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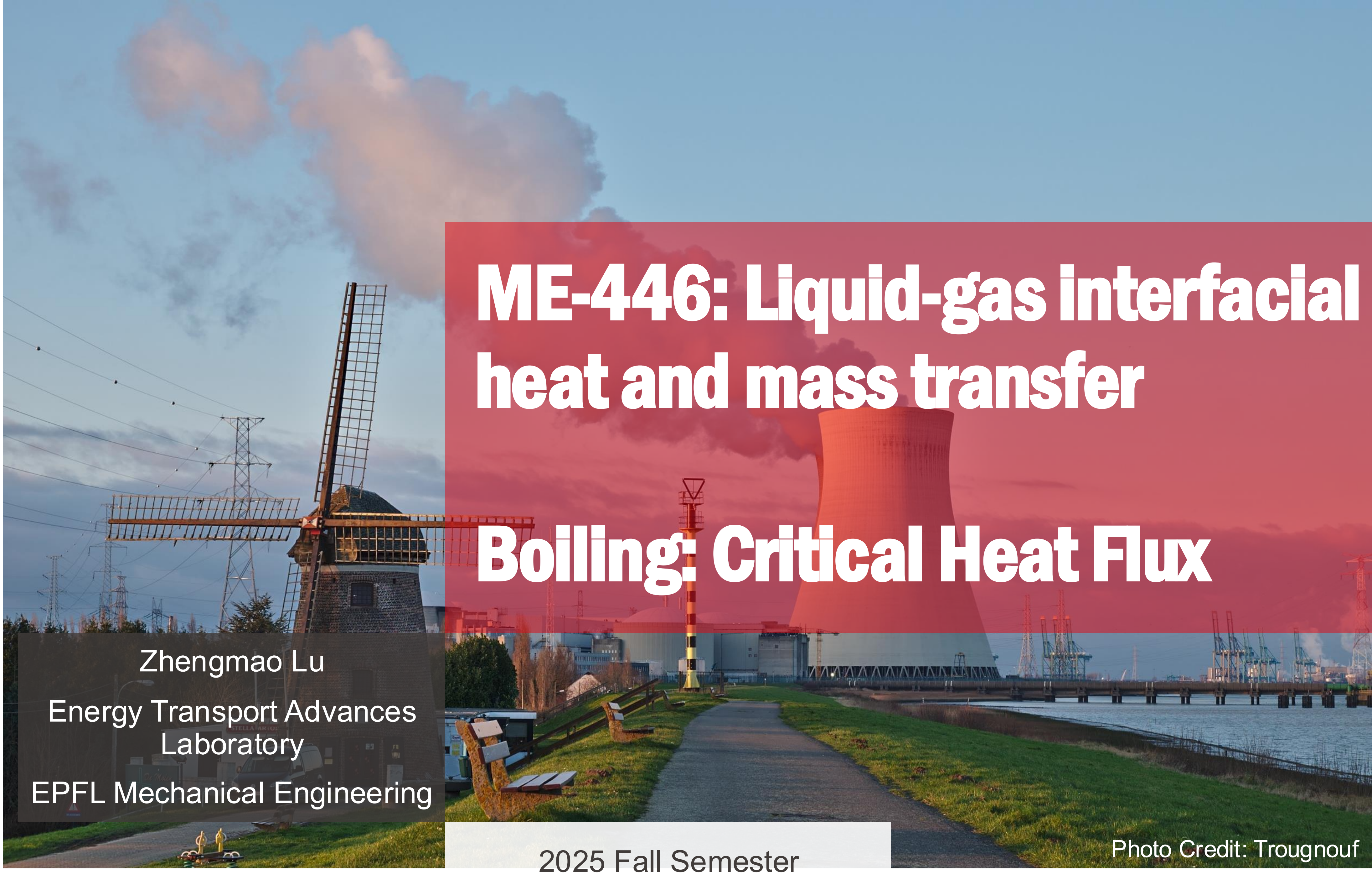

ME-446: Liquid-gas interfacial heat and mass transfer

Boiling: Critical Heat Flux

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EPFL Mechanical Engineering

2025 Fall Semester

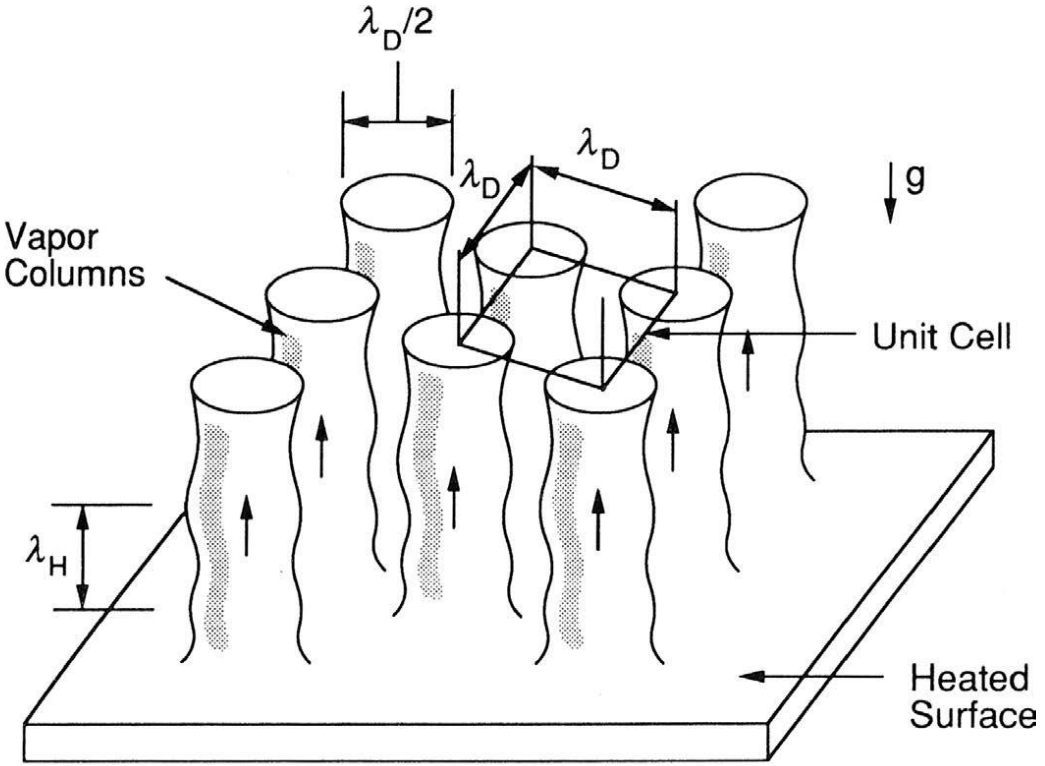
Photo Credit: Trougnouf

Last Time

- Zuber' CHF model based on hydrodynamic instability
- Force balance model for CHF
- Statistical approach for CHF

Zuber's CHF Prediction

$$u_c = \sqrt{\frac{2\pi\sigma}{\rho_v \lambda_D}} \qquad \lambda_H = \lambda_D = 2\pi\sqrt{\frac{3\sigma}{\Delta\rho g}}$$



$$u_c = \frac{q''_{max}}{\rho_v h_{lv}}\left(\frac{A_{surf}}{A_{col}}\right) = \frac{16}{\pi}\frac{q''_{max}}{\rho_v h_{lv}}$$

$$q''_{max} = 0.149\rho_v h_{lv}\left(\frac{\sigma\Delta\rho g}{\rho_v^2}\right)^{1/4}$$

Lateral Force Balance Model

$$q''_K = \rho_v h_{fg} \left(\frac{1+\cos\beta}{16}\right)\left[\frac{2}{\pi} + \frac{\pi}{4}(1+\cos\beta)\right]^{\frac{1}{2}} \left(\frac{\sigma \Delta\rho g}{\rho_v^2}\right)^{1/4}$$ (Horizontal surface)

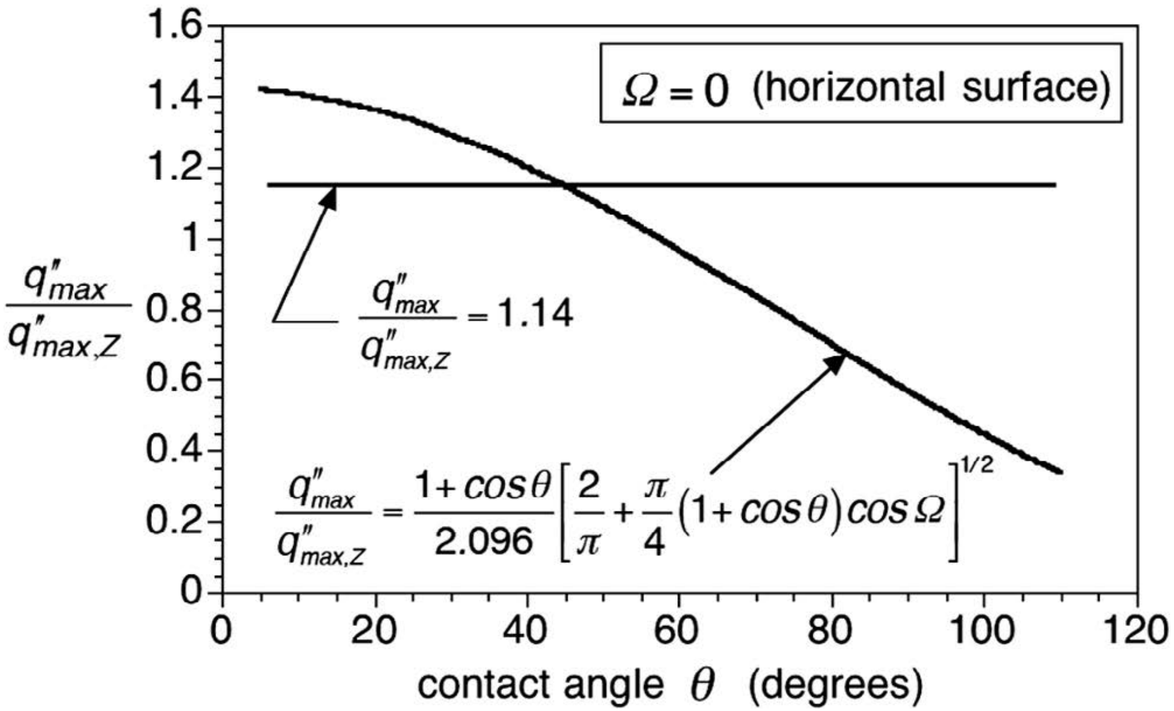


FIGURE 7.19 in Carey

$$q''_{max,Z} = 0.149 \rho_v h_{lv} \left(\frac{\sigma \Delta\rho g}{\rho_v^2}\right)^{1/4}$$

$$\frac{q''_K}{q''_{max,Z}} = \frac{1+\cos\theta}{2.096}\left[\frac{2}{\pi} + \frac{\pi}{4}(1+\cos\beta)\right]^{\frac{1}{2}}$$

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Statistical Approach for CHF

- Isolated bubbles dissipate heat better than merged bubbles

- CHF is reached when you have the **maximum number** of isolated bubbles

- With elevated temperature, 1) more nucleation sites become activated while 2) more bubbles are likely to merge into each other.

CHF Criteria

$$\frac{\partial N_{iso}}{\partial T} = 0$$

$$\frac{\partial}{\partial T}\left[\sum_{N=1}^{\infty} \frac{N_0^N}{(N-1)!} \exp\left(-N_0 - \frac{\pi N D_b^2}{A}\right)\right] = 0$$

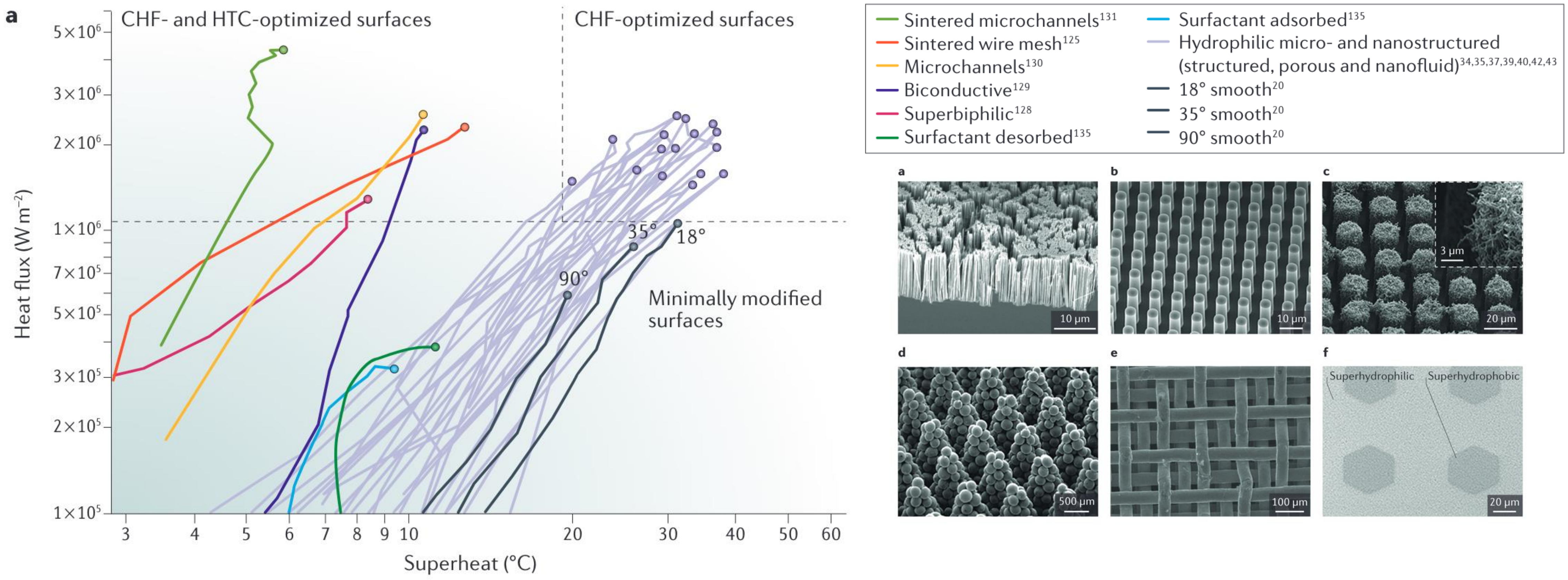
$$\Rightarrow n_0 \pi D_b^2 = 1$$

A unified relationship between the nucleation density at CHF and bubble diameter

ILOs Today

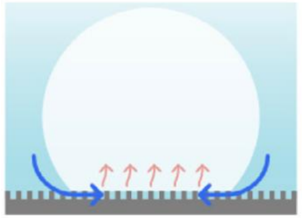
- Understand how wicking surfaces enhance CHF
- Know different flow boiling regimes
- Evaluate ONB, HTC, and CHF in flow boiling with correlations

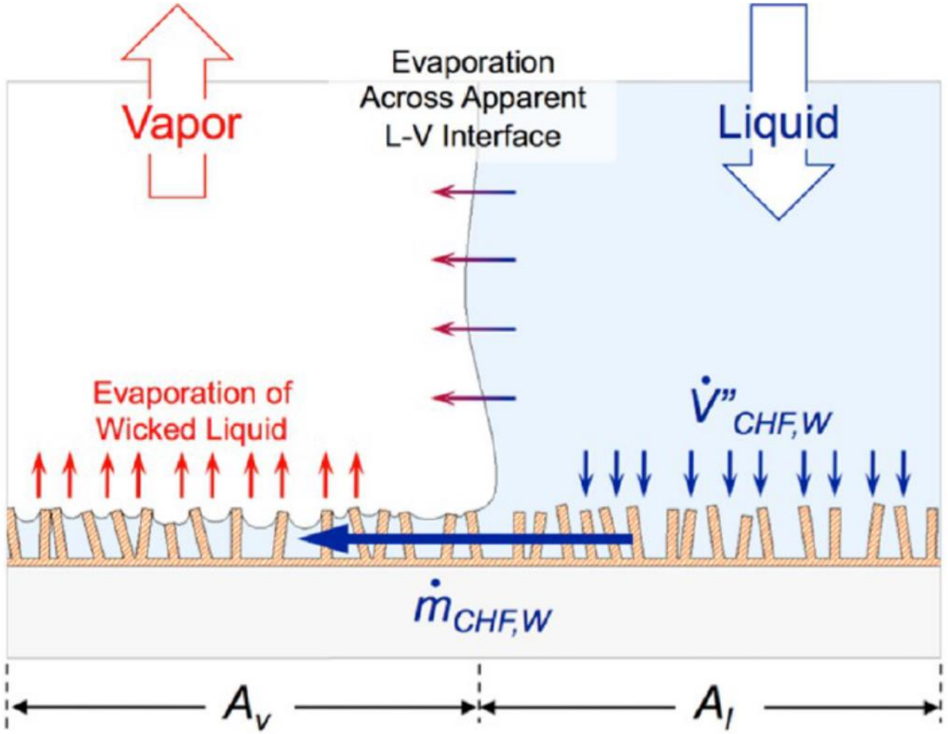
Surface Engineering for Boiling Enhancement



doi:10.1038/natrevmats.2016.92

Wicking Helps Boiling

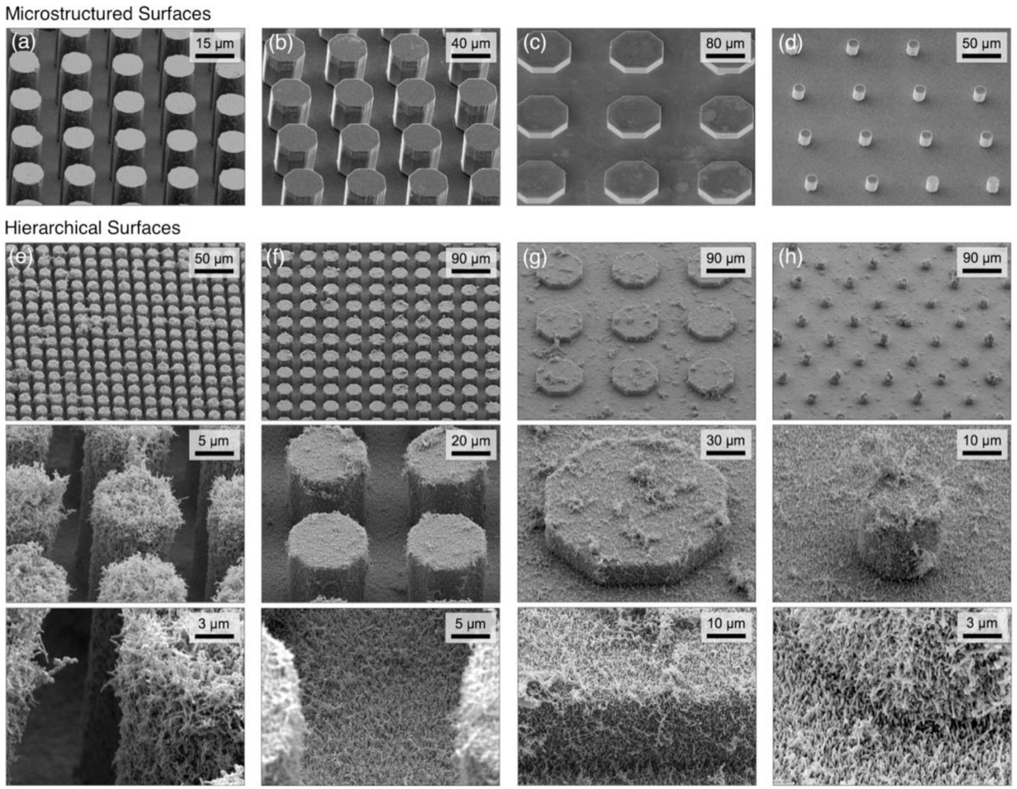


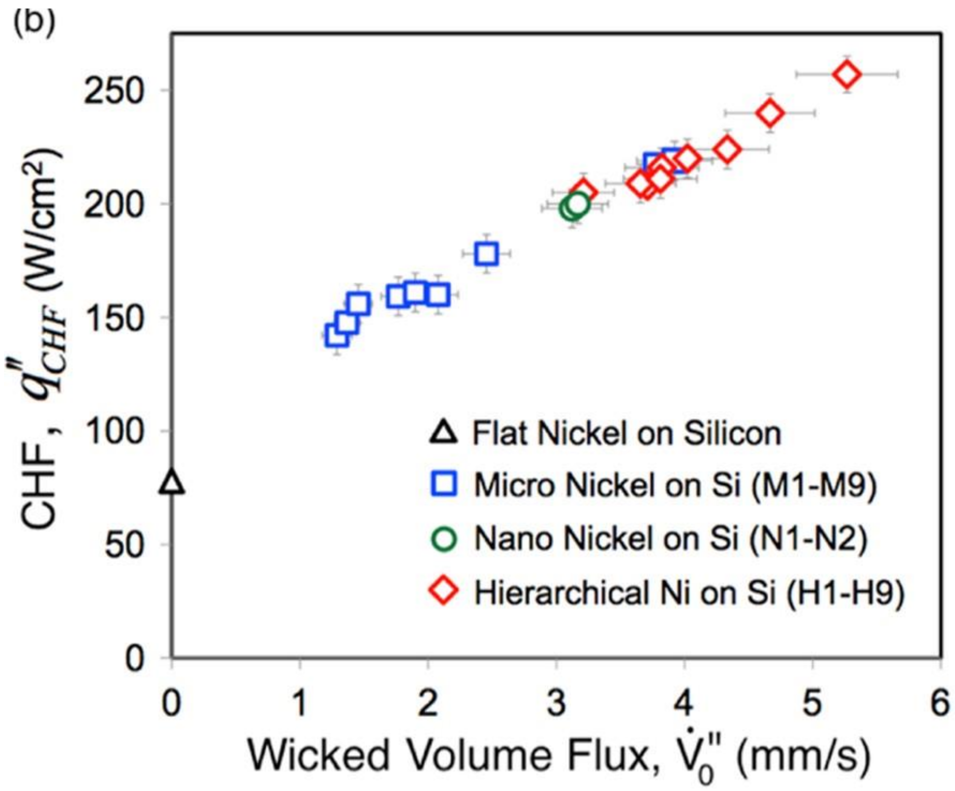


https://doi.org/10.1021/acs.langmuir.7b01522

https://doi.org/10.1021/la5030923

Wicking Helps Boiling





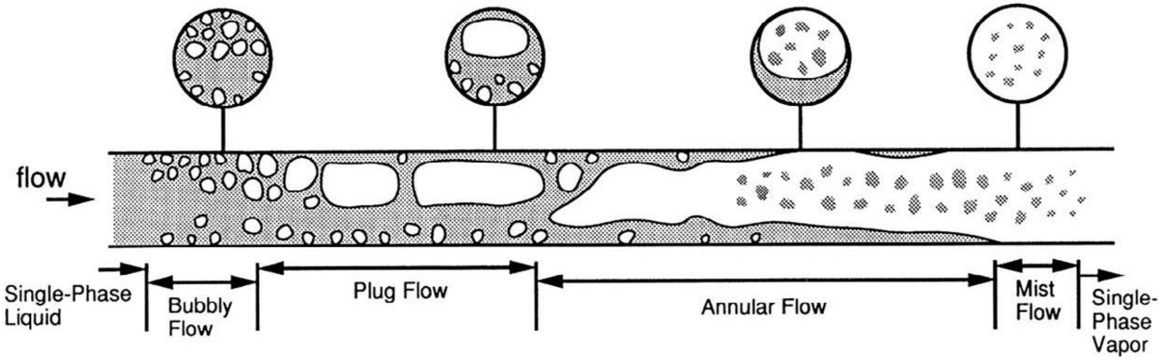
https://doi.org/10.1021/la5030923

Summary on Boiling CHF

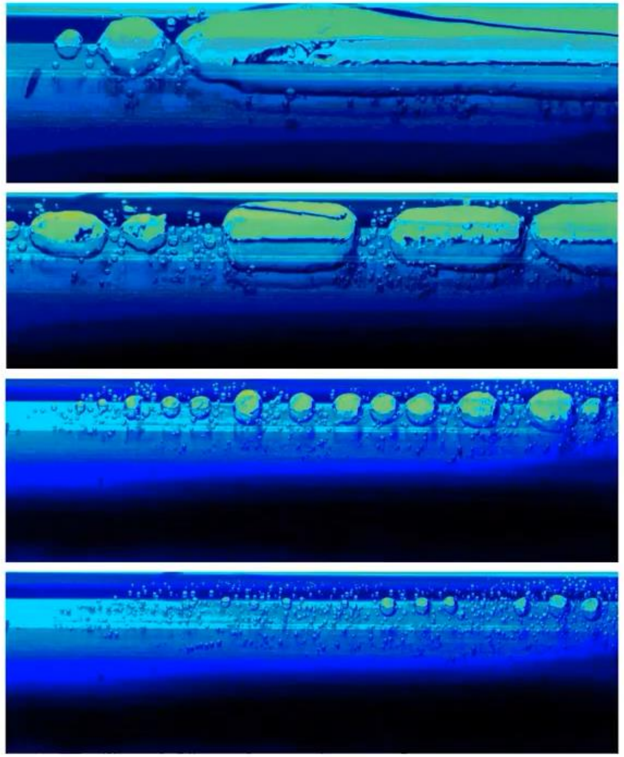
- On flat surfaces, CHF is thought to be caused by 1) hydrodynamic instabilities and/or 2) number of isolated bubbles reaching maximum
- With wicking surfaces, additional liquid supply (through capillarity) to the bubble can improve CHF

What is Flow Boiling

Different regimes in flow boiling



Flow boiling: boiling where forced convection is employed to replenish the boiling liquid and push developed vapors downstream

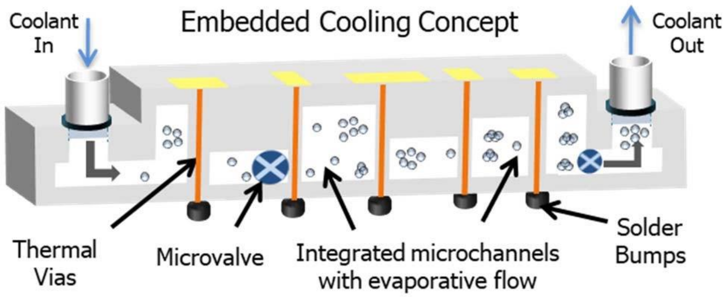


Videos slowed down 50 times

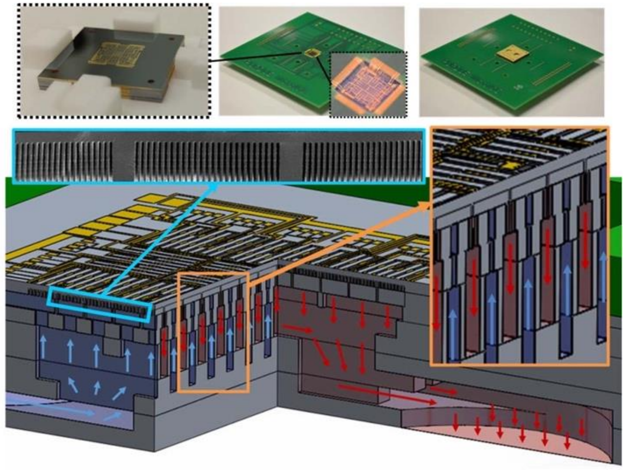
https://www.youtube.com/shorts/HNcp7zDtwx8?feature=share

Important applications

High flux electronics cooling



IEEE TCPMT 11.10 (2021): 1546-1564.

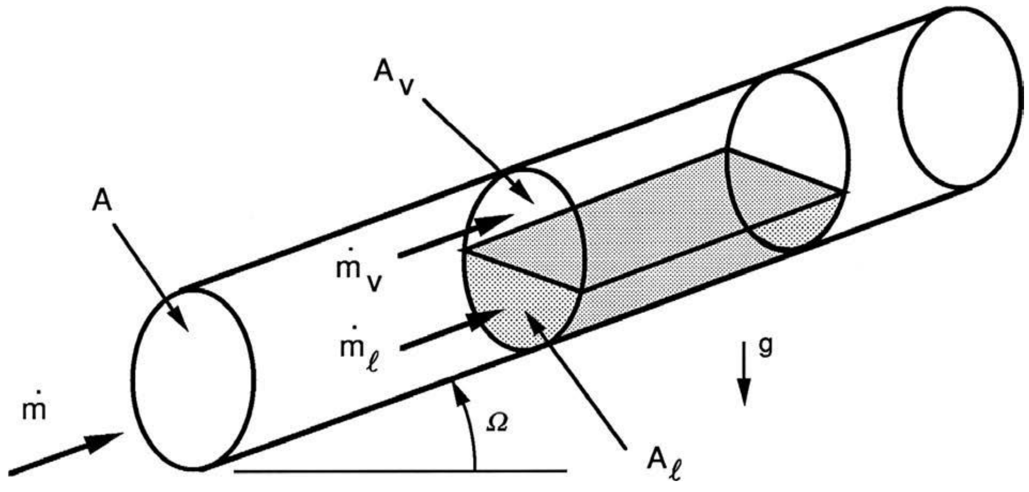


IJHMT 117 (2018) 319–330

Nuclear reactors

Credit: Tennessee Valley Authority

Definitions



Idealized model for defining flow properties
Figure 10.1 in Carey

Flow Regimes (Horizontal Tubes)

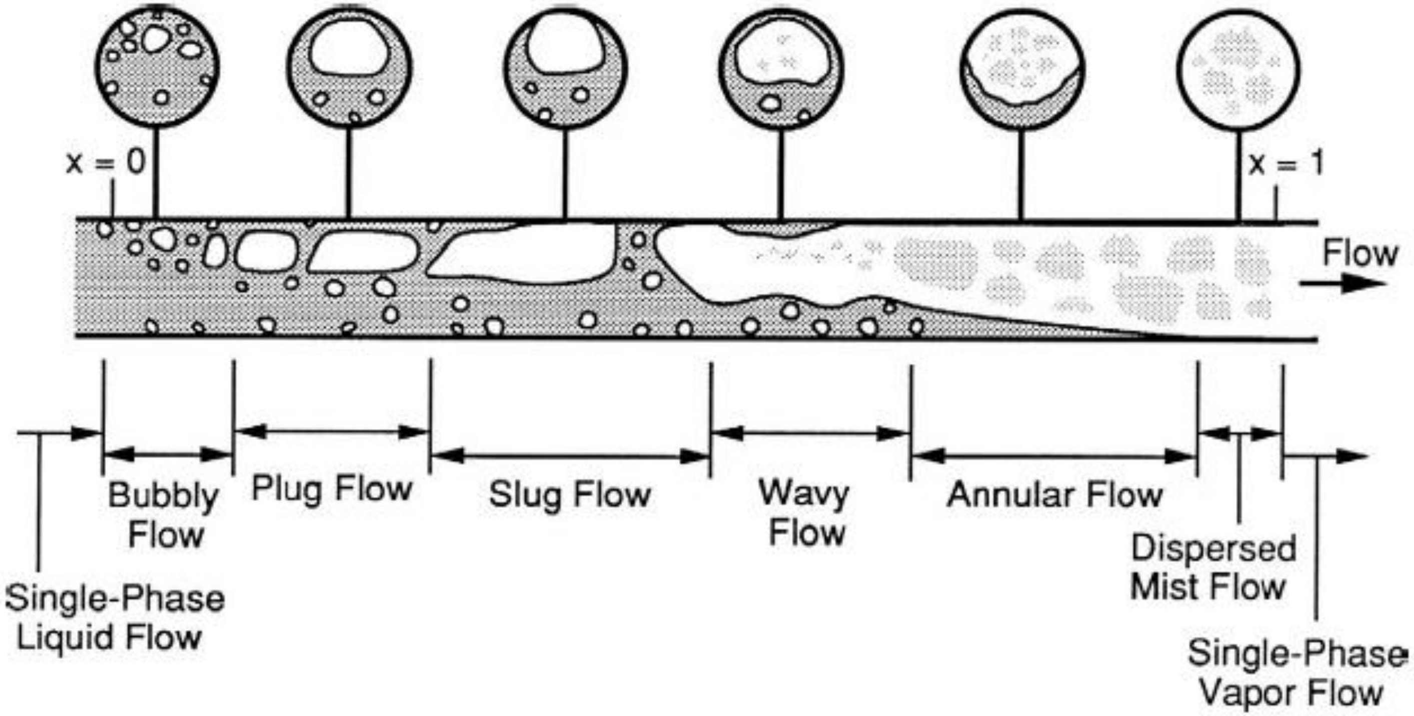


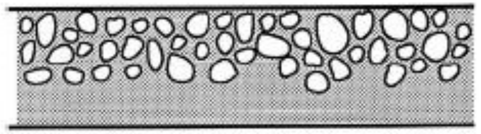
Figure 10.8 in Carey

Liquid enters the tube subcooled

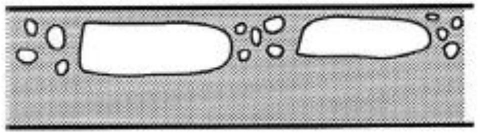
After onset of nucleation:

- Bubbly flow
- Plug flow
- Slug flow
- Stratified flow
- Wavy flow
- Annular flow
- Mist flow

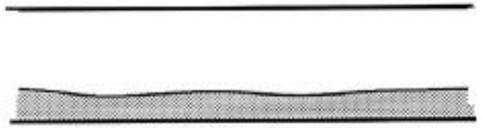
Flow Regimes (Horizontal Tubes)



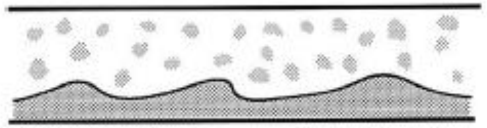
Bubbly flow: discrete bubbles dispersed in continuous liquid phase



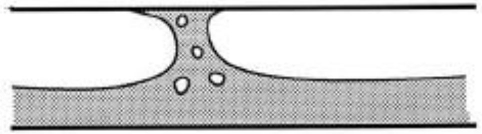
Plug flow: coalescence of small bubbles produces larger bubbles flowing in the upper portion



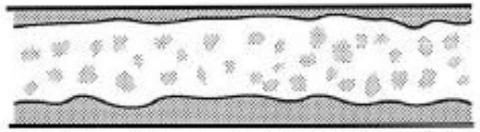
Stratified flow: liquid flowing in the bottom of the pipe is separated from vapor in the upper portion of the pipe by a relatively smooth interface (low flow rate, relatively high quality)



Wavy flow: continuous vapor core, continuous but disturbed liquid film on wall (Helmholtz instability), often with entrainment of droplets

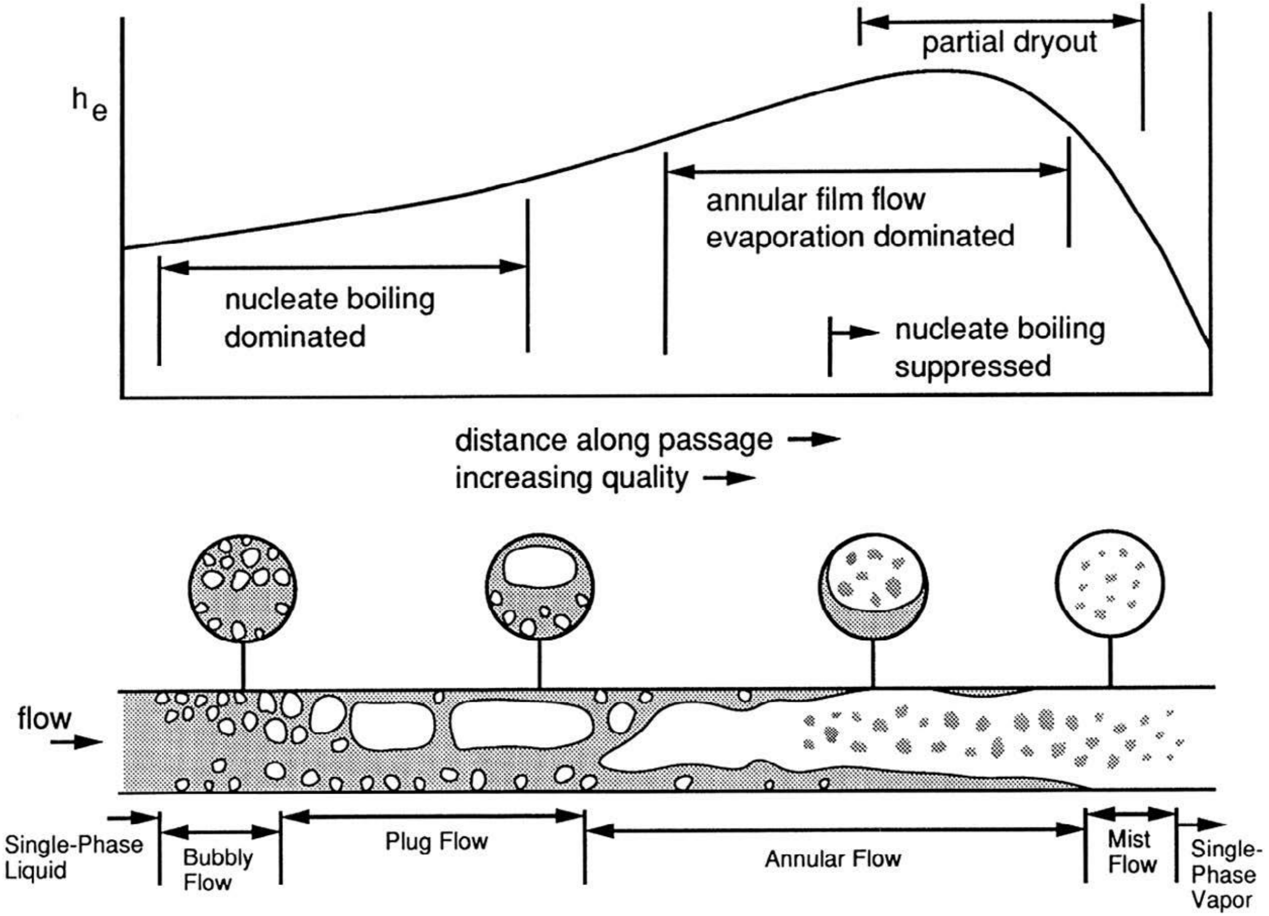


Slug flow: slugs of vapor flowing along the tube toward the upper portion



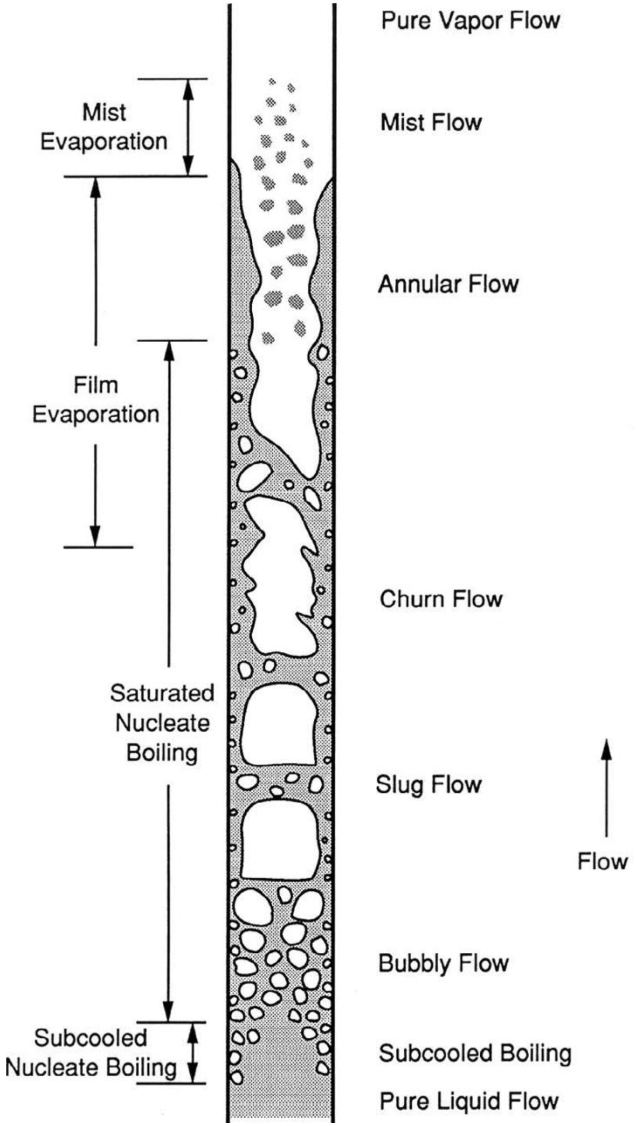
Annular flow: most liquid flowing along the wall and gas flowing in the central core, in an annular configuration with entrainment of droplets. When the liquid film dries out, it becomes **mist flow**

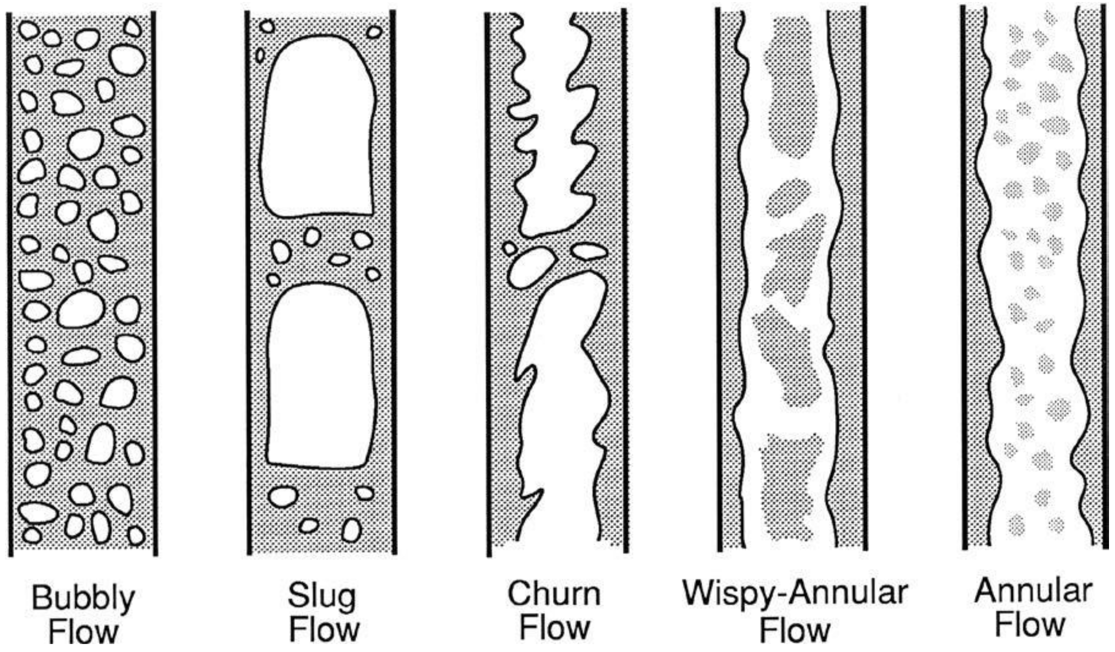
Heat Transfer Coefficient



- HTC increases after onset of nucleation and decreases as dryout occurs
- Annular flow provides best HTC

Flow Regimes (Upflow Vertical Tube)

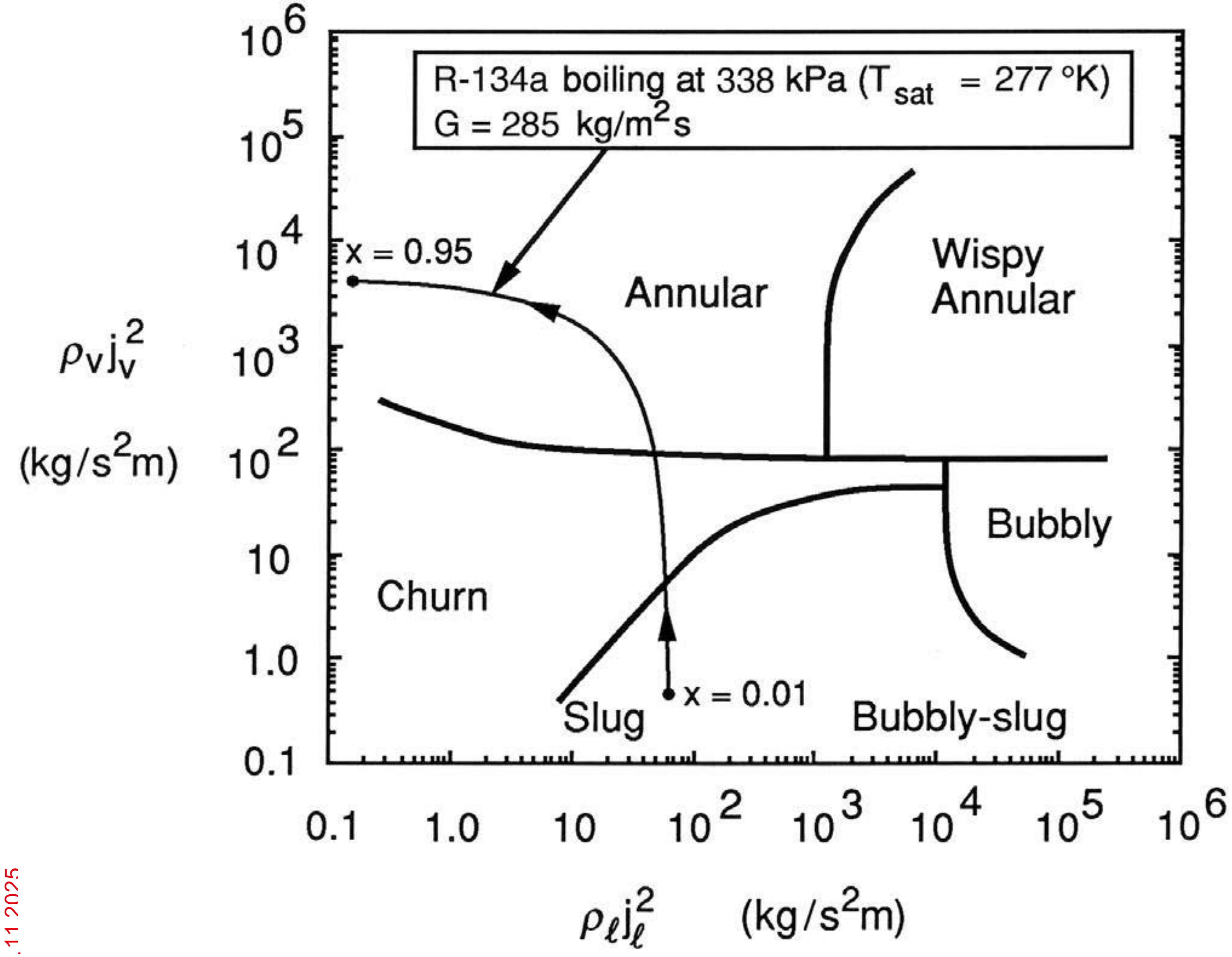




Churn flow: large bubbles with unstable, oscillatory, irregular interfaces

Wispy-annular flow: annular flow with heavy "wisps" (both liquid and vapor flow rates are high)

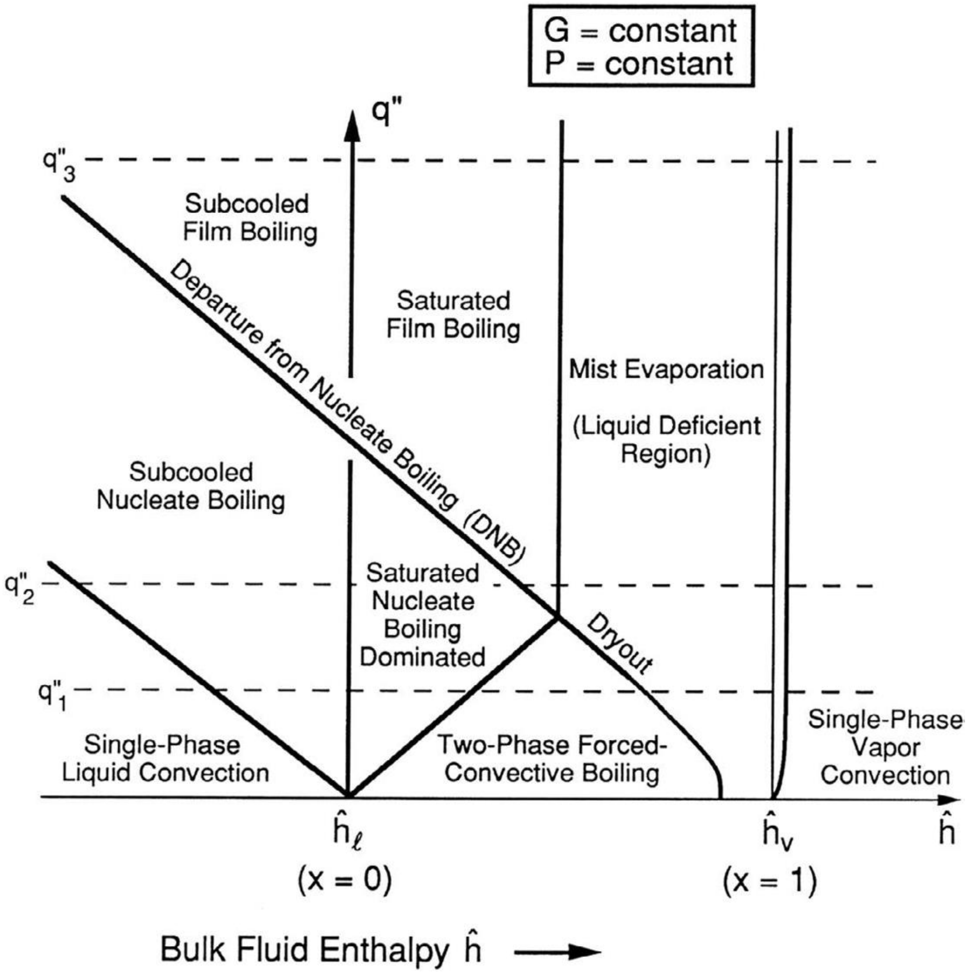
Hewitt and Roberts Flow Regime Map



Vapor volume flux $j_v = Gx/\rho_v$

Liquid volume flux $j_l = G(1-x)/\rho_l$

Boiling Regimes with Constant Wall Heat Flux

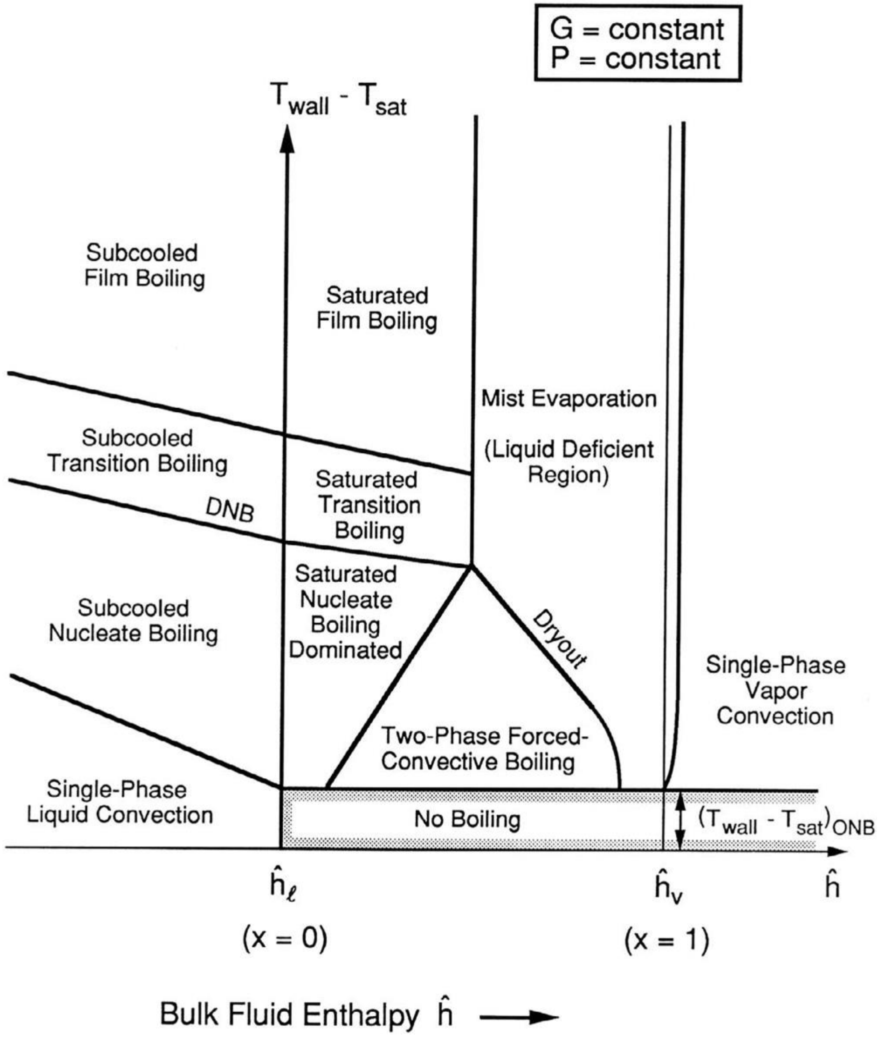


Low heat fluxes q_1'':
subcooled liquid → subcooled boiling → saturated boiling dominated → convective flow boiling → mist evaporation → pure vapor

Intermediate heat fluxes q_2'':
subcooled liquid → subcooled boiling → saturated boiling dominated → film boiling → mist evaporation → pure vapor

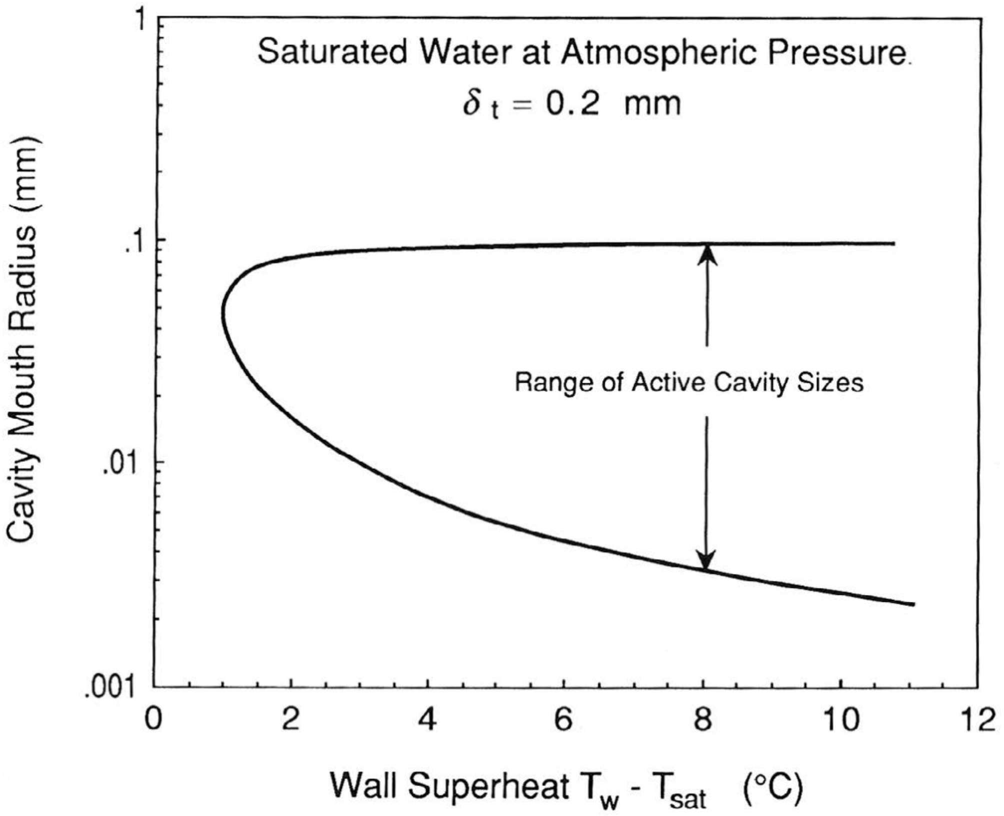
High heat fluxes q_3'':
subcooled liquid → (subcooled and saturated) film boiling → mist evaporation → pure vapor

Boiling Regimes with Isothermal Wall



- When wall superheat is less than required for onset of nucleation, no vaporization takes place
- Higher superheat: subcooled liquid → subcooled boiling → saturated boiling dominated → convective flow boiling → mist evaporation → pure vapor
- Very high superheat may lead to transition boiling/film boiling near the entrance

Onset of Boiling (Hsu's Model)



- Range of active nucleation site is determined by
  - Thermal boundary layer thickness
  - Subcooling
  - Wall superheat

Onset of Boiling in Internal Flows

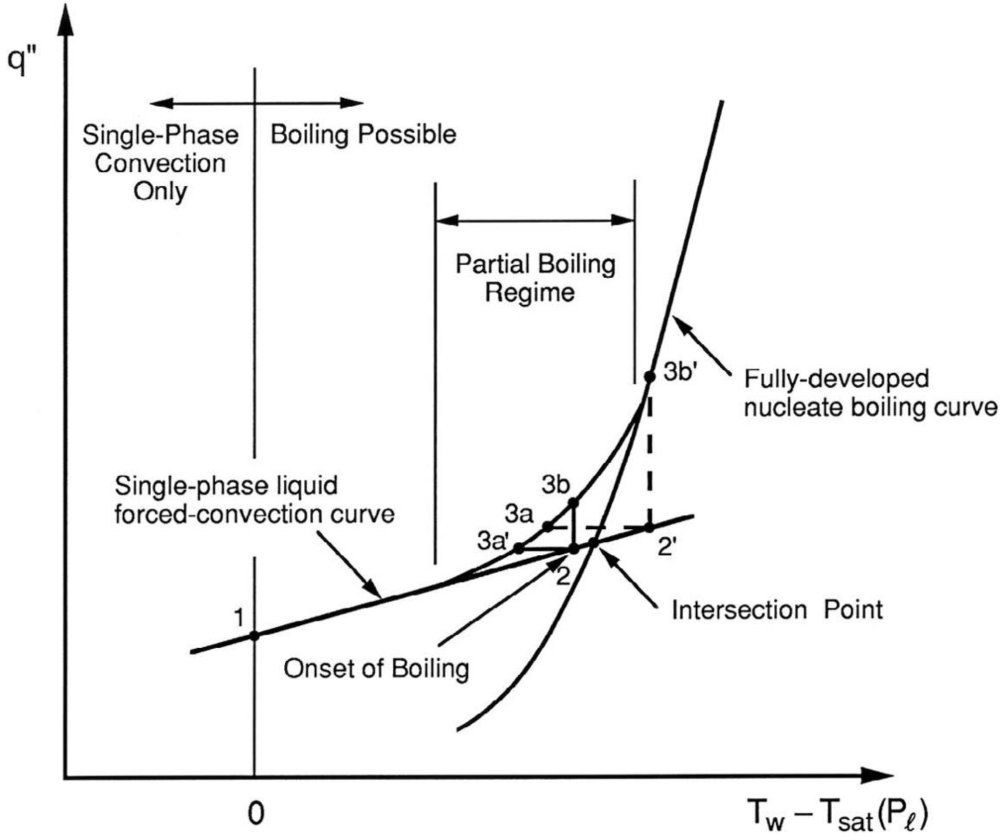
- Energy balance for the single-phase regime

Constant wall heat flux condition
(a cylindrical tube with diameter d_h)

q'' : wall heat flux
z: position along the tube (inlet: *z* = 0)
$T_l(z)$: bulk liquid temperature at *z*

G: mass flux in the tube
d_h: hydraulic diameter
c_{pl}: specific heat of liquid

Onset of Boiling in Internal Flows



Full-developed nucleate boiling

$$q'' = \gamma\left(T_w - T_{sat}(P_l)\right)^m$$

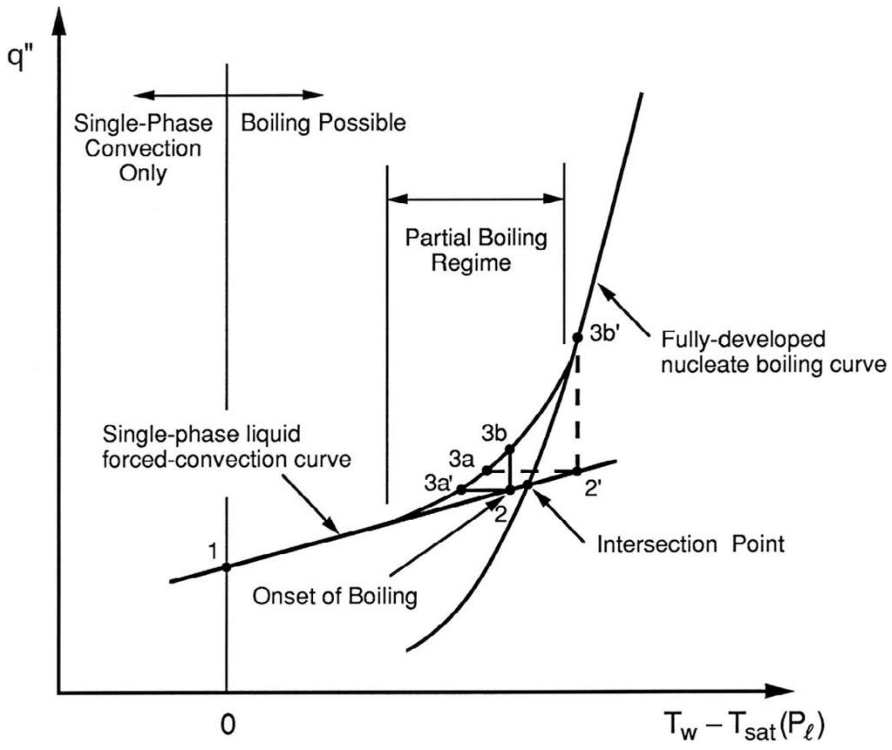
γ: a factor that depends on surface and fluid properties

m: empirically determined, typically between 2 and 4

At intersection point

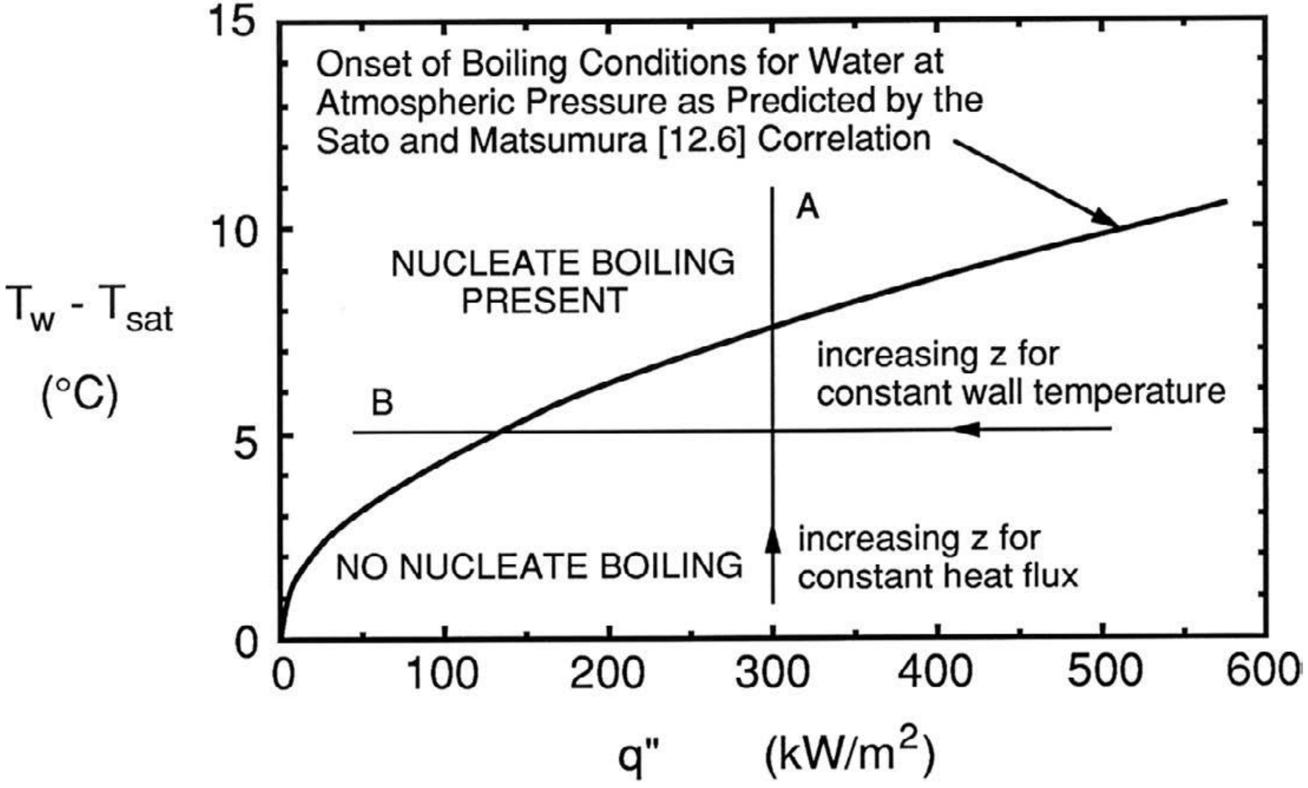
$$\left(\frac{q''}{\gamma}\right)^{1/m} = \frac{q''}{h_{le}}\left[1 + \frac{4h_{le}z}{Gc_{pl}d_h}\right] - (T_{sat} - T_{l,in})$$

Onset of Boiling in Internal Flows



- The onset may occur either before or after the intersection of the single-phase curve with the fully developed boiling curve.
- If the onset occurs at point 2, and the heat flux is held constant, the operating point may jump horizontally to point 3a′.
- If the transition is delayed to point 2′, the operating point may jump horizontally to point 3a.

Onset of Boiling in Internal Flows



Correlation provided by Sato and Matsumura

Eq. 12.14 in Carey

$$q''_{ONB} = \frac{k_l h_{lv} \rho_v}{8\sigma T_{sat}} [(T_w - T_{sat})_{ONB}]^2$$

Energy balance for the single-phase regime

$$T_w(z) - T_{sat} = \frac{q''}{h_{le}}\left[1 + \frac{4 h_{le} z}{G c_{pl} d_h}\right] - (T_{sat} - T_{l,in})$$

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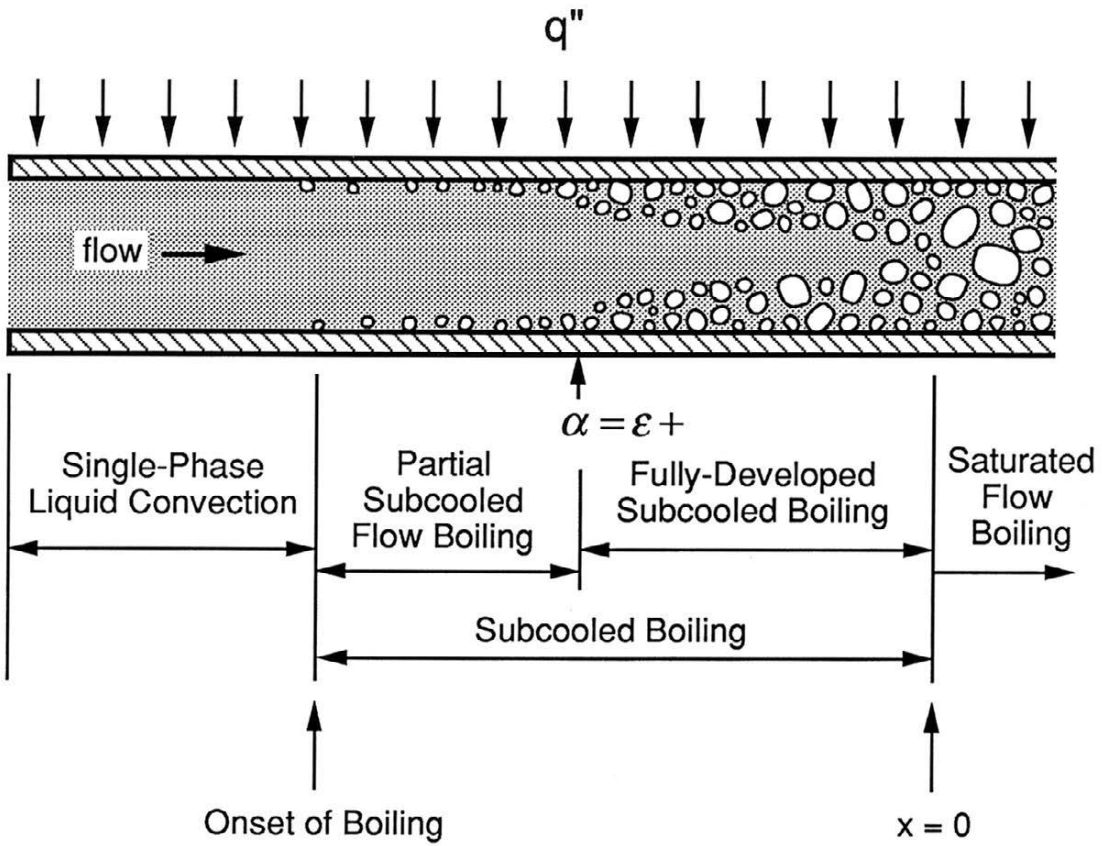
Subcooled Flow Boiling



- **Partial** boiling: vapor present only very near the wall
- **Fully-developed** boiling: vapor exists in a significant portion of the bulk flow near the wall

- Particularly interesting for high-heat-flux cooling

Subcooled Flow Boiling

- Rohsenow's postulation (Eqs. 12.26 and 12.27 in Carey)

Saturated Flow Boiling

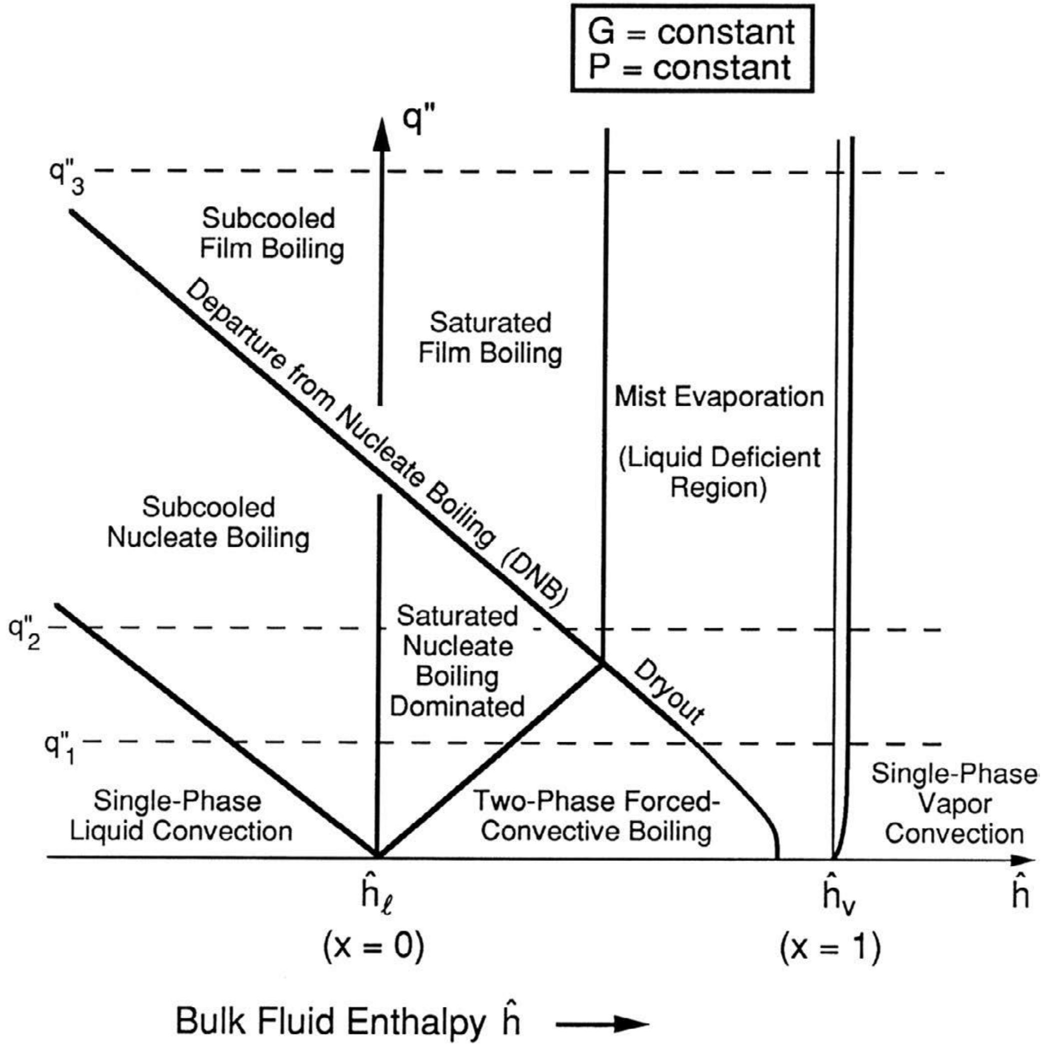


Figure 12.4 in Carey

- Saturated flow boiling is most often encountered in applications where complete or nearly complete vaporization of the coolant is desired.
- Applications:
  - evaporator of refrigeration and air-conditioning systems
  - cryogenic processing
  - boilers in power plants

Heat Transfer Correlations

- Gungor and Winterton correlation (upflow vertical tubes, diameter *D*)

$$h = h_l\left[1 + 3000\left(\frac{q''}{Gh_{lv}}\right)^{0.86} + \left(\frac{x}{1-x}\right)^{0.75}\left(\frac{\rho_l}{\rho_v}\right)^{0.41}\right]$$

$$h_l = 0.023\left(\frac{k_l}{D}\right)\mathrm{Re}_l^{0.8}\mathrm{Pr}_l^{0.4}$$ Liquid phase convective HTC

$$\mathrm{Re}_l = \frac{G(1-x)D}{\mu_l}$$ Liquid phase Reynolds number

Heat Transfer Correlations

- Kandlikar's Correlation

$$h = \max\{h_{NBD}, h_{CBD}\}$$

h_{NBD}: HTC for nucleate boiling dominant regime
h_{CBD}: HTC for convective boiling dominant regime

$$h_{NBD} = 0.6683\left(\frac{\rho_l}{\rho_v}\right)^{0.1} x^{0.16}(1-x)^{0.64}\boldsymbol{f_2(\mathrm{Fr}_{le})h_{le}} + 1058\left(\frac{q''}{Gh_{lv}}\right)^{0.7}\boldsymbol{F_K}(1-x)^{0.8}\boldsymbol{h_{le}}$$

$$h_{CBD} = 1.1360\left(\frac{\rho_l}{\rho_v}\right)^{0.45} x^{0.72}(1-x)^{0.08}\boldsymbol{f_2(\mathrm{Fr}_{le})h_{le}} + 667.2\left(\frac{q''}{Gh_{lv}}\right)^{0.7}\boldsymbol{F_K}(1-x)^{0.8}\boldsymbol{h_{le}}$$

Heat Transfer Correlations

- Kandlikar's Correlation (continued)

$$h_{NBD} = 0.6683\left(\frac{\rho_l}{\rho_v}\right)^{0.1} x^{0.16}(1-x)^{0.64}\boldsymbol{f_2(\mathrm{Fr}_{le})}h_{le} + 1058\left(\frac{q''}{Gh_{lv}}\right)^{0.7}\boldsymbol{F_K}(1-x)^{0.8}h_{le}$$

$\mathrm{Fr}_{le} = \frac{G^2}{\rho_l^2 gD}$, Froude number comparing inertial force to buoyance force

TABLE 12.1
Fluid Constant Values for the Kandlikar [12.53] Correlation

Fluid	F_K
Water	1.00
R-11	1.30
R-12	1.50
R-13B1	1.31
R-22	2.20
R-113	1.30
R-114	1.24
R-134a	1.63
R-152a	1.10
Nitrogen	4.70
Neon	3.50

$$f_2(\mathrm{Fr}_{le}) = \begin{cases} (25\mathrm{Fr}_{le})^{0.3} & \text{for } \mathrm{Fr}_{le} < 0.04 \text{ with horizontal tubes} \\ 1 & \text{for } \mathrm{Fr}_{le} > 0.04 \text{ with horizontal tubes and for all vertical tubes} \end{cases}$$

Heat Transfer Correlations

- Kandlikar's Correlation (continued)

$$h_{NBD} = 0.6683\left(\frac{\rho_l}{\rho_v}\right)^{0.1} x^{0.16}(1-x)^{0.64}\boldsymbol{f_2(\mathrm{Fr}_{le})h_{le}} + 1058\left(\frac{q''}{Gh_{lv}}\right)^{0.7} \boldsymbol{F_K}(1-x)^{0.8}\boldsymbol{h_{le}}$$

$$h_{CBD} = 1.1360\left(\frac{\rho_l}{\rho_v}\right)^{0.45} x^{0.72}(1-x)^{0.08}\boldsymbol{f_2(\mathrm{Fr}_{le})h_{le}} + 667.2\left(\frac{q''}{Gh_{lv}}\right)^{0.7} \boldsymbol{F_K}(1-x)^{0.8}\boldsymbol{h_{le}}$$

$0.5 \le \mathrm{Pr}_l \le 2000$ and $2300 \le \mathrm{Re}_{le} < 10^4$: $$h_{le} = \left(\frac{k_l}{D}\right)\frac{(\mathrm{Re}_{le}-1000)\mathrm{Pr}_l(f/2)}{1+12.7\left(\mathrm{Pr}_l^{2/3}-1\right)(f/2)^{0.5}}$$

$0.5 \le \mathrm{Pr}_l \le 2000$ and $10^4 \le \mathrm{Re}_{le} \le 5\times10^6$: $$h_{le} = \left(\frac{k_l}{D}\right)\frac{\mathrm{Re}_{le}\mathrm{Pr}_l(f/2)}{1.07+12.7\left(\mathrm{Pr}_l^{2/3}-1\right)(f/2)^{0.5}}$$

$$f = [1.58\ln(\mathrm{Re}_{le}) - 3.28]^{-2} \qquad \mathrm{Re}_{le} = GD/\mu_l$$

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Critical Heat Flux Condition (Departure from Nucleate Boiling)

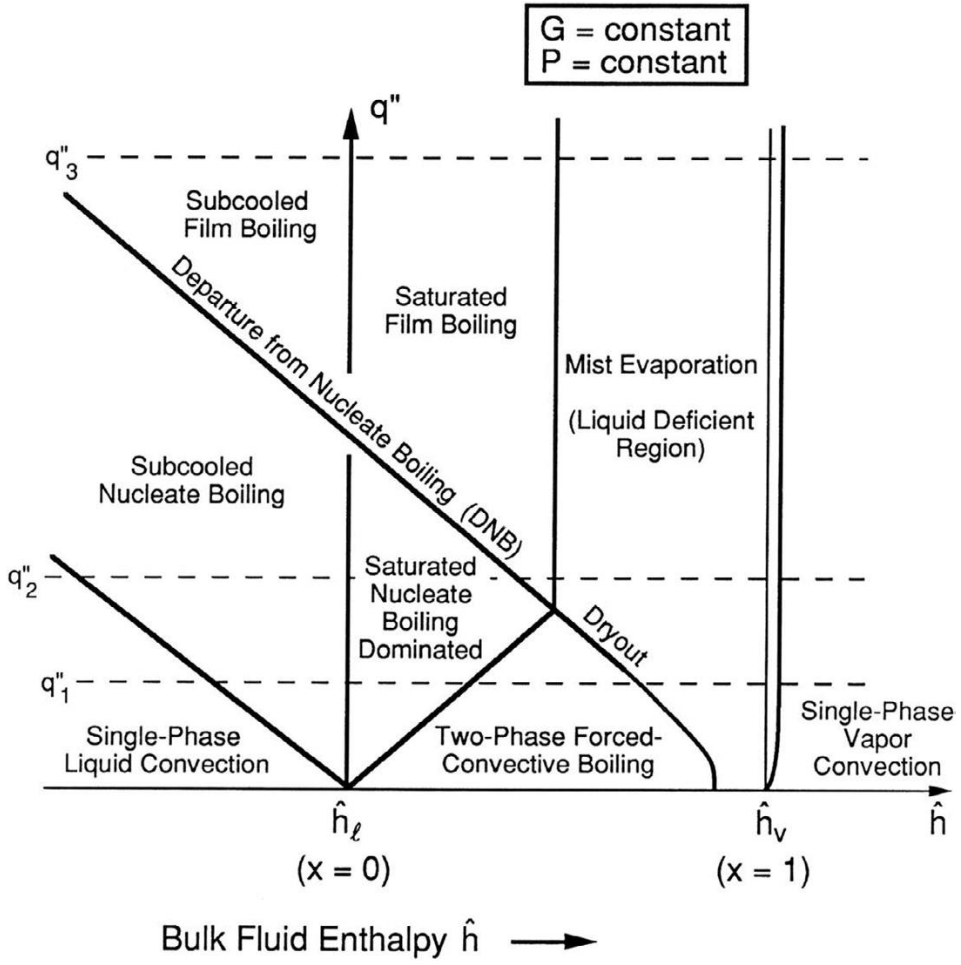

Figure 12.4 in Carey

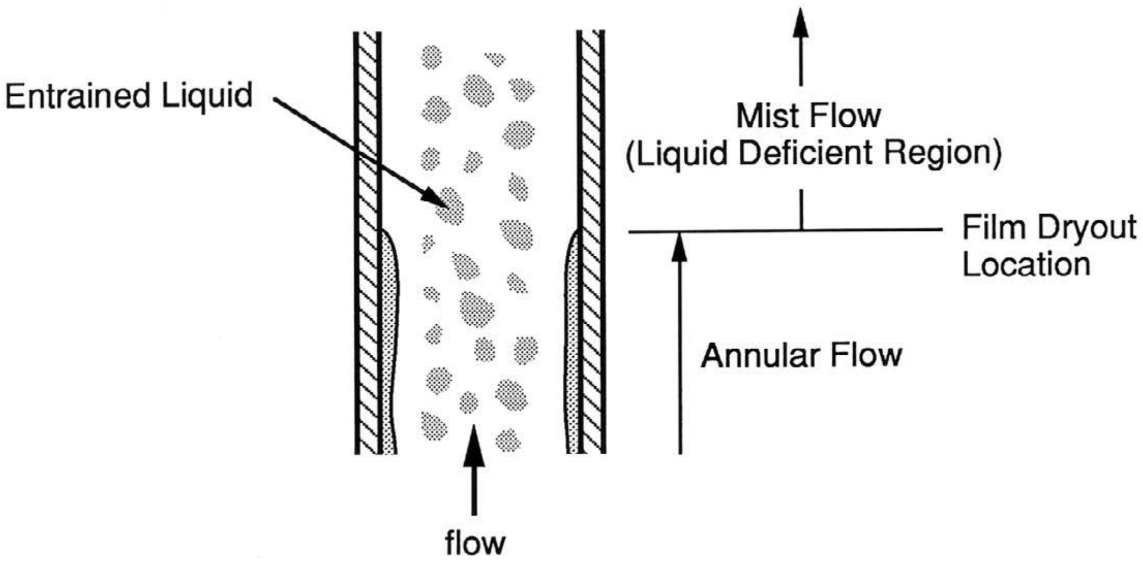

Figure 12.18 in Carey

Dry-Out Mechanisms (Hypotheses)

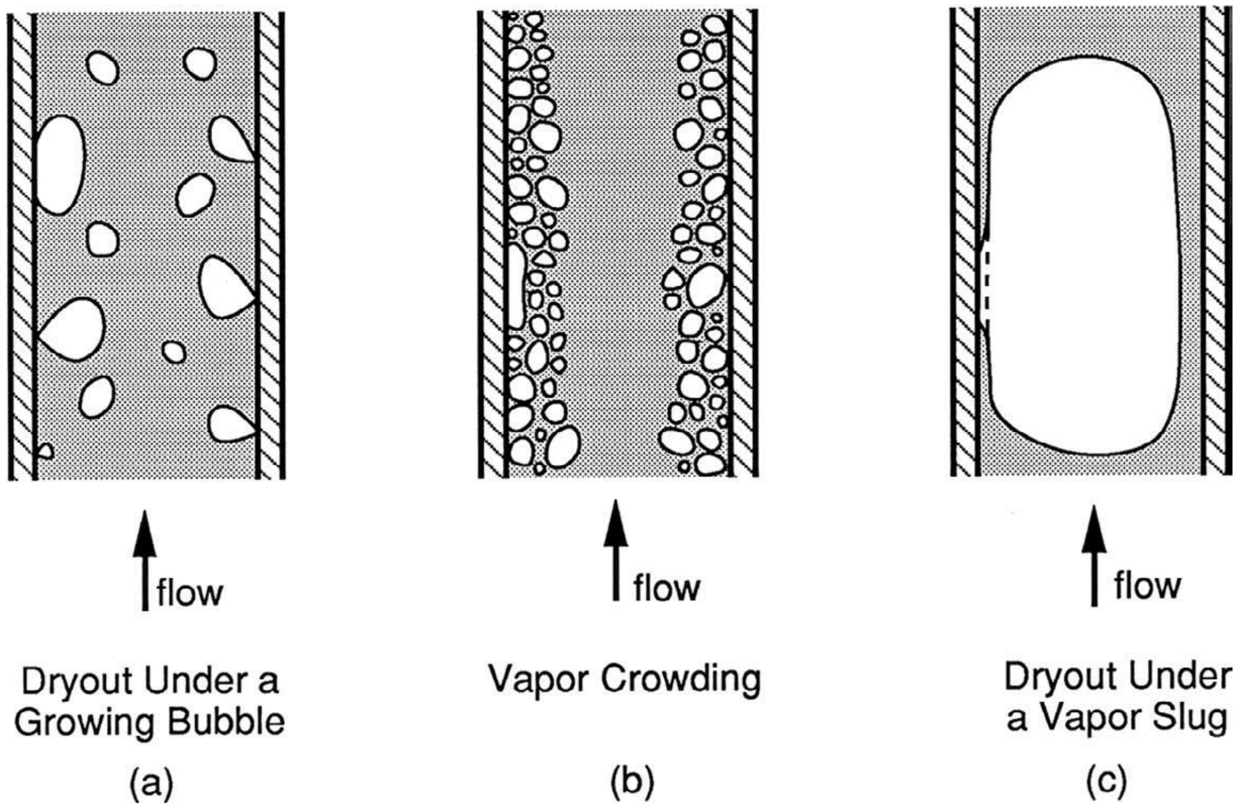

Figure 12.19 in Carey

(a) Liquid microlayer underneath the bubble evaporates faster than it can be replenished

(b) Near wall regime filled with vapor pockets, hindering liquid flow

(c) When a slug passes a heated section, the thin film completely evaporates before slug passes

CHF Correlation for Flow Boiling

- Subcooled case: Celata's correlation

$$\frac{q''_{crit}}{Gh_{lv}} = \frac{C_c}{\mathrm{Re}_{\mathrm{le}}^{0.5}} \qquad \mathrm{Re}_{\mathrm{le}} = \frac{GD}{\mu_l}$$

$$C_c = (0.216 + 0.0474P)\Psi$$ *P*: local pressure in MPa

$$\Psi = \begin{cases} 1 & \text{for } x_{out} < -0.1 \\ 0.825 + 0.986x_{out} & \text{for } -0.1 < x_{out} < 0 \end{cases}$$

$$x_{out} = \frac{c_{pl}\left(T_{l,out} - T_{sat}\right)}{h_{lv}}$$

Recommended for $P \leq 5.5$ Mpa, G/ρ_l of 2.2-40 m/s, $T_{sat} - T_{l,out}$ of 15-190 K, $0.3\ \mathrm{mm} \leq D \leq 15\ \mathrm{mm}$

CHF Correlation for Flow Boiling

- Saturated case: “The 2006 CHF look-up table” by Groeneveld *et al.*

Pressure [kPa]	Mass Flux [kg m⁻² s⁻¹]	CHF [kW m⁻²]																					
	X→	-0.50	-0.40	-0.30	-0.20	-0.15	-0.10	-0.05	0.00	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.60	0.70	0.80	0.90	1
100	0	8111	7252	6302	4802	4086	3057	1990	1142	637	415	284	223	188	165	152	142	133	123	114	110	96	55	0
100	50	8317	7271	6326	5035	4236	3453	2420	1570	1011	784	641	587	553	531	475	443	419	387	347	277	239	204	0
100	100	8390	7295	6371	5322	4586	3640	2942	2103	1558	1275	1013	885	847	811	789	758	745	715	700	600	459	359	0
100	300	10698	9288	7795	6020	5009	3865	3196	2479	1961	1707	1317	1177	1172	1159	1150	1100	1085	1041	1031	675	517	366	0
100	500	12882	10946	9224	6791	5348	3938	3369	2685	2087	1808	1412	1347	1311	1303	1282	1260	1212	1193	1071	605	450	295	0
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100	1500	22781	19225	15465	9100	6603	5358	3741	3524	3166	2917	2635	2572	2467	2378	1908	1350	1005	815	302	210	126	51	0
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100	2500	28026	23599	18346	9503	7506	6516	4502	4047	3852	3599	3228	3019	2676	2458	1148	956	708	485	290	120	46	22	0
100	3000	30294	25465	19383	9779	8063	7088	4826	4182	3976	3389	2968	2706	2369	1829	940	846	665	532	302	159	55	20	0
100	3500	32227	27043	21068	10156	8518	7302	5113	4384	4106	3196	2769	2557	2311	1729	1158	891	817	670	402	210	75	28	0
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100	6000	39525	33222	26637	13026	10396	9347	6919	5241	4423	3580	2921	2681	2447	2170	1908	1651	1418	1204	807	468	244	121	0
100	6500	40727	34244	27480	14371	10748	9701	6995	5295	4491	3620	2918	2694	2477	2209	1965	1719	1493	1281	878	523	282	142	0
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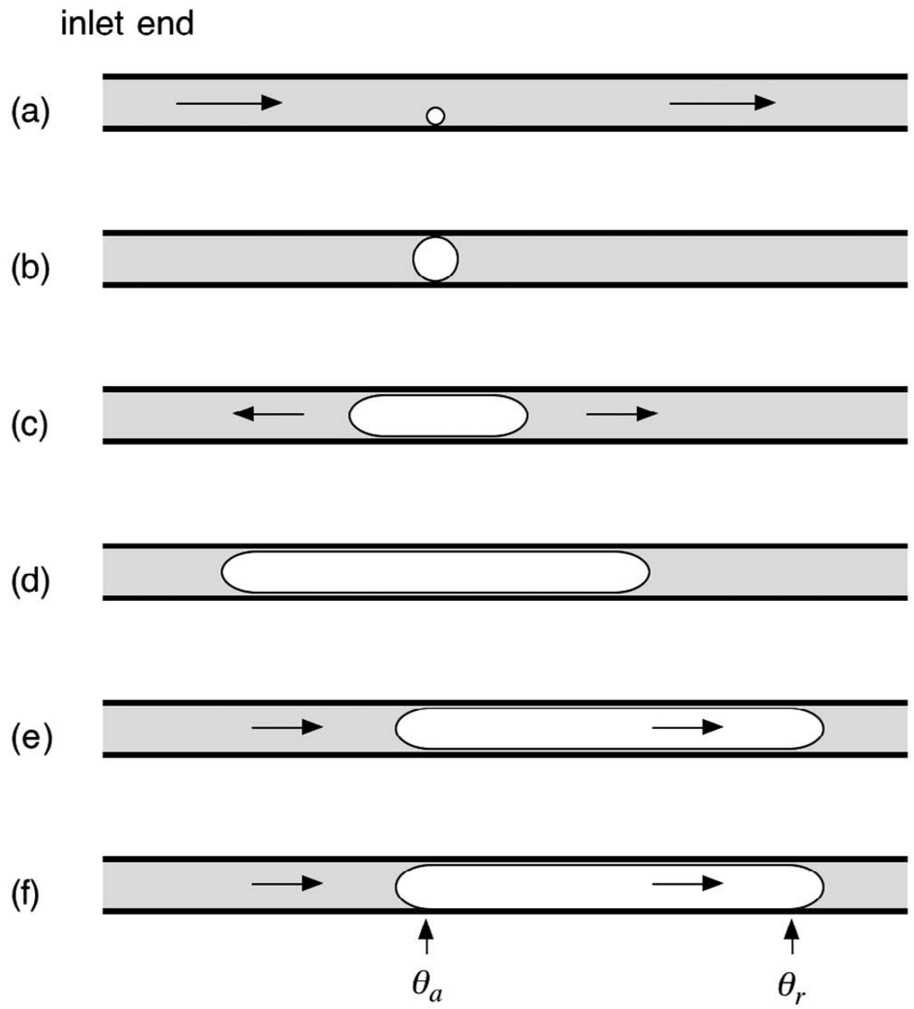
100	7500	43448	36075	28604	15822	11538	10726	7087	5381	4585	3699	2996	2751	2526	2285	2060	1838	1622	1414	1000	615	347	180	0
100	8000	44338	36803	29089	16599	12085	10900	7313	5392	4689	3780	3031	2778	2553	2320	2103	1890	1679	1473	1054	651	371	196	0

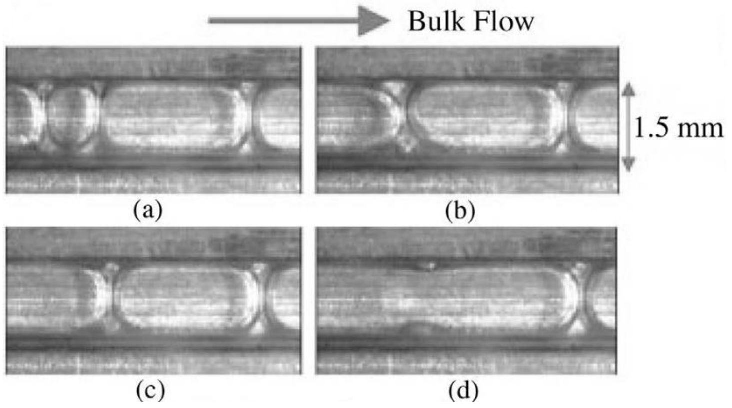
https://doi.org/10.1016/j.nucengdes.2007.02.014

https://github.com/greenwoodms06/2006_Groeneveld_CriticalHeatFlux_LUT

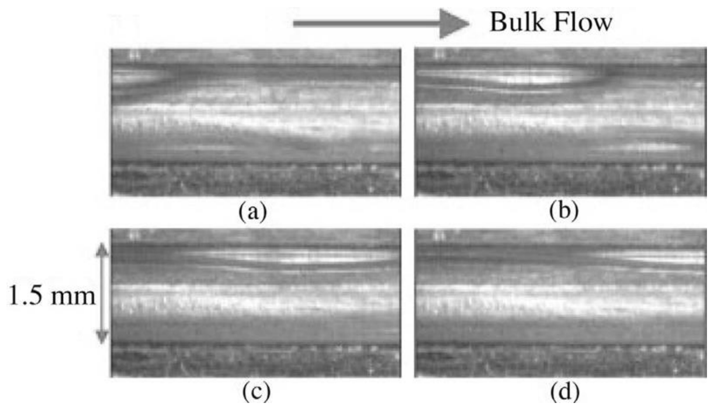
Flow Boiling in Microchannels



Slug flow



Annular flow



Density Wave Oscillations in Microchannels