Lecture No 04

Title:

TH Design of Fuel Assemblies with Single-Phase Coolant

Pressure Drop and DNB

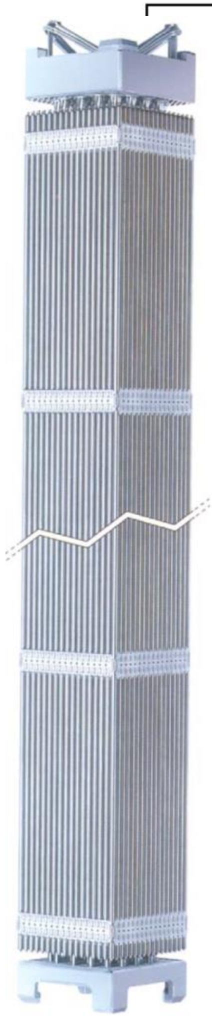
Henryk Anglart
Nuclear Reactor Technology Division
Department of Physics, School of Engineering Sciences
KTH

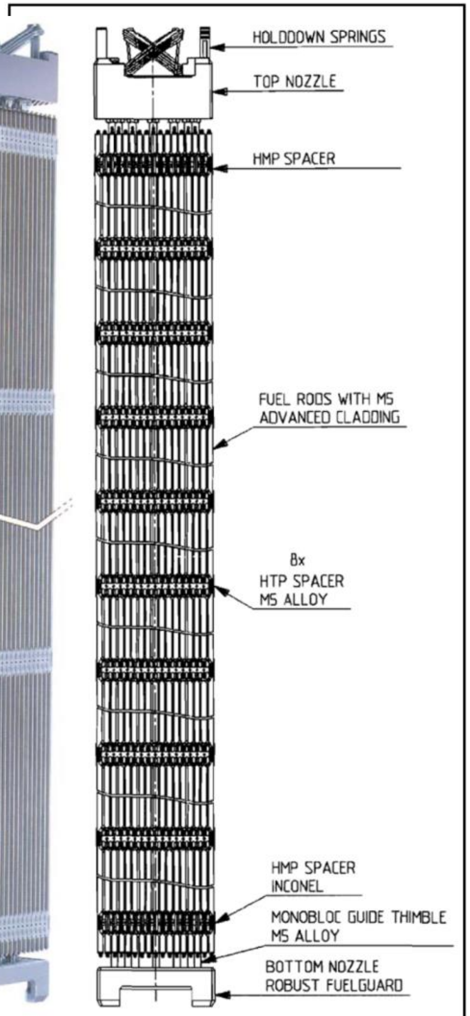
Autumn 2022

Outline of the Lecture

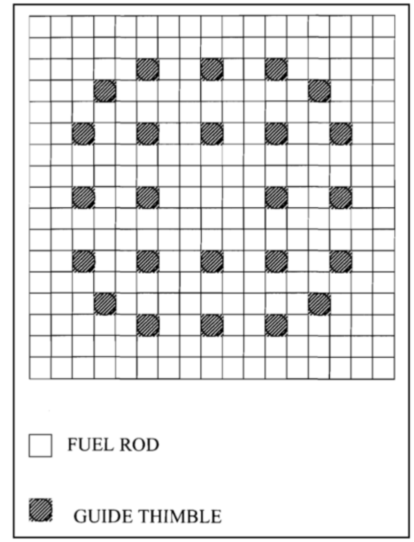
- Pressure Drop Calculation in Fuel Assemblies with Single-Phase Coolants
  - friction pressure loss
  - local losses
- Departure from Nucleate Boiling (DNB) in PWRs
  - DNB Ratio - DNBR
  - Minimum DNBR – MDNBR
  - Location of MDNBR

PWR Fuel Assembly



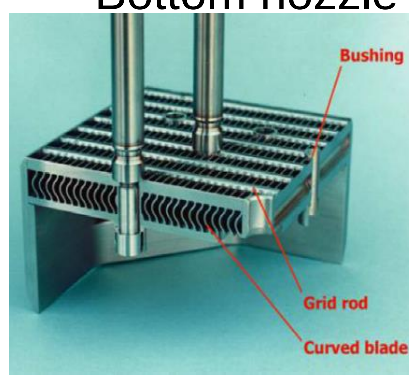


Top nozzle



Cross section

Bottom nozzle with debris filter



Pressure Drop Calculation

- Calculation of pressure drop in single phase flows, including
  - Friction pressure losses
  - Local losses from the spacer grids
  - Local losses at the assembly inlet and exit
  - Local losses due to flow area change
  - Elevation pressure drop

- The total pressure drop in a vertical channel with length *H* and hydraulic diameter D_h can be calculated from the following equation (G = const)

$$-\Delta p_{tot} = -\Delta p_{fric} - \Delta p_{loc} - \Delta p_{elev} = \left(\frac{4C_f H}{D_h} + \sum_i \xi_i \right) \frac{G|G|}{2\rho} + H\rho g$$

Friction Pressure Losses (1)

- Friction pressure losses in a channel with length *H* and hydraulic diameter D_h is calculated as:

$$-\Delta p_{fric} = \frac{4 C_f H}{D_h} \frac{G|G|}{2\rho}$$

- where C_f is the (Fanning) friction coefficient, which depends on the Reynolds number and wall roughness, defined as

$$C_f \equiv \frac{\tau_w}{\frac{1}{2}\rho U^2}$$

τ_w – wall shear stress,
$U = G/\rho$ – flow velocity

Friction Pressure Losses (2)

- Friction coefficient for pipes
  - Laminar flow (Re < 2300) $$C_f = \frac{16}{\mathrm{Re}}$$
  - Turbulent flow (Blasius formula, $10^4 < \mathrm{Re} < 10^5$) $$C_f = \frac{0.0791}{\mathrm{Re}^{0.25}}$$
  - Turbulent flow in commercial rough tubes (Colebrook formula)

$$\frac{1}{\sqrt{C_f}} = -4.0 \log_{10}\left(\frac{k / D_h}{3.7} + \frac{1.255}{\mathrm{Re}\sqrt{C_f}} \right)$$

k – wall roughness [m],

D_h – hydraulic diameter [m]

Friction Pressure Losses (3)

- Friction coefficient for pipes, cont'ed
  - Colebrook formula can be replaced with the Haaland formula (which does not require iterations)

$$\frac{1}{\sqrt{C_f}} = -3.6\log_{10}\left[\left(\frac{k/D_h}{3.7}\right)^{1.11} + \frac{6.9}{\mathrm{Re}}\right]$$

k – wall roughness [m],

D_h – hydraulic diameter [m]

Friction Pressure Losses (4)

- In fuel assemblies, friction coefficients are obtained experimentally and are in general expressed in the following form:

$$C_f = a\,\mathrm{Re}^{-b}$$

a, b > 0 – coefficients that depend on the fuel assembly design

Friction Pressure Losses (5)

- For triangular lattice with 1.0 < p/d_r < 1.5 the following correlation can be used:

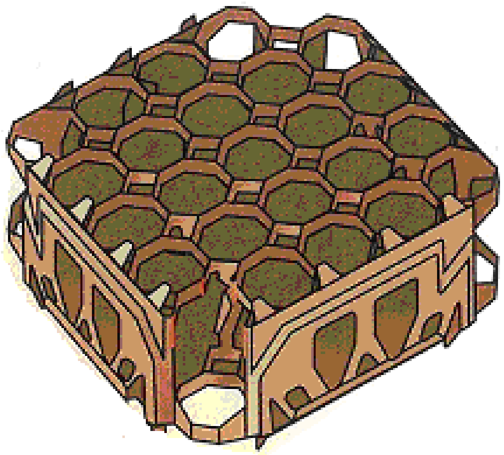
$$C_{f,b} = \frac{0.25\left(0.96\dfrac{p}{d_r} + 0.63\right)}{\left(1.82\log_{10}\mathrm{Re} - 1.64\right)^2} \qquad \mathrm{Re} > 4000$$

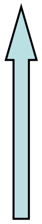
Local Losses Due to Spacer Grids

- Spacer local pressure loss
  - Geometry-dependent
  - In general, the pressure loss can be calculated as

$$\xi_{spac} = a_1 + a_2 \cdot \mathrm{Re}^{-b}$$

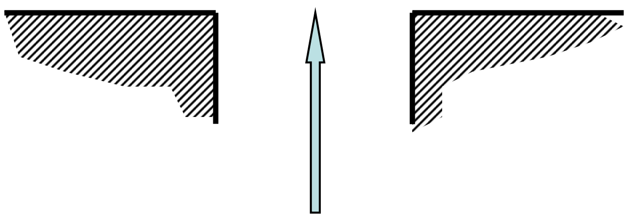
  - Constants a_1, a_2 and b are usually obtained from experiments





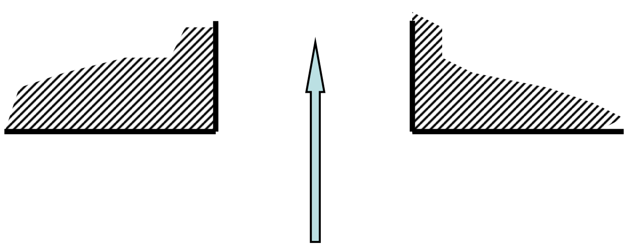
Local Losses Due to Area Changes

Exit from fuel assembly



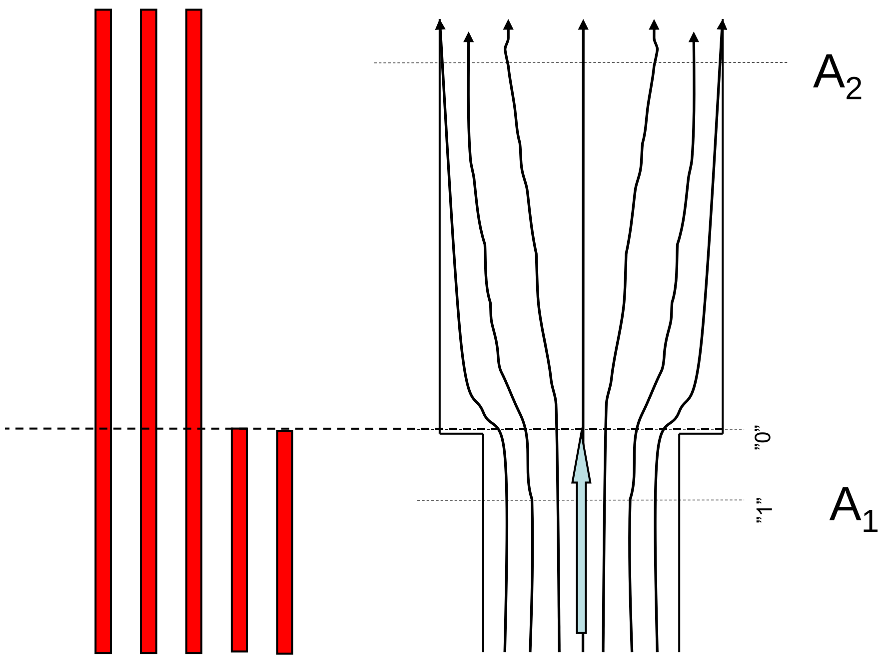
$$-\Delta p_I = \xi_{ex} \cdot \frac{G^2}{2\rho}; \qquad \xi_{ex} = 1.0$$

Inlet to fuel assembly



$$-\Delta p_I = \xi_{in} \cdot \frac{G|G|}{2\rho}; \qquad \xi_{in} = 0.5$$

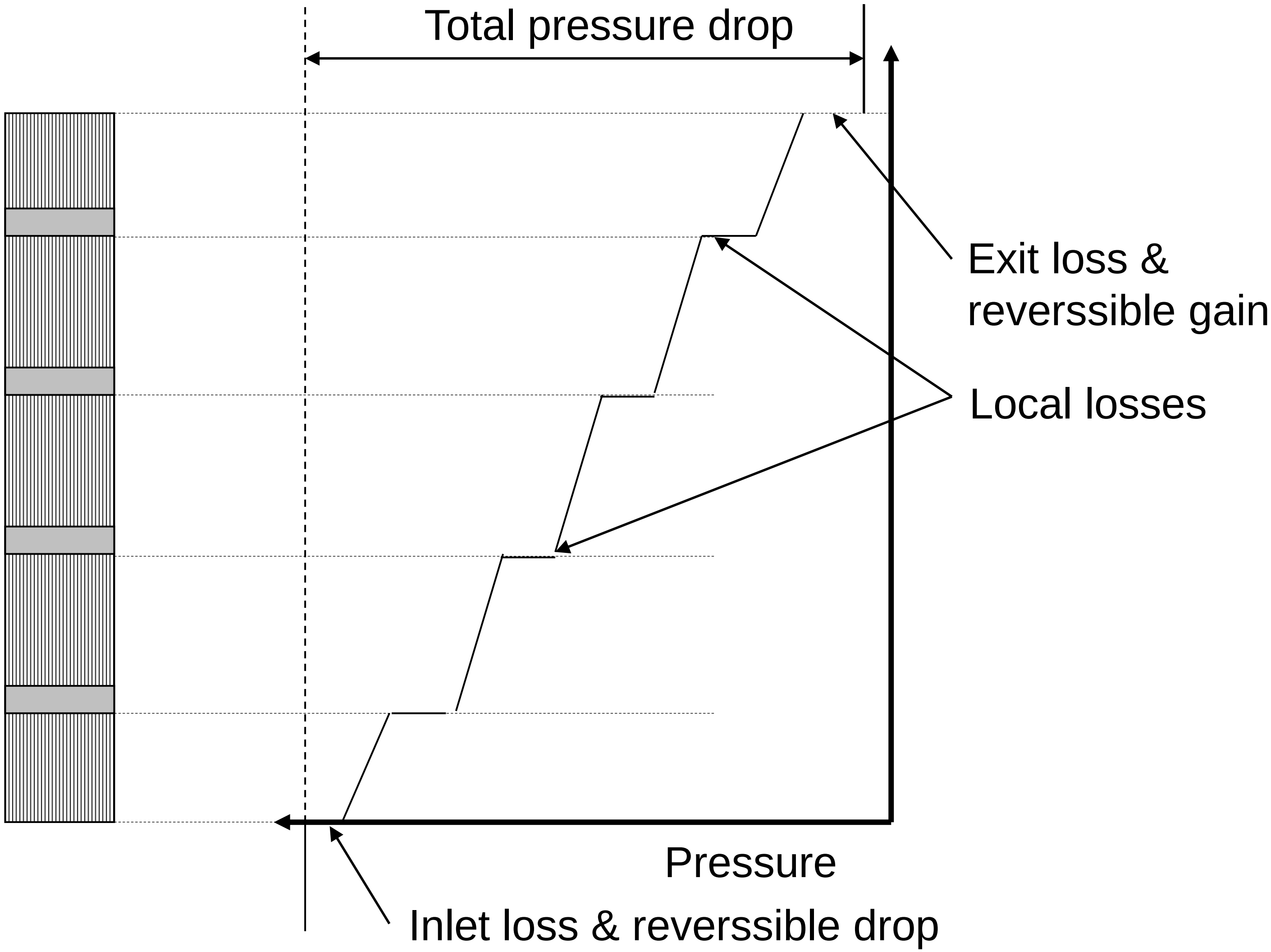
Area change due to part-length rods



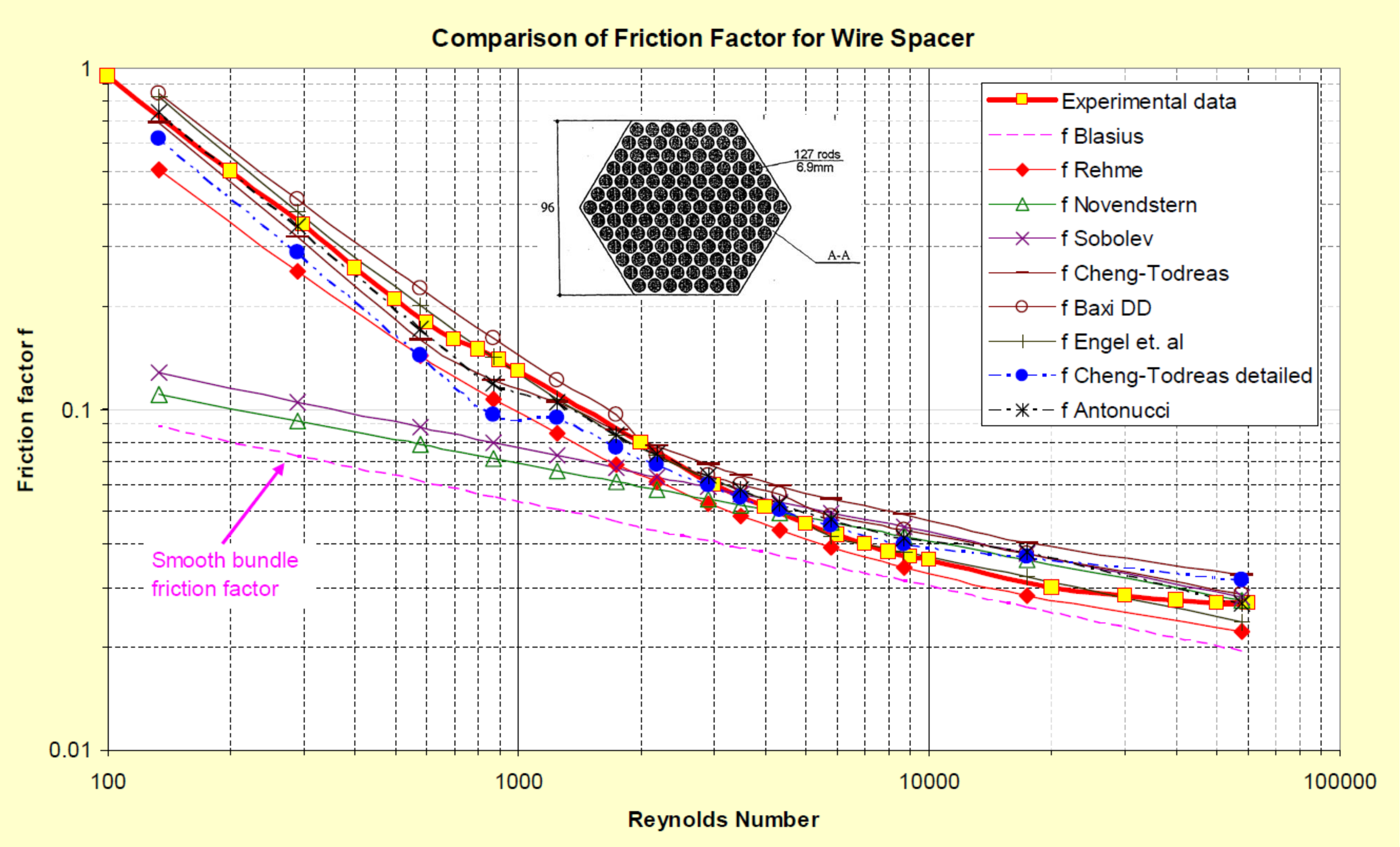
$$-\Delta p_I = \left(1 - \frac{A_1}{A_2}\right)^2 \cdot \frac{G_1|G_1|}{2\rho}; \qquad \xi_{enl} = \left(1 - \frac{A_1}{A_2}\right)^2$$

Henryk Anglart
Nuclear Reactor Technology Division
Department of Physics, KTH

Loss Distribution in Fuel Assembly



Wire Spacer Effect



Wire Spacer Effect

- The effect of the wire spacer on pressure drop is taken into account by a friction multiplier *M* as follows:

$$C_{fw-w} = M \cdot C_f$$

- A correlation for *M* proposed by Novendstern is as follows

$$M = \left[\frac{1.034}{\left(p/d_r\right)^{0.124}} + \frac{29.7\left(p/d_r\right)^{6.94} \mathrm{Re}^{0.086}}{\left(H_W/d_r\right)^{2.239}} \right]^{0.885}$$

H_W – wire lead (hight of full turn around a rod)
d_r – rod diameter
p – lattice pitch

Critical Heat Flux - CHF

- Critical Heat Flux (CHF) is one of limiting safety parameters in Light Water Reactors (LWRs)

- Previously we discussed a linear power limit to prevent fuel melting

- Heat flux limit is necessary to protect fuel cladding from damage

- Fuel and reactor core must be designed in such a way that the CHF limit is never exceeded

Experimentally observed DNB mechanisms

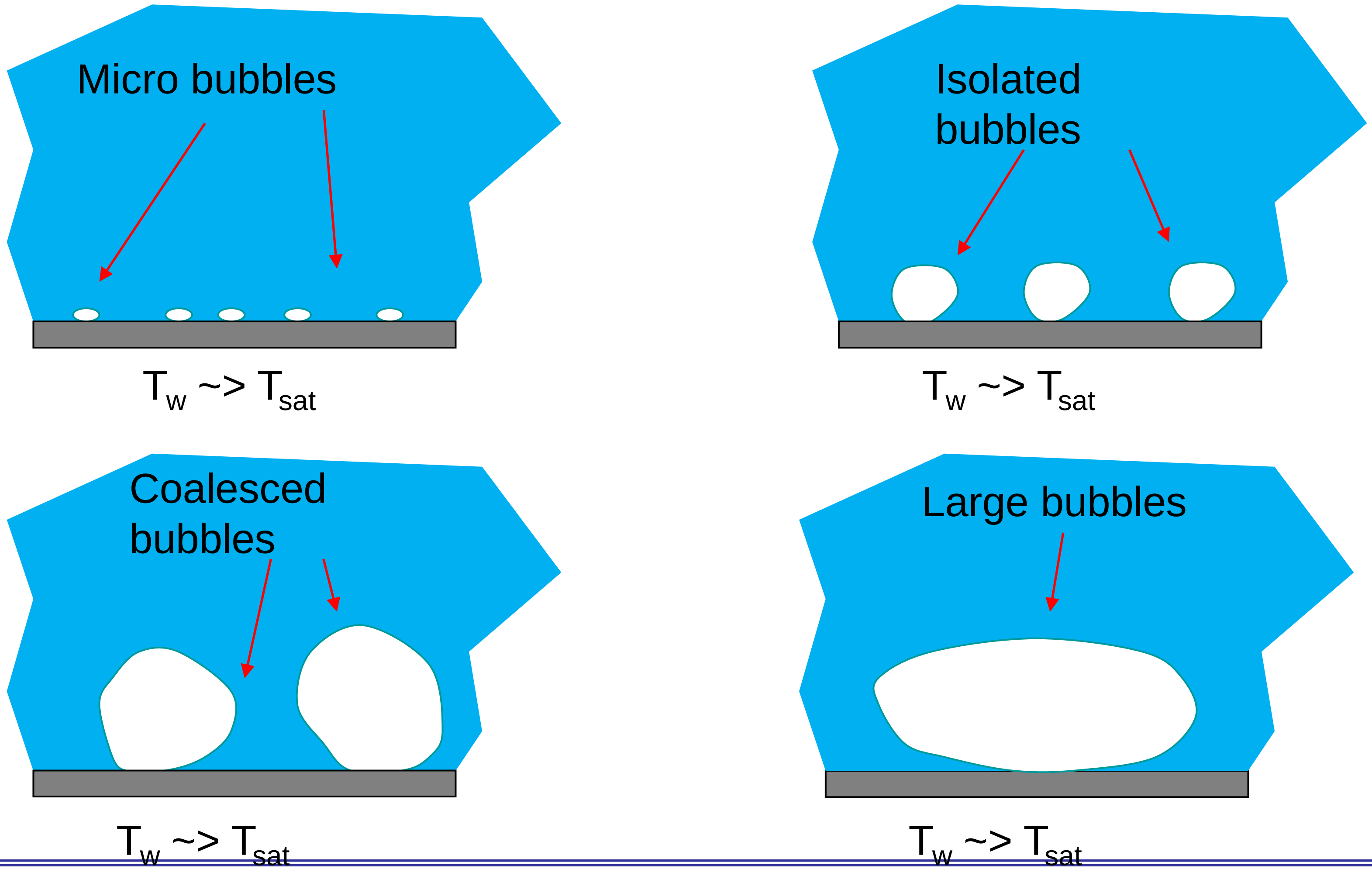
Three major DNB mechanisms have been observed in experiments

Type 1: bubbly flow, where dry patches are created below single large bubbles

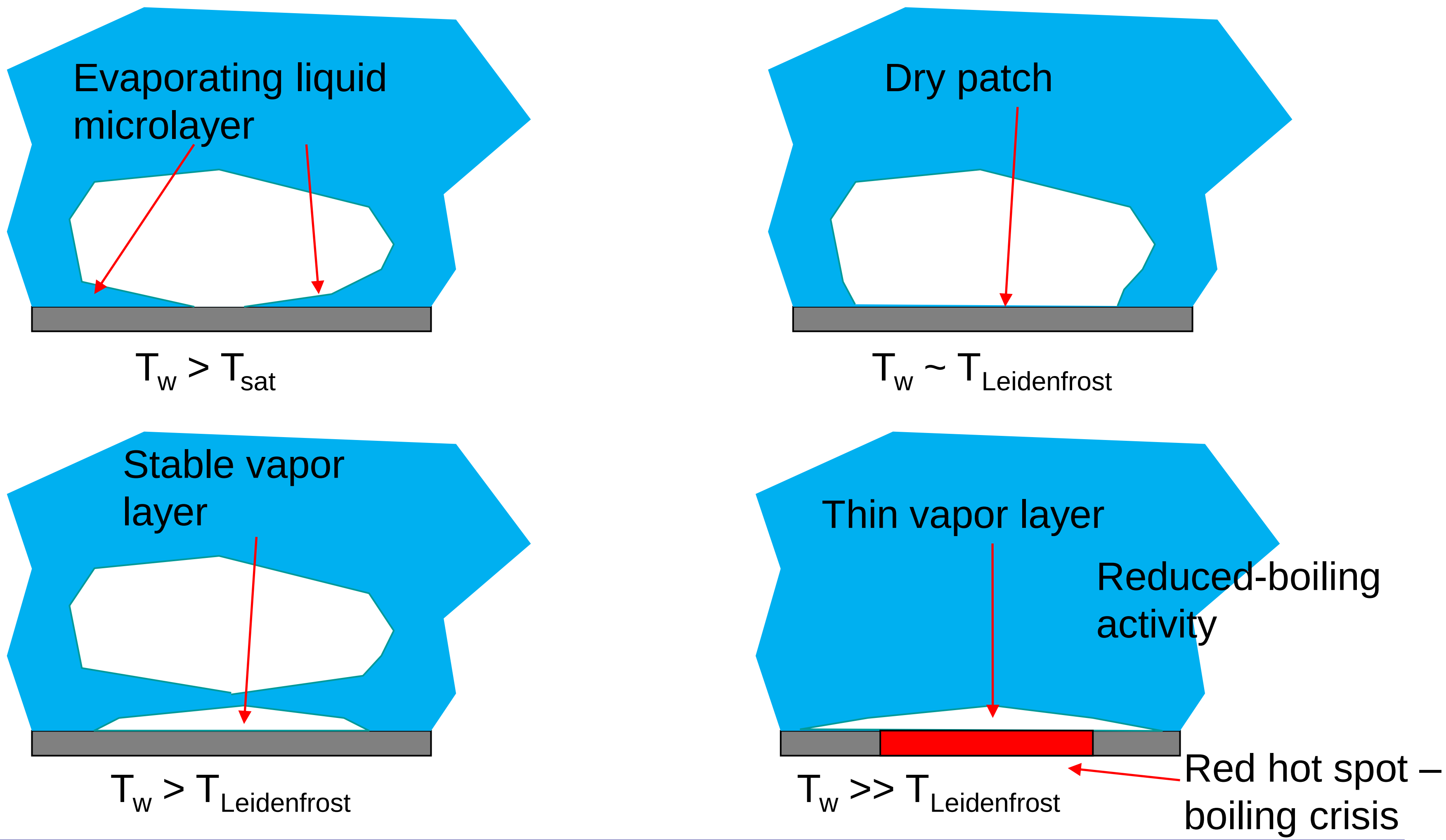
Type 2: DNB in bubbly microlayer under vapor clots

Type 3: DNB in liquid film under vapor slugs

Type 1 DNB – bubble grow



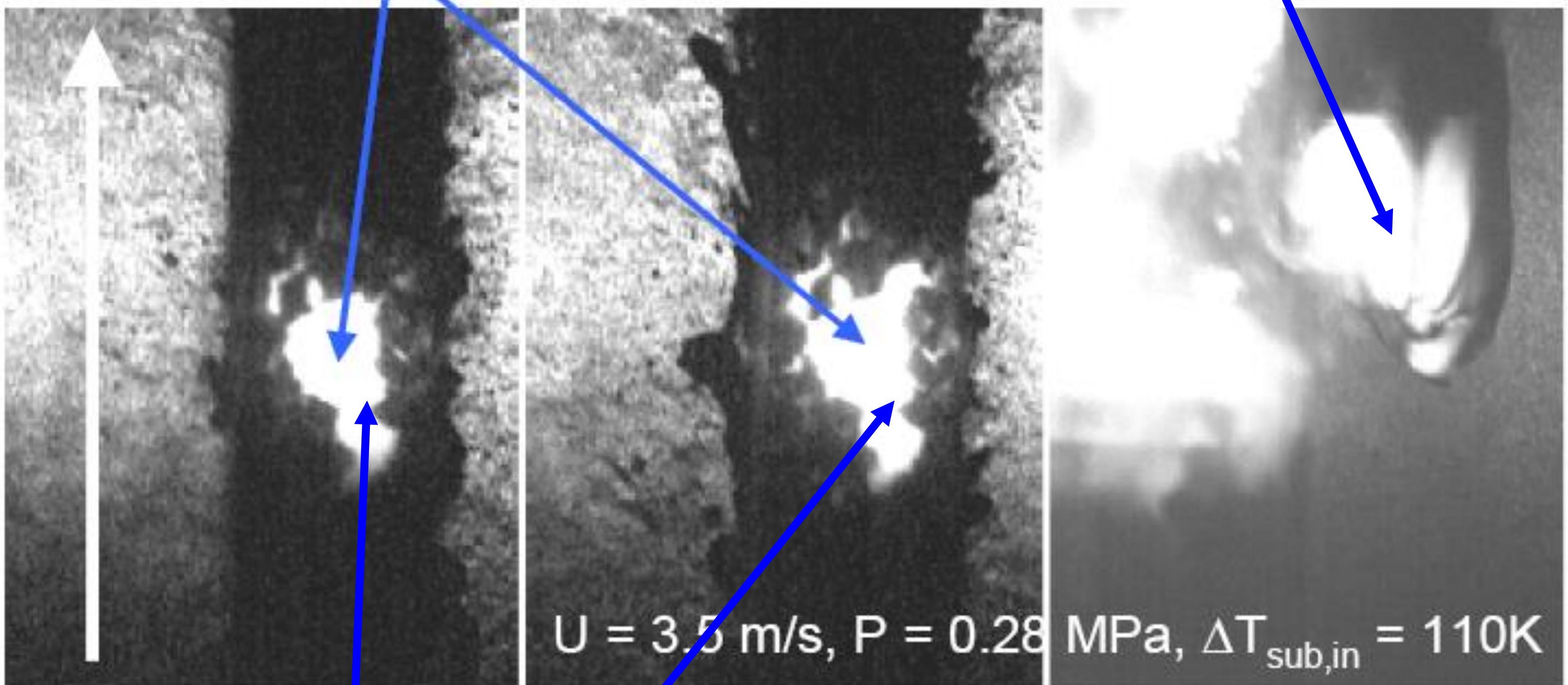
Type 1 DNB – towards crisis



Type 1 DNB – visualization

CHF location

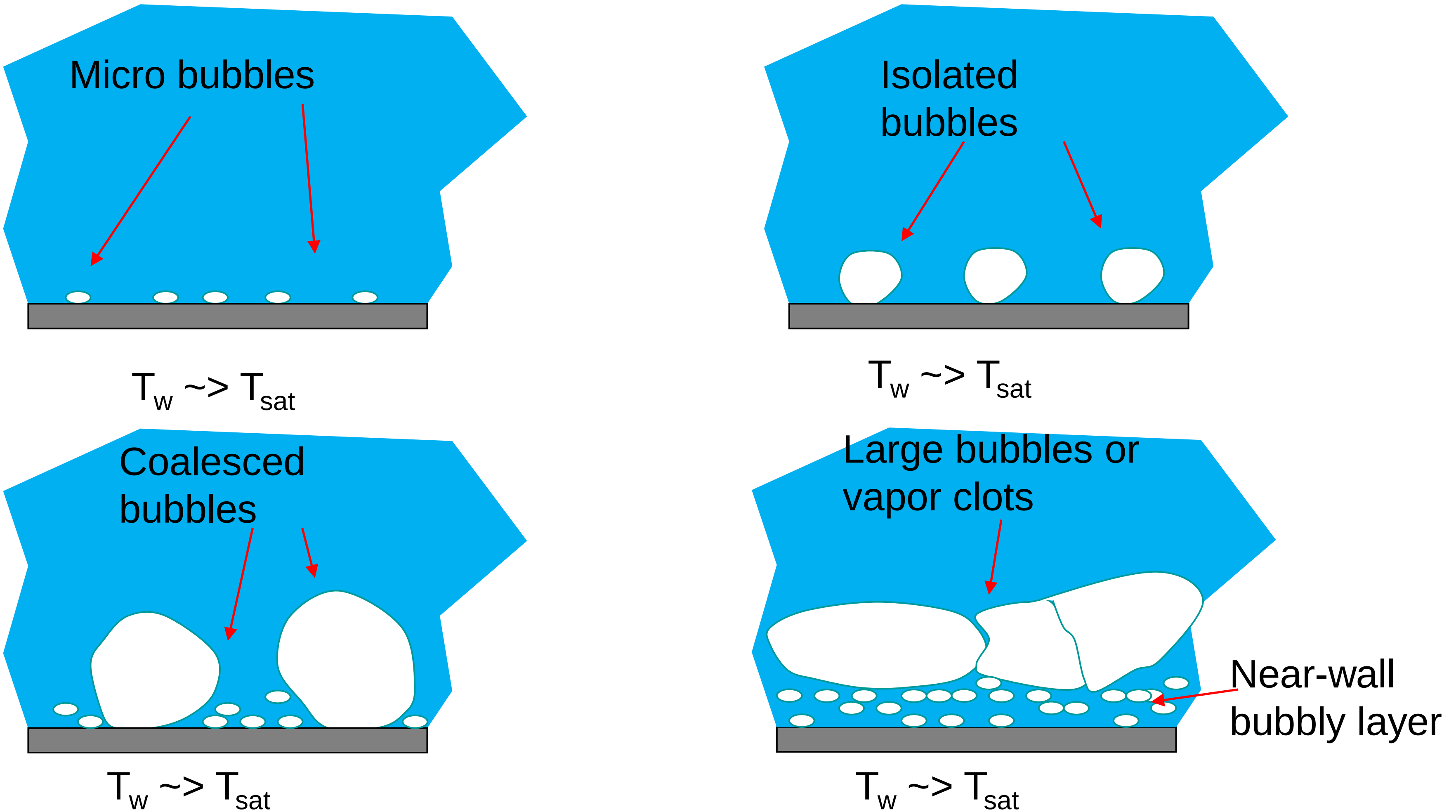
Melting-through heater



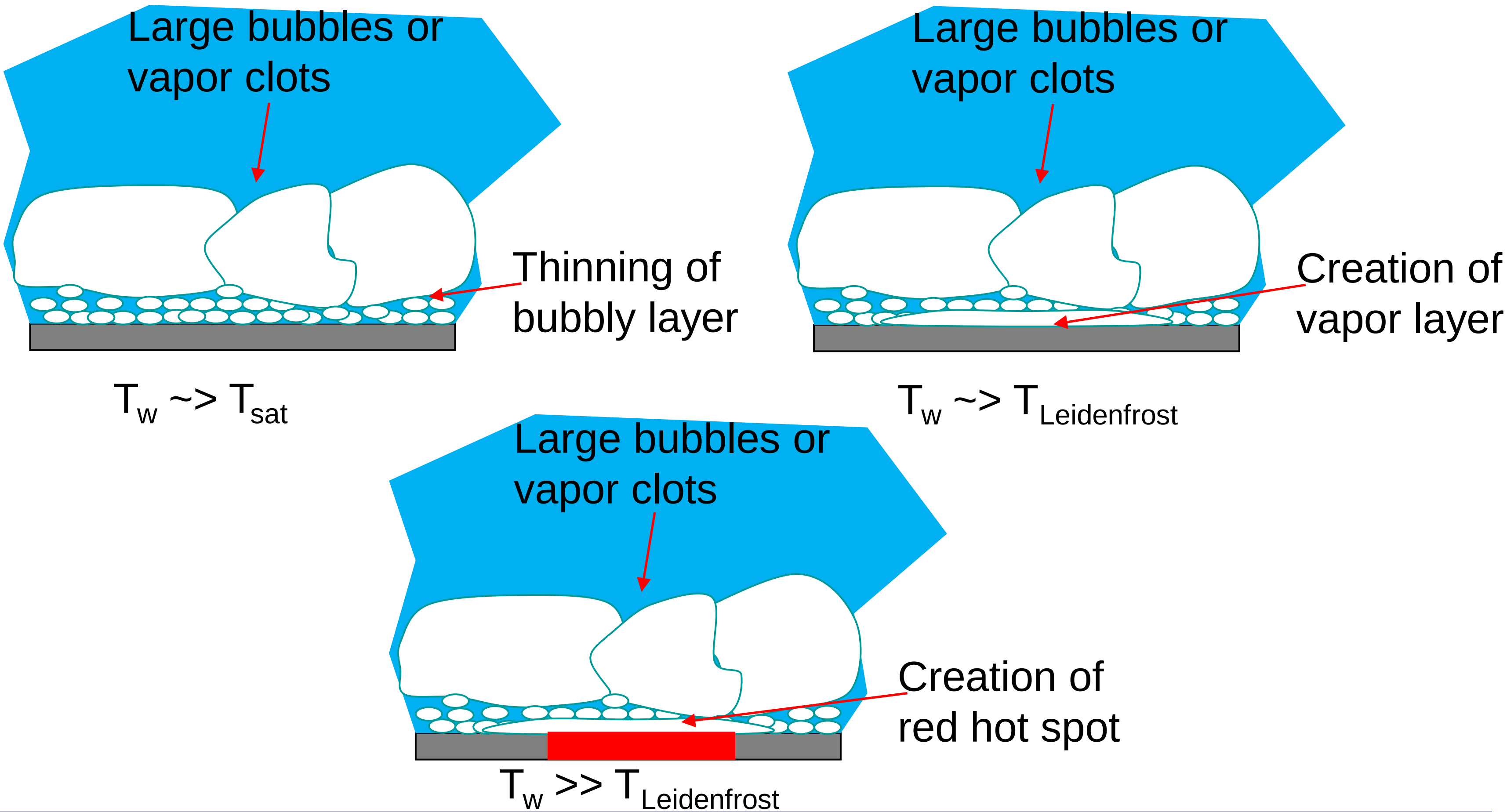
From Celata *et al.*, *Rev. Gén. Therm.* (1998)

Red and white metal

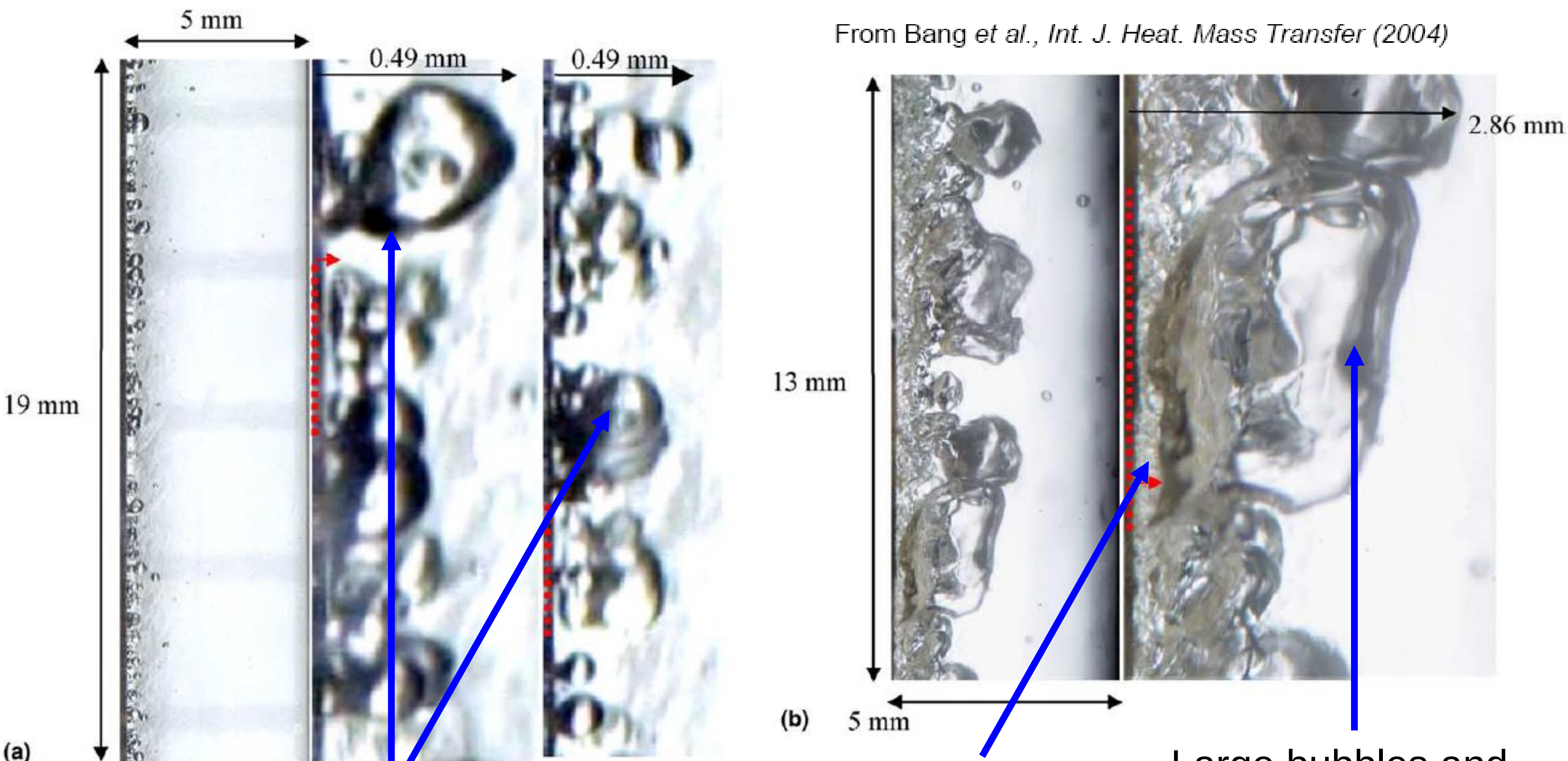
Type 2 DNB – bubble grow



Type 2 DNB – evaporating bubbly layer



Type 2 DNB – visualization

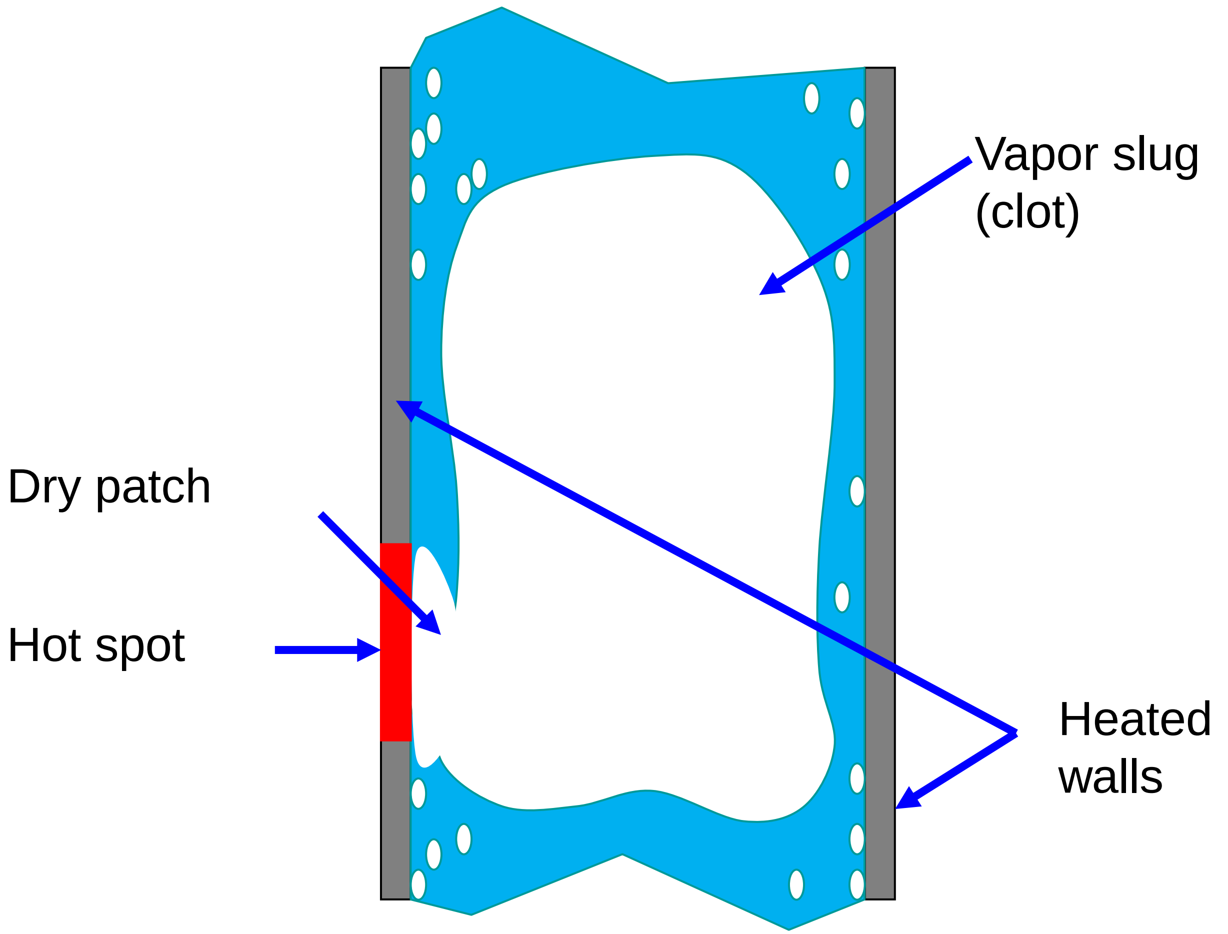


Small isolated bubbles

Bubbly microlayer

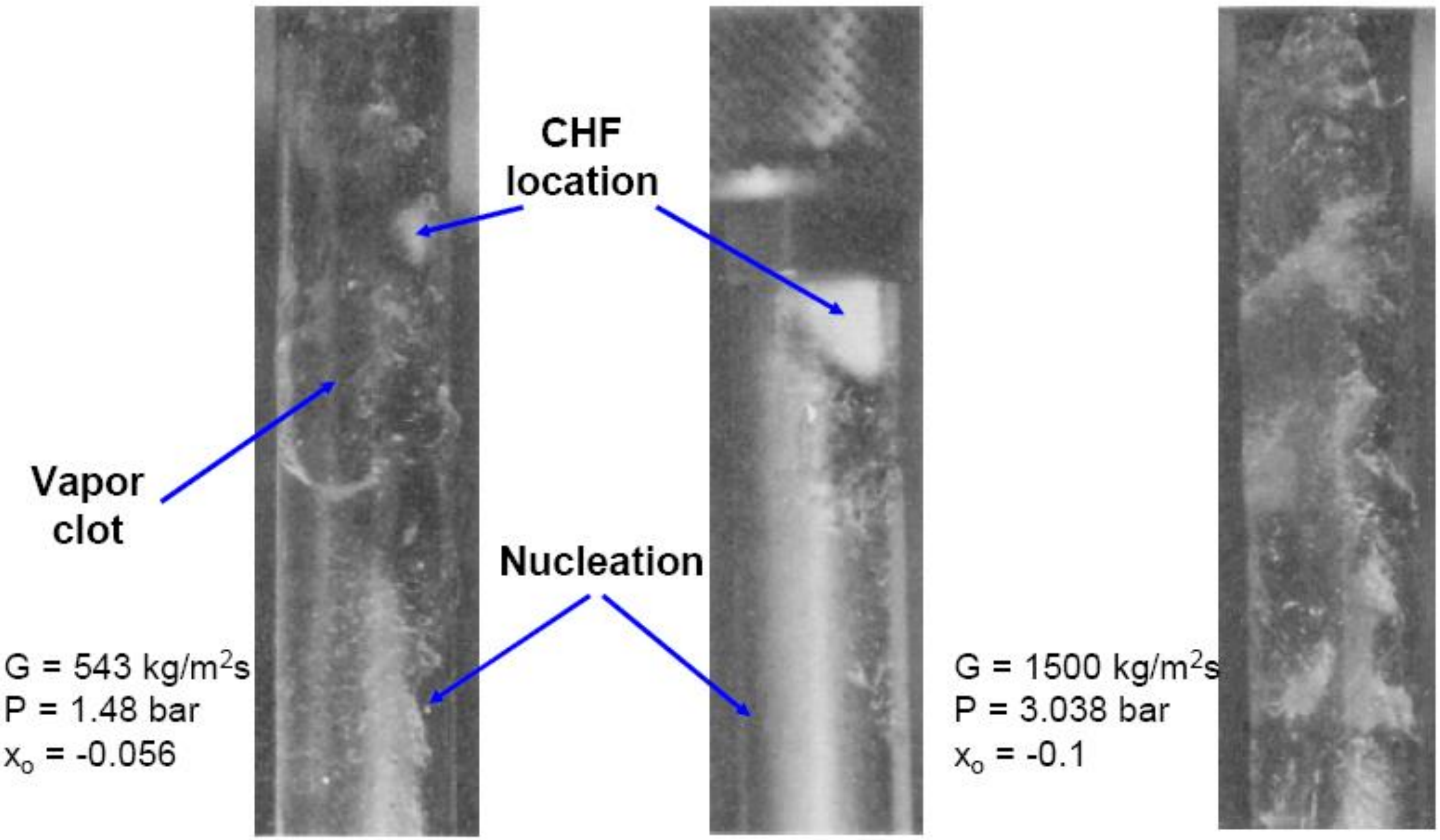
Large bubbles and vapor clots

Type 3 DNB – slug flow



Henryk Anglart
Nuclear Reactor Technology Division
Department of Physics, KTH

Type 3 DNB – visualization



From Fiori and Bergles, *4th Int. Heat Transfer Conf. (1970)*

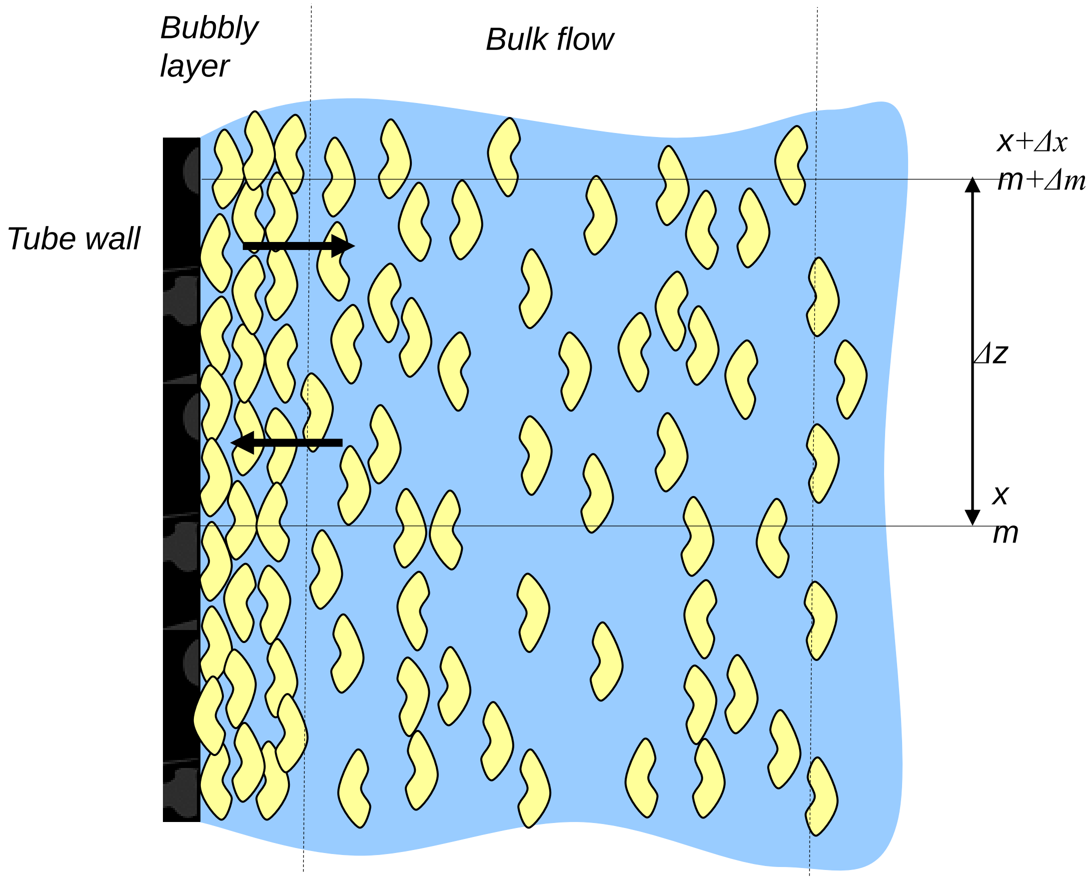
Modelling and Prediction of DNB

- Major categories of DNB models
  - Bubbly layer models
  - Liquid sublayer models
  - Bubble-nucleation models

- In practical reactor applications correlations are used
  - Such correlations are derived from experimental data
  - They have good accuracy, but their application region is limited

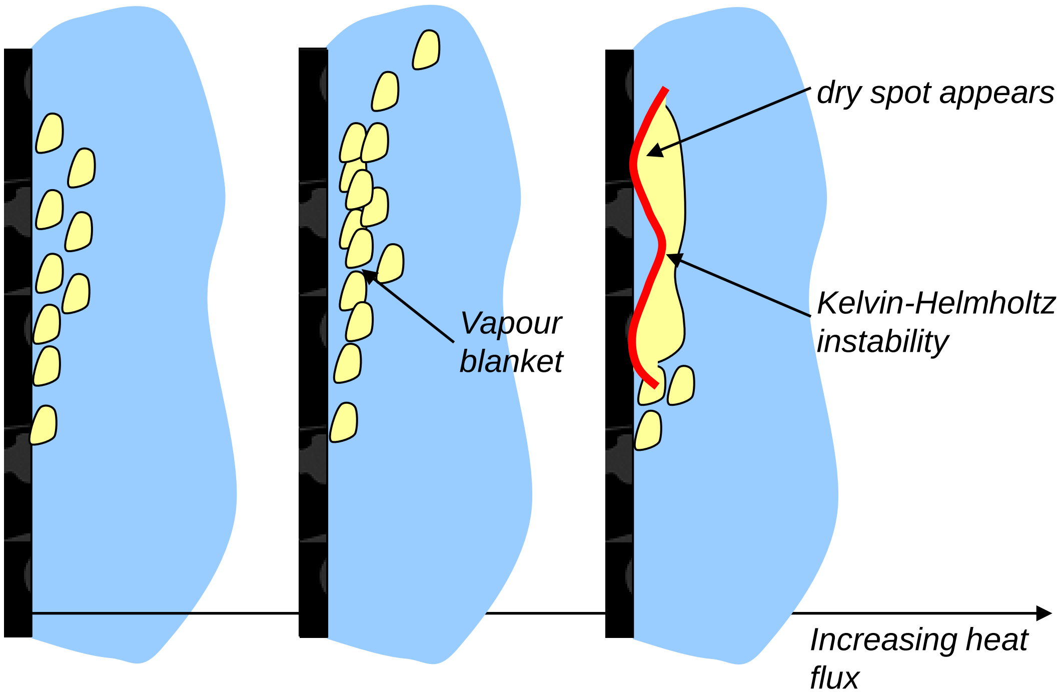
Bubble crowding model

- Bubbles are collecting close to the heated wall in a bubbly layer
- There is an interchange of mass end enthalpy between the bubble layer and the bulk flow
- DNB occurs when void fraction in the bubbly layer exceeds a critical value of 0.82
- At that point liquid is blocked and can not reach the wall



Liquid sublayer model

- Bubbles are collecting close to the heated wall
- Liquid film is created between the heated wall and the vapor blanket
- Vapor blanket becomes unstable due to Kelvin-Helmholtz instability
- Liquid film dries out and dry spots appear, leading to DNB



DNB Correlations

- Correlations are derived from experimental data obtained in rod bundles

- Typical DNB correlation has a form:

$$q''_{cr} = q''_{cr}\left(G, p, x, D_h, L, \ldots\right)$$

G – mass flux
p- pressure
x – quality =$(i-i_f)/i_{fg}$
D_h – hydraulic diameter
L – heated length

- That is, the correlation predicts the value of the critical heat flux (when DNB occurs) as a function of local parameters and channel geometry
- DNB occurs at location where $q'' > q''_{cr}$

Bowring Correlation

$$q''_{cr} = \frac{A + D \cdot G \cdot \Delta i_{subi} / 4}{C + L}$$

$$A = \frac{0.579 F_{B1} D \cdot G \cdot i_{fg}}{1 + 0.0143 F_{B2} D^{1/2} G}$$

$$C = \frac{0.077 F_{B3} D \cdot G}{1 + 0.347 F_{B4} \left(G/1356\right)^{n}}$$

$$n = 2.0 - 0.5 p_R$$

$$p_R = \frac{p}{6.895 \cdot 10^6}$$

$$F_{B1} = \begin{cases} \dfrac{p_R^{18.942} \exp\left[20.8\left(1 - p_R\right)\right] + 0.917}{1.917} & p_R \le 1 \\ p_R^{-0.368} \exp\left[0.648\left(1 - p_R\right)\right] & p_R > 1 \end{cases}$$

$$\frac{F_{B1}}{F_{B2}} = \begin{cases} \dfrac{p_R^{1.316} \exp\left[2.444\left(1 - p_R\right)\right] + 0.309}{1.309} & p_R \le 1 \\ p_R^{-0.448} \exp\left[0.245\left(1 - p_R\right)\right] & p_R > 1 \end{cases}$$

$$F_{B3} = \begin{cases} \dfrac{p_R^{17.023} \exp\left[16.658\left(1 - p_R\right)\right] + 0.667}{1.667} & p_R \le 1 \\ p_R^{-0.219} & p_R > 1 \end{cases}$$

$$\frac{F_{B4}}{F_{B3}} = p_R^{1.649}$$

$136 < G < 18600$ kg/m^{2}s – mass flux
$2 \cdot 10^5 < p < 190 \cdot 10^5$ Pa – pressure
$2 < D < 45$ mm – diameter
$0.15 < L < 3.7$ m – heated length
$\Delta i_{sub} = i_f - i_{in}$, J/kg – inlet subcooling

GE Correlation for Uniform q'' (Jansen & Levy)

$$q''_{cr} = q''_{cr70} + 6.2 \cdot 10^3 (70 - p)$$

$$q''_{cr70} = \begin{cases} 10^6 \left(2.24 + 0.55 \cdot 10^{-3} G\right) & if \quad x < x_1 \\ 10^6 \left(5.16 - 0.63 \cdot 10^{-3} G - 14.85x\right) & if \quad x_1 \le x < x_2 \\ 10^6 \left(1.91 - 0.383 \cdot 10^{-3} G - 2.06x\right) & if \quad x_2 \le x \end{cases}$$

$$x_1 = 0.197 - 0.08 \cdot 10^{-3} G \qquad x_2 = 0.254 - 0.019 \cdot 10^{-3} G$$

q''_{cr} - critical quality, [W/m²]
G – mass flux, [kg/m² s]
x – equilibrium quality
p – pressure [bar]

Applicability range:
42 < p < 102 bar
540 < G < 8100 kg/m²s
0.0 < x 0.45

6.2 < D_h < 32 mm
0.74 < L < 2.8 m

Westinghouse Correlation for Uniform q'': W-3

$$q''_{cr,U}(z) = A\left\{(2.022 - 0.0004302\, p_R) + (0.1722 - 0.0000984\, p_R)e^{[(18.177-0.004129\, p_R)x]}\right\}\times$$
$$\left[(0.1484 - 1.596x + 0.1729x|x|)G_R + 1.037\right](1.157 - 0.869x)\times$$
$$\left(0.2664 + 0.8357e^{-3.151D_e}\right)(0.8258 + 0.000794\Delta i_R)$$ in MW/m²

$$p_R = \frac{p(z)}{6.8947\cdot 10^3}$$

$p(z)$ – pressure at location z, Pa

$$\Delta i_R = \frac{i_f - i_{in}}{2326}$$

i_f – specific enthalpy at saturation, J/kg

i_{in} – specific enthalpy at inlet, J/kg

$$G_R = \frac{G(z)}{1.3562\cdot 10^3}$$

$G(z)$ - mass flux at location z, kg/m²s

$$A = 3.1544$$

$$D_e = \frac{D_h}{0.0254}$$

D_h - hydraulic diameter, m

Validity range:

$5.5 < p < 16$ MPa

$1356 < G < 6800$ kg/m²s

$5 < D_h < 18$ mm, $0.254 < L < 3.7$ m

$-0.15 < x < 0.15$

Effect of Non-Uniform Power Distribution

- GE correlation by Jansen and Levy is commonly used for PWR conditions with uniform heat distribution along the channel

- For non-uniform power distribution the W-3 correlation is applicable, where the following correction factor has to be applied:

$$F_c(z) \equiv \frac{q''_{cr,U}(z)}{q''_{cr,NU}(z)} = \frac{C}{q''(z)\left(1-e^{-C\cdot z}\right)} \int_0^z q''(z') e^{-C(z-z')} dz'$$

$q''_{cr,U}(z)$ - critical heat flux found with uniform power distribution, MW/m²

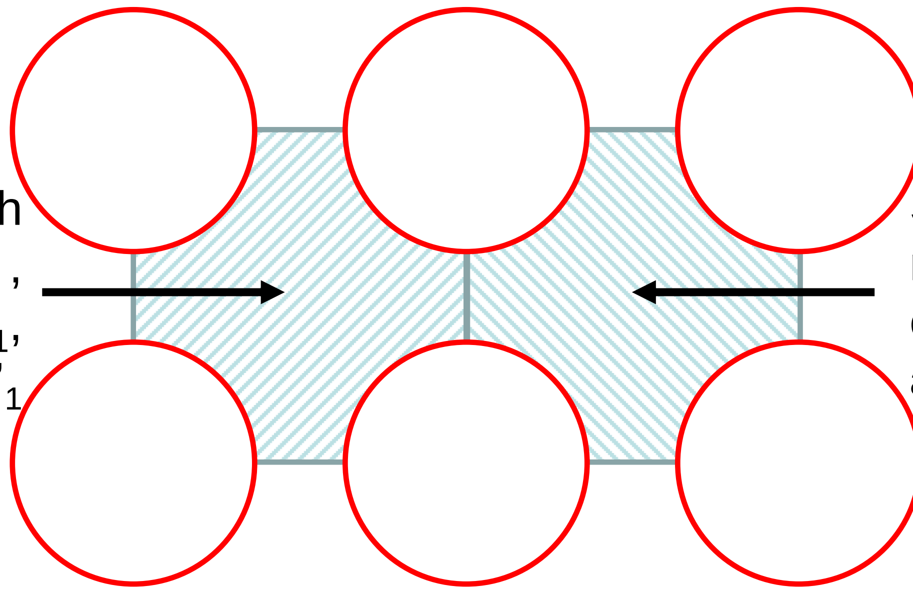
$$C = 185.6 \frac{\left(1-x_{cr,NU}\right)^{4.31}}{G^{0.478}}$$

$x_{cr,NU}$ – equilibrium quality at DNB location found with non-uniform power distribution
G – mass flux, kg/m²s

Subchannel DNB

- The DNB correlations discussed so far are applicable to whole bundle
- Sometime a more detailed approach is required, in which conditions in individual subchannels are considered

Subchannel S_1, with mass flux G_1 , equilibrium quality x_1, and mean heat flux q''_1



Subchannel S_2, with mass flux G_2 , equilibrium quality x_2, and mean heat flux q''_2

Henryk Anglart
Nuclear Reactor Technology Division
Department of Physics, KTH

Subchannel CHF Correlation

- Reddy and Fighetti developed a generalized subchannel CHF correlation for both PWR and BWR fuel assemblies (both DNB and dryout)

$$q''_{cr}(\mathbf{r}) = B\frac{A - x_{in}}{C + \dfrac{x(\mathbf{r}) - x_{in}}{q''_R(\mathbf{r})}}$$

$$A = a_1 p_R^{a_2} G_R^{(a_3 + a_4 p_R)}$$

$$B = 3.1544\times 10^6$$

$$C = c_1 p_R^{c_2} G_R^{(c_3 + c_4 p_R)}$$

$$G_R = G/1356.23$$

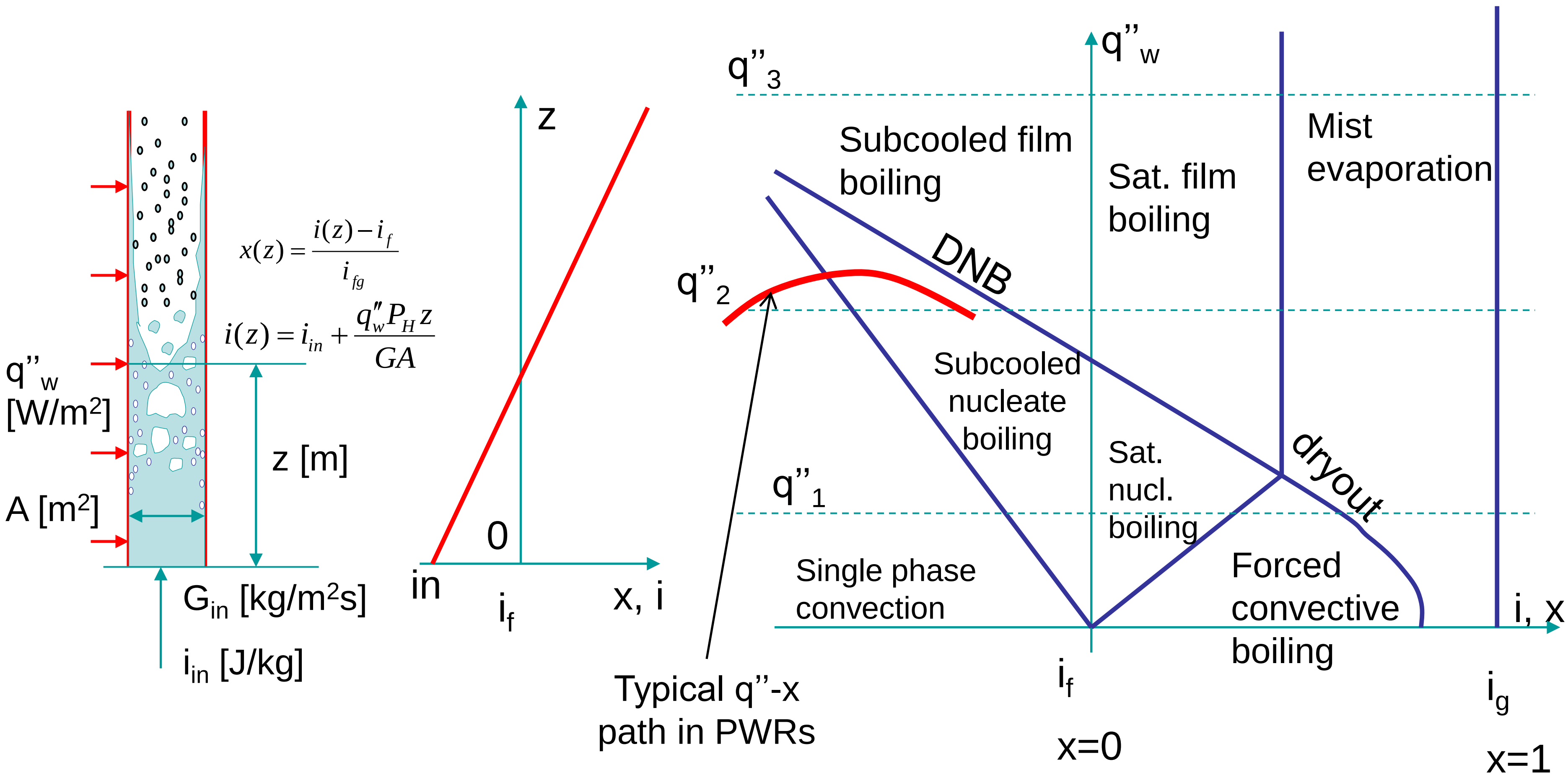
$$p_R = p/p_{cr}$$

$$q''_R(\mathbf{r}) = q''(\mathbf{r})/3.1544e6$$

q_{cr} – critical heat flux, W/m^2, xin – inlet equilibrium quality, G – mass flux, kg/m^{2}s, p – pressure, Pa, p_{cr} – critical pressure, Pa, a_1 = 0.5328, a_2 = 0.1212, a_3 = -0.3040, a_4 = 0.3285, c_1 = 1.6151, c_2 = 1.4066, c_3 = 0.4843, c_4 = -2.0749, **r** - location

Applicability range: 147 < G < 3023 kg/m^{2}s, 13.8 < p < 169.9 bar, 8.9<D_h<13.9 mm, 6.3<D_H<13.9 mm, -0.25 <x<0.75, -1.10<x_{in}<=0.0, 0.762<L<4.267 m

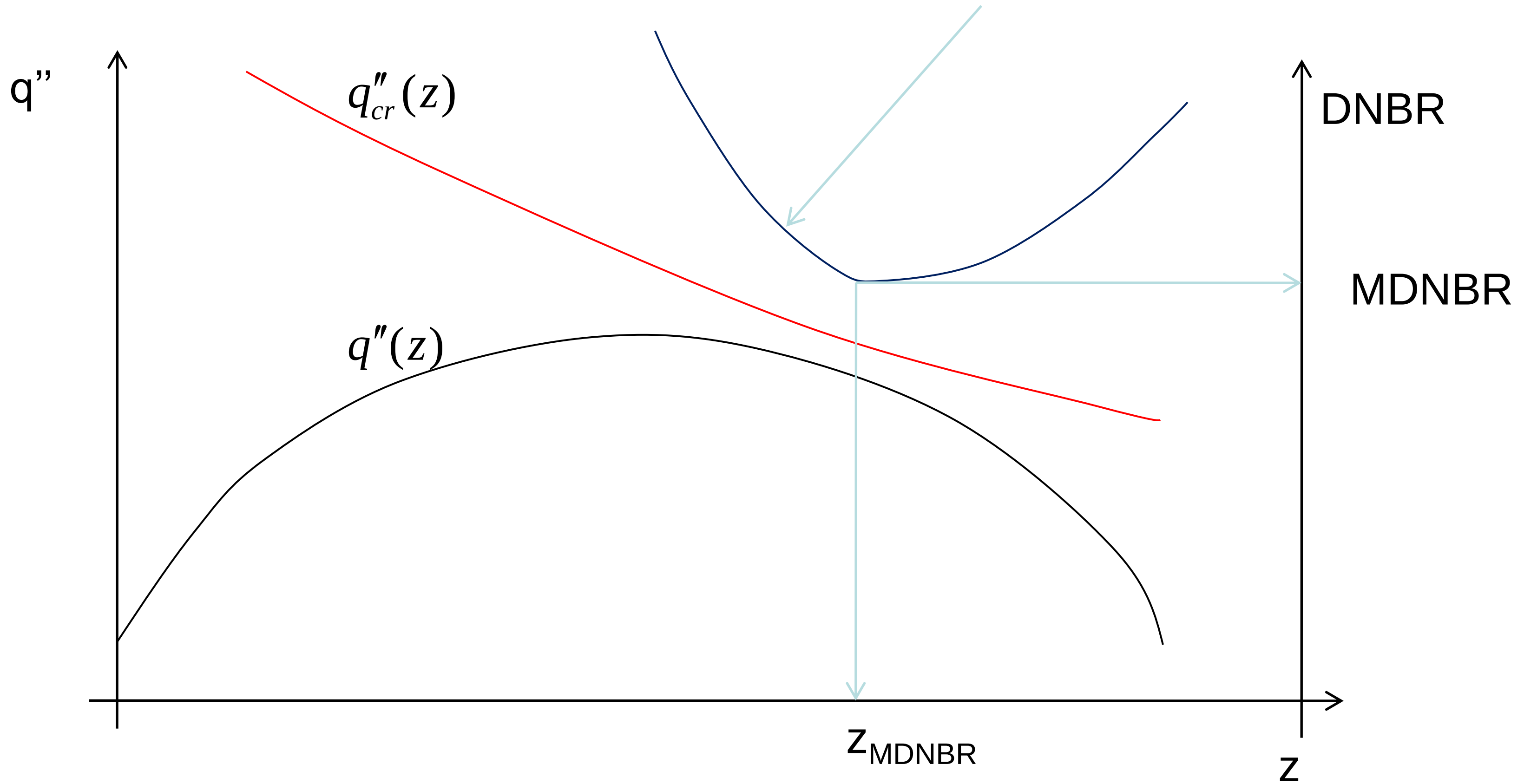
Boiling Regimes on q''-x Plain



Henryk Anglart
Nuclear Reactor Technology Division
Department of Physics, KTH

DNB Ratio - DNBR

- DNB Ratio (DNBR) is defined as: $$DNBR(z) = \frac{q''_{cr}(z)}{q''(z)}$$



DNBR, MNDBR and z_{MNDBR}

- DNBR is a local parameter function
- DNBR(z) has to be calculated along the whole assembly
- The minimum value of DNBR is called Minimum DNBR (MDNBR)
- Both MDNBR and its location z_{MNDBR} need to be determined for a bundle or subchannel when predicting thermal margins