TRACE Constitutive Models and Code Limitations

Information Systems Laboratories, Inc.

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Outline

- Closure relationships
- Flow regimes
- Special process models

TRACE Constitutive (Closure) Models

- Required Closure Relationships for Field Equations:
  - Equations of State
  - Wall Drag
  - Interfacial Drag
  - Wall Heat Transfer
  - Interfacial Heat Transfer
- TRACE has static flow regime maps to differentiate between pre-CHF and post-CHF conditions.
- Correlations/models are semi-empirical equations (not first principles) so new applications and geometries require new models.
- See TRACE Theory manual for details on models and correlations and the Assessment Manual for comparisons to data.

TRACE Constitutive (Closure) Models

Some correlations are tied to specified regions of specific components.

- Bestion interfacial drag for rod bundles is used in the core region of VESSEL components and the rod bundle region of CHAN components.
- Reflood heat transfer is only available in the core region of VESSEL, CHANNEL, and "special" PIPEs.
- New Film condensation model in "special" PIPEs and VESSELs
- Other correlations tied to less commonly used components include the CANCHAN and Helical Steam Generator models.

Flow Regimes

The TRACE hydraulic and heat transfer models are selected based upon the flow regime present in each hydrodynamic fluid cell.

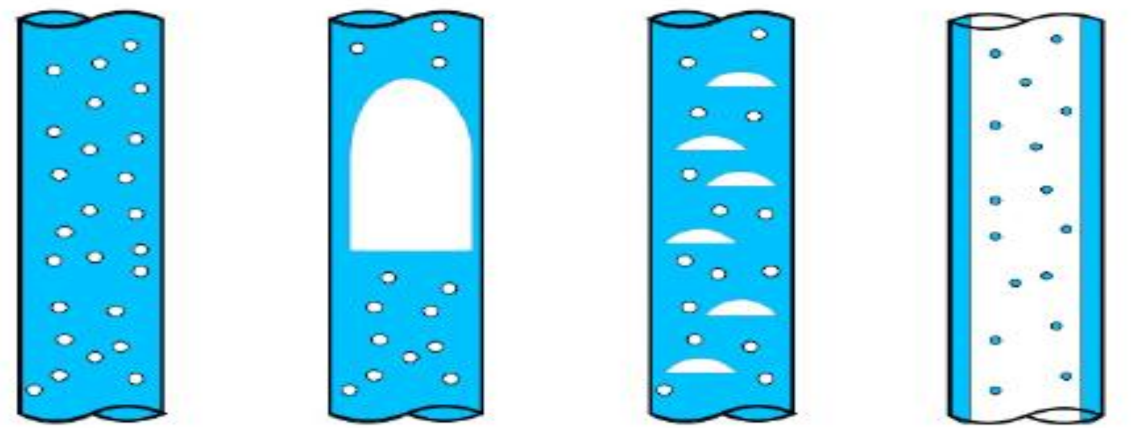
TRACE has static flow regime maps for “normal” fluid conditions in vertical and horizontal configurations, and for “reflood” fluid conditions in vertical configurations.

The flow regime map selection considers the fluid conditions (void fraction, velocities, etc.) and the wall-to-fluid heat transfer processes (based on a comparison with the critical heat flux, CHF):

- Pre-CHF heat transfer
  - Wall is wet – convection to liquid, subcooled and nucleate boiling
- Post-CHF heat transfer
  - Wall is dry – transition and film boiling, convection to vapor

Vertical Flow Map

Pre-CHF vertical flow regimes:

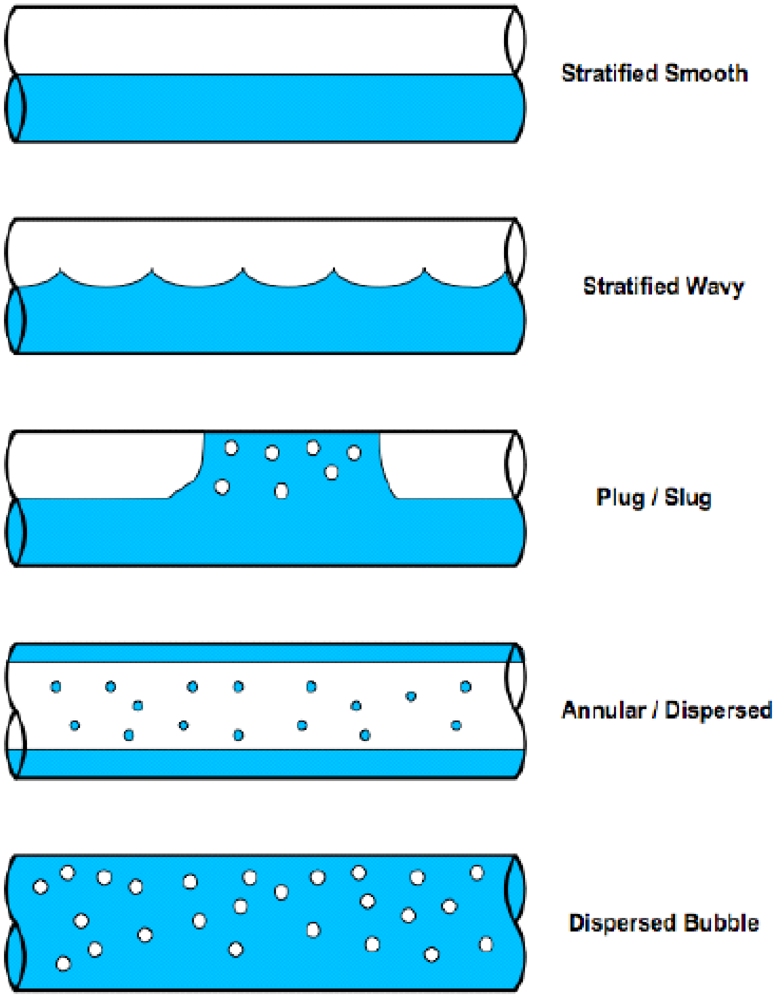


Dispersed Bubble	Slug Flow	Taylor Cap Bubble	Annular/Mist

Dispersed bubble, slug flow, and Taylor Cap bubble are collectively called "Bubbly-Slug" flows

Horizontal Flow Map

- Regimes modeled by vertical analogs
  - Dispersed Bubble
  - Annular/Dispersed
- Horizontal-specific model
  - Stratified Smooth
- Not specifically modeled
  - Stratified/Wavy
  - Plug/Slug



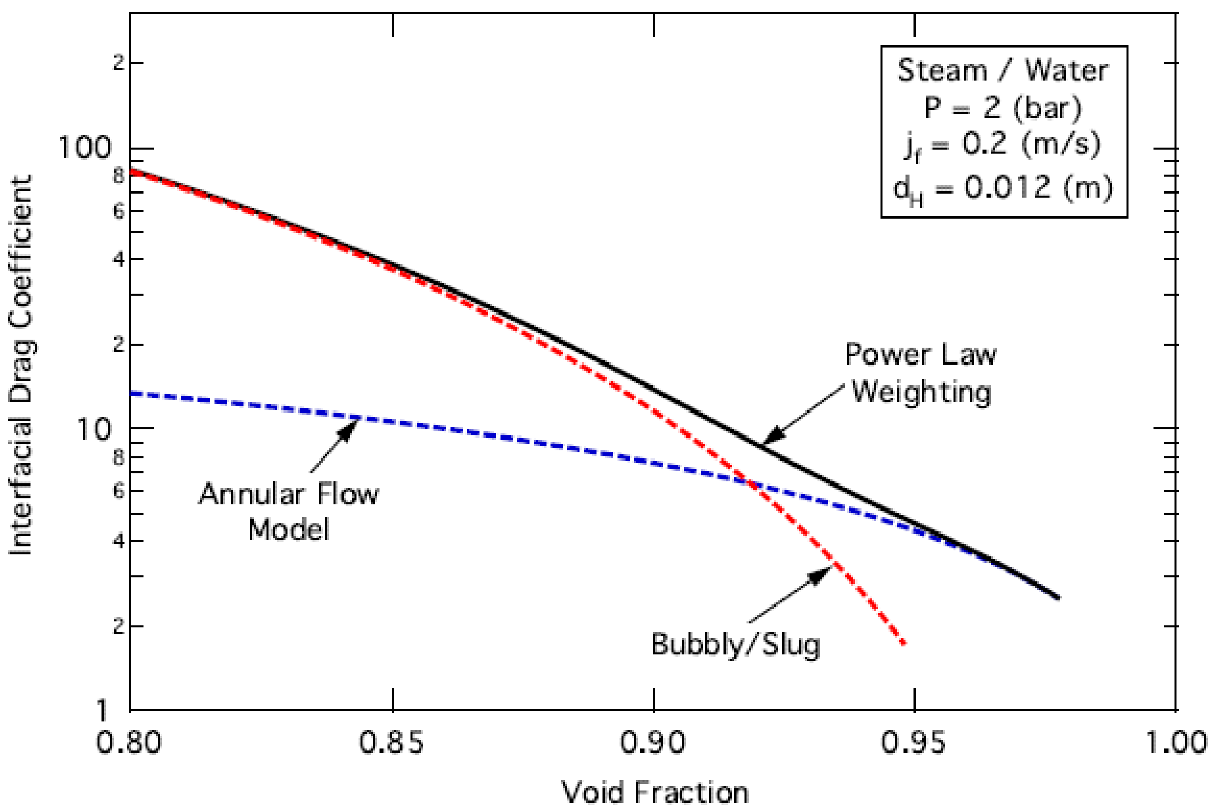
Pre-CHF Interfacial Drag Correlations

- Vertical and horizontal orientations use same interfacial drag models for bubbly, slug, and annular mist
  - Pipe: Bubbly churn-turbulent – Ishii
  - Slug & Taylor Cap Bubble – Kataoka-Ishii
  - Rud Bundle: Bestion
  - Annular: Wallis, Asali and Hanratty for cocurrent flow
  - Stratified: Ohnuki
- Horizontal orientation adds a stratified flow correlation

Interfacial Drag Transition

Pre-CHF bubbly to annular transition for interfacial drag:

- Calculate bubbly-slug drag (drift-flux based)
- Calculate annular-mist (AM) drag
- Total drag = (BS^n + AM^n)**1/n, where n = 2



Reflood Vertical Flow Map

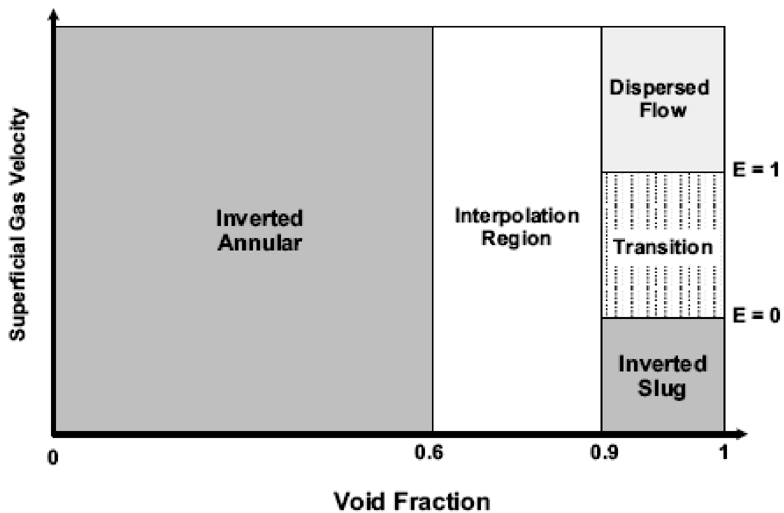
Interfacial drag coefficients for post-CHF vertical flow regimes:

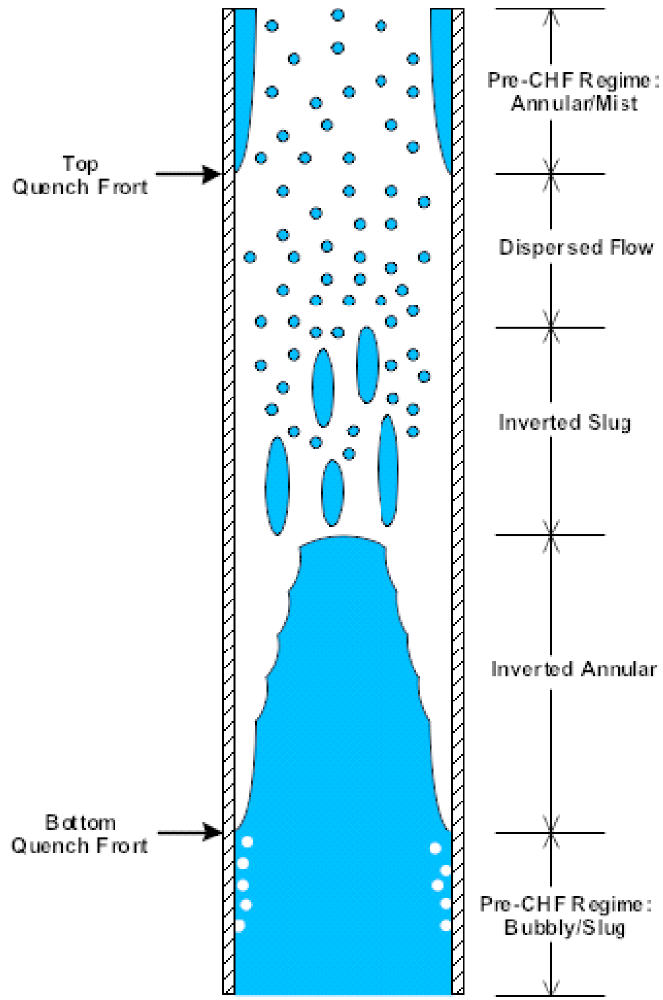
Inverted Annular – standard laminar flow between parallel plates with gas-film thickness by De Cachard

Inverted Slug - Kawaji and Banerjee

Dispersed Flow - Schiller and Nauman

E = entrainment fraction





Downcomer Interfacial Drag

- Modifications are made to the base interfacial drag in the downcomer region of a VESSEL component to accurately model bypass and refill during LBLOCAs.
- Modifications are based on comparison to full scale UPTF data.
- Downcomer drag in z direction = 0.125*normal drag
  - Activated with namelist parameter lbdrag=.true.
- Mechanistic model should be developed in future

Pre-CHF Interfacial Heat Transfer

- Approach and assumptions:
  - Utilize idealized heat transfer area for bubbles, slugs, drops, and films
  - Apply forced or natural convection heat transfer correlations
  - Linear interpolation between Bubbly-Slug and Annular mist between void fractions of 0.5 and 0.75
  - Flashing interfacial heat transfer is not mechanistic and has large values designed to keep phases close to equilibrium
- Heat Transfer correlations
  - Bubbly-Slug Flow Regime – Ranz-Marshall correlation
  - Annular/Mist
    - Annulus: Kuhn-Schrock-Peterson (laminar), Gnielinski (turbulent)
    - Droplets: Ryskin
  - Flashing – large heat transfer coefficient

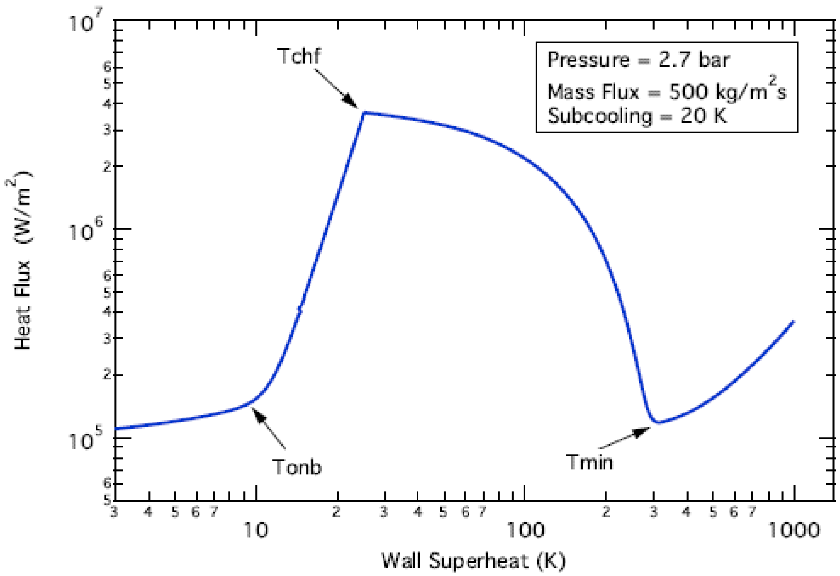
Pre-CHF Wall Heat Transfer

- Correlations are geometry and flow-dependent
- Geometries
  - Pipe
  - Rod bundle
  - Helical coil
  - CANDU arrangement
- Pre-CHF Wall Heat Transfer Regimes
  - Single phase liquid convection
  - Single phase vapor convection
  - Two-phase convection
  - Film condensation
  - Nucleate boiling
  - Subcooled boiling
- Maximum coefficient selected from laminar, turbulent, and natural circulation correlations
- Specifics on correlations are available in the Theory Manual

Nucleate Boiling Heat Transfer

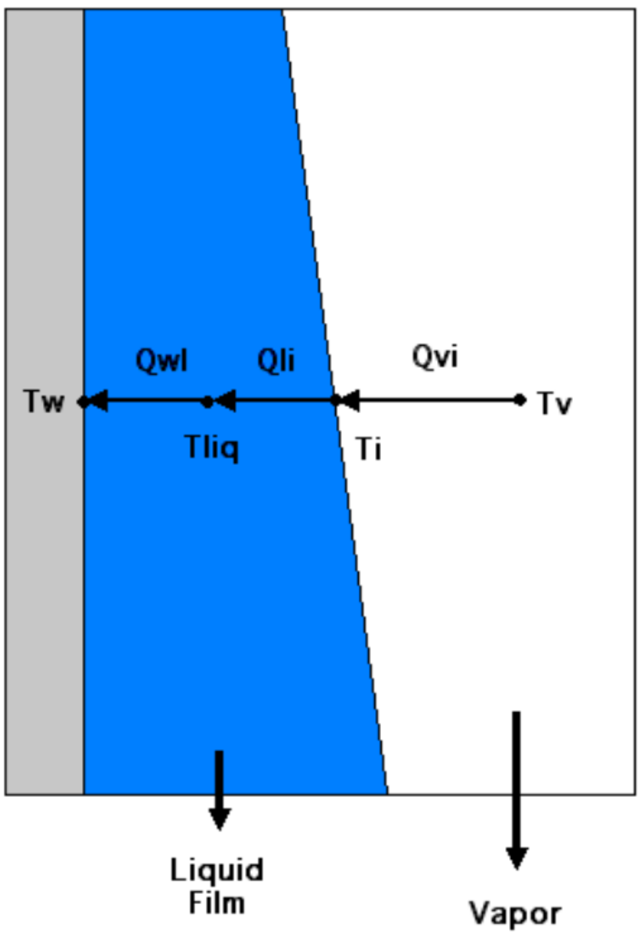
- Gorenflo model used for boiling
- Interpolation between two-phase forced convection and pool boiling.

Example Boiling Curve



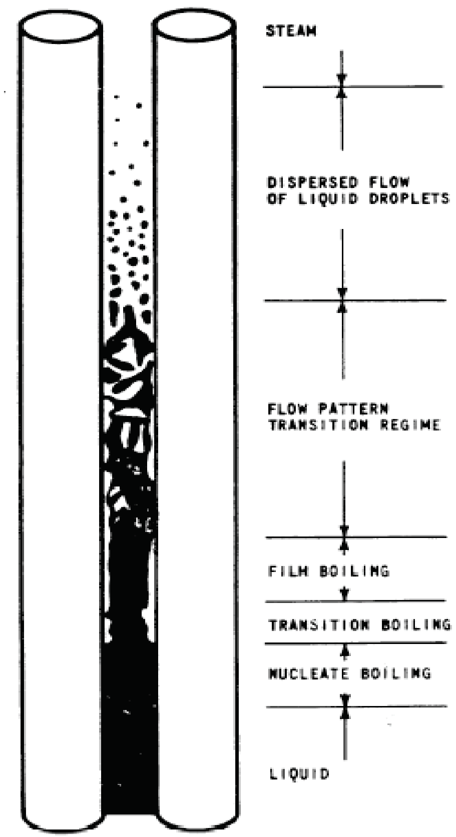
Film Condensation

- Model Requirements
  - Condensation with pure steam and steam-NC gas mixtures
  - Applicable to both falling and sheared films
- Models Needed
  - Film Thickness
    - Wall Friction
    - Interfacial Shear
  - Wall Heat Transfer
    - Wall-Liquid HTC
  - Interfacial Heat Transfer
    - Liquid-Interface HTC
    - Vapor-Interface HTC
  - Non-Condensable Gas Effect



Post-CHF Regimes

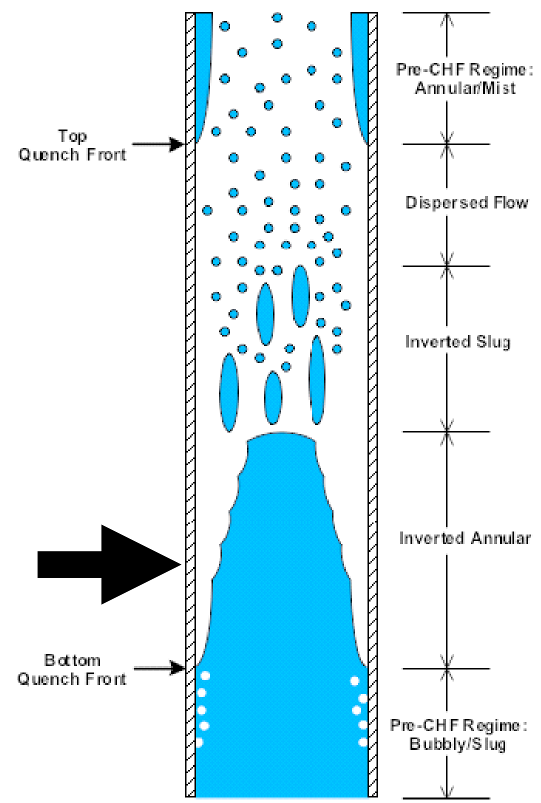
- Transition Boiling:
  - at quench front, ~ 1-2 cm long.
- Film Boiling:
  - a.k.a. inverted annular film boiling
  - occurs for high flow & subcooled conditions.
- Flow Pattern Transition Regime:
  - a.k.a. inverted slug, agitated inverted annular, or froth.
  - mixture of liquid fragments & droplets
  - occurs when inverted core disintegrates or when 2-phase mixture exists below quench front.
- Dispersed Flow:
  - a.k.a. dispersed flow film boiling.
  - superheated steam & droplets with Sauter mean diameter ~ 1 mm.



Post-CHF Regimes

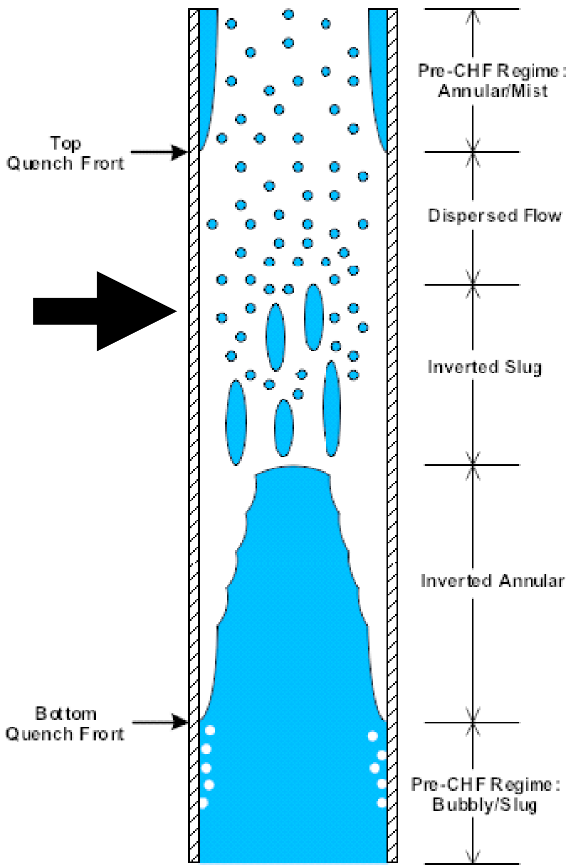
Inverted Annular Film Boiling

- Conceptual Model
  - Primary wall heat transfer mode is convection vapor film, ultimate heat sink is the subcooled liquid.
- Models Needed
  - Wall-Vapor heat transfer
  - Vapor-Interface heat transfer
  - Liquid-Interface heat transfer
  - Wall-Liquid radiation heat transfer
  - Interfacial drag
  - Criteria for regime transition (liquid core breakup)

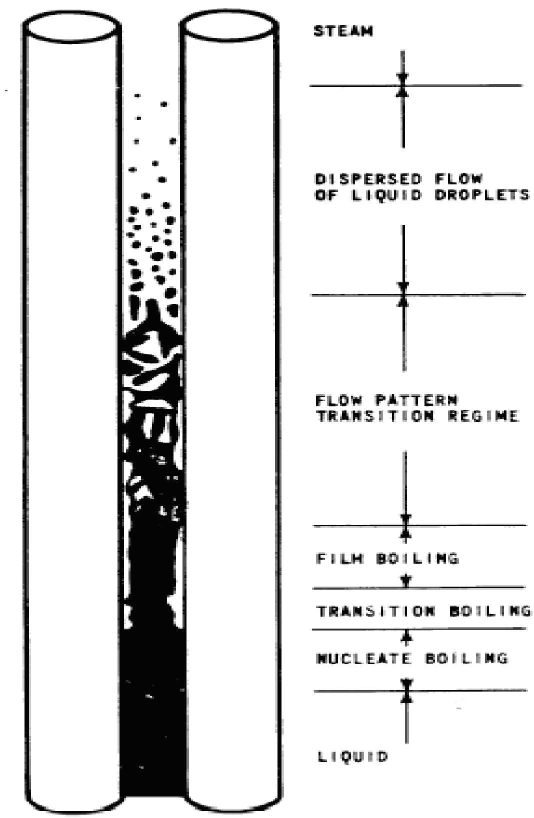


Post-CHF Regimes

- Dispersed Flow Film Boiling
  - Conceptual Model
    - Primary wall heat transfer mode is convection to vapor. Subcooled liquid droplets de-superheat vapor.
  - Models Needed
    - Wall-Vapor heat transfer
    - Vapor-Interface heat transfer
    - Liquid-Interface heat transfer
    - Wall-Liquid radiation heat transfer
    - Interfacial drag
  - Grid spacer
    - Interfacial area enhancement due to liquid droplet breakup.
    - Turbulence effects in vicinity of grids.

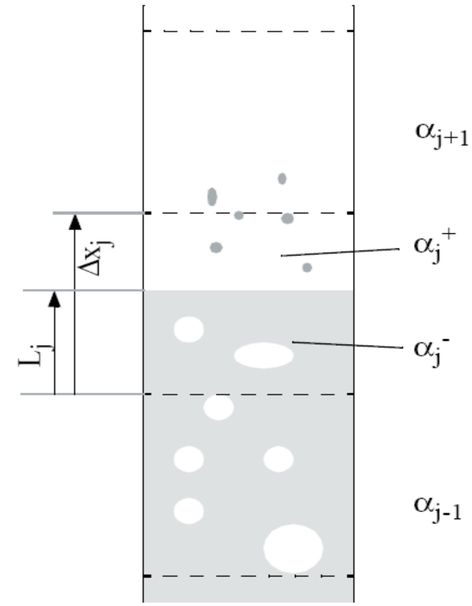


Special Process Models



Level Tracking ►

Model modifications for interfacial drag, wall drag, interfacial heat transfer and gravity head to better track void discontinuities.



◄ Reflood Model

Characteristic lengths of important phenomena are less than the hydrodynamic cell length. Uses heat structure fine-mesh rezoning to resolve axial temperature and heat flux profiles and to track a quench front within cells.

Special Process Models

Critical Flow

Velocities at a cell face are limited to the sound speed to simulate choked flow conditions. Subcooled liquid, two-phase fluid and single-phase vapor coefficients are used. Default coefficients available, or user may specify them as desired. Typically used for modeling flows through pipe breaks and relief valves.

Countercurrent Flow Limiting

Interfacial drag model for vertical configurations modified to simulate limitation of downward liquid flow by upward vapor flow. Correlations for standard simple geometries are included, along with flexibility to specify configuration-dependent correlation data if available. Typically used to simulate liquid hold-up in PWR SG tubes or above PWR and BWR upper core plates.

Special Process Models

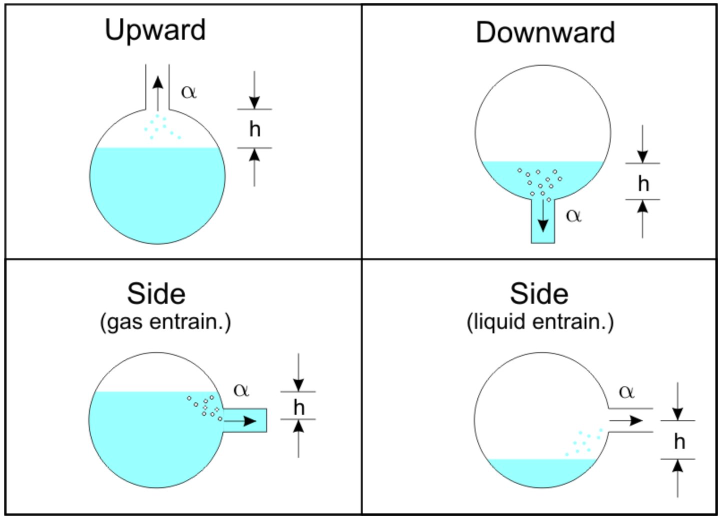
Offtake Model for Connections to Horizontal Pipes

Mainly used for SBLOCAs. The formulation contains a critical entrainment height:

$$h_b = \frac{C_1 W_k^{0.4}}{(g \rho_k \Delta \rho)^{0.2}}$$

W_k = major-phase mass-flow rate

ρ_k = major-phase density.



Offtake Geometry	Correlation Constant, C_1
Upward	1.67
Downward	1.50
Side (gas entrain.)	0.75
Side (liquid entrain.)	0.69

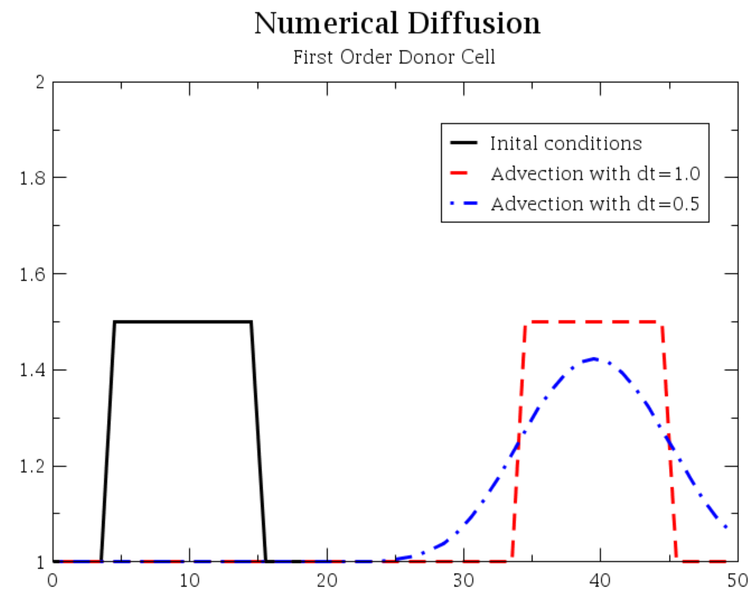
Special Process Models

Abrupt Area Change

Model calculates flow losses for expansions and contractions based on geometry and the fluid conditions. If active, the flow loss from this model is added to wall friction and user-specified flow loss.

Numerical Diffusion

- Advection numerical methods diffuse steep fronts.
- Peaks are reduced and fronts arrive too early.
- No numerical diffusion for Courant number of 1
- Can’t maintain Courant number of 1 everywhere
- Effect can be minimized by increasing nodalization in region of interest.



A TRACE Energy Equation Limitation

- TRACE does not accurately calculate the flow of energy across cell faces with large pressure differences between adjacent cells
  - Not an issue for choked flow at cell faces connecting “normal” TRACE components (such as PIPEs, VALVEs and VESSELs) to TRACE CONTAN components (that are used to model containments)
  - The problem is for choked flow at cell faces internal to (or between) the “normal” TRACE component types
    - In this situation, TRACE will underpredict the flow of energy into the cell downstream of the choking location
    - As a workaround for this problem, one can calculate the magnitude of the error with a control system and compensate by using a FLPOWER component that deposits the additional heat into the downstream cell

Questions?

Any questions before moving on?