UNENE Graduate Course
Reactor Thermal-Hydraulics Design and Analysis

McMaster University

Whitby

March 19-21, April 23-25, May 2, 2004

CATHENA T-H Models

Dr Nik Popov

Outline

- CATHENA Introduction
- CATHENA Thermal-hydraulic Models
- CATHENA Heat Transfer Models
- CATHENA Components Models
- CATHENA Constitutive Correlations

CATHENA

- Canadian Algorithm for THErmalhydraulic Network Analysis

- One-dimensional, two-fluid system thermalhydraulics code

Intrinsic Modelling Assumptions

- All variables are time & area averages
  - Results can not be expected to apply to either very short time or very short spatial increments
    - Δt must be large enough that a “time” average is meaningful. For example, larger than the time required for a bubble to pass a given location
    - Δz must be larger than the bubble diameter
- Kinetic energy terms usually neglected in comparison with thermal energy transfers
  - Implies less accuracy for high velocity gas flows – e.g., near a break or gas shock tube simulations
- Axial transfers (conduction, bulk shear) usually neglected
  - Axial conduction in fluid is included

Constitutive Assumptions

- Flow regime map is calculated based on local variables however most transition criteria are developed from steady-state, well-developed flow conditions (visual observation a long distance from inlet or other disturbances)
  - Time & distance required for transition to occur is neglected
    - Bubbles coalesce instantaneously
    - Flow stratifies instantaneously
  - Transitions will be calculated to occur more quickly than observed >> hydraulic calculations can be expected to be less “stable” than observed
- Correlations are based on steady-state, well developed conditions
  - Time required to develop boundary layers assumed in shear and heat transfer correlations is neglected >> reduced stability

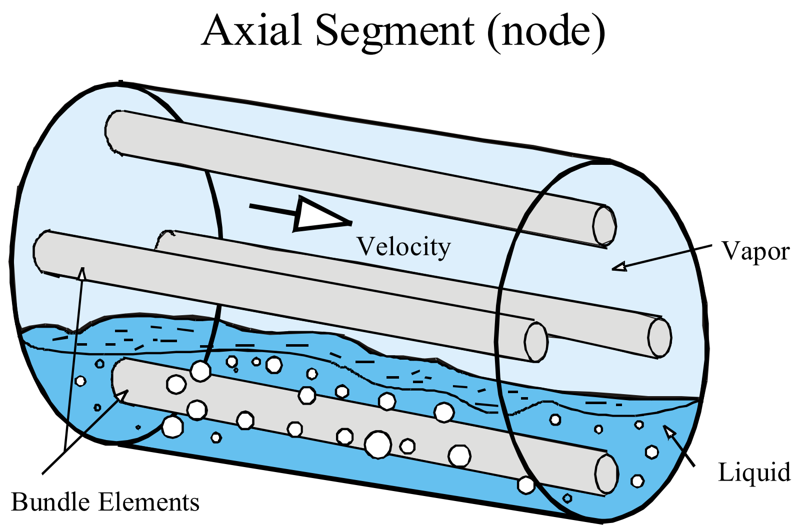
Principal Components of CATHENA

- Thermalhydraulic Model
- Solid Heat Transfer Model (GENHTP)
- Component Models
- Control System
- Pre-Processing Utilities

CATHENA Thermal-hydraulic Model

- Full Network, User Defined by Input File
- Mass Conservative
- Special Consideration of Horizontal Stratified Flow
- Automated Timestep Control Algorithm

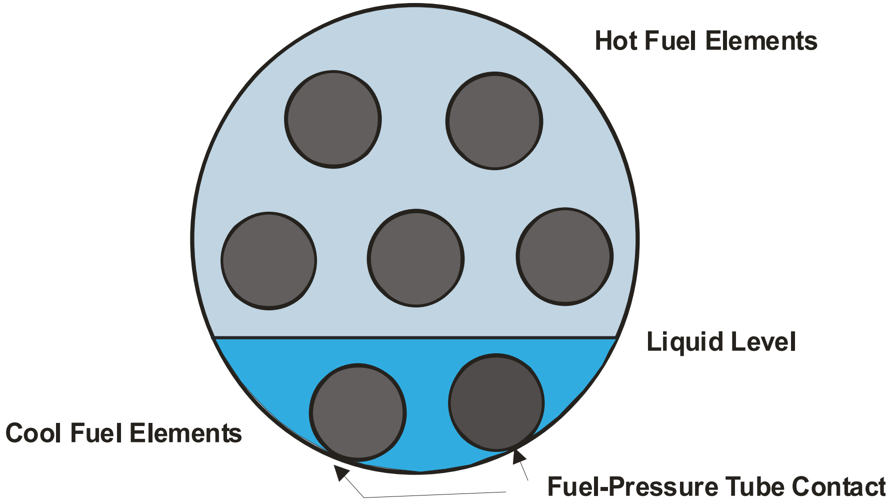
CATHENA Thermal-hydraulic Model



- non-equilibrium model (2-velocities, 2-temperatures 2-pressures) plus noncondensables
- flow regime dependent constitutive relations couple two-phase model

CATHENA Thermal-hydraulic Model

- Fluids Available
  - H_2O and D_2O
- Noncondensables (carried with vapour)
  - Air
  - N_2
  - H_2
  - He
  - Ar
  - CO_2



CATHENA Component Models

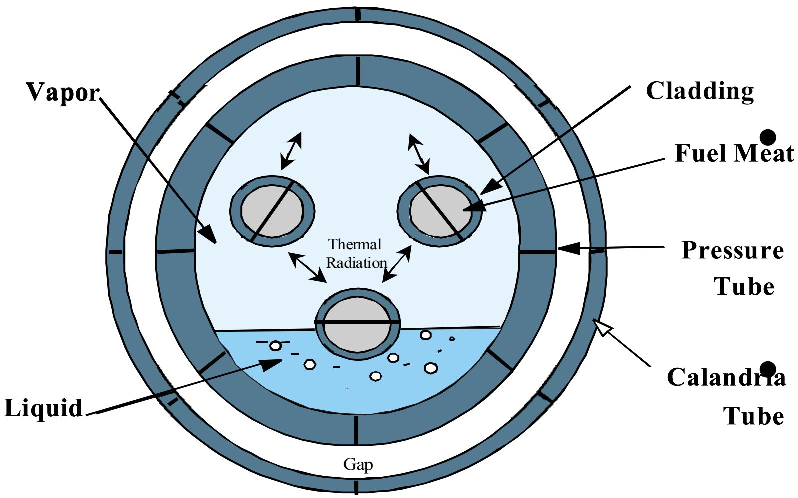
BLA CHF
CREPT PRESSURE TUBE
DELAY LINE
DISCHARGE MODEL
DYNAMIC AREA FEEDBACK
DYNAMIC VOLUME FEEDBACK
ECI ACCUMULATOR MODEL

HEAT BALANCE
HEAT EXCHANGER
JUNCTION RESISTANCE
REACTOR KINETICS
PUMP
SEPARATOR
VALVE

CATHENA Solid-to-fluid Heat Transfer Model (GENHTP)

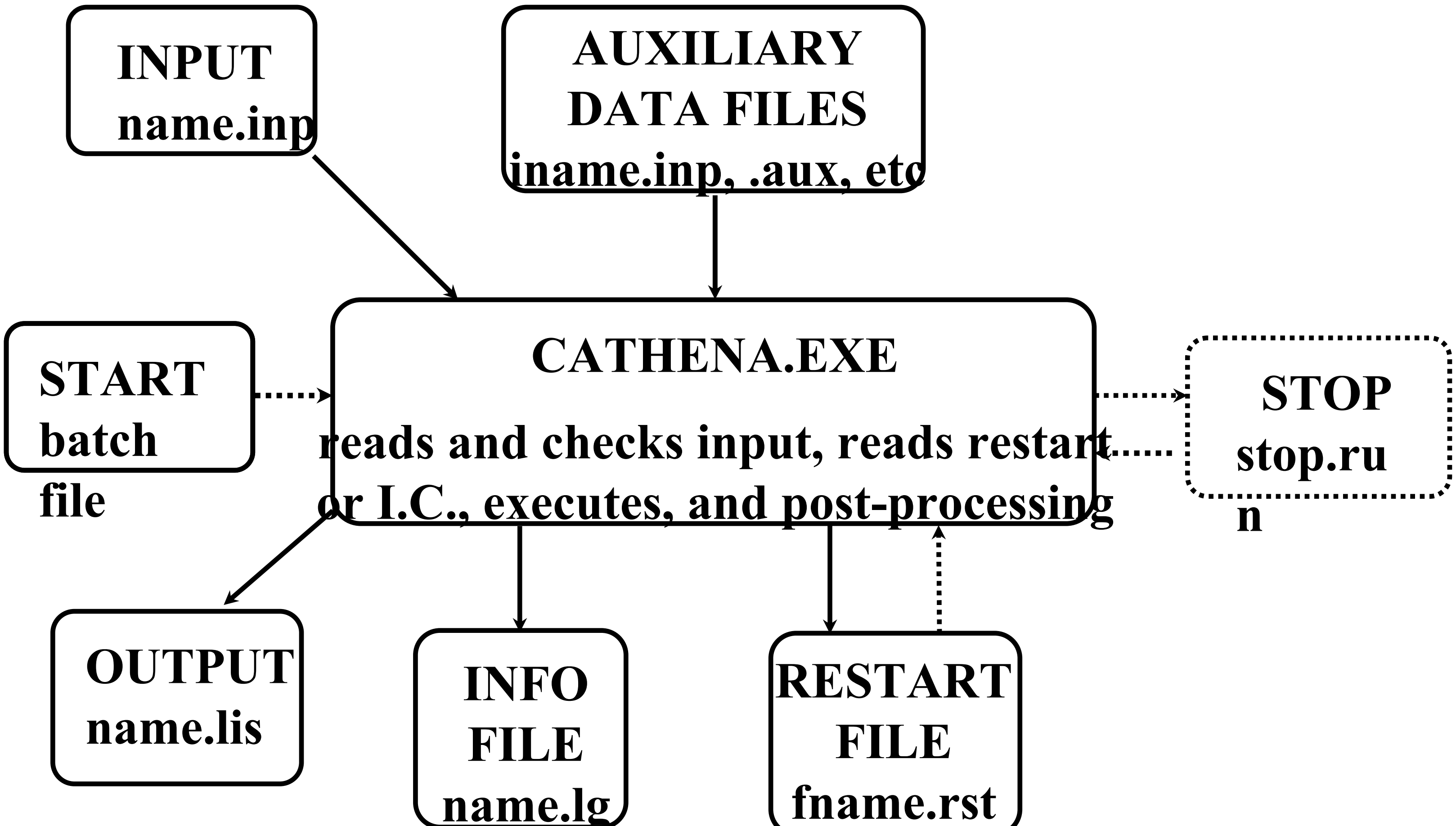
- Multiple Surfaces per Thermalhydraulic Node
- Modelling of Heat Transfer in Pin Bundles for Stratified Flow Regime
- Default Set of Heat Transfer Correlations for Entire Boiling Curve
- Several Heat Flux Integration Methods
- Built-in Temperature Dependent Property Tables

CATHENA Solid Heat Transfer Model (GENHTP)



- User specified number of heat transfer surfaces
- Thermal radiation and solid-solid contact conductance
- Zr/steam reaction and pressure-tube ballooning models available
- Thermal stratification (steam bubble)

Overview



INPUT
name.inp
AUXILIARY
DATA FILES
iname.inp, .aux, etc
START
batch
file
CATHENA.EXE
reads and checks input, reads restart
or I.C., executes, and post-processing
STOP
stop.ru
n
OUTPUT
name.lis
INFO
FILE
name.lg
RESTART
FILE
fname.rst

System Models

- BLA CHF
- CREPT PRESSURE TUBE
- DELAY LINE
- DISCHARGE MODEL
- DYNAMIC AREA FEEDBACK
- DYNAMIC VOLUME FEEDBACK
- ECI ACCUMULATOR MODEL
- HEAT BALANCE
- HEAT EXCHANGER
- JUNCTION RESISTANCE
- REACTOR KINETICS
- PUMP
- SEPARATOR
- VALVE

What is GENHTP?
Generalized Heat Transfer Package

- Model for heat transfer within all solid components
- Handles conduction within solid components and all heat transfer between solid components and the thermalhydraulic fluids (liquid, vapour, two phase mixtures)
- Examples: - radial conduction within multi-region fuel

  - radial conduction with pipe walls
  - fuel pin-to-fluid heat transfer
  - pipe walls-to-fluid heat transfer

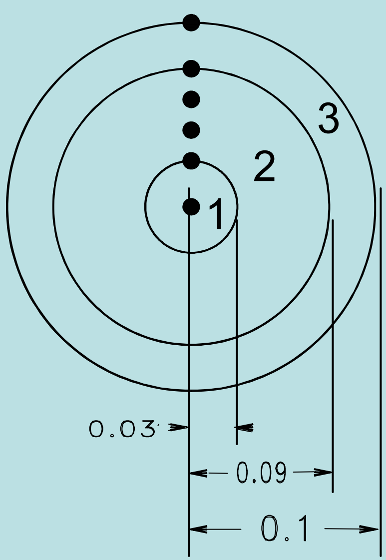
What is GENHTP?
Generalized Heat Transfer Package

- Also handles special processes
  - thermal radiation
  - solid-solid contact
  - zirconium steam oxidation
  - pressure tube deformation
  - thermal stratification (steam bubble)

Geometry - Radial

- Model assumes circular geometry (i.e., pipes, pins)
- A radial "region" is a portion of the solid that has a unique material property
- Each region can contain a user defined number of radial nodes
  - except "gap" regions - must have 2 nodes
- Nodes at region boundaries are shared

Radial Nodes/Regions



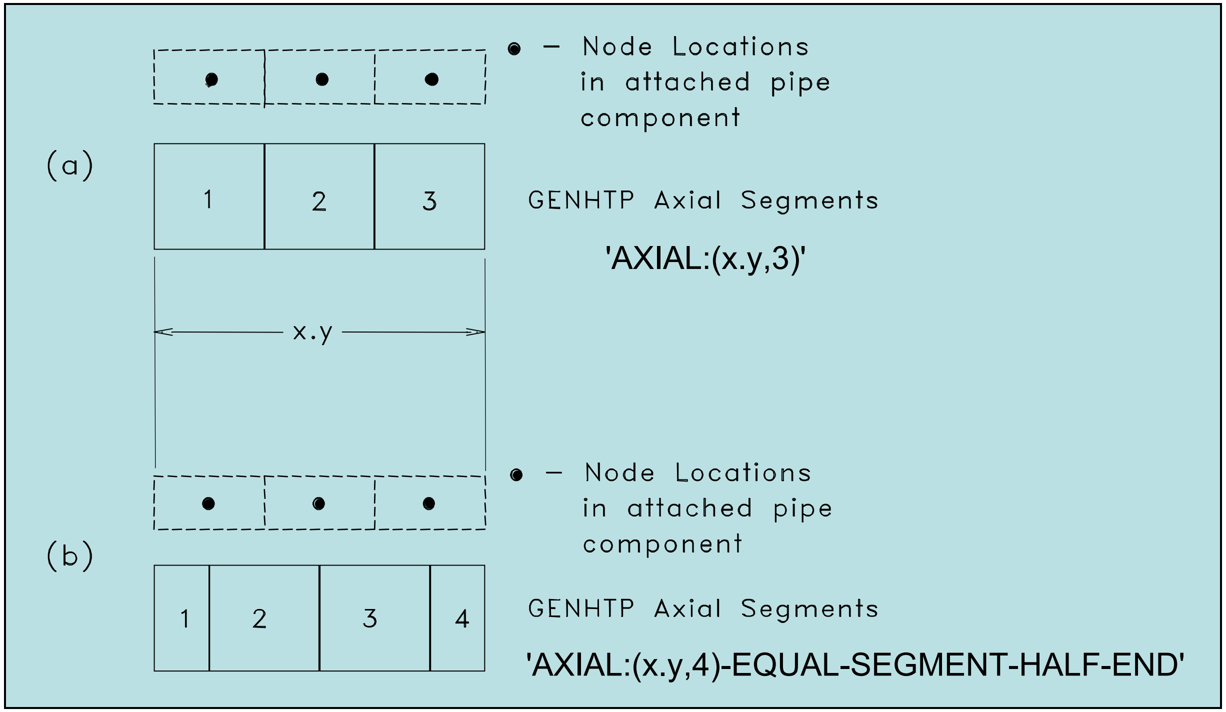
● - Radial Node

Note: Concentric Rings indicate Radial region boundaries. Radial Regions are numbered from Innermost to outermost

```
RADIAL:(3,0.,2,0.03,4,0.09,2,0.1)
```

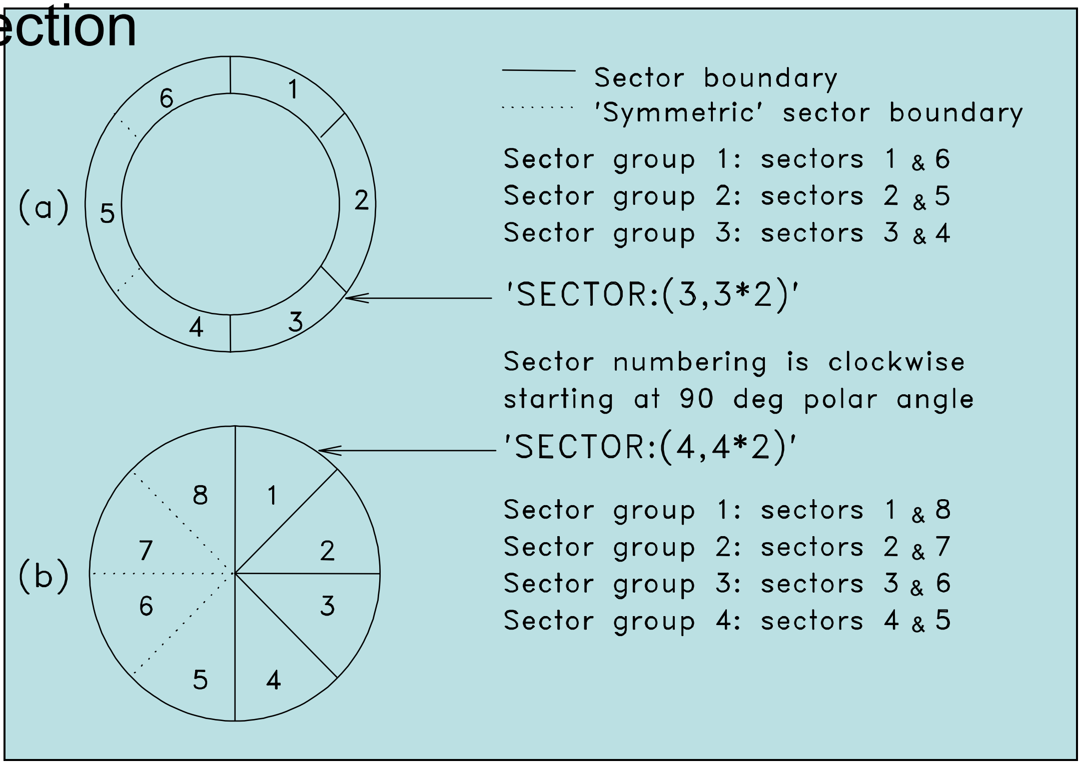
Geometry Axial

- Model can be subdivided in the axial direction into any number of axial “segments” using ‘EQUAL-SEGMENT’, ‘EQUAL-SEGMENT-HALF-END’, ‘USER-LENGTH’ or ‘USER-BOUNDARY’ options
- No axial conduction is calculated by GENHTP



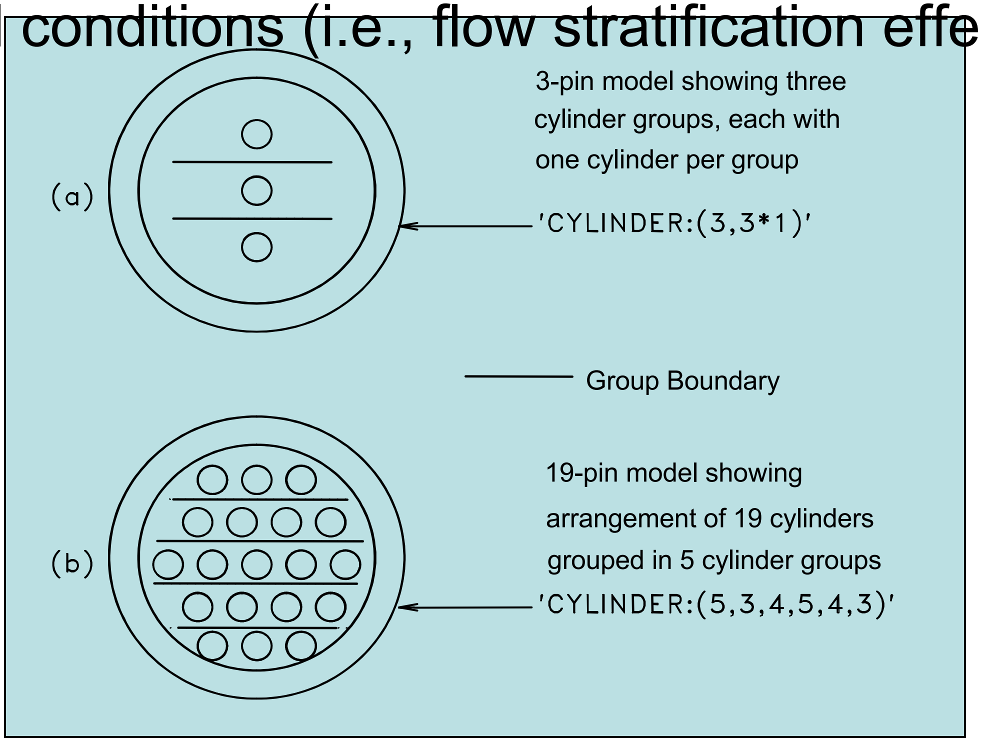
Geometry - Circumferential

- Sectors/(sector group) used to allow subdivision in circumferential direction
- Heat conduction is only solved in circumferential direction only if specified in model identifier
- Sectors assumed to start at top and proceed in clockwise direction



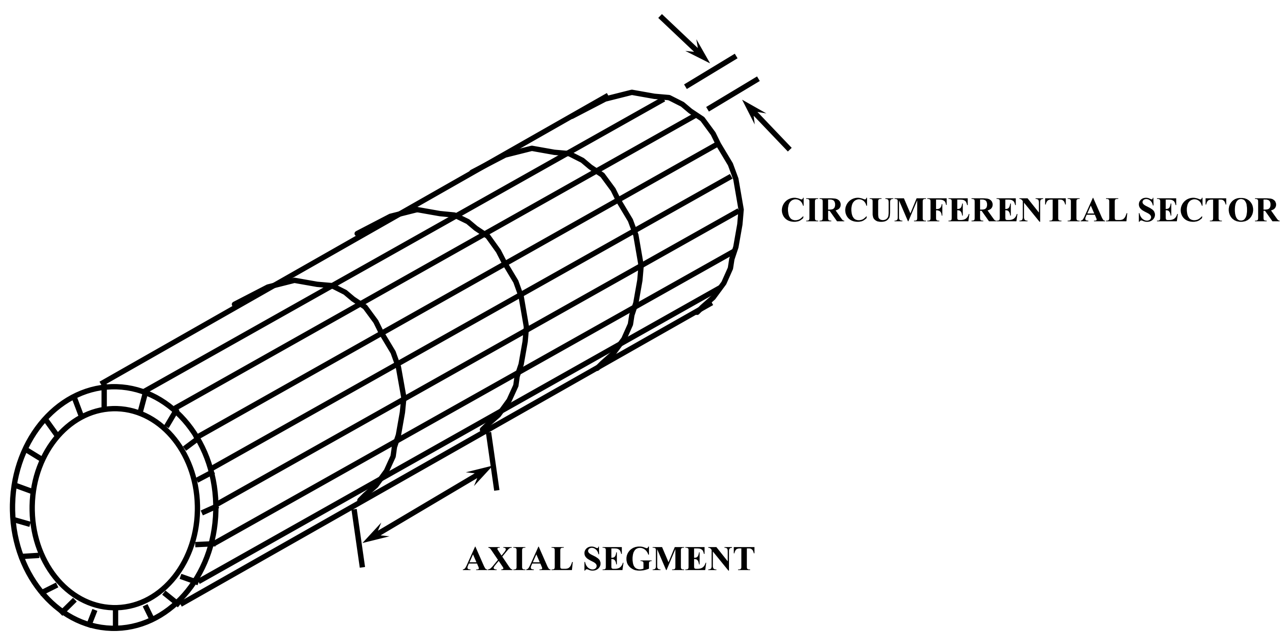
Geometry - Cylinder

- Cylinders/(cylinder group) used when modelling a group of identical elements (i.e., pins in a fuel bundle, boiler tubes)
- ‘RADIAL’, ‘AXIAL’, ‘SECTOR’ describe one element in the group, whereas ‘CYLINDER’ specifies the number of elements and groups of elements that experience identical conditions (i.e., flow stratification effects)



Boundary Conditions

- Used to define the number of boundary conditions applied to the surface(s) of the solid component model
- A large number of surfaces can be defined by the axial, circumferential and cylinder segmentation on the inner and outer surfaces of the model

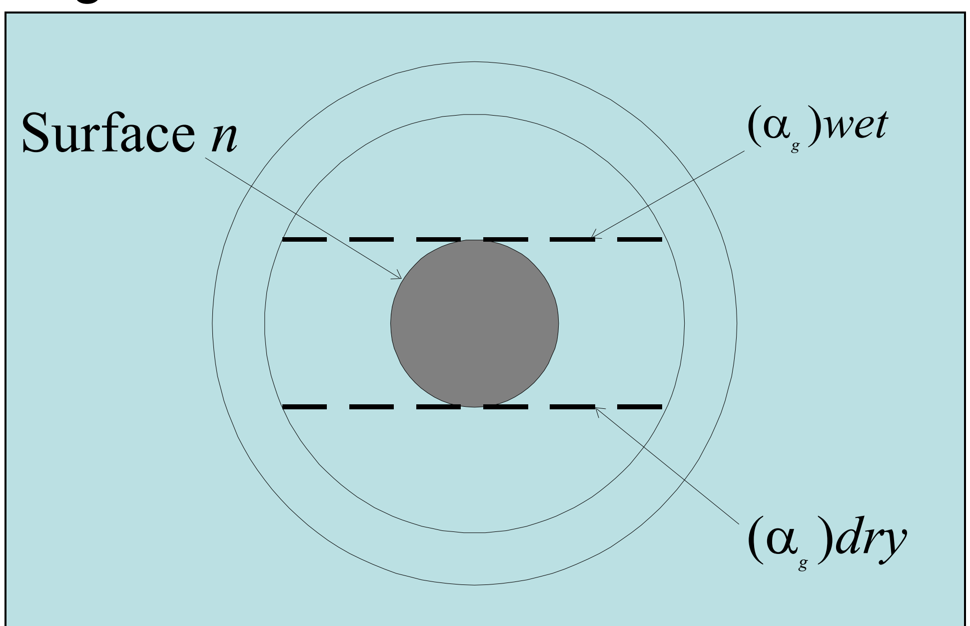


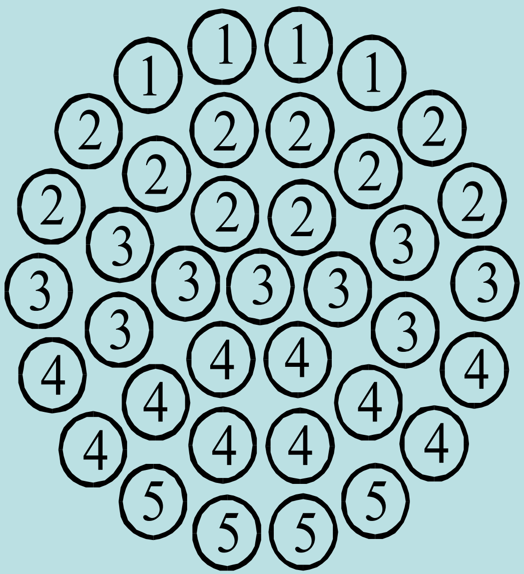
Boundary Conditions

- If no boundary condition is applied to a surface, that surface is assumed to be thermally insulated
- Two types of BC
  - hydraulic - specifies that the surface is in contact with fluid (vapour, liquid, two-phase) found in a thermalhydraulic node
  - prescribed - specifies that the surface is in contact with a user specified condition (T^f, flux)
- Special processes like solid-solid contact and thermal radiation require that a BC be specified for the surface
- User specifies the surfaces that are in contact with the BC by identifying whether inner or outer surface and the range of segments, sectors, and cylinders

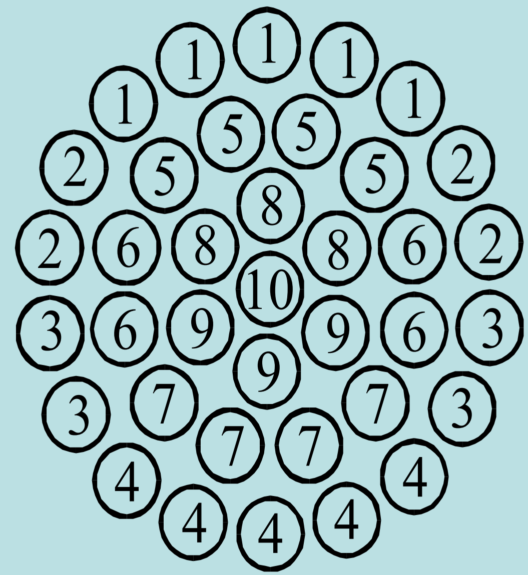
Hydraulic BC - Alpha Wet/Dry

- Entry used to identify what portions of model are in contact with steam or liquid during <u>separated</u> (stratified or annular) two-phase flow conditions
- α wet is the node void fraction that results in a surface just being below the steam/water interface
- α dry is the node void fraction that results in a surface just being above the steam/water interface



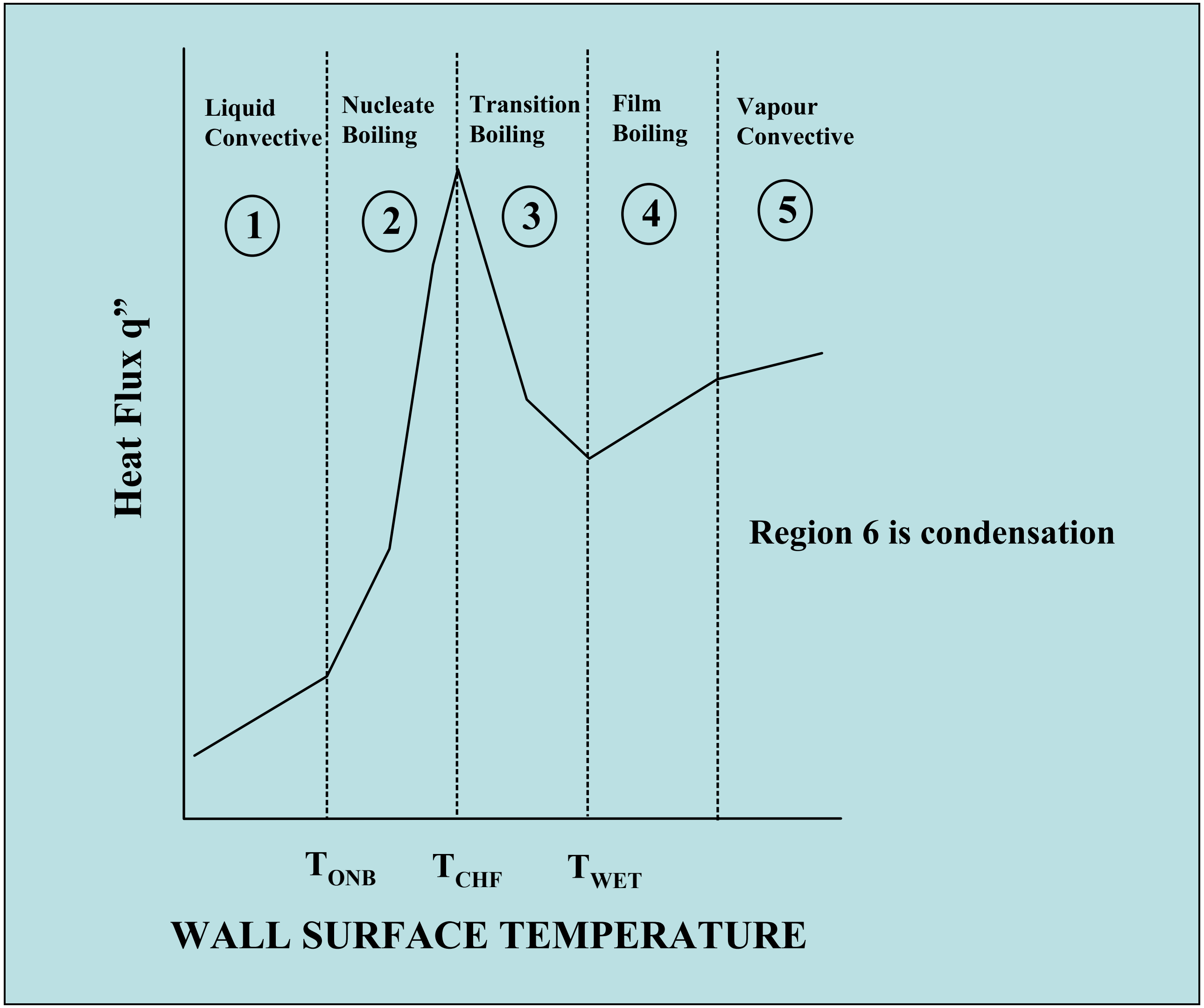


37-ROD-5



37-ROD-10

Hydraulic BC - Boiling Indices and Correlations



Hydraulic BC - Boiling Indices and Correlations

- A number or boiling indices and correlations exist within GENHTP to calculate HTC, Q
- Use of “default” correlations recommended as heat transfer calculated by this set is smooth and continuous throughout boiling region
- Optional correlations exist for specialized applications (i.e., finned fuel)

Prescribed BC

- Prescribed BC cannot be used to specify heat transfer between a thermalhydraulic node and a wall model surface
- Used to attach model surfaces to prescribed (user specified T, flux) boundary condition
- Several types exist including:
  - uniform HTC and T
  - spatially dependent HTC and T
  - time dependent HTC and T
  - temperature dependent HTC and T
  - time and spatially dependent HTC and T
  - uniform heat flux
  - time dependent heat flux
  - temperature dependent heat flux
  - time and spatially dependent heat flux
  - liquid bath
- Application example - heat losses from facility

Material Properties

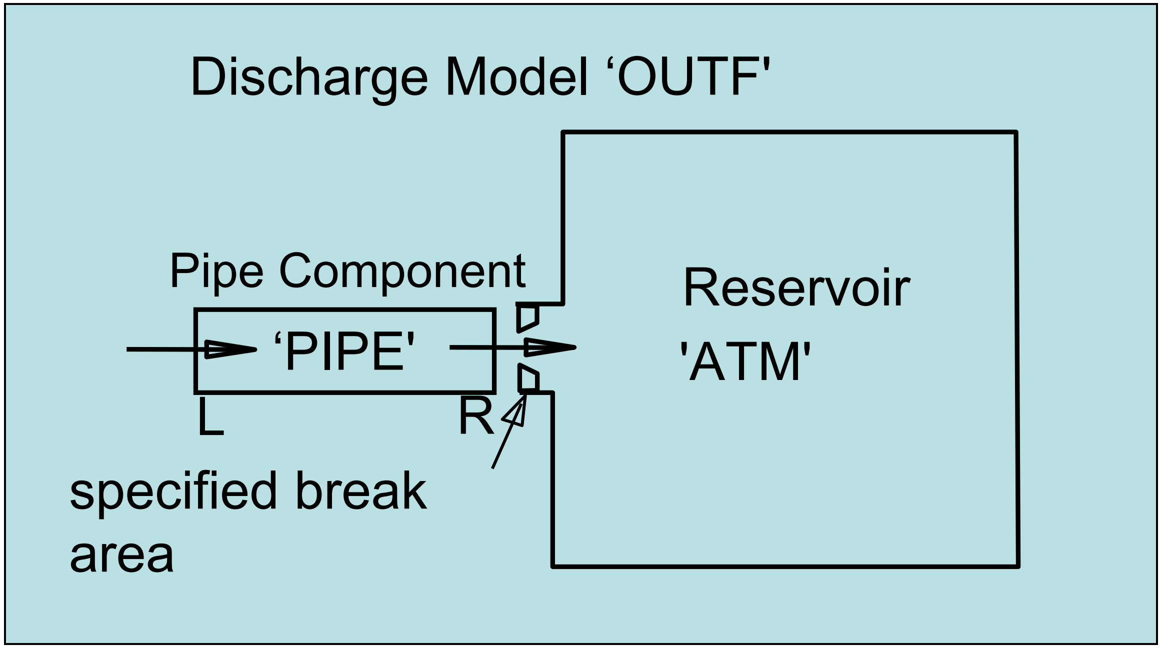
- Entry defines material thermal properties for each radial region, including annular gap
- Properties defined are thermal conductivity (K) and volumetric heat capacity (ρC_p)
- Annular gap requires conductance and emissivity
- Material options include:
  - built-in properties (UO_2, CS, SS, Zr, ZrO_2)
  - constant properties
  - temperature dependent
  - time dependent
  - constant gap properties
  - temperature dependent gap properties
  - time dependent gap properties
  - spatially distribute gap properties

Heat Generation

- Record defines the heat generation rate in each radial region of solid component except gap regions
- Heat generation options include:
  - no heat generation
  - uniform heat generation
  - spatially varying
  - time and spatially varying
  - zirconium - steam reaction
- requires that there be a Zr and a ZrO_2 region
- for unoxidized surfaces, an initial ZrO_2 region $1.0(10^{-6})$ m thick is recommended
- a number of zircaloy oxidation correlations is available but Urbanic-Heidrich is THE DEFAULT (recommended)
- Zr steam oxidation does not start until solid component temperatures reach ~ 800°C

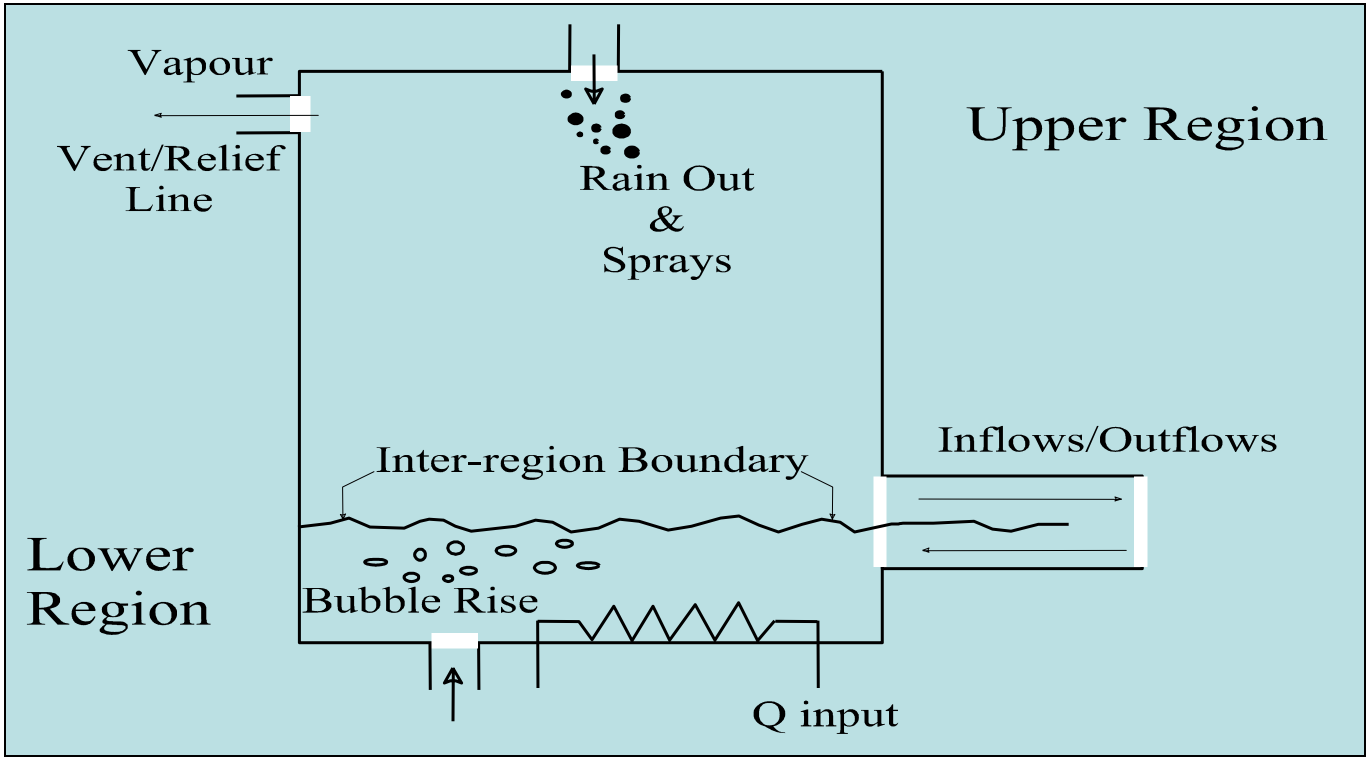
Discharge Model

- Used to model discharge flow rate from a pressurized system
- Uses Bernoulli's equations for subcritical discharge and provides several optional choked flow models
- Applied at a connection between a pipe component and reservoir component
- Only Henry-Fauske critical flow model is formulated for both H_2O and D_2O



Tank Component

- Used to model a vessel in which the liquid level is to be monitored
- Two distinct regions are considered:
  - upper region primarily occupied by gas
  - lower region primarily occupied by liquid

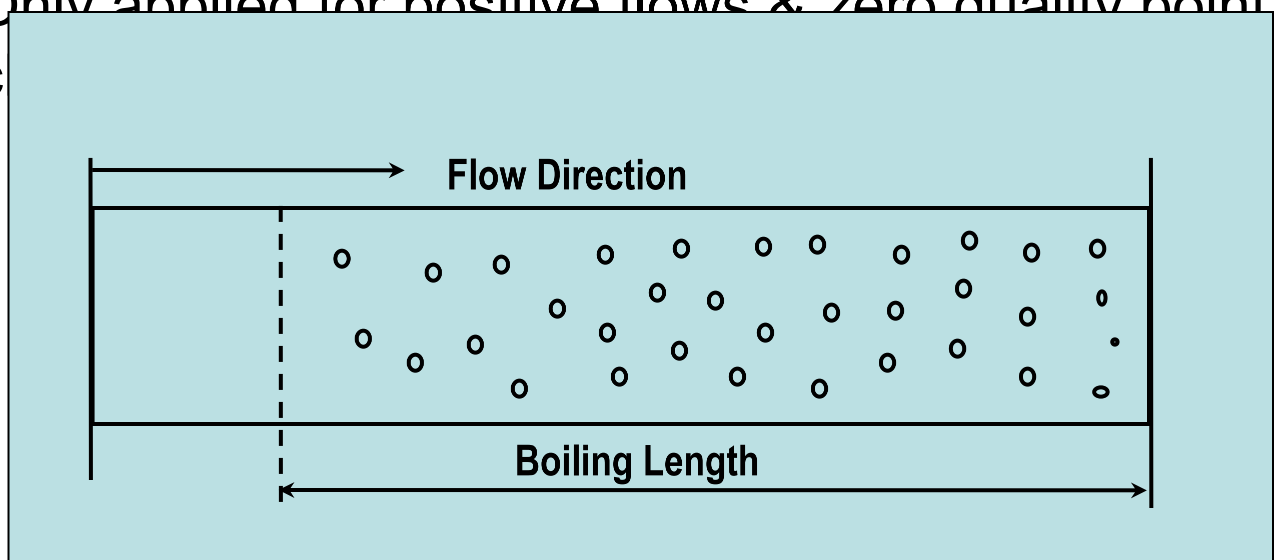


Tank Component

- Information entered includes tank label, total tank component height, component elevation change, cross-sectional area, channel type (TANK), fluid type and tank volume
- Optional information includes max bubble rise velocity, inter-region heat transfer coefficient, HTC multiplier between noncondensable gases and liquid region, and option to turn on liquid entrainment or vapour pull through at tank connection
- Tank models can only be connected to PIPE components
- Tank models cannot be directly connected together nor to a volume component
- Abrupt area change pressure loss is calculated at pipe to tank connection
- Variable area cross section possible
- No flow within the tank is considered

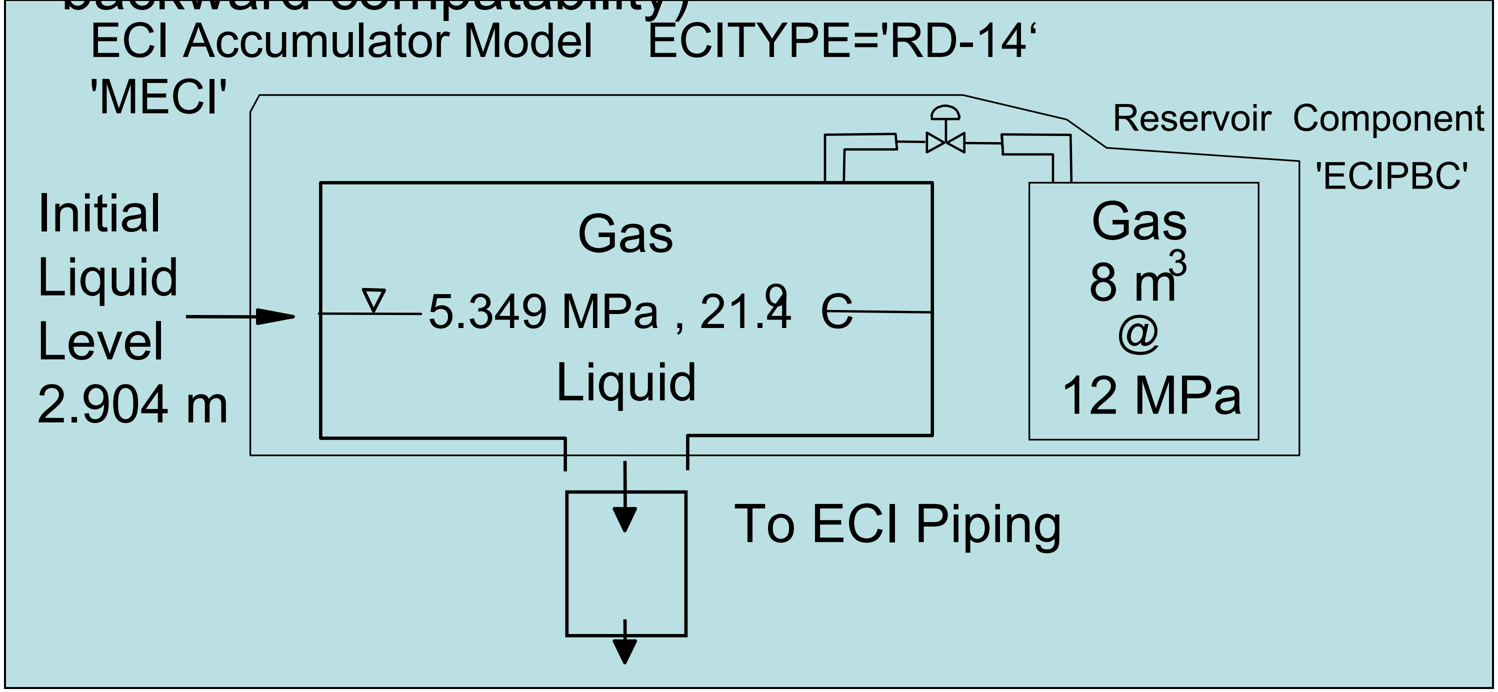
Boiling Length Average CHF

- Can only be used for pipe components
- Applies only to fuel channels (7ELMT, 37ELMT or CANFLEX)
- Used in conjunction with a GENHTP model to apply correction to CHF calculation
- Model specifies that average heat flux seen by mixture in thermalhydraulic branch be tracked
- Only applied for positive flows & zero quality point in c



ECI Accumulator

- Used to model Emergency Coolant Injection system
- Applied only at a reservoir component, controls temperature and pressure of reservoir
- Single-phase liquid is always assumed at the outlet of the tank
- *model superseded by more general tank model (kept for backward compatability)



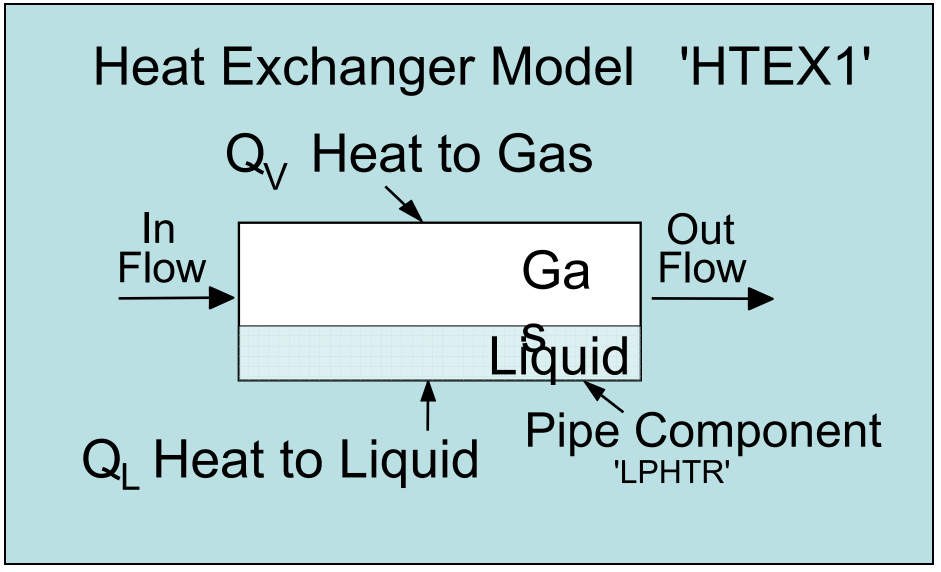
Heat Exchanger

- Used to calculate heat transfer from liquid and/or vapour in a pipe component to a “sink” (simplified heat exchanger model)

  QL (w) = HTCL . Area . (Tsink - TL)

  QV (w) = HTCV . Area . (Tsink - TV)

- Model is applied to a pipe component
- User can make heat proportional to phase fraction



Pump

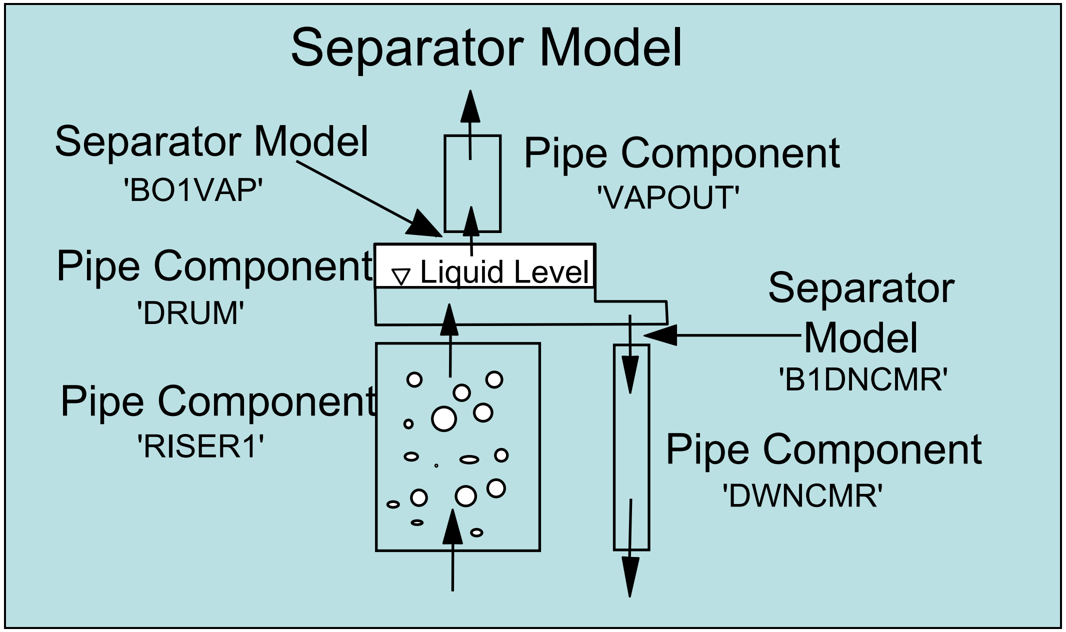
- Used to represent behaviour of a pump
- Applied between two pipe components or between a pipe and reservoir component
- Pump options include ‘ANC’, ‘RD-14’, ‘USER-1P’, ‘USER-P’, ‘MRX-ANC’, ‘FRJ-2’, ‘W2-ANC’, ‘DARLINGTON’, ‘CANDU9’
- ‘USER-1P’ - one polynomial or table to specify the homologous pump head in single phase flow
- ‘USER-P’ - four polynomials or four tables to specify the homologous pump head in all four pump sectors
- Most pump options use ‘ANC’ curve for two-phase degraded conditions

Separator

- Used to model phase separation effects due to pipe geometry and gravity or due to presence of a steam separator
- Model is applied at the connection between two pipe components
- Separation is assumed to occur only in positive flow direction

Separator

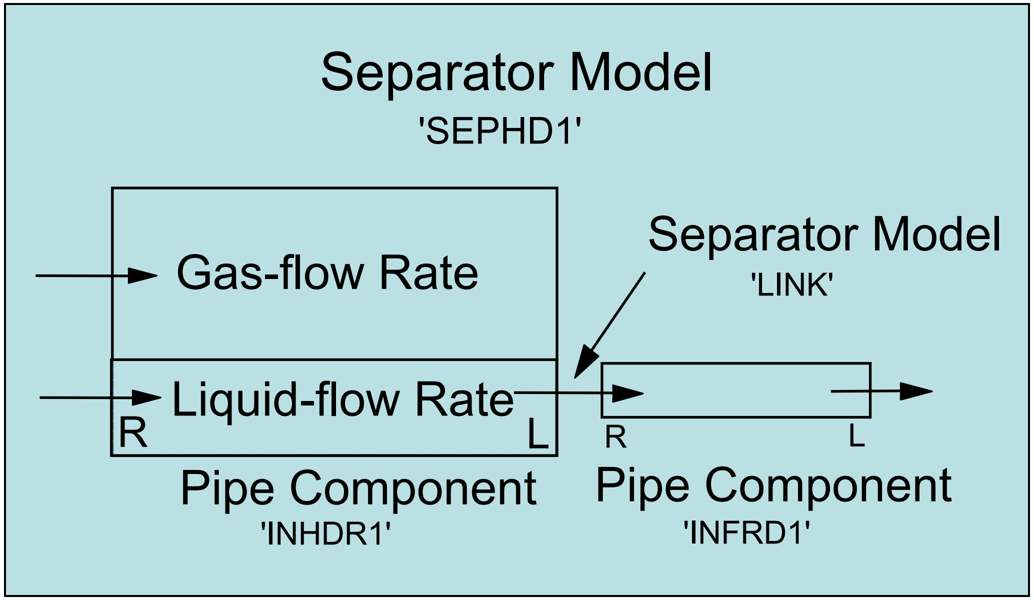
- Steam generator secondary side version of model requires two models be used
  - steam separation to steam lines
  - liquid separation to downcomer



Separator

- Horizontal pipe connection version of model is flow regime dependent
- Flow separation is dependent on liquid level in stratified flow and pipe connection geometry

*no separation effects for mixed flow regime

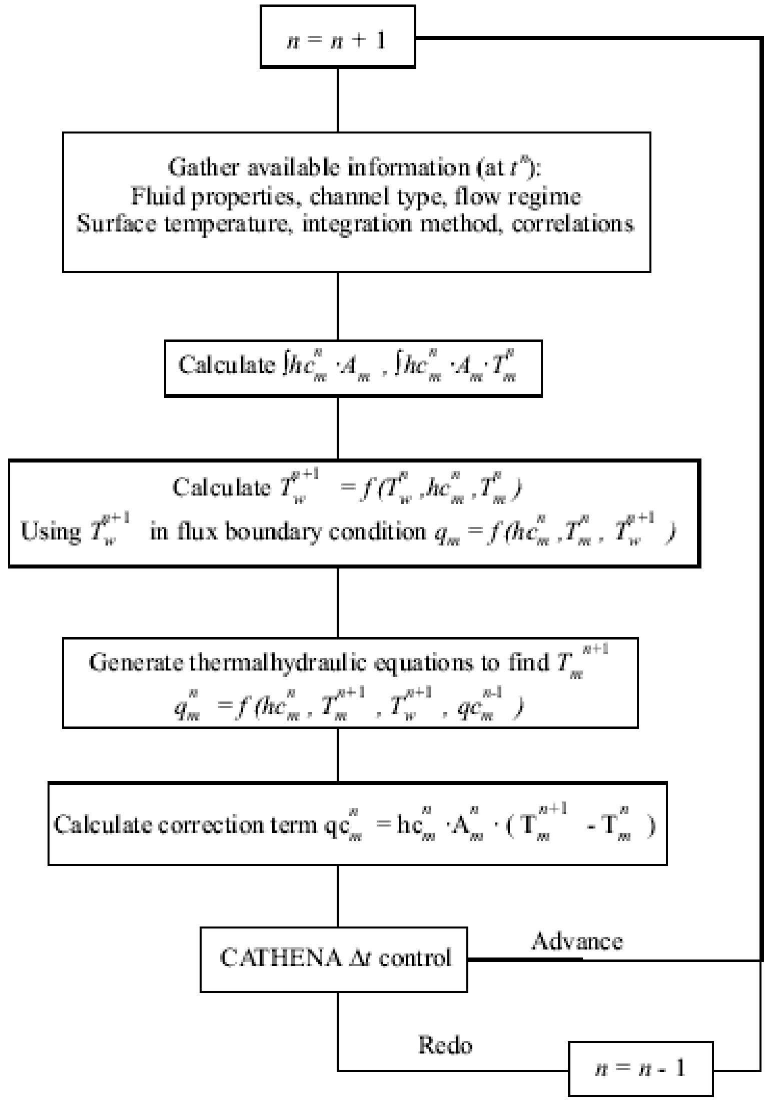


Valve

- Used to represent the flow behaviour of valves or orifices
- Applied at connection of two pipe components or pipe component and reservoir component
- Five types of valves supported
  - normal valve
  - check valve
  - MAPLE-X10 check valve
  - relief valve
  - Fisher valve
- Choked or critical flow is not considered in this model

*choked flow may be specified for the pipe connection

Thermal-hydraulic – Heat Transfer Coupling



Wall Friction

General form

$$\tau_{kw} = -\zeta_k \left[\frac{\tau^* f_{f\,bun} f_{kw}}{D_e} \rho_k |v_k| \frac{v_k}{2} + \tau_k^* f_{k\,bun} \left(\frac{k}{l} \right) \rho_m |v_m| \frac{v_m}{2} \right]$$

$$v_m = \frac{C_{0g} \alpha_g \rho_g v_g + C_{0f} \alpha_f \rho_f v_f}{\rho_m}$$

$$\rho_m = \alpha_g \rho_g + \alpha_f \rho_f$$

Wall Friction

Smooth pipe friction

$$f = \begin{cases} 0.188 Re^{-0.2} & Re \geq 1460 \\ \dfrac{64}{Re} & Re < 1460 \end{cases}$$

Rough pipe friction

$$\frac{1}{\sqrt{f}} + 2\log_{10}\left(\frac{\varepsilon}{D_e}\right) = 1.14 - 2\log_{10}\left(1 + 9.35\frac{D_e/\varepsilon}{Re\sqrt{f}}\right)$$

Homogeneous Two-Phase Multiplier

$$\tau_{kw} = -\zeta_k\left(\tau_w^* f_{f\,bun}\frac{f_{km}}{D_e} + \tau_k^* f_{k\,bun}\frac{k}{l}\right)\rho_m\left|v_m\right|\frac{v_m}{2}$$

Heat Transfer and Fluid Flow Service, H.T.F.S.

$$\Phi_f = 1 + \frac{C}{X} + \frac{1}{X^2}$$

Two-phase fluid

$$\Phi_g = X^2 + CX^2 + 1$$

Gas alone

$$X = \frac{\left[\dfrac{\partial P}{\partial z}\right]_f}{\left[\dfrac{\partial P}{\partial z}\right]_g} = \frac{\Phi_g^2}{\Phi_f^2}$$

Martinelli-Nelson Two-Phase Multiplier

$$\tau_{kw} = -\zeta_k \tau^*_{MN} \left(f_{f\,bun} \frac{f_w}{D_e} + f_{k\,bun} \frac{k}{l} \right) \frac{G_f^2}{2\rho_m}$$

$$\tau^*_{MN} = \Phi \Gamma$$

$$\Phi = \exp\left(\sum_{i=0}^{4} \sum_{j=0}^{7} a_{ij} \left(P_f^*\right)^j Y^i \right)$$

$$\Gamma = \sum_{i=0}^{5} \left(a_i + b_i P_f^*\right) \left(\ln\left(0.0036 \left|G^*\right|\right) + 0.2\right)^i$$

$$P_f^* = P_f / (6.89476 \times 10^6)$$

$Y = \ln(100 X_f + 1)$; X_f is the flow quality

$G^* = G \cdot 2.04816 \times 10^{-1}$; G is the mass flux

Friedel Two-Phase Multiplier

$$\tau^* = A + 3.21\,\frac{x_a^{0.78}\,(1-x_a)^{0.224}}{Fr_{tp}^{0.0454}\,We_{tp}^{0.035}}\left(\frac{\rho_f}{\rho_g}\right)^{0.91}\left(\frac{\mu_g}{\mu_f}\right)^{0.19}\left(1-\frac{\mu_g}{\mu_f}\right)^{0.7}$$

$$A = (1-x_a)^2 + x_a^2\,\frac{\rho_f\,f_g}{\rho_g\,f_f}$$

$$Fr_{tp} = \frac{G^2}{g D_{hy} \rho_{tp}^2}$$

$$We_{tp} = \frac{G^2 D_{hy}}{\rho_{tp}\sigma}$$

$$\rho_{tp} = \frac{\rho_f\,\rho_g}{x_a \rho_f + (1-x_a)\rho_g}$$

Crept Pressure-Tube Friedel

$$\Delta P_{fric} = \tau^*\left(\frac{\kappa_f \cdot f(\varepsilon, D_{hy}, Re)}{D_{hy}} + \kappa_k \cdot (\frac{k}{l})\right) \cdot \frac{G_{mix}^2}{2 \cdot \rho_f}$$

where $f(\varepsilon, D_{hy}, Re)$ is the Colebrook-White friction factor from Equation 4.4-5 and,

$$\tau^* = \left(1.0 + \gamma(\Phi_{LO}^2 - 1.0)\right)$$

where Φ_{LO}^2 is the Friedel two-phase friction multiplier given by,

$$\Phi_{LO}^2 = A + 3.21 \cdot \frac{x_a^{0.78} \cdot (1 - x_a)^{0.224}}{Fr_{tp}^{0.0454} \cdot We_{tp}^{0.035}} \cdot \left(\frac{\rho_f}{\rho_g}\right)^{0.91} \cdot \left(\frac{\mu_g}{\mu_f}\right)^{0.19} \cdot \left(1 - \frac{\mu_g}{\mu_f}\right)^{0.7}$$

$$A = (1 - x_a)^2 + x_a^2 \cdot \frac{\rho_f \cdot f_g}{\rho_g \cdot f_f}$$

$$Fr_{tp} = \frac{G^2}{g D_{hy} \rho_{tp}^2}$$

$$We_{tp} = \frac{G^2 D_{hy}}{\rho_{tp} \sigma}$$

$$\rho_{tp} = \frac{\rho_f \rho_g}{x_a \rho_f + (1 - x_a)\rho_g}$$

Interface Momentum Transfer

$$\tau_{ki} = (-1)^k \frac{A_i \rho_i f_i}{8} \left| v_g - v_f \right| \left(v_g - v_f \right)$$

$$f_{i,b} = \frac{24\left(1 + 0.15 Re_i^{0.687}\right)}{Re_i} + \frac{f_{i,b\infty}}{\left(1 + 4.25 \times 10^4 Re_i^{-1.16}\right)}$$ Disperse bubble

$$Re_i = \frac{\rho_{i,b} D_b \left| v_r \right|}{\mu_f}$$

Vertical Annular Interface Friction

Popov & Rohatgi model

$$A_{ib} = A_i \left(1 - \left(\frac{\alpha_g - \alpha^{lpri}}{1 - \alpha^{lpri}}\right)^{\frac{1}{2}}\right); \qquad \alpha_g > \alpha^{lpri}$$

$$A_i = \frac{4\sqrt{\alpha_g}}{D_e}$$

$$\alpha_{gc} = 1 - \min\left[E\alpha_f,\ \alpha_f\right]$$

$$E = \tanh\left(2.9 \times 10^{-6} V_*^{2.5} D_*^{1.25} Re_\delta^{0.25}\right)$$

$$V_* = \left|v_g - v_f\right| \left(\frac{\sigma g \left(\rho_f - \rho_g\right)^{\frac{1}{3}}}{\rho_g^{\frac{4}{3}}}\right)^{-\frac{1}{4}}$$

$$D_* = \frac{D_e}{\sqrt{\frac{\sigma}{g\left(\rho_f - \rho_g\right)}}}$$

$$Re_\delta = \frac{4\delta\rho_f\left|v_f\right|}{\mu_f}$$

$$\delta = \frac{D_e}{2}\left(1 - \sqrt{\alpha_g}\right)$$

Vertical Annular Interface Friction

Popov & Rohatgi model

$$f_i = f_{ia}\left(1 + 150\left(1 - \sqrt{\alpha_g + (1 - \alpha_{gc})}\right)\right) V_{r^+}^{2.5}$$

$$V_{r^+} = \max\left[1, \ \frac{\left|v_g - v_f\right|}{V_r^c}\right]$$

$$V_r^c = \frac{2.6\sigma\sqrt{\rho_f/\rho_g}\, V_\mu^{0.8}}{\max[1, Re_\delta]^{0.2}\mu_f}$$

$$f_{ia} = 2.0 \times 10^{-2}$$

$$f_{ia} = \frac{4\mu_g}{\rho_g D_e(1 - \sqrt{\alpha_g})\left|v_g - v_f\right|}$$

Interface Heat Transfer

$$\sum_k m_{ki} = 0$$

$$\sum_k \left(m_{ki} \left(h_{ki} + \frac{v_{ki}^2}{2} \right) + q_{ki} - q_{wi} - \tau_{ki} v_{ki} - P_{ki}'' \right) = 0$$

Wall-to-Fluid Integration Methods

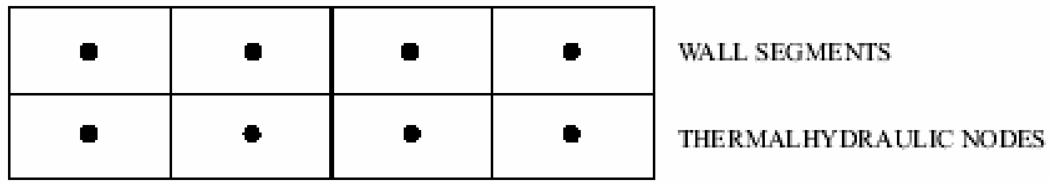
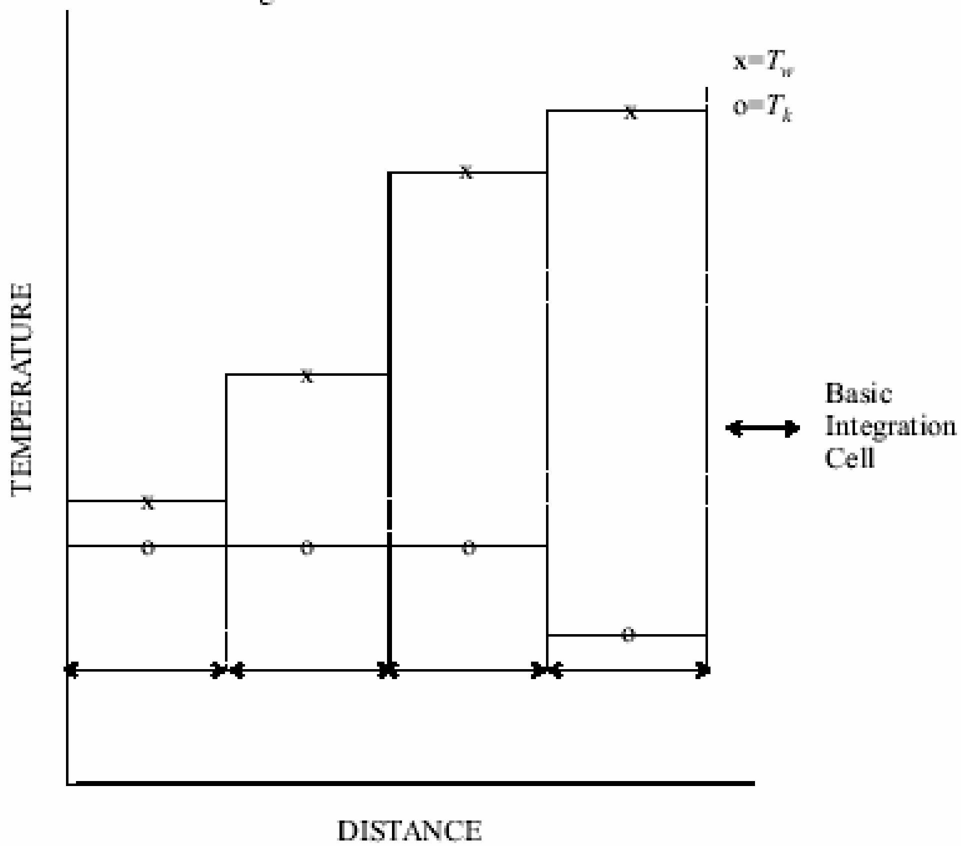


FIGURE 5.2-2: Nodalization Scheme for the Constant-Temperature-Over-Each-Segment Integration Method.



Constant Temperature Over each Segment

Wall-to-Fluid Integration Methods

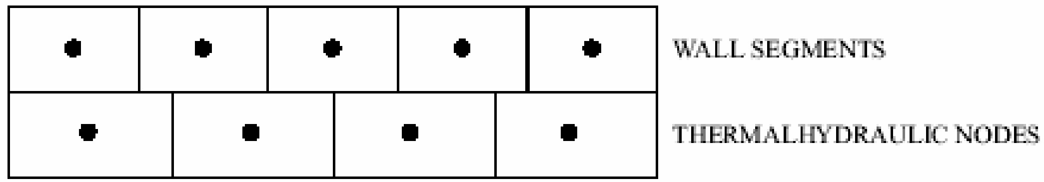
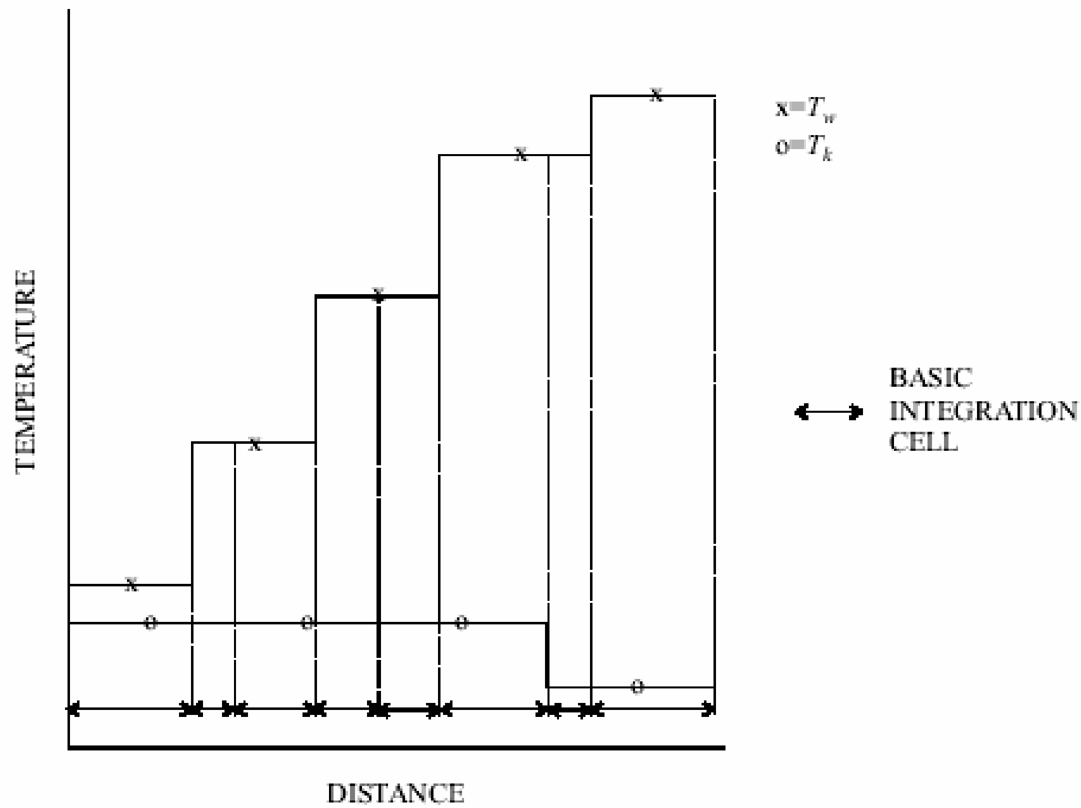


FIGURE 5.2-4: Non-Coincident Mesh Nodalization Scheme for the Constant-Temperature-Over-Each-Segment Integration Method



Non-coincident
Constant temp.
Over each
Segment

Wall-to-Fluid Integration Methods

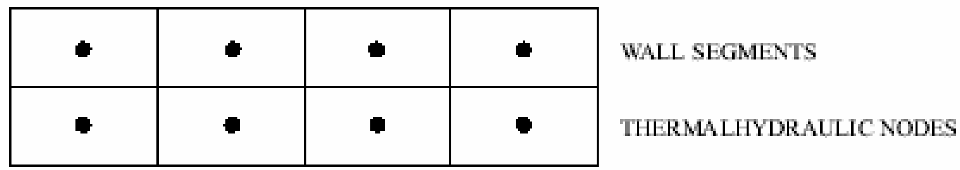
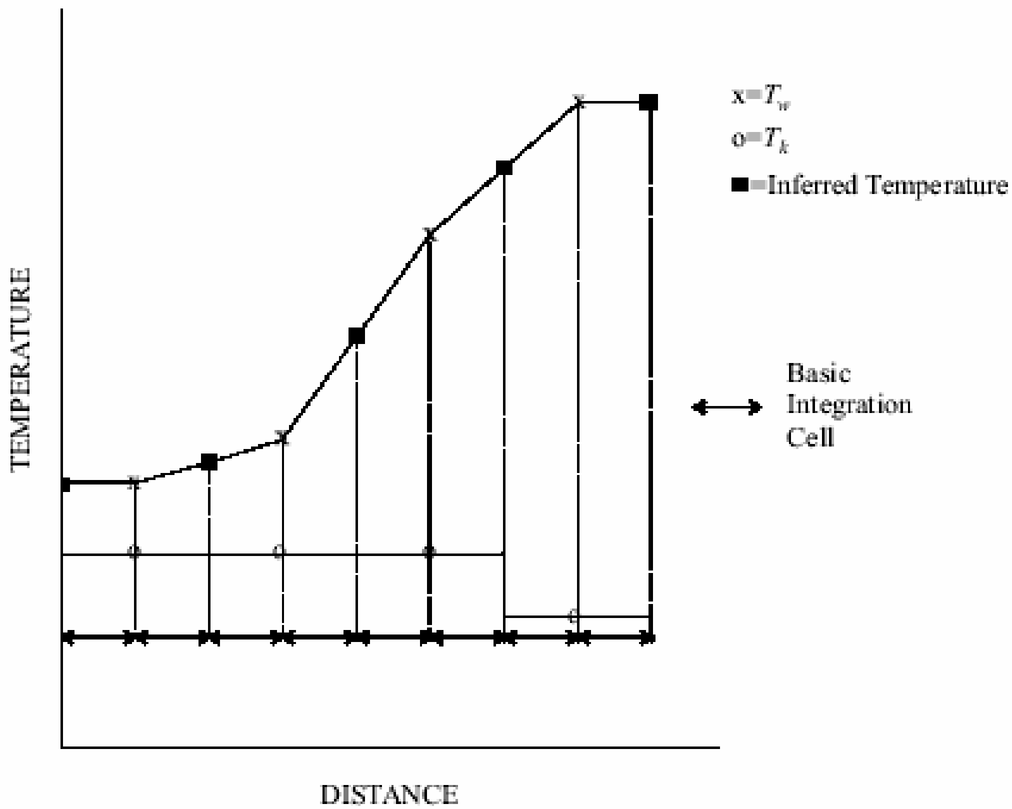


FIGURE 5.2-6: Nodalization Scheme for the Linear Inferred Temperature 3 Point Integration Method



Linear Temperature 3 point

Wall-to-Fluid Integration Methods

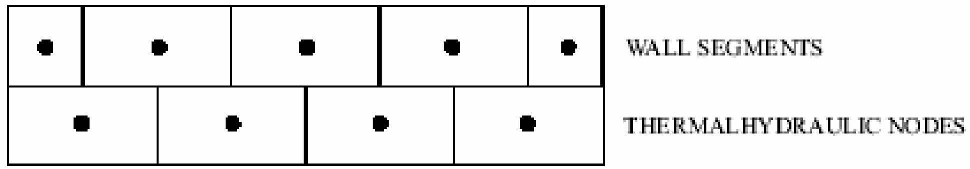
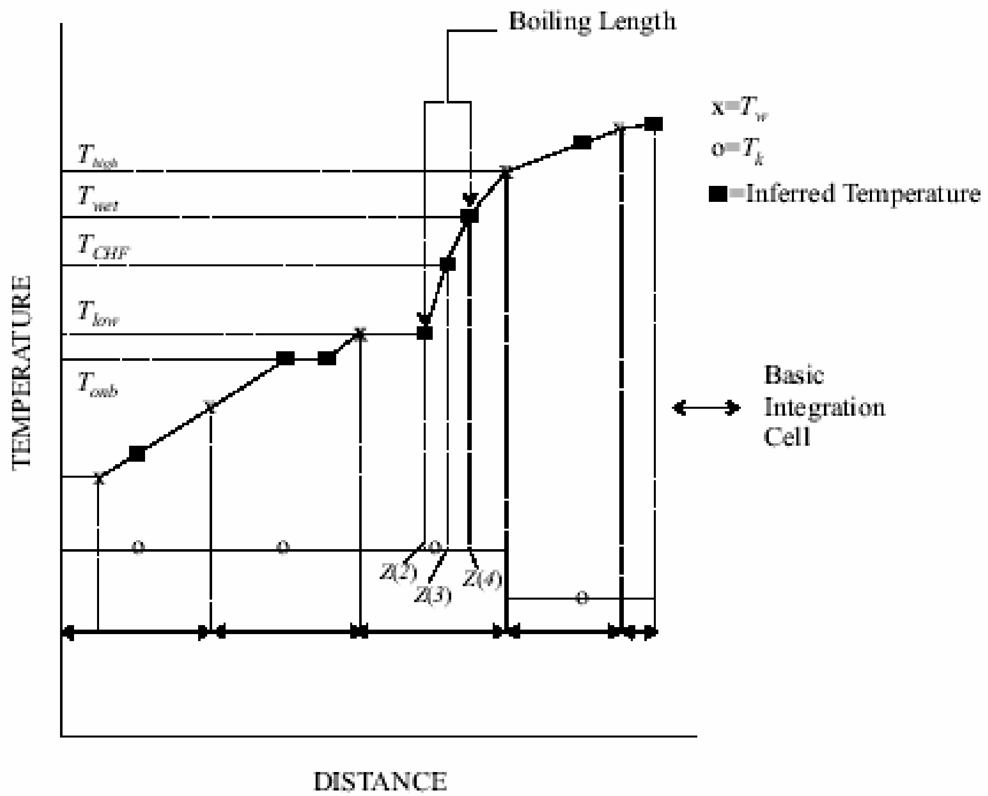
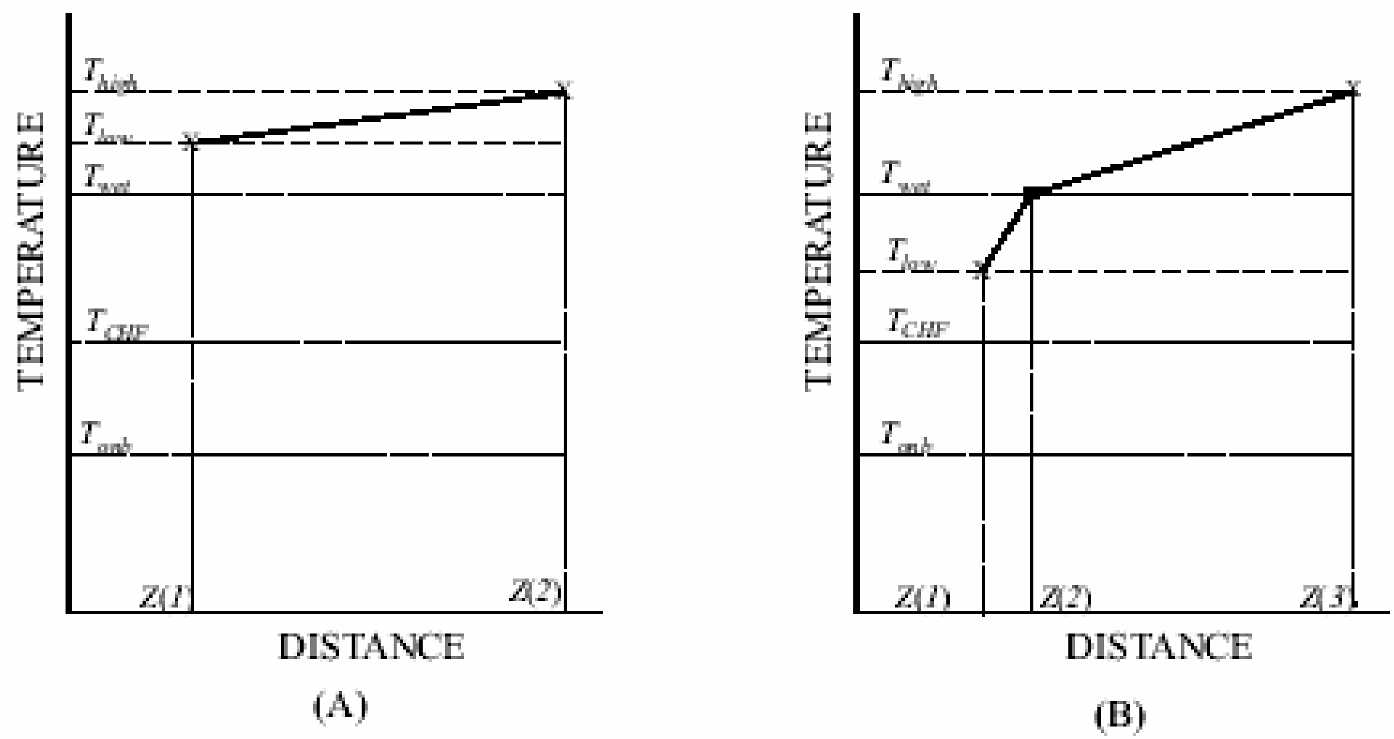


FIGURE 5.2-8: Nodalization Scheme for the Quench Inferred Temperature Integration Method

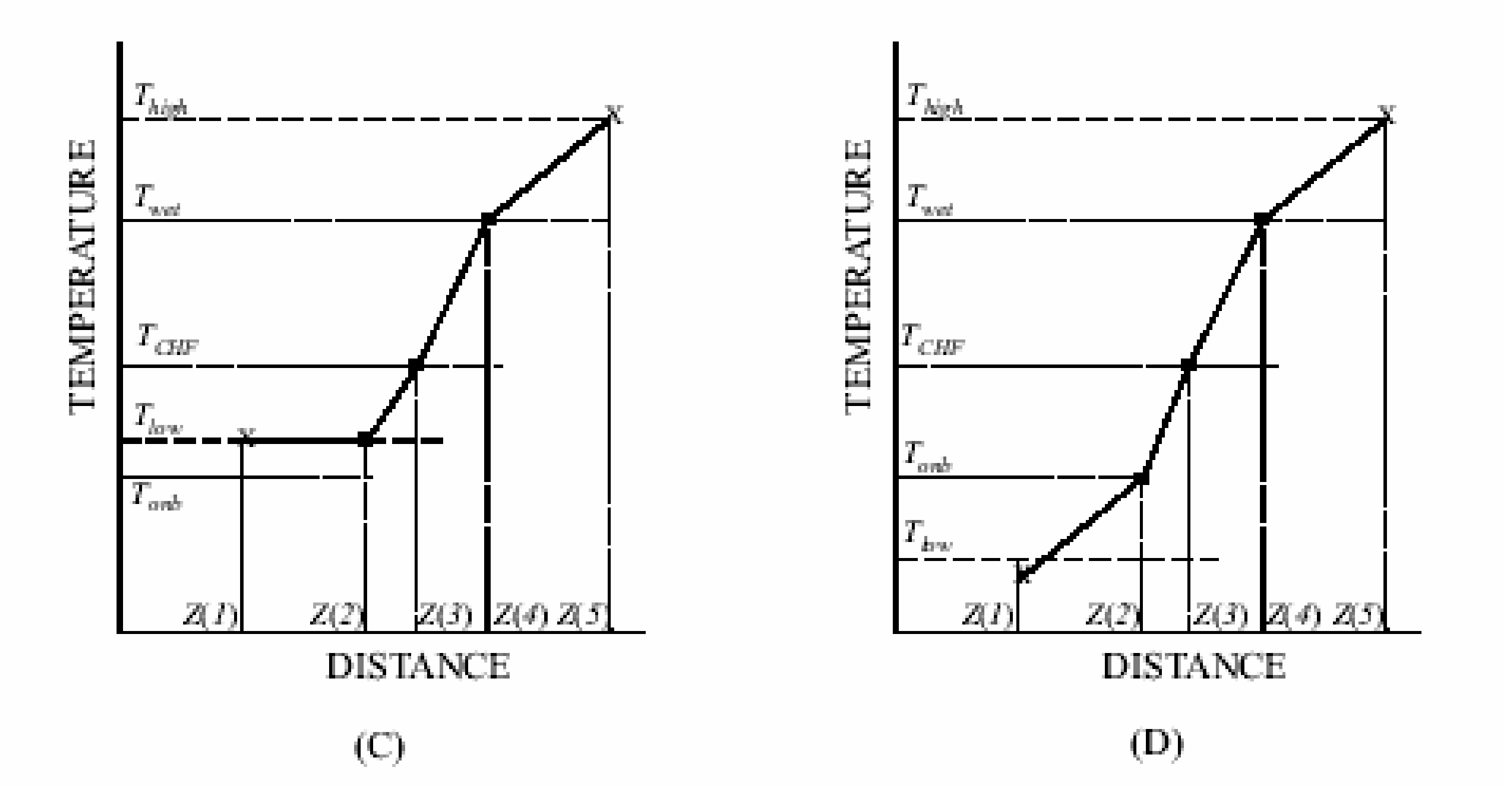


Quench Inferred Temperature

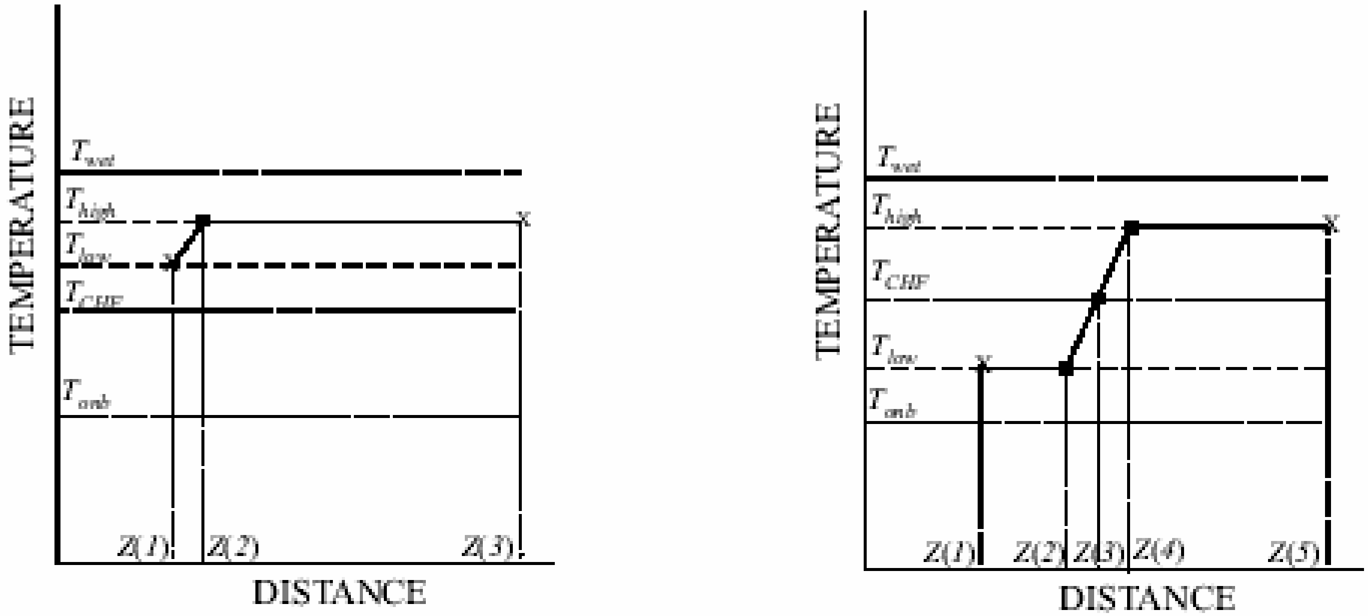
Wall-to-Fluid Integration Methods



Wall-to-Fluid Integration Methods

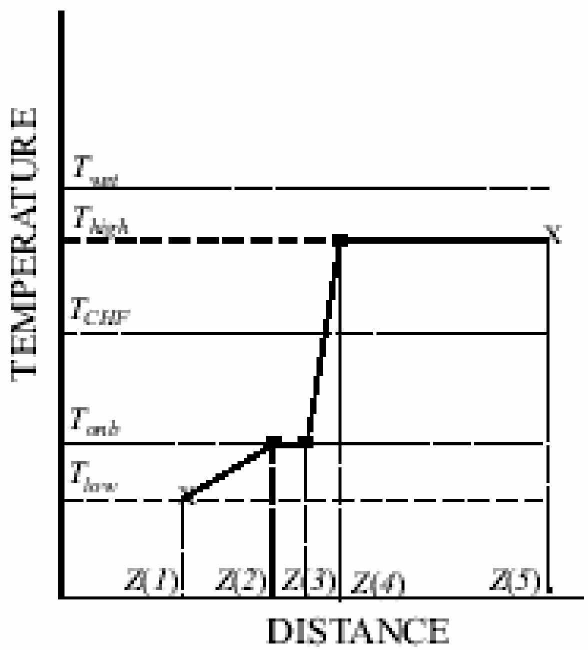


Wall-to-Fluid Integration Methods



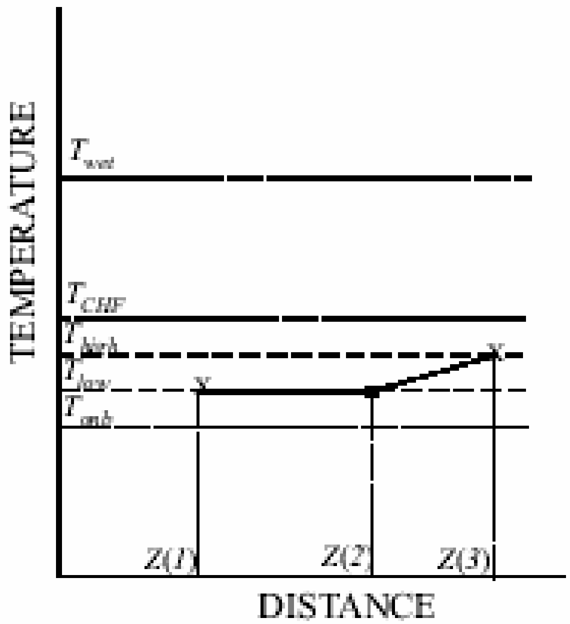
(E) (F)

Wall-to-Fluid Integration Methods

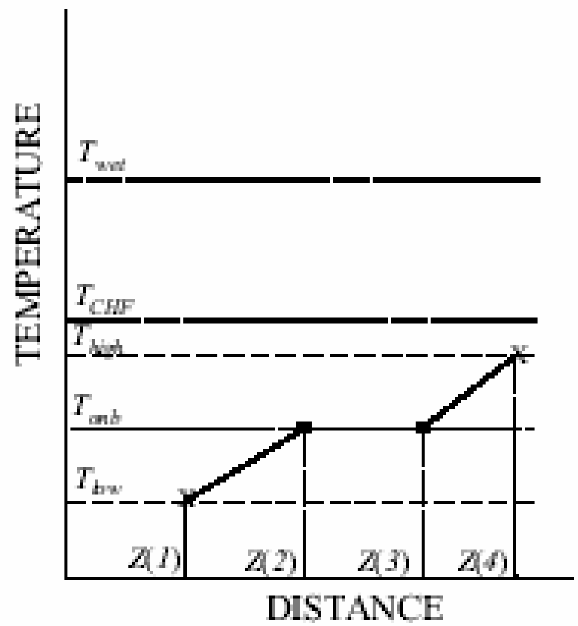


(G)

Wall-to-Fluid Integration Methods

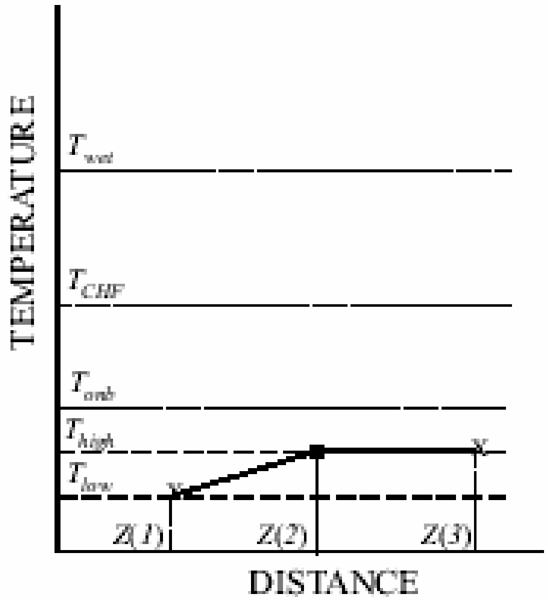


(H)



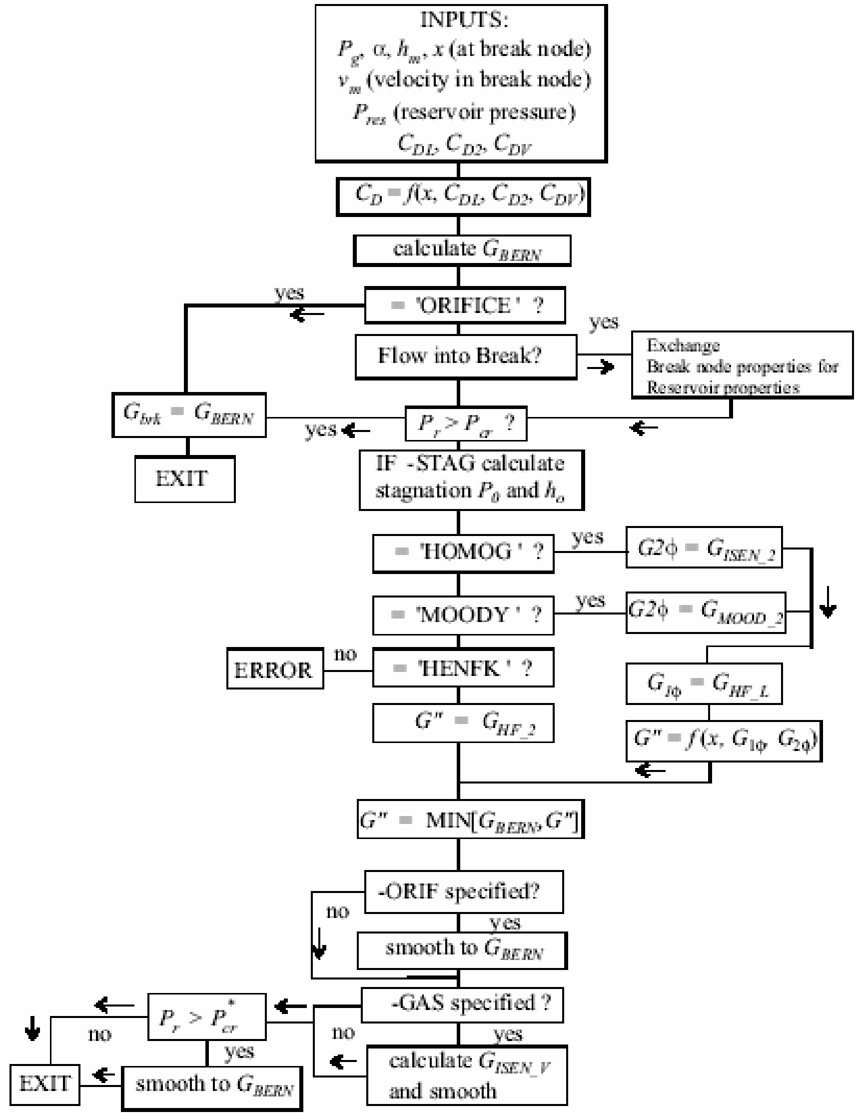
(I)

Wall-to-Fluid Integration Methods



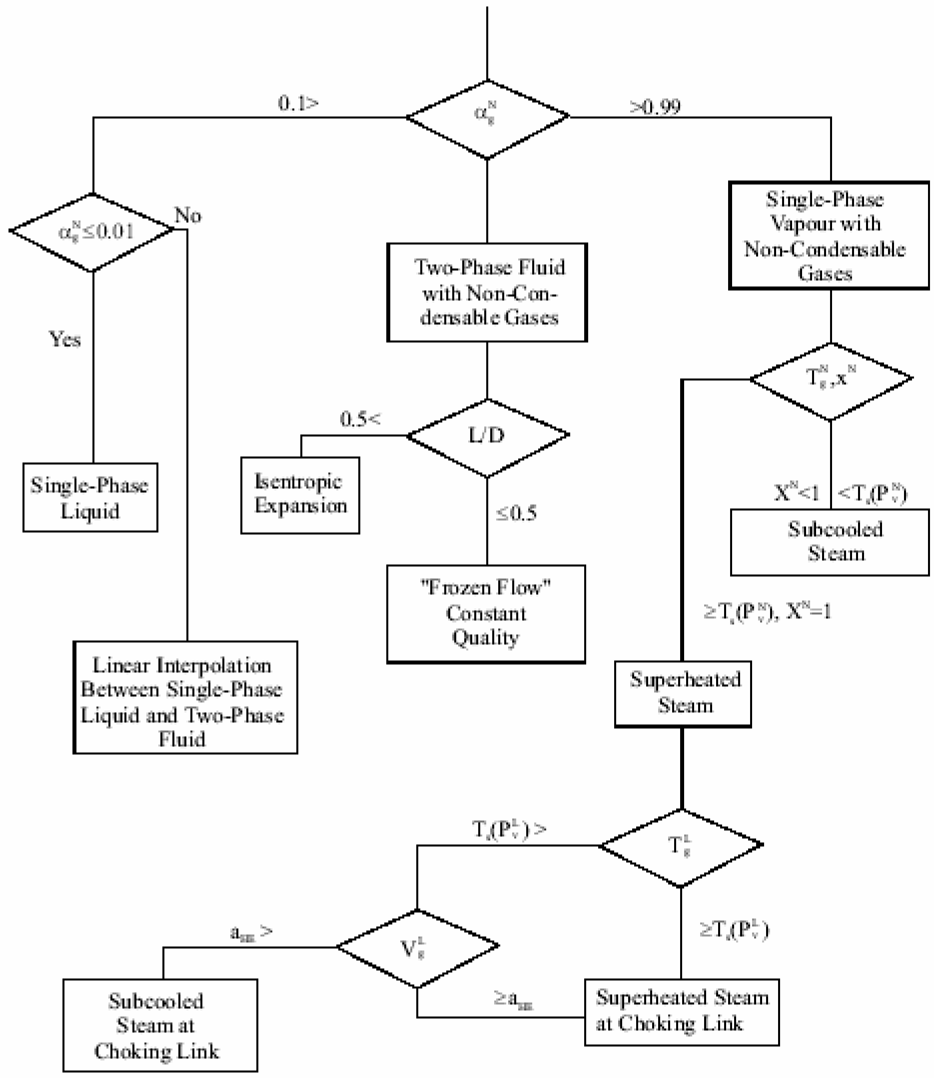
(J)

Break Model

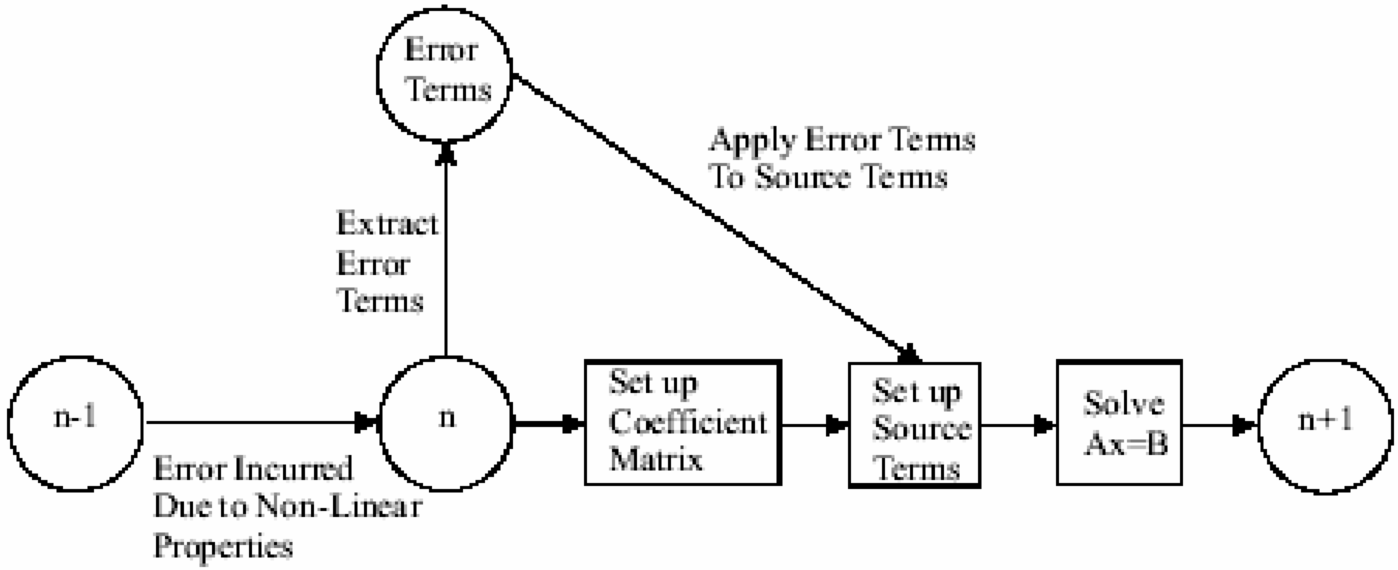


INPUTS:
P_g, α, h_m, x (at break node)
v_m (velocity in break node)
P_{res} (reservoir pressure)
C_{D1}, C_{D2}, C_{DV}
$C_D = f(x, C_{D1}, C_{D2}, C_{DV})$
calculate G_{BERN}
= 'ORIFICE' ?
yes
Flow into Break?
yes
Exchange Break node properties for Reservoir properties
$G_{brk} = G_{BERN}$
yes
$P_r > P_{cr}$?
EXIT
IF -STAG calculate stagnation P_0 and h_o
= 'HOMOG' ?
yes
$G2\phi = G_{ISEN\_2}$
= 'MOODY' ?
yes
$G2\phi = G_{MOOD\_2}$
ERROR
no
= 'HENFK' ?
$G_{1\phi} = G_{HF\_L}$
$G'' = G_{HF\_2}$
$G'' = f(x, G_{1\phi}, G_{2\phi})$
$G'' = \mathrm{MIN}[G_{BERN}, G'']$
-ORIF specified?
no
yes
smooth to G_{BERN}
-GAS specified ?
$P_r > P^*_{cr}$
no
no
yes
yes
calculate G_{ISEN_V} and smooth
EXIT
smooth to G_{BERN}

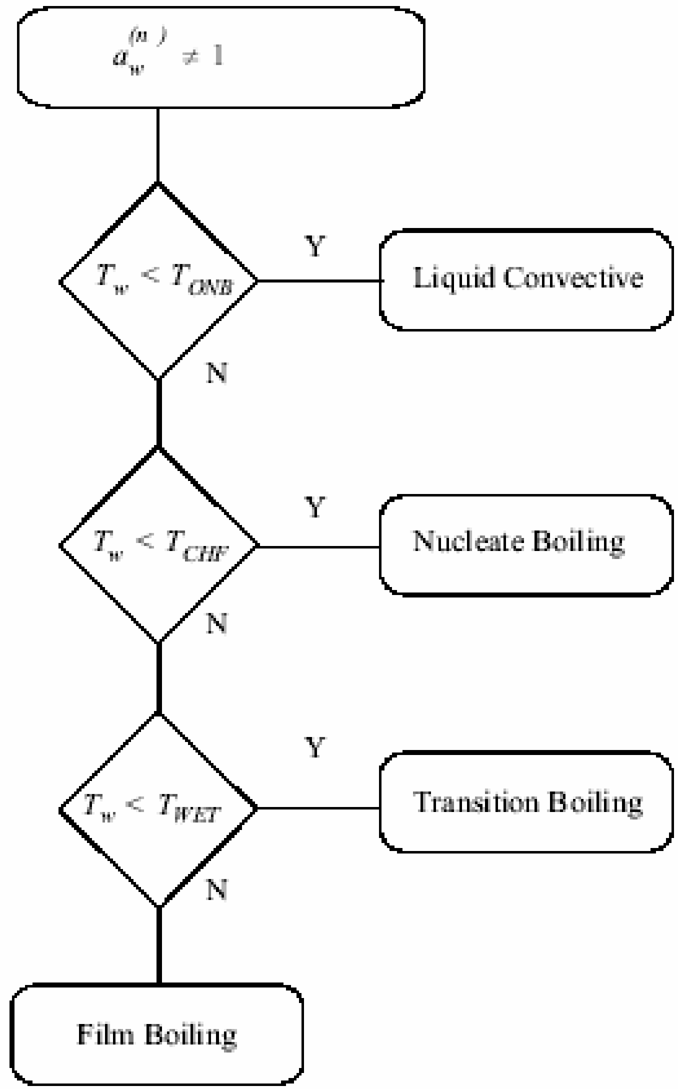
Critical Flow Model



Mass Conservation Error Correction Model



Heat Transfer Correction Logic



- Questions?