NuScale is an integral, pressurized light water reactor, where all components (reactor, steam generator and
pressurizer) are contained within the reactor vessel as illustrated below. The primary side operates by single phase
natural circulation. The steam generator is a once through design, composed of helical coil tubes where the primary
side flows on the outside of the tubes and the secondary side flows on the inside of the tubes.

1) Show how you would determine the necessary chimney height, give all equations. Terms involving integrals that
do not have closed form solutions can be left in integral form. You may assume the primary side temperature
distribution within the steam generator is known. If the solution requires an iterative solution, it is sufficient to
give the iteration equation, state which variable is to be solved for and state “solve iteratively”. You may assume
state equations of the form $P = \rho(T, P)$ and $T = T(h, P)$ are available as well as any other necessary fluid
properties. You may neglect friction in the lower (variable area) section of the chimney. (20%)

2) System pressure is maintained by controlling the relative amounts of liquid and vapor in the pressurizer.
Assuming the total pressurizer mass $M = \rho V_{prz}$ and energy $E = \rho u V_{prz}$ are known, show how you would
determine the system pressure. You may assume an equilibrium model holds in the pressurizer and that the
pressurizer volume $V_{prz}$ is known. (10%)

3) Assuming fully developed subcooled nucleate boiling occurs in the highest powered channel, give a step by step
procedure for determining the maximum clad temperature in the core. (20%)

4) Assuming the Critical Heat Flux Mechanism is DNB, and a Critical Heat Flux correlation of the form
$q_{crit} = q_{crit}(x_c, G, P, D_c)$ is available, show how you would determine the minimum DNB ratio in the core.
(10%)

5) Feedwater enters the steam generator tubes significantly subcooled and exits superheated. The heat flux from the
tube walls to the secondary side fluid at any location is proportional to the difference between the primary side
temperature and the secondary side wall temperature, i.e.

$$q^s(z) = U[T_p(z) - T_w(z)]$$
where $U$ is known and constant. Critical heat flux within the tubes can be considered dryout dominated, such that the dryout point can be determined by a critical boiling length correlation of the form

$$x_{crit} = \frac{D_h - a(G,P)}{D_e} \frac{L_{crit}}{L_{crit} + b(G,P)}$$

Assuming the primary side temperature distribution is known, show how you would determine the secondary side pressure drop. Give all equations. If equations require iteration, it is sufficient to give the iteration equation, state the variable to be solved for and state solve iteratively. If the solution requires evaluation of integrals that do not have closed form solutions, it is sufficient to state the integral can be solved numerically. You may assume that following dryout, heat transfer to the secondary side steam is single phase forced convection to a superheated vapor. You may assume any necessary state equations or fluid property tables are available. (40%)

The following information about the system may be assumed known.

**REACTOR PARAMETERS**
- Core Thermal Output: $\dot{Q}_{bx}$
- Fraction of Energy Deposited in Fuel: $\gamma_f$
- Power Peaking Factor: $F_q$
- Axial Peak to Average Ratio: $F_z$
- Number of fuel rods: $n_{rods}$
- Fuel Height: $H_f$
- Rod Diameter: $D$
- Rod Pitch (square lattice): $S$
- Core Averaged Rod Surface Heat Flux profile: $q'(z)$
- Hot Channel Rod Surface Heat Flux Profile: $q_{hot}'(z)$
- Core Inlet Loss Coefficient: $K_{in}$
- Core Exit Loss Coefficient: $K_{ex}$
- Number of grids: $n_{grids}$
- Grid Loss Coefficients: $K_{grid}$
- Grid locations: $z_j$

**CHIMNEY PARAMETERS**
- Chimney Diameter: $D_{ch}$
- Length of lower (variable area) chimney section: $L_{ch}$
- Chimney loss coefficient (referenced to chimney exit mass flux): $K_{ch}$
- Chimney roughness: $\varepsilon_{ch}$

**DOWNCOMER PARAMETERS**
- Vessel diameter: $D_v$
- Core Barrel Diameter: $D_{cb}$
- Downcomer Length: $L_{dc}$
- Total Loss Coefficient (referenced to chimney area mass flux): $K_{dc}$
- Downcomer roughness: $\varepsilon_{dc}$
STEAM GENERATOR PARAMETERS

- Number of tubes: \( n_{\text{tubes}} \)
- Tube Inner Diameter: \( D_i \)
- Tube Outer Diameter: \( D_o \)
- Primary Side Flow Area: \( A_{\text{SG}} \)
- Primary Side Equivalent Diameter: \( D_{\text{eSG}} \)
- Tube Pitch: \( S_{\text{SG}} \)
- Tube Length: \( L_{\text{SG}} \)
- Bundle Length: \( L_{hc} \)
- Primary Side Equivalent L/D: \( (L / D)_{hc} \)
- Feed Temperature: \( T_{fd} \)
- Secondary Side Pressure: \( P_{\text{sg}} \)
- Secondary Side Mass Flow Rate: \( m_{\text{sg}} \)
You may find all or some of the following relationships useful.

**Mixture Mass**

\[
A_x \frac{\partial \rho}{\partial t} + \frac{\partial G A_x}{\partial z} = 0
\]

**Mixture Energy**

\[
A_x \frac{\partial \rho u}{\partial t} + \frac{\partial G h A_x}{\partial z} = q'(z)
\]

**Mixture Momentum**

\[
\frac{1}{g_c} \frac{\partial G}{\partial t} + \frac{1}{g_c} \frac{\partial}{\partial z} \left( G^2 \left[ (1-x)^2 + \frac{x^2}{\alpha_f \rho_i} \right] A_x \right) = -\frac{\partial P}{\partial z} - \frac{f_f}{D_x} G^2 \phi_{\theta o}^2 + \sum_j K_j \phi (z - z_j) \frac{G^2}{2 \rho_f g_c} \sin \theta + \Delta P_r \delta (z - z_r)
\]

**Zuber-Findlay Correlation**

\[
\alpha = \frac{x}{C_o \left[ x + \frac{\rho_g}{\rho_i} (1-x) \right] + \frac{\rho_g V_{gj}}{G}}
\]

\[
C_o = 1.13 \text{ and } V_{gj} = 1.41 \left( \frac{\sigma_{gg} C_o}{\rho_i^2} \right)^{1/4}
\]

**Fundamental Void-Quality-Slip Relation**

\[
\alpha = \frac{1}{1 + \frac{(1-x) \left( \frac{\nu_f}{\nu_g} \right) S}{x}}
\]

**Profile Fit Model**

\[
x = x_e - (x_e)_d \exp \left( \frac{x_e}{(x_e)_d} - 1 \right)
\]

**Saha-Zuber Correlation**

\[
h_f - h_{id} = \begin{cases} 0.0022 \times q^n(z_d) \frac{D_x C_p}{k} & \text{Pe} < 70,000 \\ 154 \times \frac{q^n(z_d)}{G} & \text{Pe} > 70,000 \end{cases}
\]

**Two Phase Multiplier**

\[
\phi_{\theta o}^2 = \left( 1 + \frac{20}{k} + \frac{1}{\chi^2} \right) (1-x)^{1.75}
\]
Martinelli parameter

\[ \chi^2 = \left( \frac{\mu_f}{\mu_g} \right)^{0.2} \left( \frac{1-x}{x} \right)^{1.8} \left( \frac{\rho_g}{\rho_f} \right) \]

Homogeneous Multiplier

\[ \psi = 1 + \frac{U_{fg}}{U_f} x \]

Friction Factors

\[ f = f(\text{Re}, \varepsilon / D) \] (straight tube)

\[ f_{hc} = f_{hc}(\text{Re}, \varepsilon / D) \] (helical coils)

Heat Transfer Correlations

**Dittus-Boelter Correlation**

\[ \text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \]

**Weisman Correlation**

\[ \text{Nu} = C(S / D) \text{Re}^{0.8} \text{Pr}^{0.4} \]

**Nucleate Boiling Correlation**

\[ q^* = \xi(P)(T_w - T_{sat})^m \]

**Chen Correlation**

\[ q^* = h_{co}(G, x, P)(T_w - T_w) + h_{NB}(G, x, P, T_w)(T_w - T_{sat}) \]

**Bergles and Rohsenow**

\[ q^*(z) = q^*_{FC}(z) \left[ 1 + \left( \frac{q^*_NB(z)}{q^*_FC(z)} \left[ 1 - \frac{q^*_NB(z_n)}{q^*_NB(z)} \right] \right)^2 \right]^{1/2} \]

\[ q^*(z_n) = 15.6 P^{1.156} [T_{co}(z_n) - T_{sat}]^{2.30} \]

\[ q^*_{NB}(z) = 1 \]
SOLUTION

1) The core inlet temperature is equal to the steam generator exit temperature. Similarly, the core exit temperature is equal to the steam generator inlet temperature. Since it is given that the primary side temperature distribution within the steam generator is known, these temperatures are then known. The required core flow rate is then

\[
m_c = \frac{\dot{Q}_{RX}}{(h_{exit} - h_{in})}
\]

The chimney height necessary to provide \( m_c \) is obtained by integrating the single phase momentum equation around the flow loop. For simplicity, this will be broken down into integrals across each flow segment.

**Core**

\[
\Delta P_{core} = \left( \frac{f_{core} H_c}{D_e} + K_{in} + n_{grids} \times K_{grid} + K_{ex} \right) \frac{G_{core}^2}{2 \rho_c g_c} + \int_0^{H_c} \rho(z) \frac{g}{g_c} dz
\]

\[
G_{core} = \frac{m_{core}}{A_{core}}
\]

\[
A_{core} = n_{rods} \left[ S^2 - \pi \frac{D_o^2}{4} \right]
\]

\[
D_e = \frac{4 A_e}{P_w} = \frac{4(S^2 - \pi D_o^2 / 4)}{\pi D_o}
\]

\[
Re = \frac{G_{core} D_e}{\mu}
\]

\[
f_{core} = f(Re,0)
\]

\[
\rho(z) = \rho(T(z)) = \rho[T(h(z))]
\]

\[
h(z) = h_{in} + \frac{1}{G_c A_y f} \int_0^z q'(z') D Dz'
\]

Since all parameters are known, \( \Delta P_{core} \) can be solved for directly.

**Chimney**

\[
\Delta P_{ch} = \frac{G_{ch}^2}{2 \rho_c g_c} - \frac{G_{ch}^2}{2 \rho_c g_c} + \left( \frac{f_{ch} L_{ch}}{D_{ch}} + K_{ch} \right) \frac{G_{ch}^2}{2 \rho_c g_c} + \rho_{ch} \frac{g}{g_c} L_{ch}
\]

\[
G_{ch} = \frac{m_c}{A_{ch}} \quad \text{where} \quad A_{ch} = \frac{\pi D_{ch}^2}{4}
\]
\[ G_{ch} = \frac{\dot{m}_c}{A_{ch}} \quad \text{where} \quad A_{ch} = \frac{\pi D_{ch}^2}{4} \]

\[ \text{Re} = \frac{G_{ch} D_{ch}}{\mu} \]

\[ f_{ch} = f(\text{Re}, \varepsilon_{ch}/D_{ch}) \]

\[ \rho_{ch} = \rho(T_{exit}) \]

**Steam Generator**

\[ \Delta P_{sg} = f_{sg} \times (L/D)_{hc} \times \frac{G_{sg}^2}{2 \rho g_c} - \int_0^{z_w} \rho(z) \frac{g}{g_c} dz \]

\[ G_{sg} = \frac{\dot{m}_c}{A_{sg}} \]

\[ \text{Re} = \frac{G_{sg} D_{sg}}{\mu} \]

\[ f_{sg} = f(\text{Re}, 0) \]

\[ \rho(z) = \rho(T(z)) \]

where \( T(z) \) is known.

**Downcomer**

The downcomer has two different flow areas, that in the area of the chimney, and that in the area of the core.

\[ \Delta P_{dc} = \frac{G_{dc,ex}^2}{2 \rho g_c} - \frac{G_{dc,in}^2}{2 \rho g_c} + \left( \frac{f_{dc,ex} (L_{ch} - L_{hc})}{D_{dc,ex}^2} \right) + K_{dc} \left( \frac{G_{dc,in}^2}{2 \rho g_c} \right) + \frac{f_{dc,in} H_c}{D_{dc,in}} \frac{G_{dc,in}^2}{2 \rho g_c} - \rho_{dc} \frac{g}{g_c} (L_{ch} + H_c - L_{hc}) \]

\[ G_{dc,ex} = \frac{\dot{m}_c}{A_{dc,ex}} \quad \text{where} \quad A_{dc,ex} = \frac{\pi(D_v^2 - D_{ch}^2)}{4} \quad \text{and} \quad D_{dc,ex} = D_v - D_{ch} \]

\[ G_{dc,in} = \frac{\dot{m}_c}{A_{dc,in}} \quad \text{where} \quad A_{dc,in} = \frac{\pi(D_v^2 - D_{ch}^2)}{4} \quad \text{and} \quad D_{dc,in} = D_v - D_{ch} \]

\[ \text{Re}_{ex} = \frac{G_{dc,ex} D_{dc,ex}}{\mu} \]

\[ \text{Re}_{in} = \frac{G_{dc,in} D_{dc,in}}{\mu} \]
$$f_{dc, in} = f(\text{Re}_{dc}, \epsilon_{dc} / D_c)$$

$$\text{Re}_{in} = \frac{G_{dc}}{\rho_{dc} D_c \omega}$$

$$\rho_{dc} = \rho(T_{\text{inlet}})$$

The pressure drops sum to zero such that

$$\Delta P_{\text{core}} + \Delta P_{ch} + \Delta P_{sg} + \Delta P_{dc} = 0$$

is a single linear equation in the chimney height which may be solved directly.
2) The effective mixture density in the pressurizer is

\[
\frac{M}{V_{\text{prz}}} = \rho = (1 - \alpha) \rho_f(P) + \alpha \rho_g(P)
\]

or

\[
\rho = \rho_f(P) - \alpha[\rho_f(P) - \rho_g(P)]
\]

Similarly, the effective mixture energy is

\[
\frac{E}{V_{\text{prz}}} = \rho u = (1 - \alpha) \rho_f(P) u_f(P) + \alpha \rho_g(P) u_g(P)
\]

or

\[
\rho u = \rho_f(P) u_f(P) + \alpha[\rho_g(P) u_g(P) - \rho_f(P) u_f(P)]
\]

which are two equations in the unknown variables \( \alpha \) and \( P \). The void fraction may be solved for in terms of density as

\[
\alpha = \frac{\rho_f - \rho}{\rho_f - \rho_g}
\]

and substituted into the energy equation to yield

\[
\rho u = \rho_f(P) u_f(P) + \frac{(\rho_f - \rho)}{(\rho_f - \rho_g)} [\rho_g(P) u_g(P) - \rho_f(P) u_f(P)]
\]

which is a single nonlinear equation in the system pressure that can be solved iteratively.
3) **Boiling Boundaries**

Since the fluid enters subcooled, the channel will experience single phase forced convection, mixed boiling and fully developed nucleate boiling. For a given heat flux profile \( q'(z) \), the incipient boiling (nucleation) point \( z_n \) is the boundary between the single phase forced convection and mixed boiling regions and is obtained by solution of

\[
q'(z_n) = 15.6 P^{1.16} \left[ T_{co}(z_n) - T_{sat} \right]
\]

where

\[
T_{co}(z_n) = T_{\infty}(z_n) + \frac{q'(z_n)}{h_c}
\]

\[
T_{\infty}(z_n) = T_{\infty}(0) + \frac{1}{\dot{m}C_p} \int_0^{z_n} q'(z) \pi dz
\]

\[
\dot{m} = G A_x
\]

\[
A_x = S^2 - \pi D^2 / 4
\]

\[
h_c = \frac{k}{D_c} C(S / D) \left[ \frac{GD_{ce}}{\mu} \right]^{0.8} \left[ \frac{C_p \mu}{k} \right]^{1/3}
\]

and

\[
D_c = \frac{4[S^2 - \pi D^2 / 4]}{\pi D}
\]

which can be solved iteratively for \( z_n \). The fully developed nucleate boiling point \( z_B \) is the boundary between mixed boiling and fully developed nucleate boiling and is the solution of

\[
q'(z_B) = q'_{FC}(z_B) \left[ 1 + \frac{q'(z_B)}{q'_{FC}(z_B)} \left( \frac{1 - q'_{NB}(z_n)}{q'(z_B)} \right)^{2/3} \right]^{1/2}
\]

where

\[
q'_{FC}(z_B) = h_c [T_{co}(z_B) - T_{\infty}(z_B)]
\]

\[
T_{co}(z_B) = T_{sat} + \left( \frac{q'(z_B)}{g} \right)^{1/m}
\]

\[
T_{\infty}(z_B) = T_{\infty}(0) + \frac{1}{\dot{m}C_p} \int_0^{z_B} q'(z) \pi dz
\]

\[
q'_{NB}(z_n) = \xi [T_{co}(z_n) - T_{sat}]^m
\]
\[ T_{co}(z_n) = T_{co}(z_n) + \frac{q'(z_n)}{h_c} \]

which can be solved iteratively for \( z_B \).

**Temperature distributions**

For \( z_{sat} \) satisfying

\[ T_{sat} = T_{co}(0) + \frac{1}{\dot{m}C_p} \int_0^{z_{sat}} q'(z)\pi dz \]

the fluid temperature as a function of position is given by

\[ T_{co}(z) = \begin{cases} 
T_{co}(0) + \frac{1}{\dot{m}C_p} \int_0^z q'(z')\pi dz' & z < z_{sat} \\
T_{sat} & z \geq z_{sat}
\end{cases} \]

For \( z \in [0, z_n] \) heat transfer is by single phase forced convection and the wall temperature is given by

\[ T_{co}(z) = T_{co}(z) + \frac{q'(z)}{h_c} \]

For \( z \in [z_n, z_B] \) mixed boiling is the heat transfer mechanism and the wall temperature is obtained iteratively from

\[ q'(z) = q_{FC} (z) \left[ 1 + \left( \frac{q_{NB}^*(z)}{q_{FC}(z)} \left( 1 - \frac{q_{NB}^*(z_n)}{q_{NB}(z)} \right) \right)^2 \right]^{1/2} \]

where

\[ q_{NB}^*(z) = \xi [T_{co}(z) - T_{sat}]^m \]

and

\[ q_{FC}(z) = h_c [T_{co}(z) - T_{co}(z)] \]

the only unknown at any axial position being \( T_{co}(z) \).

For \( z > z_B \) heat transfer is by fully developed nucleate boiling and the wall temperature can be obtained directly by
\[ T_{e\theta}(z) = T_{sat} + \left[ \frac{q^*(z)}{\xi} \right]^{1/m} \]

Substituting \( q^*_{tot}(z) = q^*(z) \), the wall temperature distribution can then be solved along the channel height and searched for its maximum value.
4) Minimum DNB Ratio

The enthalpy distribution in the hot channel is given by

\[ h(z) = h_{in} + \frac{1}{m} \int_0^z q_{hot}(z) \pi Ddz \]

such that the quality distribution in the channel is

\[ x_c(z) = \frac{h(z) - h_f}{h_{fg}} \]

Assuming the other parameters are independent of position, critical heat flux as a function of position in the channel is given by

\[ q_{crit}^*(z) = q_{crit}^*(G, P, x_c(z), D_c) \]

The minimum DNB ratio is obtained by computing

\[ DNBR(z) = \frac{q_{crit}^*(z)}{q_{hot}^*(z)} \] over the channel height and searching for its minimum value.
5) The pressure drop in any tube is the sum of the acceleration, friction, and elevation losses,

\[ P_0 - P_H = \Delta P_{acc} + \Delta P_{friction} + \Delta P_{elev} \]

Since the fluid enters significantly subcooled, and exits superheated, three regions exist: a) a subcooled liquid region, b) a two phase mixture region and c) a superheated vapor region.

**Acceleration Losses**

\[ \Delta P_{acc} = \frac{G^2}{g_c} \left( \frac{1}{\rho_g (L_{SG})} - \frac{1}{\rho_l(0)} \right) \]

**Friction Pressure Drop**

\[ \Delta P_{friction} = \frac{f_{hc} z_d}{2D_e \rho_f g_c} + f_{hc} \frac{G^2}{2\rho_f g_c} \int_{z_d}^{z_f} \phi_g(z')dz' + \frac{f_{hc} (L_{SG} - z_g)}{2D_e \rho_g g_c} \]

where \( z_d \) is the bubble departure point and \( z_g \) is the dryout point.

**Elevation Losses**

\[ \Delta P_{elev} = \int_0^{L_{SG}} \rho(z) \frac{g}{g_c} \sin(\theta)dz \]

The mixture density is defined to be

\[ \rho(z) = \begin{cases} 
\rho_l(z) & z < z_d \\
(1 - \alpha(z))\rho_l(z) + \alpha(z)\rho_g & z \in [z_d, z_g] \\
\rho_g(z) & z_g < z_g
\end{cases} \]

where the liquid phase density is given in terms of the liquid phase enthalpy by

\[ \rho_l = \begin{cases} 
\rho_l(h_l) & h_l < h_f \\
\rho_f & h_l = h_f
\end{cases} \]

the vapor phase density is given by

\[ \rho_g = \begin{cases} 
\rho_g(h) & h_g < h \\
\rho_g(P) & h < h_g
\end{cases} \]

The liquid phase enthalpy is given by

\[ h_l(z) = \frac{h(z) - x(z)h_g}{1 - x(z)} \]
and the vapor phase properties can be taken to be saturated vapor properties at the system pressure. Solution then requires expressions for the enthalpy, flow quality and void distributions.

The integrals in the pressure drop equations are evaluated numerically.

**Enthalpy Distribution**

The enthalpy distribution given by the simple energy balance

\[ h(z) = h_{in} + \frac{1}{\dot{m}} \int_0^z q^*(z') \pi D dz' \]

where

\[ q^*(z) = U \left[ T_p(z) - T_w(z) \right] \]

\[ \dot{m} = \frac{m_{sg}}{n_{tubes}} \] and the inlet enthalpy is known from the inlet feed temperature.

Since the primary side temperature distribution and \( U \) are known, if the wall temperature distribution is known the heat flux is known. For the moment, assume the wall temperature distribution is known.

**Bubble Departure Point**

The Bubble Departure Point can be obtained from the Saha-Zuber Correlation

\[
\begin{align*}
\frac{G}{D_c} & = 70,000 \left( \frac{\pi}{154} \right) \quad \text{Pe} < 70,000 \\
\frac{G}{D_c} & = 154 \times \frac{q^*(z_d)}{G} \quad \text{Pe} > 70,000 
\end{align*}
\]

where \( \text{Pe} = \frac{GD_c \times C_p}{k} = \text{Re} \times \text{Pr} \) is the Peclet Number and the enthalpy at the bubble departure point is given by

\[ h_{id} = h_{in} + \frac{1}{\dot{m}} \int_0^{z_d} q^*(z) \pi D dz . \]

where \( D_c = D_1 \) . For a given heat flux distribution the bubble departure point can be found iteratively.

**Quality Distributions**

The flow quality as a function of position is given by the Levy profile fit model

\[
x = \begin{cases} 
0 & z < z_d \\
(x_e - (x_e)_d) \exp \left( \frac{x_e - (x_e)_d}{(x_e)_d} - 1 \right) & z > z_d 
\end{cases}
\]

where \( x_e \) is the local equilibrium quality and \( (x_e)_d \) is the equilibrium quality at the bubble departure point, i.e.
\[(x_e)_d = \frac{h_{id} - h_f}{h_{fg}}\]

where the local equilibrium quality is given by

\[x_e(z) = \frac{h(z) - h_f}{h_{fg}}\]

**Void Distribution**

The Zuber-Findlay Correlation for void fraction is

\[\alpha_g(z) = \frac{x(z)}{C_0 \left[ x(z) + \frac{\rho_g}{\rho_f(z)} [1 - x(z)] \right] + \frac{\rho_g V_{gl}(z)}{G}}\]

where \(C_0 = 1.13\) and \(V_{gl}(z) = 1.41 \left\{ \sigma_{gg} \left( \frac{\rho_f(z) - \rho_g}{\rho_f(z)} \right) \right\}^{\frac{1}{4}}\)

Note: This form of the Zuber-Findlay correlation automatically gives a vapor volume fraction of zero for quality equal to zero.

The problem then reduces to determining the secondary side wall temperature distribution. The energy balance equation can then be integrated numerically.

**Wall Temperature Distribution**

Since the secondary side enters subcooled and leaves superheated, four different heat transfer mechanisms must be considered.

1) Single Phase Forced Convection Region, \(z \in [0, z_{sat}]\)

Prior to the wall temperature reaching the saturation temperature, heat transfer is by single phase forced convection and the wall temperature is the solution of

\[U[T_p(z) - T_w(z)] = h_e[T_w(z) - T_e(z)]\]

or

\[T_w(z) = \frac{UT_p(z) + h_e T_e(z)}{U + h_e}\]

The convective heat transfer coefficient can be obtained from the Dittus Boelter Correlation, such that

\[h_e = \frac{k}{D_e} 0.023 \left( \frac{GD_e}{\mu} \right)^{0.8} \left( \frac{C_p \mu}{k} \right)^{0.4}\]

where
\[ D_e = D_t \]
\[ G = \frac{\dot{m}}{A_e} \]
\[ A_e = \pi D_e^2 / 4 \]

Fluid temperature is available from \( T_e(z) = T_e(h(z), P_{sg}) \), and the energy balance

\[ h(z) = h_{in} + \frac{1}{\dot{m}} \int_0^z U[T_p(z') - T_w(z')] \pi D_e dz' \]

which can be integrated numerically. The location where the wall temperature reaches the saturation temperature is the solution of

\[ T_w(z_{sat}) = T_{sat} = \frac{U T_p(z_{sat}) + h_w(z_{sat})}{U + h_c} \]

which can be solved iteratively for \( z_{sat} \).

2) Nucleate Boiling and Forced Convection Vaporization Regions \( z \in [z_{sat}, z_{crit}] \)

Once the wall temperature exceeds the saturation temperature, the Chen correlation can be used to calculate the wall temperature up to the point of dryout. The wall temperature is then the solution of

\[ U[T_p(z) - T_w(z)] = h_{io}(G, x(z), P)[T_w(z) - T_{sat}] + h_{lb}(G, x(z), P, T_w(z))[T_w(z) - T_{sat}] \]

where the liquid only heat transfer coefficient \( h_{io} \) is consistent with the Dittus-Boelter correlation. The fluid temperature is again available from the enthalpy, as is the quality through

\[ x(z) = \frac{h(z) - h_f}{h_{fg}} \]

Such that at any location, the equation

\[ U[T_p(z) - T_w(z)] = h_{io}(G, x(z), P_{sg})[T_w(z) - T_{sat}] + h_{lb}(G, x(z), P_{sg}, T_w(z))[T_w(z) - T_{sat}] \]

is a single nonlinear equation in the wall temperature and can be solved iteratively.

The dryout point can be obtained from the critical boiling length correlation as

\[ \frac{D_a}{D_e} = \frac{a L_{crit} + b}{L_{crit} + b} = \frac{D_a}{D_e} \int_0^{z_{crit}} U[T_p(z) - T_w(z)] \pi D_o dz \]

where

\[ \dot{m}(h_f - h_{in}) = \int_0^{z_{crit}} U[T_p(z) - T_w(z)] \pi D_o dz \]
The wall temperature distribution is known from solution of the Chen Correlation, so the above are two nonlinear equations in the variables $H_o$ and $z_{crit}$ and can be solved iteratively. The integrals are preformed numerically.

3) Superheated region $z \in [z_{crit}, L_{SG}]

In the superheated region, heat transfer is again by single phase forced convection. As in the subcooled region, the wall temperature is given by

$$T_w(z) = \frac{U T_{w}(z) + h_c T_w(z)}{U + h_c}$$

Where the Weisman correlation is again used to compute the convective heat transfer coefficient and the fluid temperature is given from the enthalpy. Fluid properties in the Weisman correlation are those for superheated steam.