NTEC Module: Water Reactor Performance and Safety

Lecture 6 : Introduction to two-phase heat transfer

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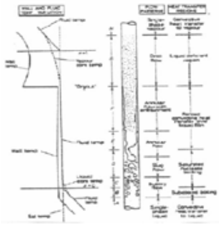
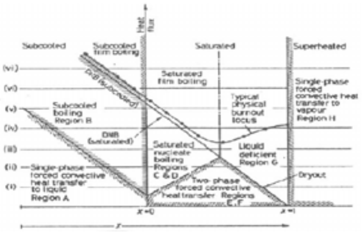
Forced convective boiling:

Relation between wall temperature and regimes



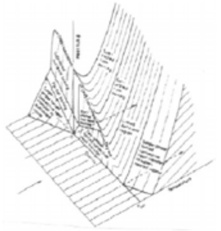
Forced convective boiling:

Heat transfer regimes as function of heat flux and quality



Forced convective boiling:

Models used in codes: The “boiling surface”.



- Assumes unique surface for given , p. to geometry
- Shape of surface will vary with pressure and mass flux, reflecting changes of flow regime.

Forced convective boiling:
Nucleate boiling heat transfer correlations

Correlation not taking account of surface effects. Foster& Zuber AIChEJ vol.1 p532(1955).

$$\alpha_{FZ} = \frac{\dot{q}}{\Delta T_{SAT}} = \frac{0.00122 \Delta T_{SAT}{}^{0.24} (\Delta p_{SAT})^{0.75} C_{pL}^{0.45} \rho_L^{0.49} \lambda_L^{0.79}}{(\sigma)^{0.5} h_{LG}^{0.34} \eta_L^{0.29} \rho_G^{0.24}}$$

Correlation taking account of surface effects (Rohsenow Trans. ASME vol.74,p.96,1952)

$$\frac{c_{pL} \Delta T_{SAT}}{h_{LG}} = C_{SF} \left\{ \frac{\dot{q}}{\mu_L h_{LG}} \sqrt{\frac{\sigma}{g(\rho_L - \rho_o)}} \right\}^{0.33} \left\{ \frac{c_{pL} \eta_L}{\lambda_L} \right\}^n$$

C_{SF} depends on surface finish and fluid eg: water/platinum: 0.013, water/stainless: 0.020. N = 1.0 for water; n = 1.7 for other fluids.

Forced convective boiling:
Chen superposition correlation

$$\alpha = \alpha_{NB} + \alpha_{FC}$$

$$\alpha_{NB} = S \alpha_{FZ}$$

$$\frac{\alpha_{FC}}{\alpha_L} = F = fn\left(\frac{1}{X_{tt}}\right)$$

NB – “Nucleate boiling”
FC – “Forced convection”
FZ – Forster/Zuber (Slide 10)

Chen, Ind. Eng.Proc. Des.Dev., vol.5,p. 322, 1966

$S = fn\,(\mathrm{Re})$; $\mathrm{Re} = \mathrm{Re}_L\, F^{1.25}$

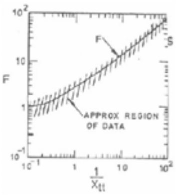
SATURATED REGION: $\dot{q} = \alpha \Delta T_{SAT}$

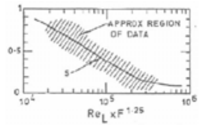
SUBCOOLED REGION: $\dot{q} = \alpha_W (T_W - T_B) + \alpha_{KB} (T_W - T_{SAT})$

(For this region take $\mathrm{Re} = \mathrm{Re}_L$ In calculation of S)

T_B = Bulk liquid temperature

Forced convective boiling:
Chen graphical correlations for *F* and *S*





Formulae (Butterworth)

$$F = 2.35\left({}^{1}\!/\!{}_{X_{tt}} + 0.213) \right)^{0.396}$$

$$S = \frac{1}{1 + 2.53 \times 10^{-6}\, \mathrm{Re}^{1.17}}$$

Take $F = 1$ for $1/X_{tt} \leq 0.1$

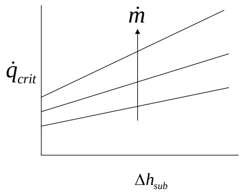
Critical heat flux: Definition

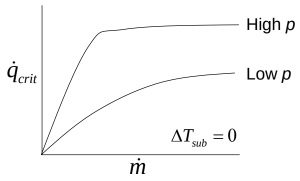
CHF Synonyms: “Dryout”, “Burnout”, “Boiling Crisis”, “DNB”, “Boiling transition”

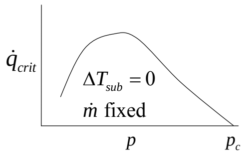
Definitions:

1. For *heat flux controlled* system, CHF corresponds to INORDINATE INCREASE in surface temperature following small change in system parameter (eg. Heat flux, mass flux, inlet subcooling).
2. For *surface temperature controlled* system, CHF corresponds to condition where there is an INORDINATE DECREASE in surface heat flux following a change in system parameter.

Parametric effects on CHF: Fixed length and diameter



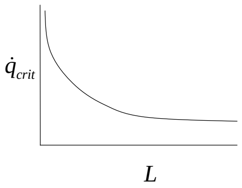


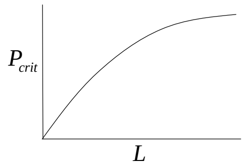


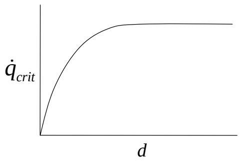
$$\Delta T_{sub} = T_{sat} - T_{in}$$

$$\Delta h_{sub} = c_{pL} \Delta T_{sub}$$

Parametric effects on CHF: Fixed mass flux and $\Delta h_{sub} = 0$



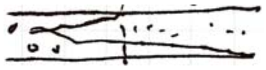




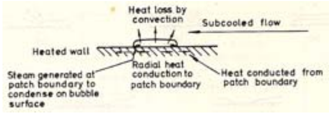
d = tube diameter

P_{crit} = power input to achieve CHF

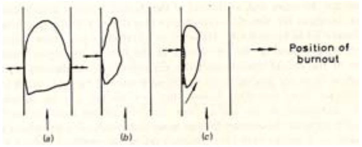
Note: Horizontal channels have lower CHF due to segregation



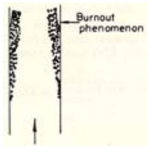
Critical heat flux mechanisms: Sub-cooled and low quality



(A) Hot spot under single bubble

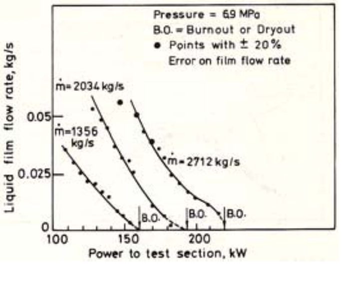


(B) Dryout under slug or vapour clot

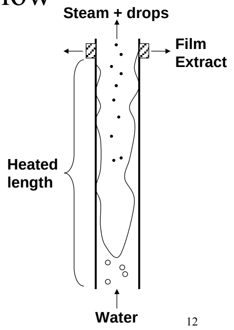


(C) Vapour bubble crowding – bubble boundary layer

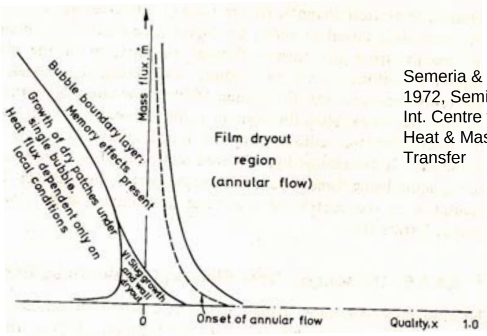
Link between CHF (dryout) and liquid film flow



Hewitt, Proc. 4th Int. H. T. Conf., Tokyo, 1970

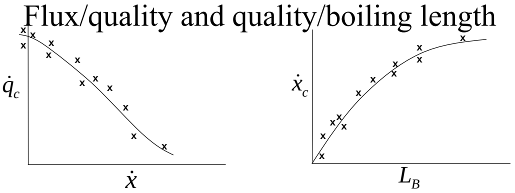


Tentative diagram of regions of operation of CHF mechanisms



Semeria & Hewitt, 1972, Seminar Int. Centre for Heat & Mass Transfer

Basic correlation types: Flux/quality and quality/boiling length



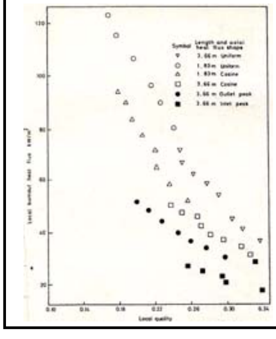
Burnout at end of tube - same data

If $\dot{q}_c = fn(\dot{x})$ for fixed $D, \dot{m}$

$$L_B = \frac{D\dot{m}h_{LG}\dot{x}_c}{4\dot{q}_c} = fn(\dot{x}_c)$$

$$\therefore \ x = fn(L_B)$$

Effect of non-uniform heat flux: Flux/quality relationship



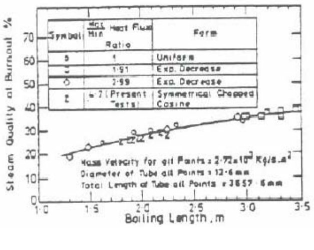
Results of Shiralkar (1972)

(Shiralkar NEDM – 13279, 1972)

Very poor representation of non-uniform flux data

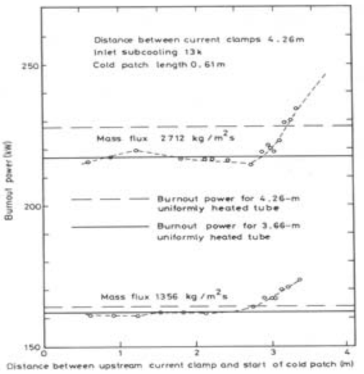
Critical heat flux correlations:

Effect of non-uniform heat flux on quality/boiling length relationship



$\dot{x} / L_B$ much better representation of data.
Recommended For $\dot{x} > 10\%$

Failure of both flux/quality and quality/boiling length correlations. 1: Cold patch experiments

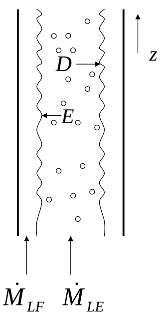


CHF (burnout) power increases if part of tube is unheated!

Water evaporating in a 12.6 mm vertical tube at 6.89 MPa

Bennet et al (1967)

Phenomenological methods for predicting CHF: Annular flow



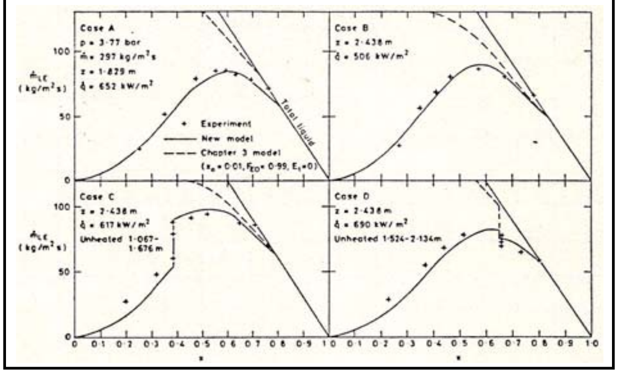
$$\dot m_{LF} = \frac{\dot M_{LF}}{\left(\pi d^2/4\right)}$$

$$\frac{d\dot m_{LF}}{dz} = \frac{4}{D}\left[D - E - \frac{\dot q}{h_{LG}}\right]$$

D and $E -$ deposition and entrainment rates per unit area of tube surface.

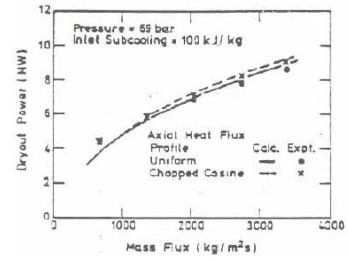
Whalley et al., 5th Int. H. T. C., Tokyo, 1974, Paper B6.11

Phenomenological methods for predicting CHF: Prediction of entrainment curves



Critical heat flux prediction in annular flow:

Application of model to rod bundle CHF



Transients: Extension of film dryout methodology (James and Whalley, 1978)

Equations for core and film:

$$\frac{\partial}{\partial t}[\rho_L(1-\varepsilon_{GC})]+\frac{\partial \dot{m}_{LF}}{\partial z}=\frac{4}{d}(D-E-\dot{q}/h_{LG}-F_{LF}) \qquad \text{Film mass balance}$$

$$\frac{\partial}{\partial t}[\rho_L\varepsilon_{GG}\varepsilon_d)]+\frac{\partial \dot{m}_{LE}}{\partial z}=\frac{4}{d}(E-D-F_{LE}) \qquad \text{Core mass balance}$$

$$\frac{\partial}{\partial t}[\rho_G\varepsilon_{GC}(1-\varepsilon_d)]+\frac{\partial \dot{m}_G}{\partial z}=\frac{4}{d}(\dot{q}/h_{LG}+F_{LF}+F_{LE}) \qquad \text{Vapour mass balance}$$

$$\frac{\partial}{\partial t}[\rho_L e_{iL}(1-\varepsilon_{GC})+\rho_L e_{iL}\varepsilon_{GC}\varepsilon_d+\rho_G e_{iG}\varepsilon_{GC}(1-\varepsilon_d)]+\frac{\partial}{\partial z}(h_L\dot{m}_{LF}+h_L\dot{m}_{LE}+h_G\dot{m}_G)=\frac{4\dot{q}}{d}$$

Overall energy balance

F_{LF} and F_{LE} are the rates of flashing of the film and drops per unit interface area

e_{iL} and e_{iG} are the internal energies of the liquid and vapour phases

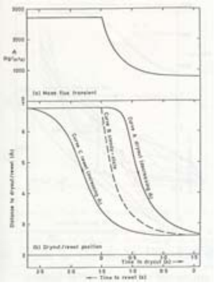
Critical heat flux prediction in annular flow:
Application of model to CHF in flow transient

$$\dot{m}(t) = 785 + 1926\exp(-t/0.275) \quad (\text{kg/m}^2\text{s}) \qquad (35)$$

Comparison with Moxon and Edwards data

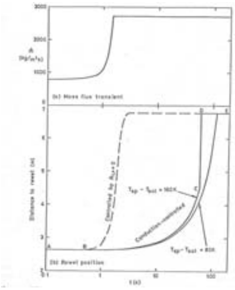
Run No	Heat flux (kW/r¹)	Subcooling (kJ/kg)	Time to dryout (s)			
			Experiment	Old Model (PW31)	New Model (PW31A)	New model Pseudo Steady-state
45/276	955	58.15	0.95	0.65	0.80	0.36
45/275	960	53.50	0.89	0.03	0.77	0.34
45/286	1155	46.52	0.40	0.34	0.32	0.08
45/284	1174	48.15	0.30	0.34	0.35	0.07

Dryout and rewetting I: Hewitt and Govan (1990)

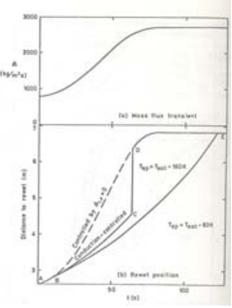


Transitions occur when film flow rate at wet/dry boundary is zero as calculated from transient film flow model.

Dryout and rewetting II: Hewitt and Govan (1990)

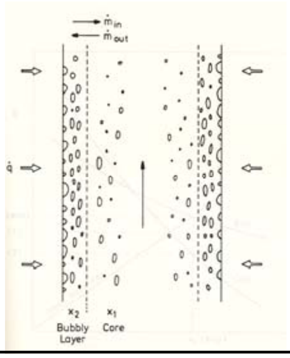


(a) Fast transient



(b) Slow transient

Phenomenological methods for predicting CHF: Modelling of low quality CHF: Weisman and Pei (1983) model

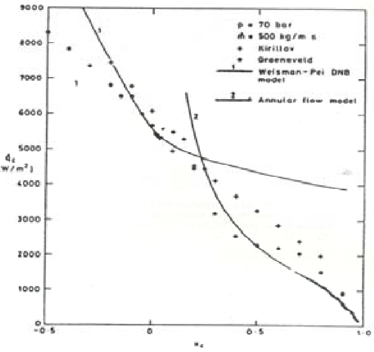


CHF condition corresponds to situation where:

$$\dot{q}_b = \dot{m}_{out}(x_2 - x_1)h_{LG}$$

Where q_b is that part of the heat flux which goes into generating bubbles.
Critical condition corresponds to void fraction in the wall layer of 0.82

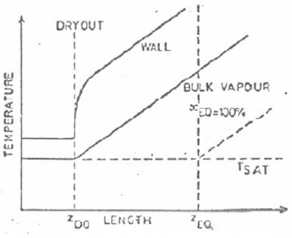
Phenomenological methods for predicting CHF: CHF modelling methods: Comparison with data



International data tables for CHF for water in uniformly heated tubes at 70 bar

Lowest value applies. Higher value from Weisman and Pei model may apply to hot spots in annular flow region.

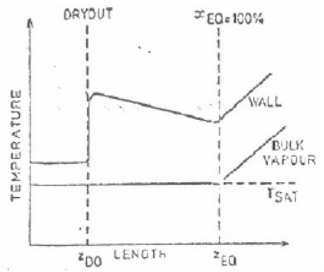
Post-CHF (post dryout) heat transfer:
Nil evaporation case



↑ Post-dryout
-- Dryout

Droplets do not evaporate in post-dryout region.
All heat goes into heating Steam.
(Low $\dot{m}$, low p)

Post-CHF (post dryout) heat transfer:
Equilibrium case



Droplets evaporate at rate sufficient to maintain vapour at T_{SAT}.

Vapour velocity increases and T_w decreases along channel.