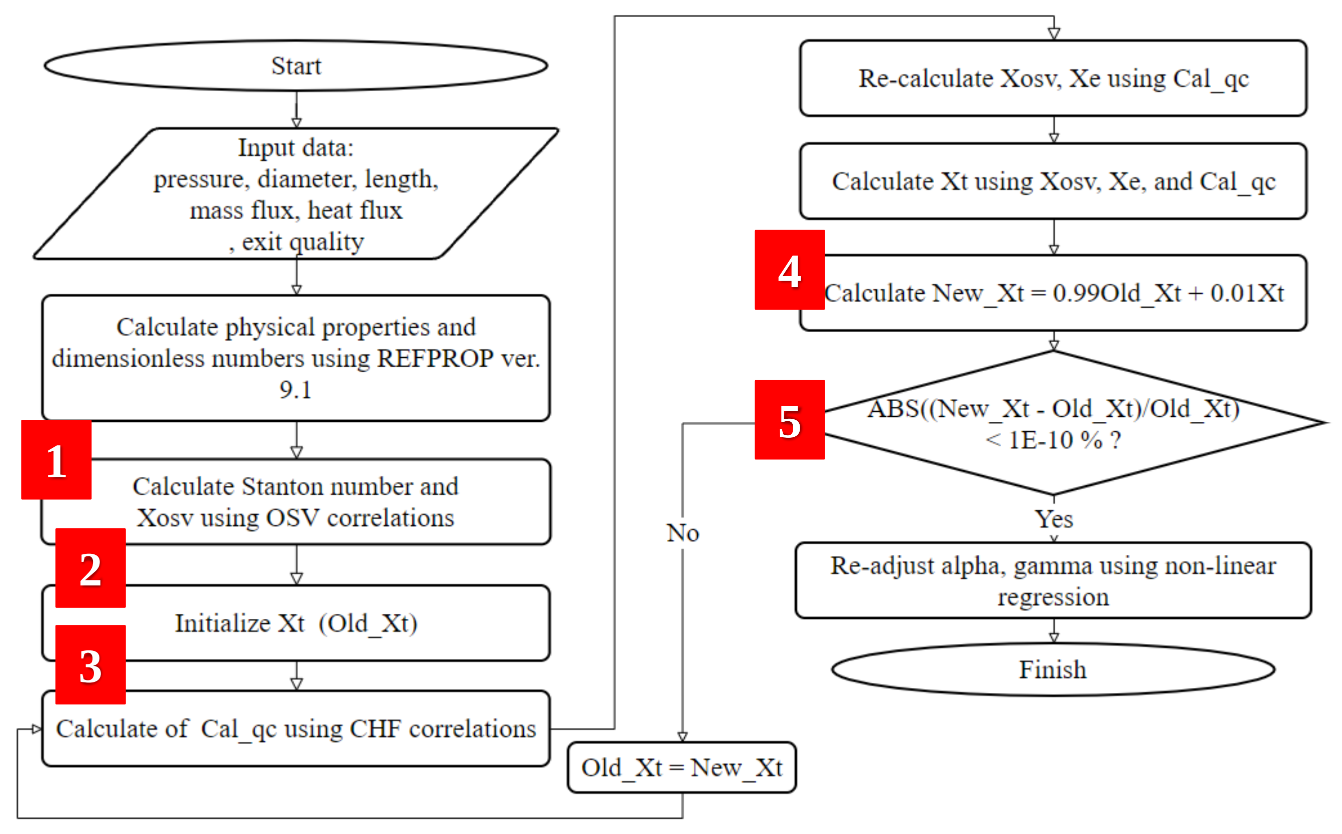

Fig. 4. DKU-PDL algorithm for X_t using calculated CHF by correlations

1 Choose the OSV correlation (in this study, we select Saha and Zuber correlation)

2 Choose X_t following the initial condition of X_i and X_{OSV}

3 Choose CHF correlation (in this study, we select Deng correlation)
cf. the CHF correlation can be separated by two concepts:
1) CHF correlation for initial $q_{CHF,init}$
2) CHF correlation as update function for calculating q_n

4 In this study, we adopt the iterative method Gauss-Seidel method for the integration form of rate equation. If the other method is adopted, the algorithm is needed to change reasonably, but it is also almost the same result.

5 The convergence threshold : 1e-10

3. Result and Discussion (1/2)

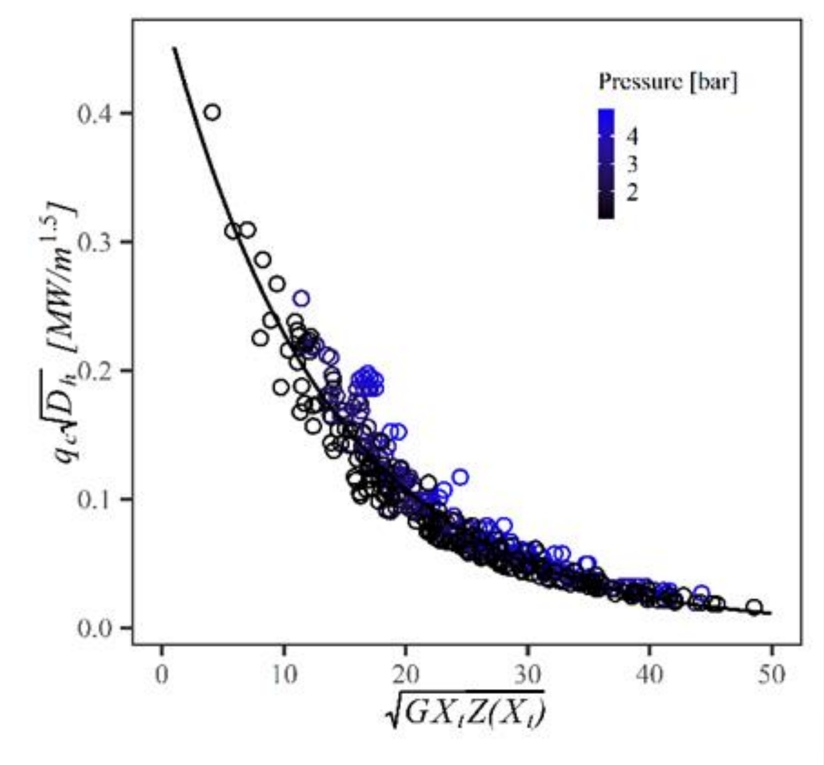

Fig. 5. CHF Trend on a $q_c\sqrt{D_h}$ versus $\sqrt{GX_tZ(X_t)}$ at low pressure (below 5 bar)

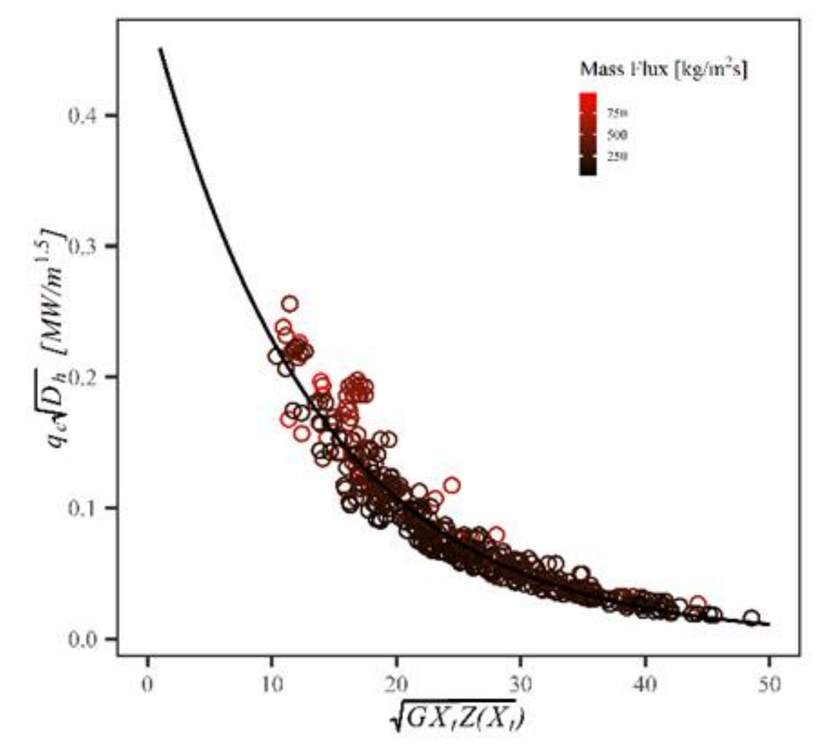

Fig. 6. CHF Trend on a $q_c\sqrt{D_h}$ versus $\sqrt{GX_tZ(X_t)}$ at low pressure (below 5 bar)

Pressure [bar]	No. of data	α	γ
5 below	400	0.487	-0.0755
100 – 105	359	1.300	-0.0750

- ✓ OSV correlation: Saha and Zuber (1974)
- ✓ Initial CHF correlation : Deng correlation (1998)
- ✓ Iterative and Predictive CHF correlation : Deng correlation (1998)
- ✓ Numerical method : Gauss-Seidel Method

- ✓ Fig. 2 shows that the low-pressure data, under 3 bar, results in good prediction but the other data near the 5 bar is overpredicted.
- ✓ This result shows that the α and γ are sensitive at low pressures. On the effect of mass flux in low pressure conditions, Fig. 3 shows that the α and γ are less dependent on the mass flux.

3. Result and Discussion (2/2)

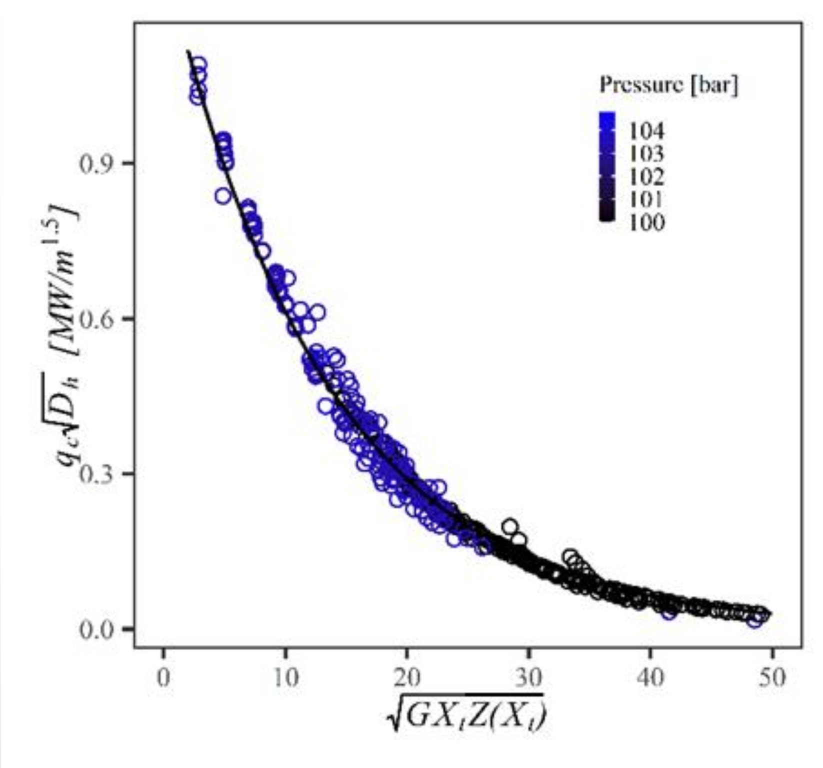

Fig. 7. CHF Trend on a $q_c\sqrt{D_h}$ versus $\sqrt{GX_tZ(X_t)}$ at high pressure (100 – 105 bar)

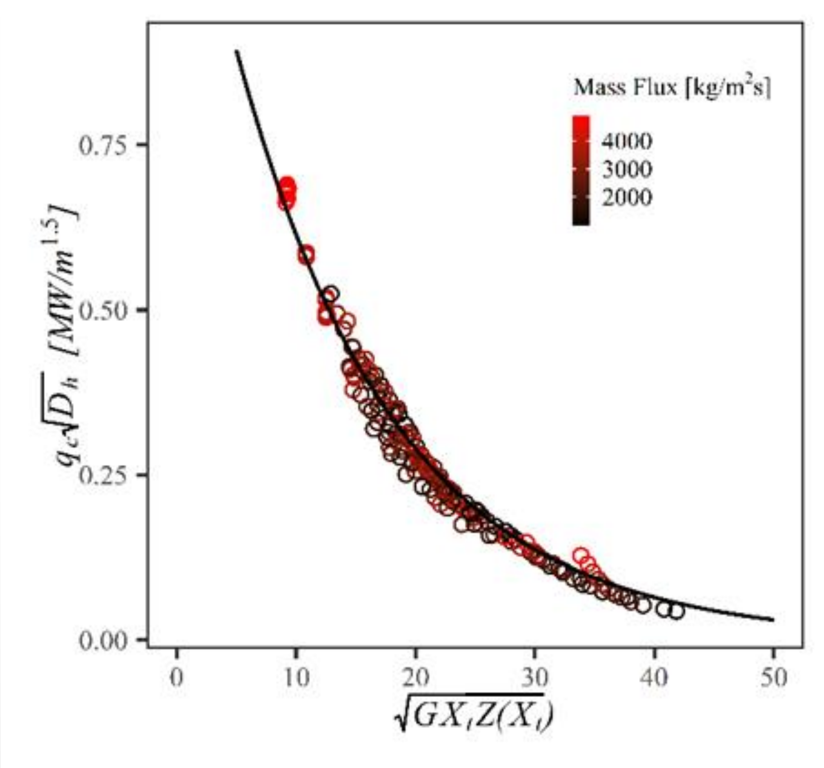

Fig. 8. CHF Trend on a $q_c\sqrt{D_h}$ versus $\sqrt{GX_tZ(X_t)}$ at high pressure (100 – 105 bar)

Pressure [bar]	No. of data	α	γ
5 below	400	0.487	-0.0755
100 – 105	359	1.300	-0.0750

- ✓ OSV correlation: Saha and Zuber (1974)
- ✓ Initial CHF correlation : Deng correlation (1998)
- ✓ Iterative and Predictive CHF correlation : Deng correlation (1998)
- ✓ Numerical method : Gauss-Seidel Method

- ✓ Fig. 4 shows CHF data $q_c\sqrt{(D_h\ )}$ versus $\sqrt{GX_tZ(X_t)}$ at high pressures between 100 and 105 bar.
- ✓ The α and γ are more independent to pressure in this region, which is a contrast to the low-pressure results. Also shown as Fig. 5, the alpha and gamma are relatively independent to high mass flux.

4. Conclusion and Future Work

Conclusion

- A numerical approach using the local condition hypothesis can be useful for predicting CHF.
- Thus far DKU-PDL algorithm is useful for optimizing X_t using calculated CHF regardless of the experimental value.
- Once initialized X_t in Eq. (2) and CHF can be determined by the correlation, by the validation of old X_t and new X_t step by step.
- Saha and Zuber [6] correlation and Deng [7] CHF correlation have been used to calculate the X_t for CHF and the value of α and γ in forced-convective subcooled vertical tubes are re-adjusted. α is the bias in term of natural log linearization of Eq. (4), and it is of a more critical value than γ in predicting CHF.

Future works

- the CHF correlation without α and γ is re-initialized step of X_t and q_c. For the focus on that, the optimization of α and γ for convergence loop is needed. And the other general form instead of $\sqrt{GX_tZ(X_t)}$ is essentially needed because it is slightly insufficient to some of pressure range.

Thank you
Q&A

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