Lecture No 06

Title:
Boiling Channel – Part II: Saturated Boiling, Dryout and Post-dryout Heat Transfer

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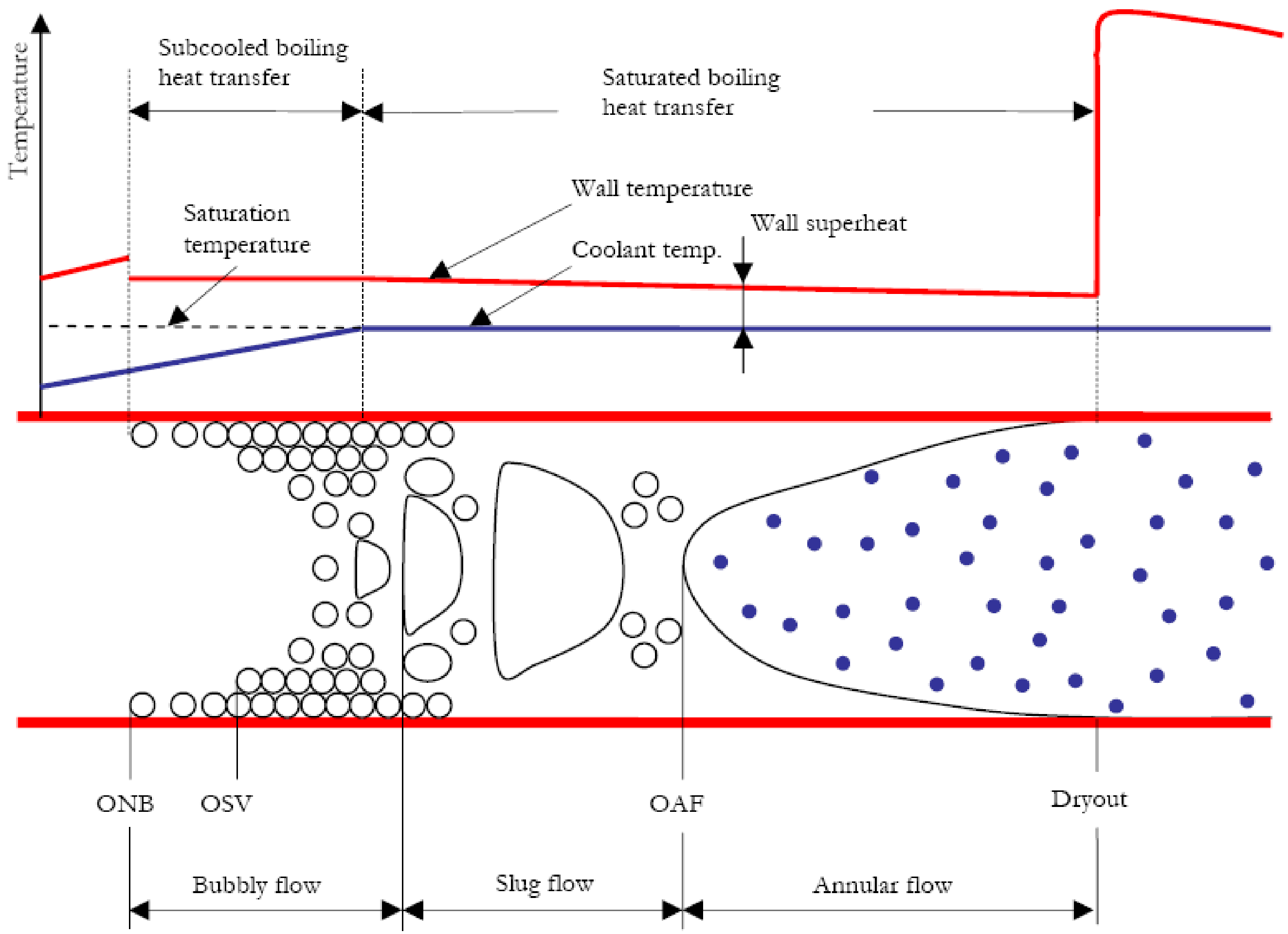
Outline of the Lecture

- Saturated nucleate and convective boiling
  - Introduction
  - Chen correlation
- Dryout
  - Levitan-Lantsman correlation
  - Boiling length approach: CISE correlation
  - Hench and Gillis correlation
  - Critical Power Ratio - CPR
- Post-dryout heat transfer

Two Phase Flow Regimes

- Typical flow and heat transfer regimes in a boiling channel



ONB – onset of nucleate boiling
OSV – onset of significant void
OAF – onset of annular flow

Introduction

- Saturated nucleate flow boiling in a boiling channel starts at the location z_{SUB} where $i(z_{SUB})=i_f$ or $T_b(z_{SUB})=T_{sat}$
- This heat transfer regime typically corresponds to bubbly and slug two-phase flow, as well as initial region of annular flow, where thick liquid film prevails
- With increasing mixture quality, a liquid film at walls is well established and heat transfer regime switches from nucleate boiling to forced convection with evaporating film, where nucleation is suppressed

Early Correlations

- Initially the following approach was employed to find the heat transfer coefficient in flow boiling heat transfer:

$$\frac{h_{2\phi}}{h_{lo}} = a_1 \frac{q''}{G i_{fg}} + a_2 X_{tt}^{-b}$$

Various values of coefficients a_1, a_2 and b have been proposed

Martinelli parameter:

$$X_{tt} \equiv \frac{(dp/dz)_f}{(dp/dz)_g} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_f}\right)^{0.5} \left(\frac{\mu_f}{\mu_g}\right)^{0.1}$$

h_{lo} is the single-phase convective heat transfer coefficient for liquid only flow in the same channel with mass flux G

Authors	a_1	a_2	b
Dengler and Addoms*	0	3.5	0.5
Benett et al.*	0	2.9	0.66
Schrock and Grossman	7400	1.11	0.66
Collier and Pulling	6700	2.34	0.66

*) Valid for annular flow only (hence a_1=0)

Superposition of Heat Transfer Coefficients

- Another approach proposed in saturated flow boiling, covering both the nucleate boiling and the convection with evaporating film, is based on superposition of heat transfer coefficients:

$$h_{2\phi} = h_{nb} + h_{fc}$$

  - here $h_{2\varphi}$ is the total heat transfer coefficient in the saturated two-phase region, h_{nb} is the contribution due to nucleate boiling and h_{fc} is the contribution due to forced convection.

- Usually the Dittus-Boelter type of equation is used to determine h_{fc}:

$$h_{fc} = 0.023\left(\frac{\lambda_{2\phi}}{D}\right)\mathrm{Re}_{2\phi}^{0.8}\,\mathrm{Pr}_{2\phi}^{0.4}$$

here index 2φ indicates effective values for two-phase flow

F-Parameter

- The effective two-phase Reynolds number is determined in relation to the Reynolds number for saturated liquid only, using F-parameter defined as:

$$F \equiv \left(\frac{\mathrm{Re}_{2\phi}}{\mathrm{Re}_f}\right)^{0.8} = \left[\frac{\mathrm{Re}_{2\phi}\,\mu_f}{G(1-x)D}\right]^{0.8}$$

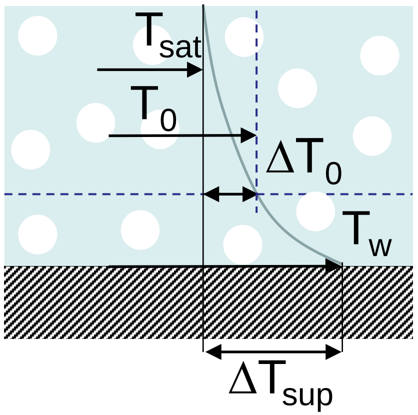
- We assume, that $\mathrm{Pr}_{2\varphi}$ is well represented by Pr_f and $\lambda_{2\varphi}$ by λ_f
- Thus, the convective heat transfer coefficient is

$$h_{fc} = 0.023\left(\frac{\lambda_f}{D}\right)\left[\frac{G(1-x)D}{\mu_f}\right]^{0.8}\mathrm{Pr}_f^{0.4}\cdot F$$

Here, only F is unknown and needs further explanations

Nucleate Boiling Fraction

- To represent the nucleate boiling fraction in the total heat transfer coefficient, the Forster and Zuber (1955) correlation, developed for pool boiling conditions, is frequently used:



$$h_{nb} = 0.00122 \left[\frac{\lambda_f^{0.79} c_{pf}^{0.45} \rho_f^{0.49}}{\sigma^{0.5} \mu_f^{0.29} i_{fg}^{0.24} \rho_g^{0.24}} \right] \Delta T_0^{0.24} \Delta p_0^{0.75}$$

$$\Delta T_0 \equiv T_0 - T_{sat}; \quad \Delta p_0 \equiv p_{sat}(T_0) - p_{sat}(T_{sat})$$

Here λ_f is the thermal conductivity of saturated liquid, c_{pf} – specific heat, ρ_f – density, μ_f-dynamic viscosity, σ-surface tension, i_{fg}-latent heat, ρ_g-gas density, Δp_0 – pressure difference found at mean fluid superheat temperature and the system saturation temperature, ΔT_0 – mean fluid superheat for bubble to grow in the thermal boundary layer

S-Parameter

- The mean superheat of the fluid for bubble to grow, ΔT_0, is lower than the wall superheat, ΔT_w; this effect was neglected in the Forster-Zuber correlation, but it cannot be neglected in forced convection
- Thus, the ratio of the two superheats is defined as a suppression factor *S*:

Thus: $$S \equiv \left(\frac{\Delta T_0}{\Delta T_{\sup}}\right)^{0.99} = \left(\frac{\Delta T_0}{\Delta T_{\sup}}\right)^{0.24}\left(\frac{\Delta p_0}{\Delta p_{sat}}\right)^{0.75}$$

Here we postulate that $\left(\frac{\Delta p_0}{\Delta p_{sat}}\right) \sim \left(\frac{\Delta T_0}{\Delta T_{\sup}}\right)$

$$h_{nb} = 0.00122\left[\frac{\lambda_f^{0.79} c_{pf}^{0.45} \rho_f^{0.49}}{\sigma^{0.5} \mu_f^{0.29} i_{fg}^{0.24} \rho_g^{0.24}}\right] \Delta T_{\sup}^{0.24} \left(\underbrace{p_s(T_w) - p_f}_{\Delta p_{sat}}\right)^{0.75} \cdot S$$

- Where S->0 for high velocity and S->1 for low velocity

Chen Correlation (1)

- Major correlation developed along these lines was proposed by Chen
- This correlation is widely used in nuclear thermal hydraulics
- The correlation covers the entire range of the saturated boiling: from the point where equilibrium quality is zero (x_e=0) to the location where boiling crisis occurs (dryout or DNB)
- Validity range for accuracy within 11%:
  - pressure 0.17 to (originally) 3.5 MPa, extended to 6.9 MPa
  - liquid inlet velocity: 0.06 to 4.5 m/s
  - heat flux up to 2.4 MW/m^2, quality from 0 to 0.7

Chen Correlation (2)

- The correlation is formulated as follows:

$$h = h_{mic} + h_{mac}$$

We use here "*mic*" and "*mac*" to represent nucleate boiling (nb) and forced-convection (fc) contributions, respectively

- Where

$$F = \begin{cases} 1 & X_{tt}^{-1} \le 0.1 \\ 2.35\left(0.213 + \dfrac{1}{X_{tt}}\right)^{0.736} & X_{tt}^{-1} \ge 0.1 \end{cases}$$

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\left(\frac{\mu_f}{\mu_g}\right)^{0.1}$$

$$S = \left(1 + 2.56 \cdot 10^{-6} F^{1.463} \cdot \mathrm{Re}_f^{1.17}\right)^{-1}$$

$$\mathrm{Re}_f = \frac{G(1-x)D}{\mu_f}$$

$$h_{mac} = 0.023\left(\frac{\lambda_f}{D}\right)\mathrm{Re}_f^{0.8}\,\mathrm{Pr}_f^{0.4} \cdot F$$

$$\mathrm{Pr}_f = \frac{c_{pf}\mu_f}{\lambda_f}$$

SI units!

$$h_{mic} = 0.00122\left[\frac{\lambda_f^{0.79} c_{pf}^{0.45} \rho_f^{0.49}}{\sigma^{0.5}\mu_f^{0.29} i_{fg}^{0.24}\rho_g^{0.24}}\right]\Delta T_{\mathrm{sup}}^{0.24}\left(p_s(T_w) - p_f\right)^{0.75} \cdot S$$

Chen Correlation (3)

given q'', x, p, G, D; guess ΔT_{sup}

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\left(\frac{\mu_f}{\mu_g}\right)^{0.1}$$

$$\mathrm{Re} = \frac{G(1-x)D}{\mu_f}$$

$$F = \begin{cases} 1 & X_{tt}^{-1} \le 0.1 \\ 2.35\left(0.213 + \dfrac{1}{X_{tt}}\right)^{0.736} & X_{tt}^{-1} \ge 0.1 \end{cases}$$

$$S = \left(1 + 2.56 \cdot 10^{-6} F^{1.463} \cdot \mathrm{Re}^{1.17}\right)^{-1}$$

$$h_{mac} = 0.023\left(\frac{\lambda_f}{D}\right)\mathrm{Re}^{0.8}\,\mathrm{Pr}_f^{0.4} \cdot F$$

$$h_{mic} = 0.00122\left[\frac{\lambda_f^{0.79} c_{pf}^{0.45} \rho_f^{0.49}}{\sigma^{0.5} \mu_f^{0.29} i_{fg}^{0.24} \rho_g^{0.24}}\right]\Delta T_{sup}^{0.24}\left(p_s(T_w) - p_f\right)^{0.75} \cdot S$$

$$h = h_{mic} + h_{mac}$$

$$\Delta T_{sup}^{new} = q''/h$$

$$\left\|\Delta T_{sup}^{new} - \Delta T_{sup}\right\| < \varepsilon$$

Yes

No

$$\Delta T_{sup} = \Delta T_{sup}^{new}$$

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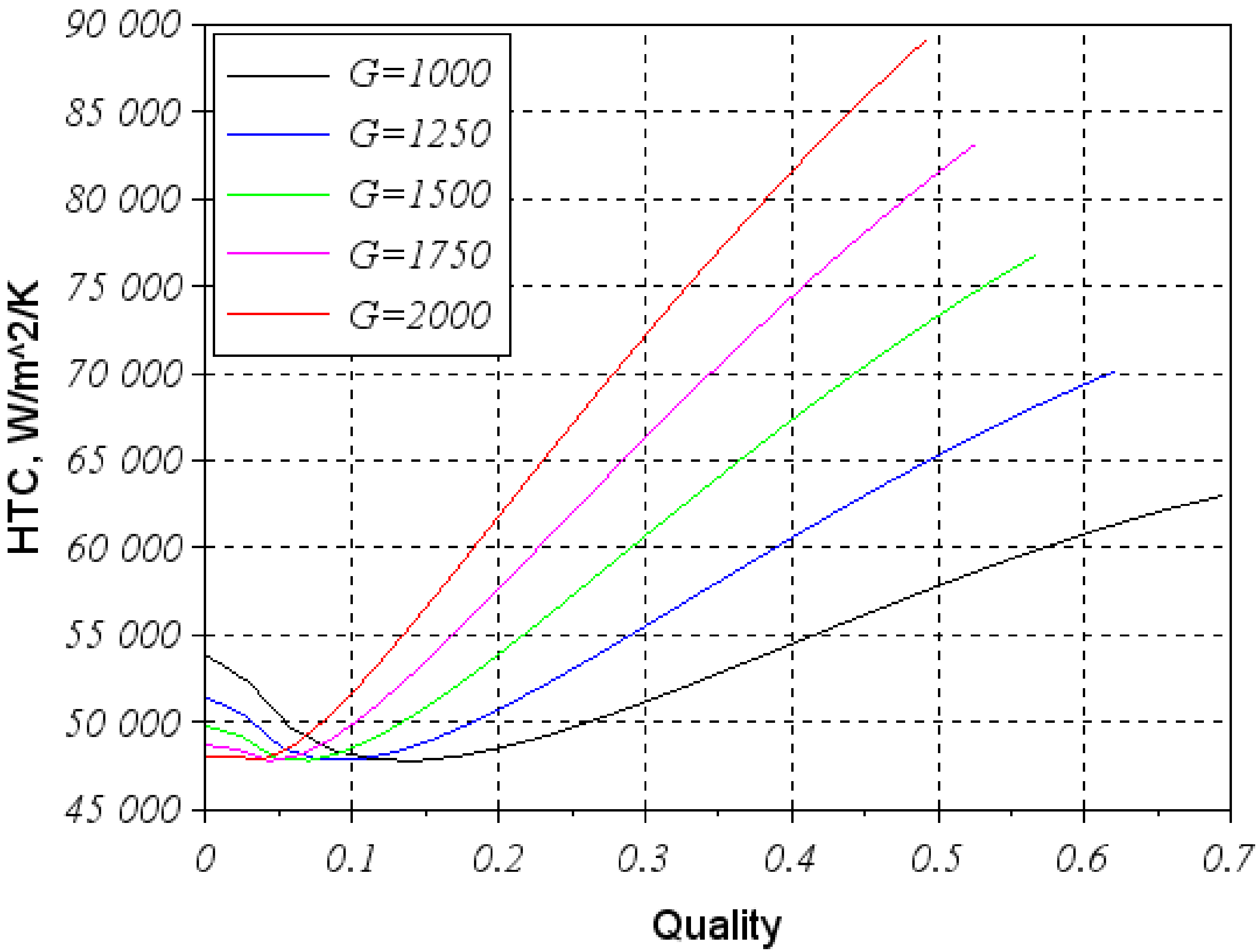
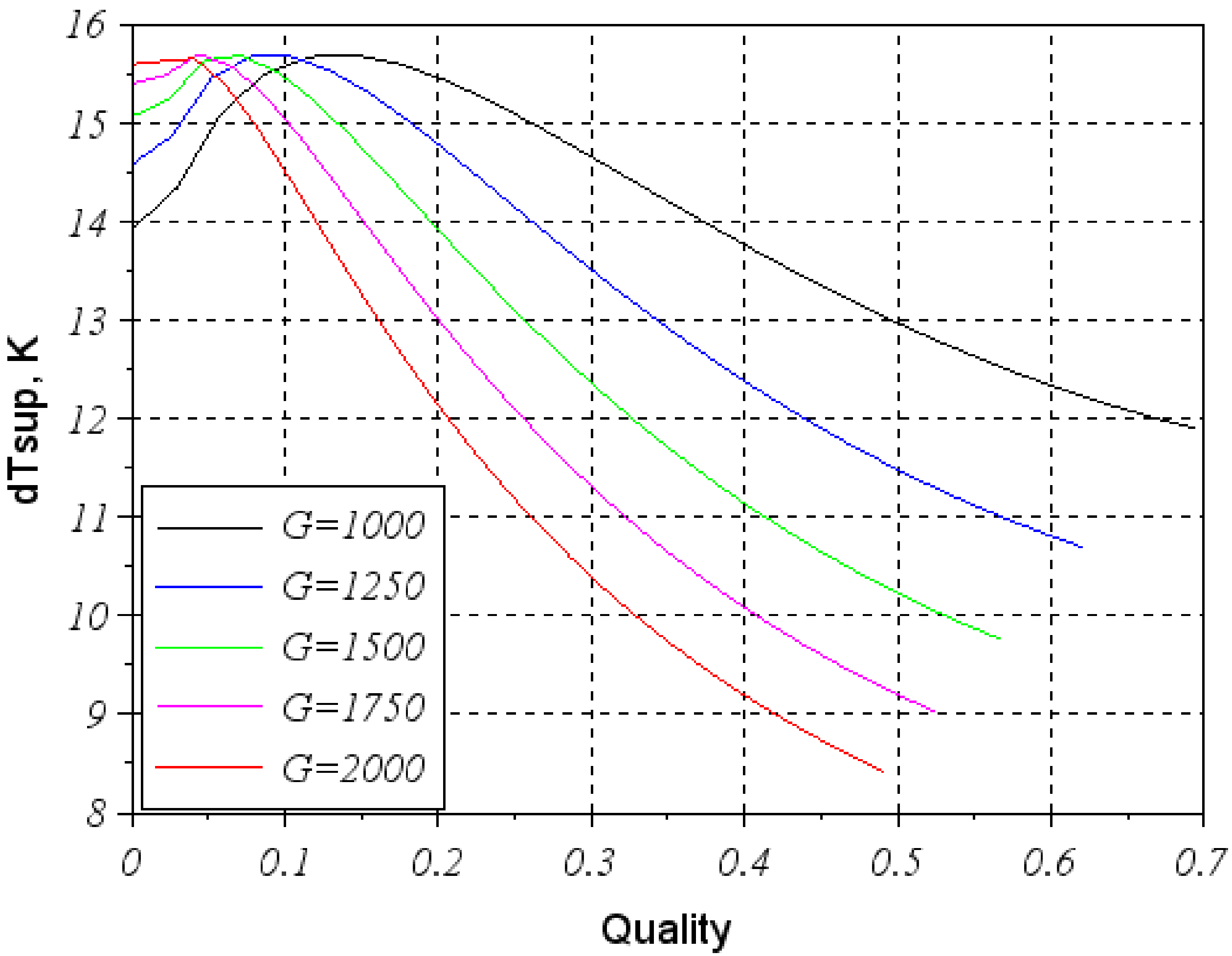
Chen Correlation Prediction



Prediction of heat transfer coefficient HTC

pressure 70 bar
D = 10 mm
q''=750 kW/m^2
G in kg/m^2/s

Chen Correlation Prediction



Prediction of wall superheat dTsup

pressure 70 bar
D = 10 mm
q''=750 kW/m^2
G in kg/m^2/s

Dryout (1)

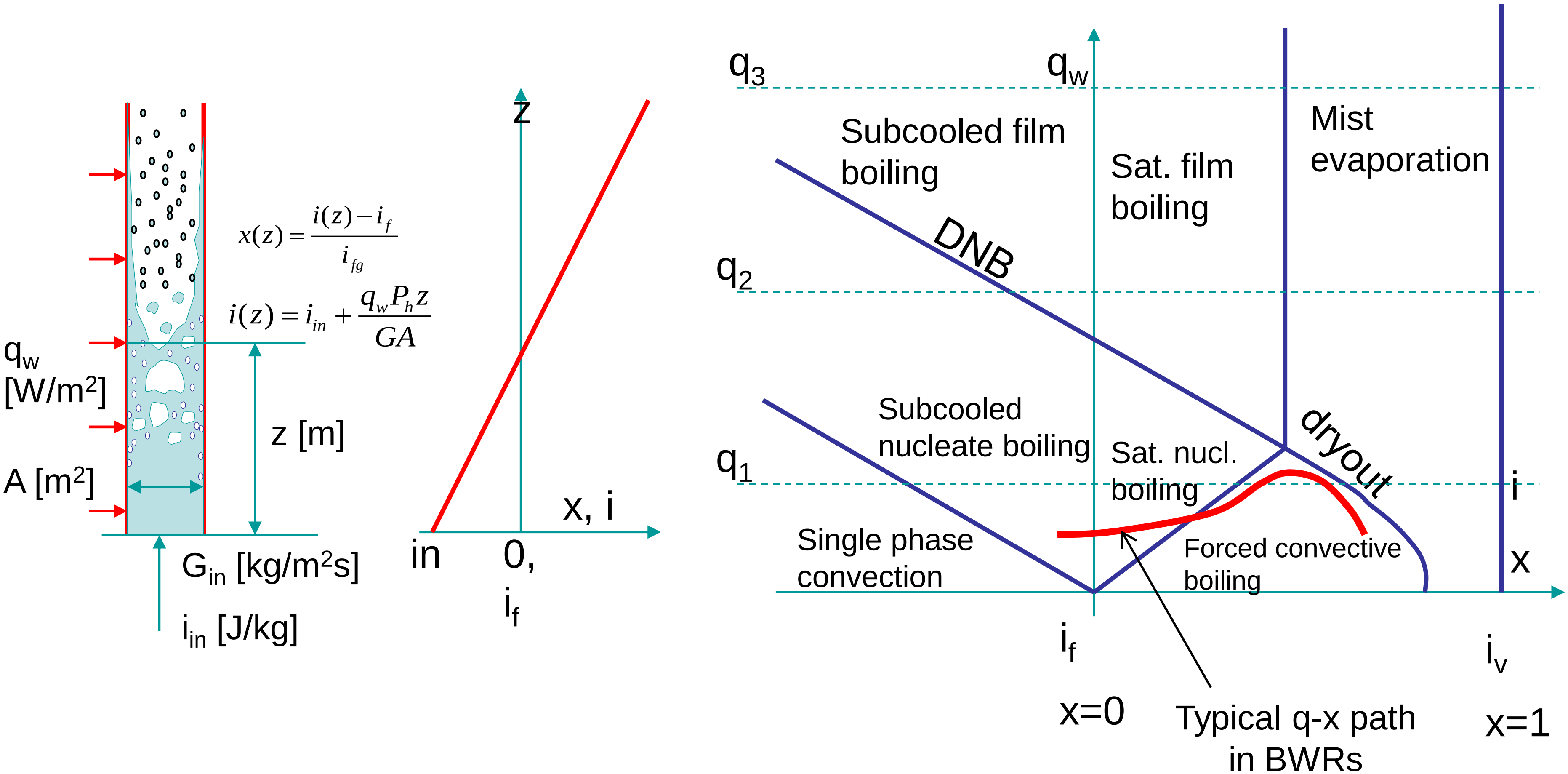
- Dryout occurs in channels with high quality
- This type of CHF is a concern in BWRs
- Typical dryout correlation has a form

$$x_{cr} = x_{cr}\left(G, p, D_h, L_B, \ldots\right)$$

G – mass flux [kg/m^{2}s],
p – pressure [Pa],
D_h – hydraulic diameter [m],
L_B – boiling length [m]

- That is, the correlation predicts the quality at which dryout occurs

Dryout (2)



$x(z) = \frac{i(z) - i_f}{i_{fg}}$
$i(z) = i_{in} + \frac{q_w P_h z}{GA}$
q_w
[W/m^2]
A [m^2]
z [m]
G_{in} [kg/m^{2}s]
i_{in} [J/kg]
z
x, i
in
0,
i_f
q_3
q_w
q_2
q_1
Subcooled film
boiling
Sat. film
boiling
Mist
evaporation
DNB
dryout
Subcooled
nucleate boiling
Sat. nucl.
boiling
Single phase
convection
Forced convective
boiling
i
x
i_f
x=0
Typical q-x path
in BWRs
i_v
x=1

Dryout (3)

- Example of a dryout correlation – Levitan-Lantsman

$$x_{cr}\Big|_{8mm} = \left[0.39 + 1.57\frac{p}{98} - 2.04\left(\frac{p}{98}\right)^2 + 0.68\left(\frac{p}{98}\right)^3\right]\left(\frac{G}{1000}\right)^{-0.5} \qquad x_{cr} = x_{cr}\Big|_{8mm} \cdot \left(\frac{8}{D_h}\right)^{0.15}$$

  p – pressure (bar), *G* mass flux (kg/m^2.s), D_h – hydraulic diameter, mm

- To predict the dryout it is thus necessary to find quality in a channel and compare it with the critical value

- Dryout will occur if at any point: $x(z) >= x_{cr}(z)$

Dryout (4)

- Exercise:
  - calculate a critical quality in a uniformly-heated pipe with:
  - $G = 754.3$ kg/m^2/s
  - $D = 11$ mm
  - $p = 70$ bar
  - Find distance from the inlet where dryout occurs if inlet subcooling is $\Delta T_{sub} = 10$ K and the heat flux is 750 kW/m^2

- Solution:

$$x_{crit}\big|_{8mm} = \left[0.39 + 1.57\frac{p}{98} - 2.04\left(\frac{p}{98}\right)^2 + 0.68\left(\frac{p}{98}\right)^3\right]\left(\frac{G}{1000}\right)^{-0.5} = \left[0.39 + 1.57\frac{70}{98} - 2.04\left(\frac{70}{98}\right)^2 + 0.68\left(\frac{70}{98}\right)^3\right]\left(\frac{754.3}{1000}\right)^{-0.5} \simeq 0.827$$

$$x_{crit} = x_{crit}\big|_{8mm} \cdot \left(\frac{8}{D}\right)^{0.15} = x_{crit}\big|_{8mm} \cdot \left(\frac{8}{11}\right)^{0.15} = 0.789$$

Dryout (5)

- We use the energy balance to find the dryout location
- Solution: $i(z_{DO}) = i_{in} + \frac{q''_w P_H z_{DO}}{GA} \Rightarrow \frac{i(z_{DO}) - i_f}{i_{fg}} = \frac{i_{in} - i_f}{i_{fg}} + \frac{q''_w P_H z_{DO}}{GAi_{fg}} \Rightarrow x_{cr} = x_{in} + \frac{q''_w P_H z_{DO}}{GAi_{fg}}$

$$z_{DO} = \frac{GAi_{fg}\left(x_{cr} - x_{in}\right)}{q''_w P_H}$$

where T_{sat} = XSteam('Tsat_p',70) = 285.83 °C; $T_{in} = T_{sat}$ – 10 K = 275.83 °C, i_{in} = XSteam('h_pT',70,Tin) = 1214.54 kJ/kg; $x_{in} = (i_{in}-i_f)/i_{fg}$ = -0.03514

$$z_{DO} = \frac{754.3 \cdot \pi \cdot 0.011^2 \cdot 1.505 \cdot 10^6 \left(0.789 + 0.03514\right)}{4 \cdot 750 \cdot 10^3 \cdot \pi \cdot 0.011} \cong 3.430 \text{ m}$$

Boiling Length Approach: CISE Correlation

- Original CISE correlation was developed for tubes
- General Electric extended the correlation to rod bundles based on their experimental data

$$x_{cr} = \frac{A \cdot L_B^*}{B + L_B^*}\left(\frac{1.24}{R_f}\right)$$

$L_B^* = L_B / 0.0254$ L_B – boiling length to dryout in [m]

R_f – radial peaking factor, [-]

$$A = 1.055 - 0.013\left(\frac{p_R - 600}{400}\right)^2 - 1.233 G_R + 0.907 G_R^2 - 0.285 G_R^3$$

$$G_R = G/1356.23$$

$$p_R = p/6894.757$$

$$B = 17.98 + 78.873 G_R - 35.464 G_R^2$$

Valid for 7x7 bundle; B=>B/1.12 for 8x8 bundle

G [kg/m^2.s]; p [Pa]

Hench and Gillis Correlation

$$x_{cr} = \frac{0.50 \cdot G_R^{-0.43} \cdot Z}{165 + 115 \cdot G_R^{2.3} + Z} \times \left[2 - J_1 + \frac{0.19}{G_R}\left(J_1 - 1\right)^2 + J_3 \right] + 0.006 - 0.0157 p_R - 0.0714 p_R^2$$

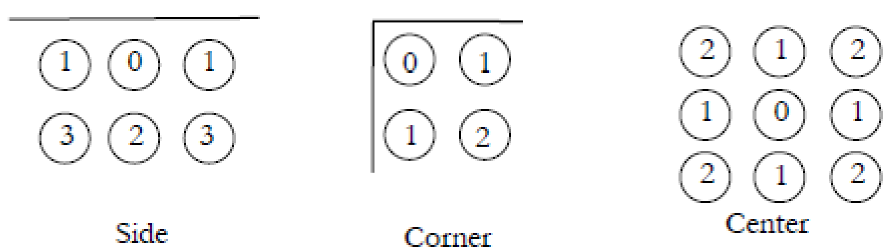
$G_R = G/1356.23$ *G* – mass flux, kg/m^{2}s

$Z = n\pi d_r L_B / A$ *n* – number of rods, d_r – rod diameter, m; L_B – boiling length to dryout, m

$p_R = \left(p/6894.7 - 800\right)/1000$ *A* – bundle flow area, m^2, *p* – pressure, Pa

$$J_1 = \begin{cases} \frac{1}{32}\left(25R_{f0} + 3\sum R_{f1} + R_{f2}\right) & \text{for corner rods} \\ \frac{1}{32}\left(22R_{f0} + 3\sum R_{f1} + 2R_{f2} + \sum R_{f3}\right) & \text{for side rods} \\ \frac{1}{32}\left(20R_{f0} + 2\sum R_{f1} + \sum R_{f2}\right) & \text{for central rods} \end{cases}$$

$$J_3 = \begin{cases} 0 & \text{for corner rods} \\ \frac{0.07}{G_R + 0.25} - 0.05 & \text{for side rods} \\ \frac{0.14}{G_R + 0.25} - 0.10 & \text{for central rods} \end{cases}$$



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Critical Power Ratio - CPR

- CPR (Critical Power Ratio) for a fuel assembly is defined as:

$$CPR = q_{cr}/q_{ac}$$

here: q_{cr} [W] is the total power of a bundle at which dryout occurs

q_{ac} [W] is the actual power of the bundle

CPR – Example 1 (1)

- **Example 1**: Calculate CPR for a BWR fuel assembly with total power Q = 10MW. The bundle operates at the following conditions: G = 2000 kg m^{-2} s^{-1}, pressure p = 7 MPa, inlet subcooling 10K. Bundle data: rod diameter = 10 mm, number of rods = 100, rectangular box with width = 140 mm. Use the Levitan&Lantsman correlation for dryout prediction.

CPR – Example 1 (2)

- The outlet quality can be calculated as:

$$x_{ex} = x_{in} + \frac{q}{GAi_{fg}} \Rightarrow q = GAi_{fg}\left(x_{ex} - x_{in}\right)$$

- If the bundle power is critical, then

$$x_{ex,cr} = x_{in} + \frac{q_{cr}}{GAi_{fg}} \Rightarrow q_{cr} = GAi_{fg}\left(x_{ex,cr} - x_{in}\right)$$

- And thus the CPR is found as

$$CPR = \frac{q_{cr}}{q} = \frac{GAi_{fg}\left(x_{ex,cr} - x_{in}\right)}{GAi_{fg}\left(x_{ex} - x_{in}\right)} = \frac{x_{ex,cr} - x_{in}}{x_{ex} - x_{in}}$$

CPR – Example 1 (3)

- The inlet quality can be calculated as:

$$x_{in} = \frac{i_{in}(T_{in}, p) - i_f}{i_{fg}} = \frac{1214542 - 1267437}{1505132} \approx -0.03514$$

- and the exit quality is found as

$$x_{ex} = x_{in} + \frac{q}{GAi_{fg}} = -0.03514 + \frac{10 \cdot 10^6}{2 \cdot 10^3 \left(0.14^2 - 100\pi\, 0.01^2 / 4\right) 1505132} \approx 0.24767$$

- The critical quality is obtained from the Levitan&Lantsman correlation as (finding D_h=12.7mm):

$$x_{ex,cr} = \left[0.39 + 1.57\frac{70}{98} - 2.04\left(\frac{70}{98}\right)^2 + 0.68\left(\frac{70}{98}\right)^3\right]\left(\frac{2000}{1000}\right)^{-0.5}\left(\frac{8}{12.7}\right)^{0.15} \approx 0.474$$

CPR – Example 1 (4)

- CPR is now obtained as

$$CPR = \frac{q_{cr}}{q} = \frac{x_{ex,cr} - x_{in}}{x_{ex} - x_{in}} \approx \frac{0.474 + 0.035}{0.2477 + 0.035} \approx 1.8$$

- This result indicates a high value of CPR, significantly higher than 1. It would indicate a safe operation of the bundle.
- However, we used a correlation that is valid for pipes, not for bundles.
- To check a validity of this result, let us calculate CPR using a correlation valid for rod bundles.

CPR – Example 2 (1)

- **Example 2**: Calculate CPR for a BWR fuel assembly with total power Q = 10MW with axial and radial uniform power distribution.
- The bundle operates at the following conditions: G = 2000 kg m^{-2} s^{-1}, pressure p = 7 MPa, inlet subcooling 10K.
- Bundle geometry: bundle length 3.7 m, rod diameter = 10 mm, number of rods = 100, rectangular box with width = 140 mm.
- Use the GE-extended CISE correlation for the dryout prediction, assuming the same *B*-value as for 8x8 bundle.

CPR – Example 2 (2)

- **SOLUTION:** The inlet quality can be calculated as:

$$x_{in} = \frac{i_{in}(T_{in}, p) - i_f}{i_{fg}} = \frac{1214542 - 1267437}{1505132} \approx -0.03514$$

- and the exit quality is found as

$$x_{ex} = x_{in} + \frac{q}{GAi_{fg}} = -0.03514 + \frac{10 \cdot 10^6}{2 \cdot 10^3 \left(0.14^2 - 100\pi\, 0.01^2/4\right) \times 1505132} \approx 0.24767$$

- The critical quality is obtained from the GE-extended CISE correlation (R_f=1 and we assume first that $x_{cr,0}$=x_{ex}):

We find the boiling length $L_{B,0}$ as:

$$\left.\begin{aligned} L \cdot P_H \cdot q''_{cr,0} &= \left(x_{cr,0} - x_{in}\right) GAi_{fg} \\ L_{B,0} \cdot P_H \cdot q''_{cr,0} &= \left(x_{cr,0}\right) GAi_{fg} \end{aligned}\right\} \Rightarrow L_{B,0} = L \frac{x_{cr,0}}{x_{cr,0} - x_{in}} \cong 3.252 \text{ m}$$

CPR – Example 2 (3)

- Thus, new $x_{cr,1}$ is found as: $$x_{cr,1} = \frac{A \cdot L^*_{B,0}}{B + L^*_{B,0}} \left(\frac{1.24}{R_f} \right) \cong 0.250$$

- For this critical power, the boiling length is $L_{B,1} = L \frac{x_{cr,1}}{x_{cr,1} - x_{in}} \cong 3.244 \text{ m}$
- One more iteration gives:

$$x_{cr,2} = \frac{A \cdot L^*_{B,1}}{B + L^*_{B,1}} \left(\frac{1.24}{R_f} \right) \cong 0.250$$

So we take x_{cr} = 0.25 as the critical quality

- CPR is now obtained as

$$CPR = \frac{q_{cr}}{q} = \frac{x_{ex,cr} - x_{in}}{x_{ex} - x_{in}} \approx \frac{0.25 + 0.035}{0.2477 + 0.035} \approx 1.008$$

- As we can see, CPR has significant lower value and is very close to 1. There is a high probability of dryout.

CPR – Example 3 (1)

- **Example 3**: Calculate CPR for a BWR fuel assembly with total power Q = 10MW with axial and radial uniform power distribution.
- The bundle operates at the following conditions: G = 2000 kg m^{-2} s^{-1}, pressure p = 7 MPa, inlet subcooling 10K.
- Bundle geometry: bundle length 3.7 m, rod diameter = 10 mm, number of rods = 100, rectangular box with width = 140 mm.
- Use the Hench-Gillis correlation for the dryout prediction.

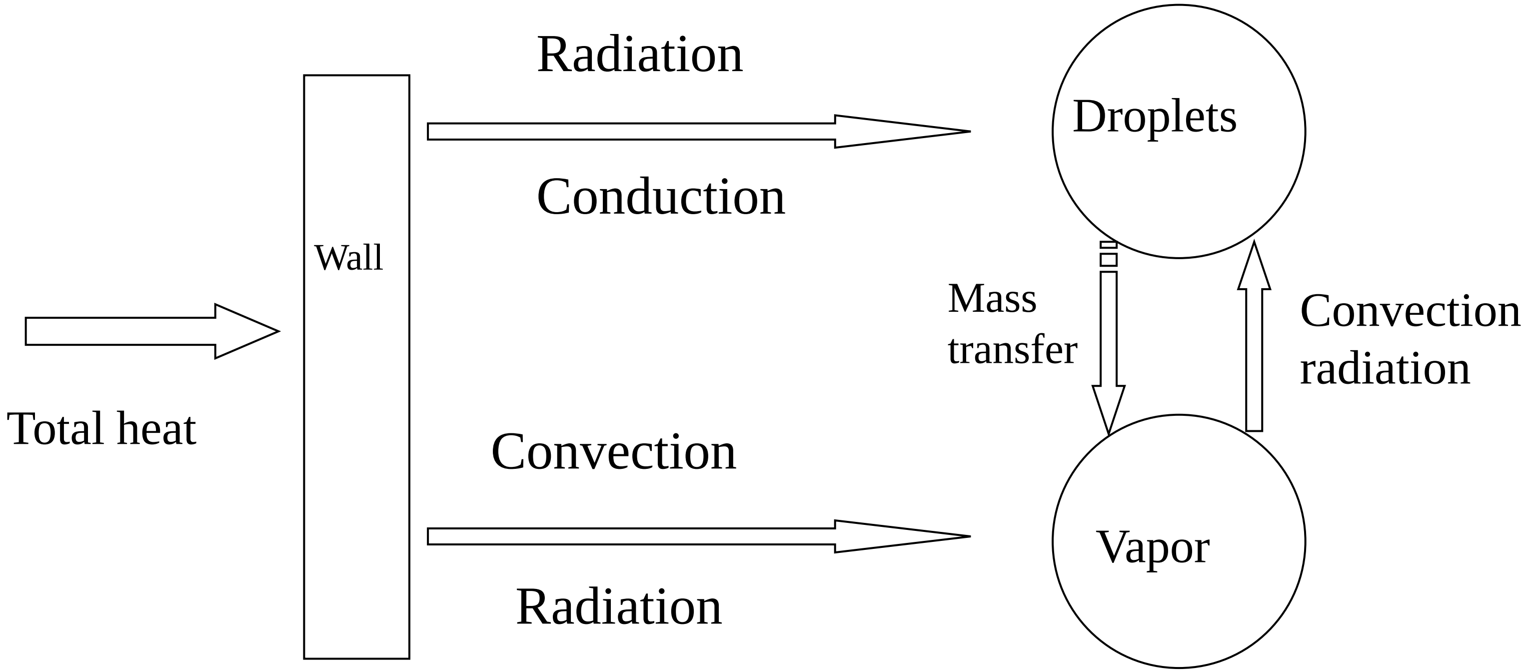
CPR – Example 3 (2)

- We need to program the correlation and find x_{cr} for each rod. We guess the boiling length L_B = 3.2 m
- The minimum x_{cr} is found for internal rods and is 0.27
- CPR is now obtained as

$$CPR = \frac{q_{cr}}{q} = \frac{x_{ex,cr} - x_{in}}{x_{ex} - x_{in}} \approx \frac{0.27 + 0.035}{0.2477 + 0.035} \approx 1.08$$

- CPR has now a value similar to the one obtained with the GE-CISE correlation.
- We should also iterate to find the correct value of the boiling length L_B, but CPR will not change much.

Post-dryout Heat Transfer (1)



Post-dryout Heat Transfer (2)

- Mechanistic models are taking into account all heat transfer mechanisms but they are very complex
- Simplified approach can be based on using a proper correlation for heat transfer coefficient
- Groeneveld proposed the following correlation for heat transfer in the dispersed flow regime

$$\mathrm{Nu_g} = \frac{hD}{\lambda_g} = a\left[\left(\frac{GD}{\mu_g}\right)\left(x + \frac{\rho_g}{\rho_f}(1-x)\right)\right]^b \mathrm{Pr}_{g,w}^c Y^d \quad \text{where} \quad Y = 1 - 0.1\left(\frac{\rho_f}{\rho_g} - 1\right)^{0.4}(1-x)^{0.4}$$

- Coefficients *a-d* as well as validity ranges are given in the compendium. Note that $\mathrm{Pr}_{g,w}$ is the vapor Prandtl number evaluated at the wall temperature

Exercise - PDO

- Exercise:
  - calculate wall temperature at 3.66 distance from inlet in a uniformly-heated pipe with:
  - $G = 754.3\ kg/m^2/s$
  - $D = 11\ mm$
  - $p = 70\ bar$
  - $\Delta T_{subi} = 10\ K$
  - $q'' = 750\ kW/m^2$

Use Levitan&Lantsman correlation to predict critical quality and Groeneveld correlation for a tube to predict the Nusselt number in the post-dryout region (from compendium we have a = 0.00109, b = 0.989, c = 1.41, and d = -1.15)

Exercise - PDO

- SOLUTION: In the example on Slides 18-19 we found that dryout will occur at distance z_{DO} = 3.43 m from the inlet for the specified consitions.
- The thermodynamic quality of water-vapour mixture at *z* = 3.66 m can be found from the energy balance

$$x_{z=3.66} = x = x_{in} + \frac{q''_w P_H z_{3.66}}{GAi_{fg}} = -0.03514 + \frac{4\times750\times10^3\times\pi\times0.011\times3.66}{754.3\times\pi\times(0.011)^2\times1.505\times10^6} \cong 0.856$$

- We see that it is higher than the critical quality (0.789), so there is post-dryout heat transfer in this cross-section
- We calculate Y

$$Y = 1-0.1\left(\frac{\rho_f}{\rho_g}-1\right)^{0.4}(1-x)^{0.4} = 1-0.1\left(\frac{739.7}{36.52}-1\right)^{0.4}(1-0.856)^{0.4} = 0.8496$$

Exercise - PDO

- We calculate a constant term in Groeneveld's correlation:

$$\mathrm{Nu_g} = \frac{hD}{\lambda_g} = a\left[\left(\frac{GD}{\mu_g}\right)\left(x + \frac{\rho_g}{\rho_f}(1-x)\right)\right]^b \mathrm{Pr}_{g,w}^c Y^d = C \cdot \mathrm{Pr}_{g,w}^c,$$

where,

$$C = a\left[\left(\frac{GD}{\mu_g}\right)\left(x + \frac{\rho_g}{\rho_f}(1-x)\right)\right]^b Y^d = 0.00109\left[\left(\frac{754.3 \times 0.011}{1.896 \times 10^{-5}}\right)\left(0.856 + \frac{36.52}{739.7}(1-0.856)\right)\right]^{0.989} Y^{-1.15} = 431.2$$

- The gas Prandtl number has to be found at the wall temperature, which is not known yet. We assume Pr~1, so

$$\mathrm{Nu_g} = \frac{hD}{\lambda_g} = 431.2 \cdot \mathrm{Pr}_{g,w}^c \approx 431.2 \Rightarrow h = 431.2 \cdot \lambda_g / D \cong 431.2 \times 0.06437 / 0.011 \cong 2523 \frac{\mathrm{W}}{\mathrm{m^2K}}$$

Exercise - PDO

- Thus we can find the wall temperature as

$$T_w = T_{sat} + \frac{q''_w}{h} = 285.83 + \frac{750\times 10^3}{2523} = 583.1\,°\mathrm{C}$$

- Using XSteam, we find Pr(T=583.1°C) = 0.931. Thus, the heat transfer coefficient is now:

$$\mathrm{Nu_g} = \frac{hD}{\lambda_g} = 431.2\cdot \mathrm{Pr}^c_{g,w} = 431.2\times 0.931^{1.41} \approx 389.9 \Rightarrow h = 389.9\cdot\lambda_g / D \cong 389.9\times 0.06437/0.011 \cong 2282\,\frac{\mathrm{W}}{\mathrm{m^2K}}$$

- And the new wall temperature is: $T_w = T_{sat} + \frac{q''_w}{h} = 285.83 + \frac{750\times 10^3}{2282} = 614.5\,°\mathrm{C}$

- One more iteration gives T_w = 619.2 °C, which we take as the solution (exact solution is 619.7 °C).