Transient performance of Single-phase Natural Circulation Systems (Lecture-7)

Vijayan P. K.

Raja Ramanna Fellow,

Bhabha Atomic Research Centre, Trombay, Mumbai 400085, INDIA

QUEST Course on

Natural Circulation Based Passive Systems for Advanced Reactors

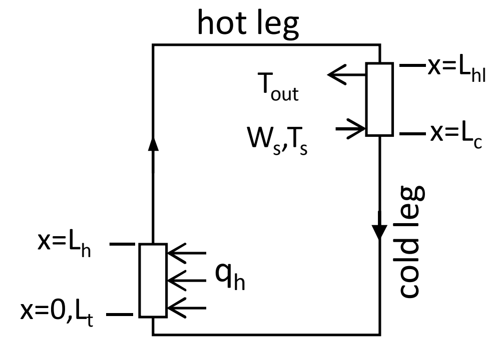
CONTENTS

- Introduction
- Transient governing equations for single-phase flow
- Discretization of the governing equations
  - Explicit, Implicit and the semi-implicit schemes
- Solution procedure
- Typical transient solutions
  - Start-up from rest,
  - Power ramp, etc.
- Parametric effects
- Closure

Governing Equations for Transient Analysis of Natural Circulation Loops

Consider the natural circulation loop with a heat source and a heat sink connected by insulated pipes as shown in figure. In 1-D system, the only coordinate x runs around the loop with origin at the beginning of the heater.

Neglecting viscous dissipation and pressure work, the mass, momentum and energy equations can be written as



A simple rectangular NCL

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}(\rho u) + \frac{\partial}{\partial x}(\rho u u) = -\frac{\partial p}{\partial x} + \rho g \cos\theta - \frac{f \rho u^2}{2D} \qquad (2)$$

$$\frac{\partial}{\partial t}(\rho c p T) + \frac{\partial}{\partial x}(\rho u c p T) - k\frac{\partial^2 T}{\partial x^2} = \begin{Bmatrix} \frac{4q_h}{D} & \text{heater} \\ 0 & \text{pipes} \\ -\frac{4U_i}{D}(T - T_s) & \text{cooler} \end{Bmatrix} \qquad (3)$$

In equations (2) and (3), the entire RHS is the source term. If we assume the fluid to be incompressible, then ∂ρ/∂t =0. Hence the mass conservation equation becomes

$$\frac{\partial u}{\partial x} = \frac{\partial w}{\partial x} = 0$$

Using this result in the momentum equation gives us

$$\rho \frac{du}{dt} = -\frac{\partial p}{\partial x} + \rho g \cos\theta - \frac{f \rho u^2}{2D}$$

Rewriting this in terms of the mass flow rate we obtain

$$\frac{1}{A}\frac{dW}{dt} = -\frac{\partial p}{\partial x} + \rho g \cos\theta - \frac{f W^2}{2 D \rho A^2}$$

Integrating equation (2) over the closed loop, the pressure terms vanish leading to the equation

$$\frac{L_t}{A}\frac{dW}{dt} = g \oint \rho dz - \frac{f L_t W^2}{2 D \rho A^2}$$

Where dx cos θ = dz has been used and z is the elevation.

Transient Analysis of Single-phase Natural circulation loops

$$\frac{L_t}{A}\frac{dW}{dt} = g\oint \rho dz - \frac{fL_t W^2}{2D\rho A^2}$$

Using Boussinesq approximation & assuming the density variation in the BFT, $\rho = \rho_o\left[1-\beta(T-T_0)\right]$

where ρ_o is the density at the reference temperature T_o and $\beta = \frac{1}{v}\frac{\partial v}{\partial T}$ Substituting this in the momentum equation, we get

$$\frac{L}{A}\frac{dW}{dt} = g\beta\rho_0 \oint T dz - \frac{fLW^2}{2DA^2\rho_0}$$

$$\frac{\partial T}{\partial t} + \frac{W}{A\rho_0}\frac{\partial T}{\partial x} - \alpha\frac{\partial^2 T}{\partial x^2} = \begin{cases} \dfrac{4q}{D\rho_0 Cp} & heater \\ 0 & pipes \\ -\dfrac{4U}{D\rho_0 Cp}(T-T_s) & cooler \end{cases}$$

The energy and the momentum equations are coupled and nonlinear and no analytical solutions exist for the transient case. However, for the steady state case, analytical solution exists and is useful in benchmarking the transient numerical code.

<u>Constitutive (or closure) relations:</u> For numerical solution models are required for the

1) friction factor, f
2) overall heat transfer coefficient, U and the
3) fluid properties (Equation of state for the fluid)

Friction Factor in Circular Pipes

Adiabatic single-phase flow

Fully developed laminar flow:

$f = 64/Re$ for $0<Re<2000$

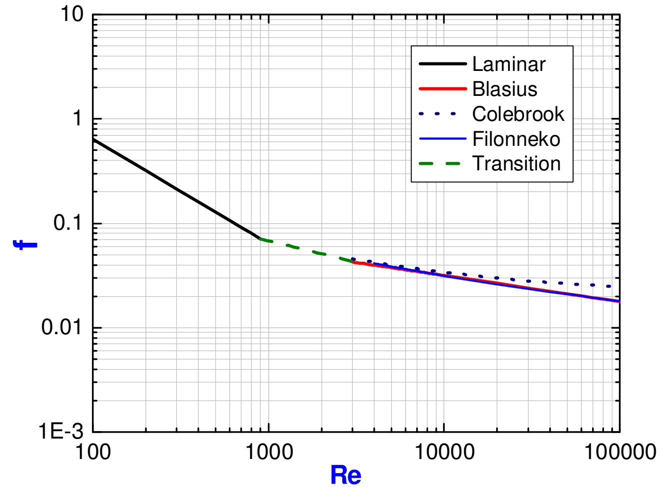
Turbulent flow:

(a) Blasius (1913): $f = 0.316\,Re^{-0.25}$ $3000 \le Re \le 10^5$

(b) Colebrook (1938): $\frac{1}{\sqrt{f}} = 0.86 \ln\left(\frac{e/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right)$ $Re > 3000$

(c) Filonenko (1948): $f = [1.82 \log(Re) - 1.64]^{-2}$ $4000 \le Re \le 10^{12}$

Transition region: $f=1.2063/Re^{0.416}$ $898 \le Re \le 3196$



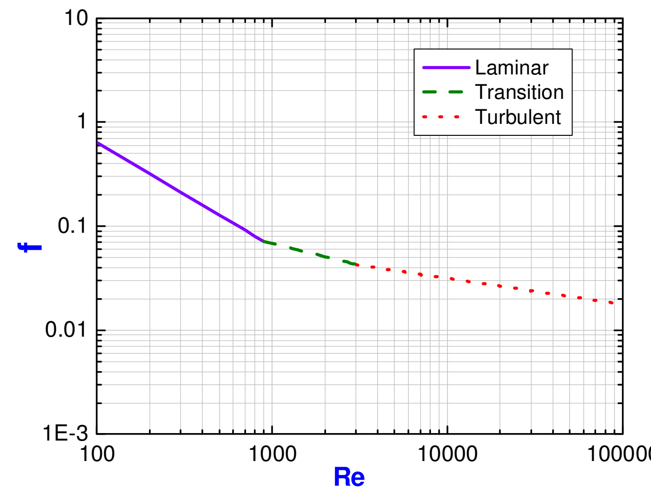
Adiabatic single-phase friction

Switch over from laminar to transition and from transition to turbulent

if $f = \max(f_L \,\&\, f_{tr})$ from laminar to transition

if $f = \max(f_{tr} \,\&\, f_t)$ from transition to turbulent

These are important for predicting unstable NC flows with repetitive flow reversal



Laminar, transition and turbulent region friction factors without discontinuity

Heat Transfer Coefficient in Single-phase Flow

Film Heat Transfer Coefficient (h)

Natural circulation flow heat transfer coefficients could be significantly different due to the presence of secondary flows. The effect of secondary flows become stronger at low flow rates compared to large flow rates. However, for prediction purposes it is customary to use forced flow correlations

h, is normally expressed in terms of Nusselt Number : $Nu = hd / k$

Single phase Laminar flow

- Constant wall temperature: local Nusselt Number reaches a value of 3.65 asymptotically
- Constant heat flux: local Nusselt number reaches a value of 4.36 asymptotically

Single phase Turbulent flow

Dittus Boelter equation : $Nu = 0.023 \; Re^{0.8} . Pr^{0.4}$

Applicable for $0.6 \leq Pr \leq 160$, $Re \geq 10000$ and $L/D \geq 10$

Sieder Tate equation : $Nu = 0.023 \; Re^{0.8} . Pr^{0.4} . (\mu_w / \mu_b)^{0.14}$

Applicable for $0.7 \leq Pr \leq 16700$, $Re \geq 10000$ and $L/D \geq 10$

Transient solution

- The transient energy and momentum equations need to be solved.
- Depending on the discretisation scheme adopted for these equations, we can have
  - **Explicit-Explicit Scheme** in which both momentum and energy equations are solved explicitly
  - **Imlicit-Explicit Scheme** in which the momentum equation is solved implicitly and the energy equation is solved explicitly
  - **Fully Implicit Scheme** in which both momentum and energy equations are solved implicitly

Transient Solution

Explicit-Explicit method

Both the energy and momentum equations are solved explicitly. The explicit form of the energy equation can be written as follows:

$$\frac{T_i^{n+1}-T_i^n}{\Delta t}+\frac{W_n}{A\rho_0}\left(\frac{T_i^n-T_{i-1}^n}{\Delta x}\right)-\alpha\left(\frac{T_{i+1}^n-2T_i^n+T_{i-1}^n}{\Delta x^2}\right)=\begin{cases}\dfrac{4q}{D\rho_0 Cp} & heater\\ 0 & pipes\\ -\dfrac{4U}{D\rho_0 Cp}\left(T_i^n-T_s\right) & cooler\end{cases}$$

Explicit equations for the temperature at the new time step n+1 can be obtained as follows

$$T_i^{n+1}=\left(\frac{\alpha\Delta t}{\Delta x^2}\right)T_{i+1}^n+\left(1-\frac{W_n\Delta t}{A\rho_0\Delta x}-\frac{2\alpha\Delta t}{\Delta x^2}\right)T_i^n+\left(\frac{W_n\Delta t}{A\rho_0\Delta x}+\frac{\alpha\Delta t}{\Delta x^2}\right)T_{i-1}^n+\frac{4q\Delta t}{D\rho_0 Cp}$$ heater

$$T_i^{n+1}=\left(\frac{\alpha\Delta t}{\Delta x^2}\right)T_{i+1}^n+\left(1-\frac{W_n\Delta t}{A\rho_0\Delta x}-\frac{2\alpha\Delta t}{\Delta x^2}\right)T_i^n+\left(\frac{W_n\Delta t}{A\rho_0\Delta x}+\frac{\alpha\Delta t}{\Delta x^2}\right)T_{i-1}^n$$ pipes

$$T_i^{n+1}=\left(\frac{\alpha\Delta t}{\Delta x^2}\right)T_{i+1}^n+\left(1-\frac{W_n\Delta t}{A\rho_0\Delta x}-\frac{2\alpha\Delta t}{\Delta x^2}-\frac{4U\Delta t}{D\rho_0 Cp}\right)T_i^n+\left(\frac{W_n\Delta t}{A\rho_0\Delta x}+\frac{\alpha\Delta t}{\Delta x^2}\right)T_{i-1}^n+\frac{4UT_s\Delta t}{D\rho_0 Cp}$$ cooler

The backward difference formula has been used for the convection term (Upwind scheme)

In general these equations can be written as $a_i^{n+1}T_i^{n+1}=a_{i+1}^nT_{i+1}^n+a_i^nT_i^n+a_{i-1}^nT_{i-1}^n+b$

Where the coefficients a_i^{n+1}, a_{i+1}^n and a_{i-1}^n are all positive. The coefficient of T_i^n can however, become negative. The limiting time step can be obtained as

$$\Delta t=\frac{1}{\dfrac{W_n}{A\rho_0\Delta x}+\dfrac{2\alpha}{\Delta x^2}+\dfrac{4U}{D\rho_0 Cp}} \quad \text{(a)}$$

from the equation for the cooler if the space step is the same everywhere. The time step is also a function of the flow rate. Hence it is required to be recalculated after every time step.

Solution procedure – Contd.

The explicit form of the momentum equation is obtained as

$$\frac{L_t}{A}\frac{W_{n+1}-W_n}{\Delta t} = g\beta\rho_0 \oint T_i^n\,dz - \frac{pL_t W_n^{2-b}\mu^b}{2D^{1+b}A^{2-b}\rho_0}$$

where $f = p/\mathrm{Re}^b$ has been used. Rearranging we get

$$W_{n+1} = \frac{Ag\beta\rho_0\Delta t}{L_t}T_{\mathrm{int}}^n + W_n\left(1-\frac{pL_t\mu^b\Delta t W_n^{1-b}}{2D^{1+b}A^{1-b}\rho_0}\right)$$

where $T_{\mathrm{int}}^n = \oint T_i^n\,dz$ is obtained by Simpson’s or trapezoidal rule.

The time step from the momentum equation is obtained as

$$\Delta t = \left[\frac{2D^{1+b}A^{1-b}\rho_0}{p\mu^b W_n^{1-b}}\right] \qquad \text{(b)}$$

Note that Δt is not only a function of w_n but also independent of Δx

The actual time step to be used for time marching shall be the lower of the two values obtained from equations (a) and (b). Again it is to be reiterated that the time step being a function of the flow rate itself shall be recalculated after every time step. So the solution procedure can be summarized as

1) Calculate the minimum in time steps using Eqs. (a) and (b).
2) Calculate the nodal temperatures using the FD form of the energy Eqn.
3) Calculate the temperature integral using Simpson’s rule
4) Calculate the flow rate using the FD form of the momentum Eqn.
5) Repeat steps (1) to (4) until steady state is achieved.

Solution procedure – Contd.

Implicit Procedure for the Momentum Equation It may be noted that T_i^{n+1} is available when we are ready to solve the momentum equation. Further, usually, the momentum equation limits the time step and it cannot be enhanced by refining the nodalization so that the use of an implicit scheme for the momentum equation sometimes become inevitable. In this case, the momentum equation is discretised as

$$\frac{L_t}{A}\frac{W_{n+1}-W_n}{\Delta t} = g\beta\rho_0 \oint T_i^{n+1} dz - \frac{pL_t W_{n+1}^{2-b}\mu^b}{2D^{1+b}A^{2-b}\rho_0}$$ which can be recast as $$BW_{n+1}^{2-b} + W_{n+1} = C$$ where

$$B = \frac{p\mu^b \Delta t}{2D^{1+b}A^{1-b}\rho_0} \quad \text{and} \quad C = W_n + \frac{Ag\beta\rho_0 \Delta t T_{\text{int}}^{n+1}}{L_t}.$$

The above is a polynomial in W_{n+1} and can be solved using any of the methods for solving polynomials. The simple bisection method or Newton-Raphson method can be used, with the latter giving a faster convergence. The solution procedure can be summarized as

1) Calculate the minimum in time steps using Eqs. (a)
2) Calculate the nodal temperatures using the FD form of the energy equation
3) Calculate the temperature integral using Simpson's rule
4) Calculate the flow rate from the above Eq. using the Newton-Raphson method.
5) Repeat steps (a) to (d) until steady state is achieved.

Comment: No iterations are involved in the marching process. However, a polynomial equation is to be solved, which may involve iterations.

Solution procedure – Contd.

The fully implicit Scheme: The finite difference form of the energy equation is

$$\frac{T_i^{n+1}-T_i^n}{\Delta t}+\frac{W_{n+1}}{A\rho_0}\left(\frac{T_i^{n+1}-T_{i-1}^{n+1}}{\Delta x}\right)-\alpha\left(\frac{T_{i+1}^{n+1}-2T_i^{n+1}+T_{i-1}^{n+1}}{\Delta x^2}\right)=\begin{cases}\dfrac{4q}{D\rho_0 Cp} & heater\\ 0 & pipes\\ -\dfrac{4U\left(T_i^{n+1}-T_s\right)}{D\rho_0 Cp} & cooler\end{cases}$$

The general FDE applicable for all the three equations can be written as

$$aT_i^{n+1}=bT_{i+1}^{n+1}+cT_{i-1}^{n+1}+d$$

where $a=1+\dfrac{W_{n+1}\Delta t}{A\rho_0\Delta x}+\dfrac{2\alpha\Delta t}{\Delta x^2}$ for heater and pipes $a=1+\dfrac{W_{n+1}\Delta t}{A\rho_0\Delta x}+\dfrac{2\alpha\Delta t}{\Delta x^2}+\dfrac{4U\Delta t}{\rho_0 DCp}$ for the cooler. $b=\dfrac{\alpha\Delta t}{\Delta x^2}$; $c=\dfrac{W_{n+1}\Delta t}{A\rho_0\Delta x}+\dfrac{\alpha\Delta t}{\Delta x^2}$

for the heater, pipes and cooler. The coefficient d for the various segments are given by

$$d=\begin{cases}T_i^n+\dfrac{4q\Delta t}{D\rho_0 Cp} & heater\\ T_i^n & pipes\\ T_i^n+\dfrac{4U\Delta t T_z}{D\rho_0 Cp} & cooler\end{cases}$$

The TDMA procedure can be used to solve the energy equation. However, the coefficients of the FDE has W_{n+1} as a parameter making it nonlinear and the solution procedure iterative. The momentum equation is treated implicitly as described above. The solution procedure can be summarized as below:

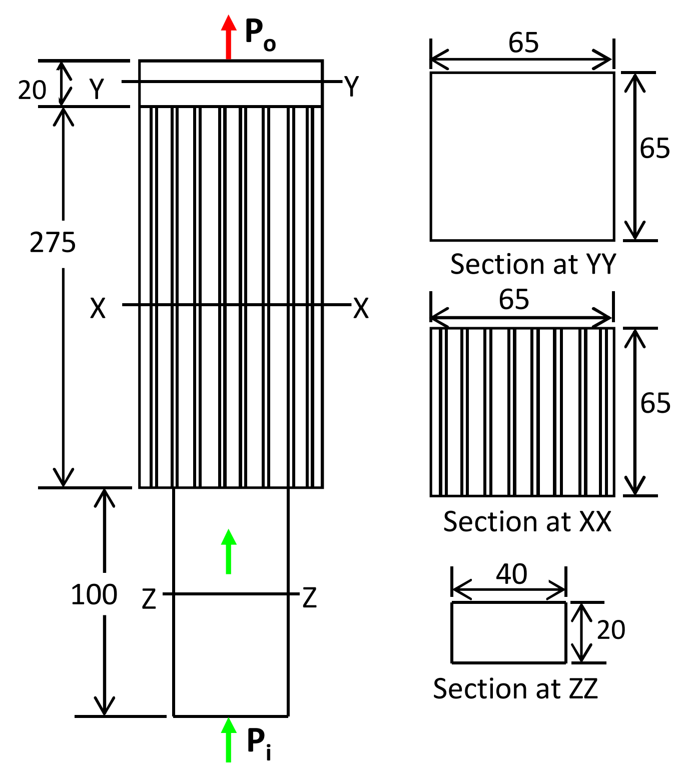
1) Assume a flow rate, W_{n+1} and calculate the nodal temperatures from the FD form of the energy equation using the TDMA procedure.
2) Calculate the integral using Simpson's rule.
3) Recalculate W_{n+1} using the Newton-Raphson procedure from the momentum Eq.
4) Check whether the W_{n+1} is same as that used in the calculation of the nodal temperatures. If not assume a new value of W_{n+1} and repeat steps (1 to 3) until convergence is obtained.
5) Continue the procedure till steady state is achieved.

Note that the marching procedure is iterative in this case. It also involves the solution of a polynomial

Problems

KAMINI is a swimming pool type reactor in which the core is kept vertical inside the pool. The core consists of nine fuel subassemblies arranged in a 3x3 matrix. Each fuel assembly consists of 8-equispaced plate type fuel elements arranged in a 65mmx65mm square channel. Each fuel plate has a thickness 2mm and width of 65 mm. Each fuel assembly has an unheated tail portion of 100 mm length with a rectangular cross section of 40mmx20mm. Above the tail portion, the active core of length 275 mm is located. Above the core an unheated length of 20 mm is provided with 65mmx65mm square cross section. Calculate the transient behavior of the reactor when the power is suddenly raised to 30 kW. The initial temperature in the pool and the fuel assembly can be taken to be 40 ^{0}C. Calculate the power at which boiling occurs in the reactor?

Fig. 2.25: Schematic of the fuel assembly of KAMINI reactor



Solution

The governing equations can be written as

$$\gamma \frac{dW}{dt} = P_i - P_o - g\int_i^o \rho_o\left[1-\beta\left(T-T_0\right)\right]dz - \frac{fW^2 L\xi}{2\rho_o A^3} \; where\; \gamma = \sum_{i=1}^{N}\oint \frac{ds}{A(s)}$$

where ξ is the wetted perimeter. The local losses due to area changes are not accounted here. On integration of the buoyancy force term we get,

$$\gamma \frac{dW}{dt} = g\rho_o\beta\int_i^o \left(T-T_o\right)dz - \frac{fW^2 L\xi}{2\rho_o A^3}$$

The energy equation can be written as

$$\frac{\partial T}{\partial t} + \frac{W}{A\rho_o}\frac{\partial T}{\partial s} = \left\{\begin{matrix} \dfrac{q\xi_h}{A\rho_o Cp} & heater \\ 0 & Unheated\ channel \end{matrix}\right\}$$

Finite difference equations for the momentum and energy equations can be obtained as

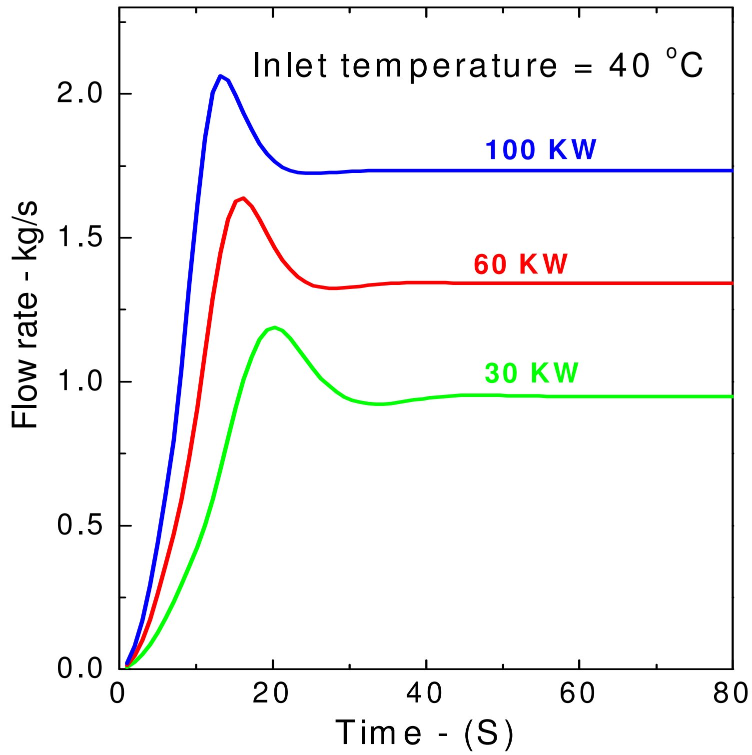
$$\gamma \frac{W_{n+1}-W_n}{\Delta t} = g\rho_o\beta\int_i^o \left(T_i^{n+1}-T_{in}\right)dz - \frac{aW_{n+1}^{2-b} L\xi\mu^b}{2D^b A^{3-b}\rho_o}$$

$$\frac{T_i^{n+1}-T_1^n}{\Delta t} + \frac{W_n}{A\rho_0}\frac{T_i^n - T_{i-1}^n}{\Delta s} = \left\{\begin{matrix} \dfrac{q\xi_h}{A\rho_0 Cp} & core \\ 0 & unheated\ channel \end{matrix}\right\}$$

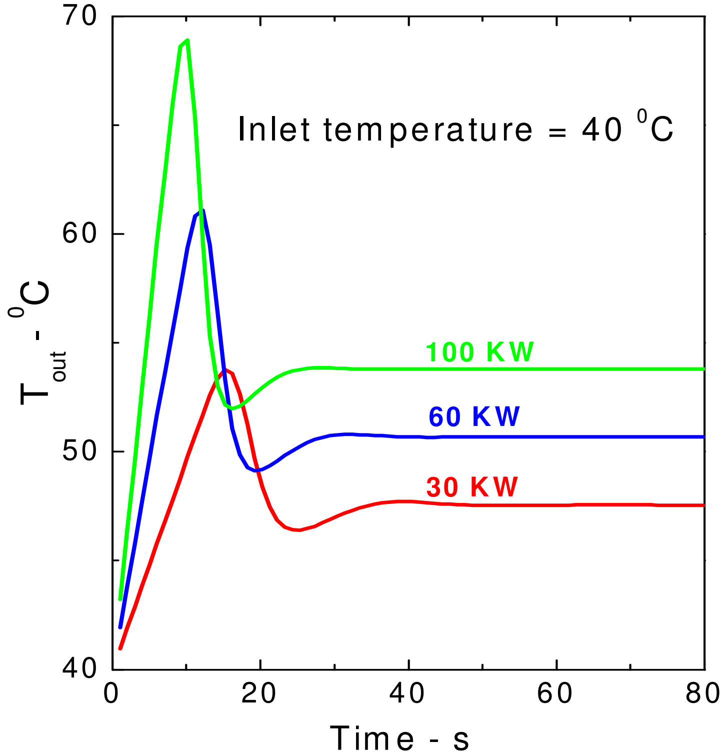
The boundary and initial conditions

(1) at t=0, $T=T_{in}=40\ ^0C$, q=0, W=0 and at t>0, $T_i=T_{in}$ = 40^0C (inlet temperature).

Results are shown in Fig. 2.26. At 400 kW, the core outlet temperature becomes equal to the saturation value.



(a) Mass flow rate

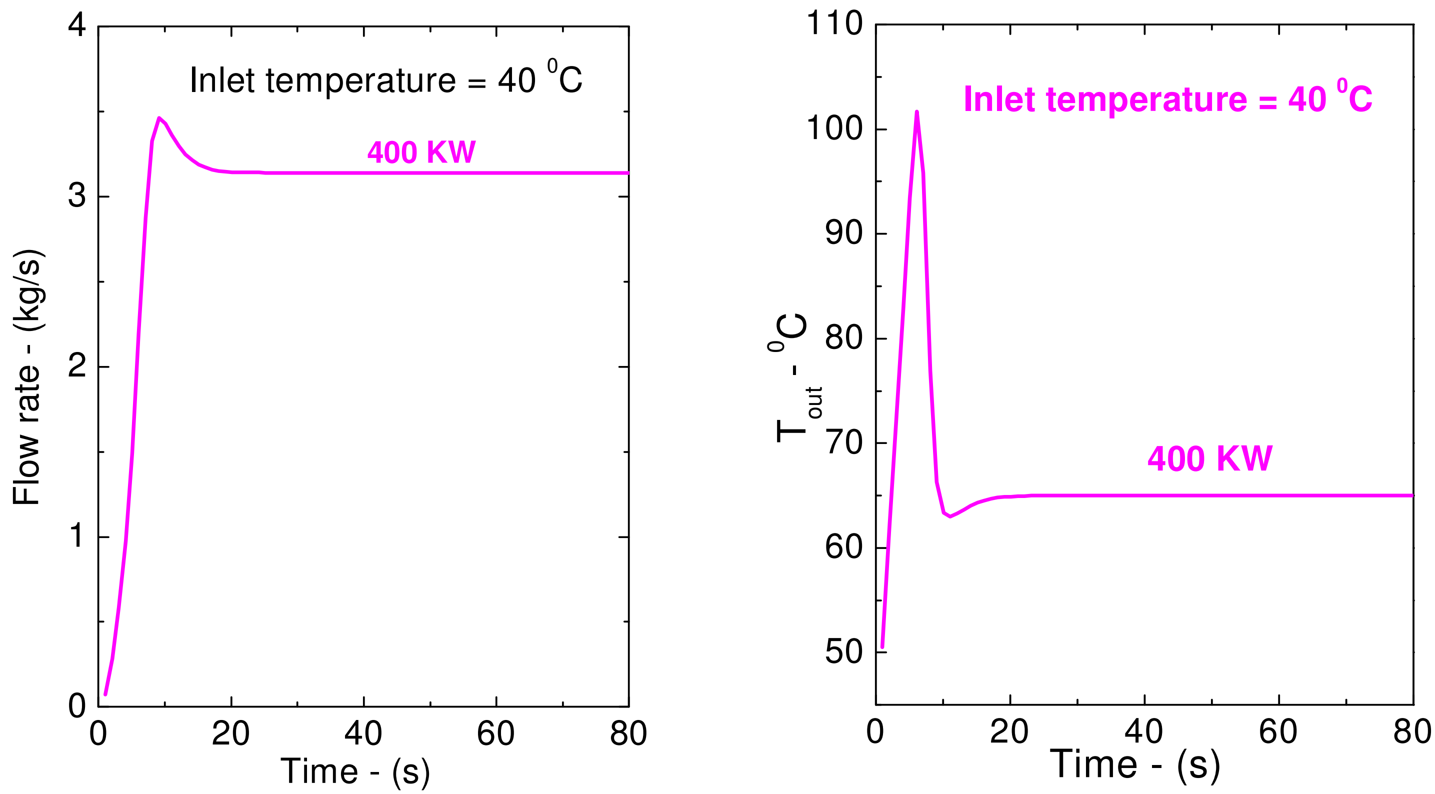


(b) Outlet temperature

Fig. 2.26 Effect of power on the flow and temperature transient in KAMINI reactor

The Transient Behaviour

Assuming that boiling occurs when the core outlet temperature reaches the saturation value corresponding to the pressure, the power can be calculated as 400 kW.



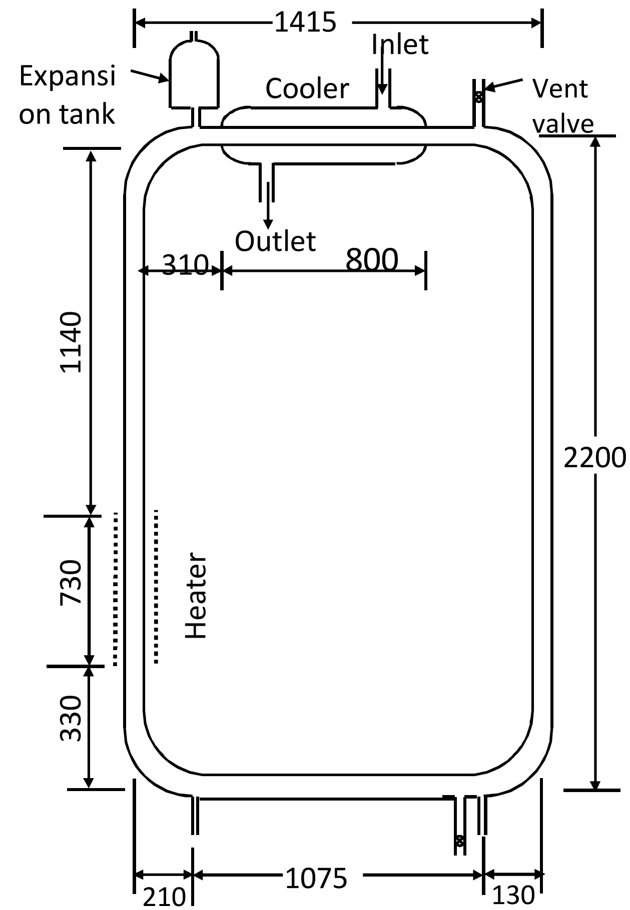
(a) Mass flow rate (b) Outlet temperature

Fig. 2.27 Power required to achieve boiling in KAMINI reactor

Boiling is observed only during the transient and that too, if power is instantane-ously raised to 400 kW from zero. However, at steady state single-phase conditi-ons prevail.

Flow Initiation in a Rectangular Loop

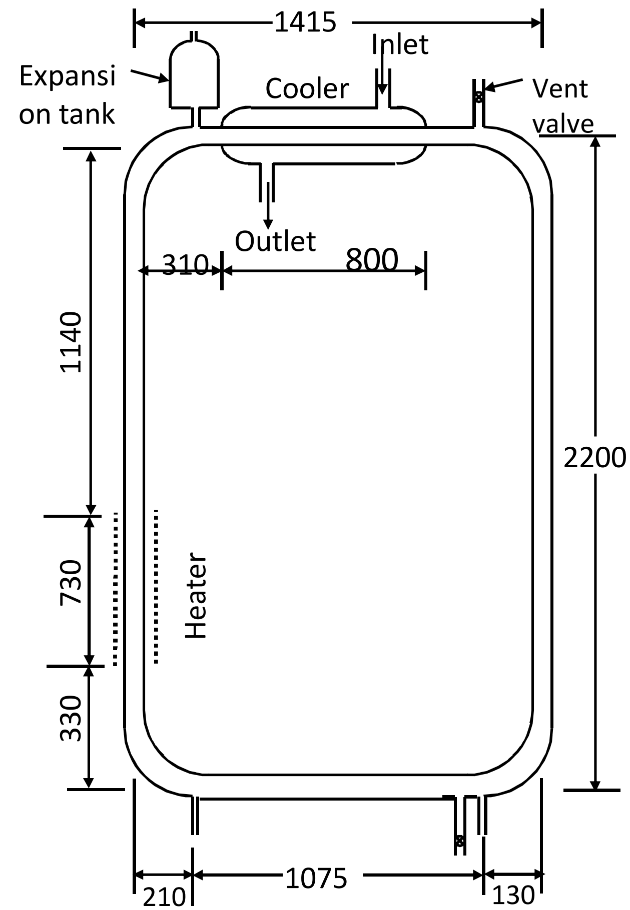
- Consider the uniform diameter NCS with inside diameter of 26 mm made of glass with the length scales as shown in figure. The tube-in-tube cooler has the inner tube outside diameter of 28 mm and outer tube inside diameter of 32 mm and is supplied with cooling water at 10 ^{0}C and 10 lpm. If the entire loop fluid is stagnant at 10 ^{0}C initially, calculate the transient behaviour if the loop heater is suddenly supplied with a uniform heat flux of 16.8 kW/m^2



Geometry of the natural circulation loop considered

Step change in power for a Rectangular Loop

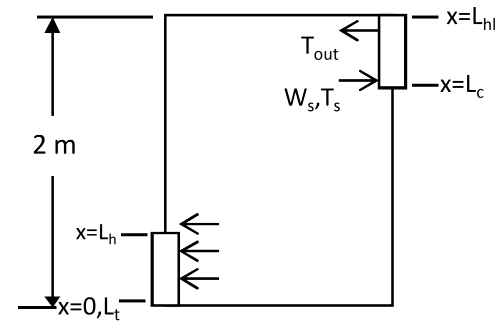
- Consider the uniform diameter NCS with inside diameter of 26 mm made of glass with the length scales as shown in figure. The tube-in-tube cooler has the inner tube outside diameter of 28 mm and outer tube inside diameter of 32 mm and is supplied with cooling water at -10 ^{0}C and 20 lpm. The loop is operating at steady state with uniform heat flux of 16.8 kW/m^2. Calculate the transient behaviour if the heat flux is doubled suddenly.



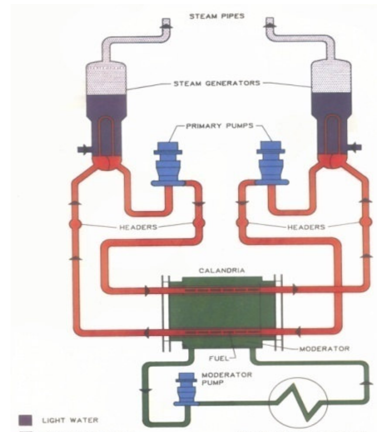
Geometry of the natural circulation loop considered

Problem

- **<u>Problem:</u>** Consider the closed loop shown in Fig. 2.24. Assuming the loop is made up of glass having a uniform diameter of 2.5 cm and total height 2m with identical heated and cooled lengths of 80 cm calculate the transient behavior of the water filled loop when a power of 500 W is suddenly applied to the heater. The heat transfer coefficient at the cooler can be taken as 300 W/m^2K. The initial conditions correspond to stagnant conditions with initial temperature of 25^0C throughout the loop. The width of the horizontal pipes can be taken as 1m so that L_t = 6 m. L_h = 80 cm, L_{hl}=2.2 m, L_c-L_{hl} = 80 cm and T_s = 25^0C.
- The initial boundary and initial conditions are at t=0, T=25^0C for throughout the loop and W=0. Continuity of temperatures is used as the boundary condition i.e. T(x=0) =T(x=L_t) for all t.



Transition from Pumped to Natural Circulation



PHWR-220

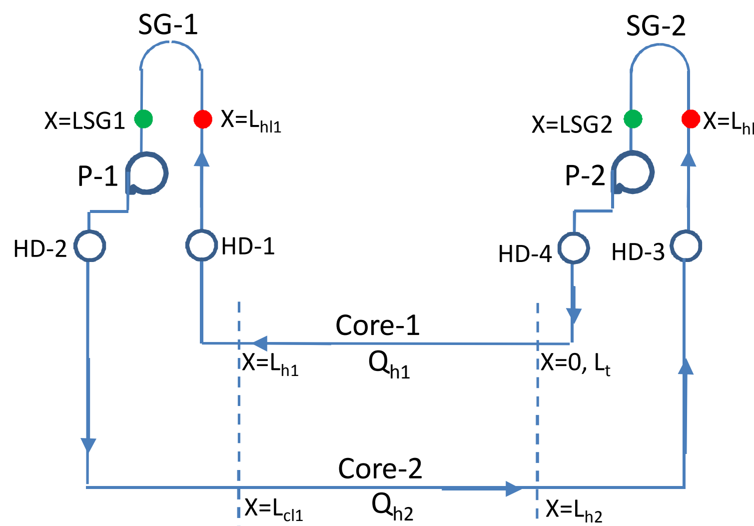
- Consider the Narora 220 Mwe PHWR is operating at 100% FP power. Suddenly the class-IV power failure occurs. Calculate the transient behaviour of flow, temperature and pressure in the primary system if the secondary side is boxed up and the pressure is maintained at 48 bar with the help of ASDV discharge. Assume the decay power curve is given and the flow coastdown by the primary pump is also given as speed vs time.

$$\gamma \frac{dw}{dt} = g\beta\rho_0 \oint T dz - \frac{Rw^2}{2\rho_0} + \rho_0 g H(t) \quad \textit{Momentum Conservation}$$

$$\textit{where } \gamma = \sum_{i=1}^{N} \frac{ds}{A(s)} \; ; R = \sum_{i=1}^{N} \left\{ \left(\frac{fL}{D} + K \right) \frac{1}{A^2} \right\}_i$$

- $\textit{and } H(t) =$ Instantaneous pump developed head

$$\frac{\partial T}{\partial t} + \frac{W}{A\rho_0} \frac{\partial T}{\partial x} - \alpha \frac{\partial^2 T}{\partial x^2} = \begin{cases} \dfrac{4q(t)}{D\rho_0 Cp} & \textit{heater} \\ -\dfrac{4U_a(T - T_a)}{D\rho_0 Cp} & \textit{pipes} \\ -\dfrac{4U}{D\rho_0 Cp}(T - T_s) & \textit{cooler} \end{cases}$$



Nodalisation of PHTS

Transition from Pumped to Natural Circulation – Contd.

- **Pump model**: The instantaneous pump developed head is calculated using the correlation applicable to homologous pumps

$$H(t) = \left(\frac{N(t)}{N_0}\right)^2 H_0$$

- The measured data on instantaneous speed of the pump as shown in the figure can be used.
- **Decay power variation** shown in figure is used to calculate q(t) for both the heaters.
- **PHT system pressure**

$$V_l \frac{d\rho}{dt} = \frac{dm}{dt} \text{ where } V_l \text{ is total loop volume and } m \text{ is the total mass inventory} \qquad (1)$$

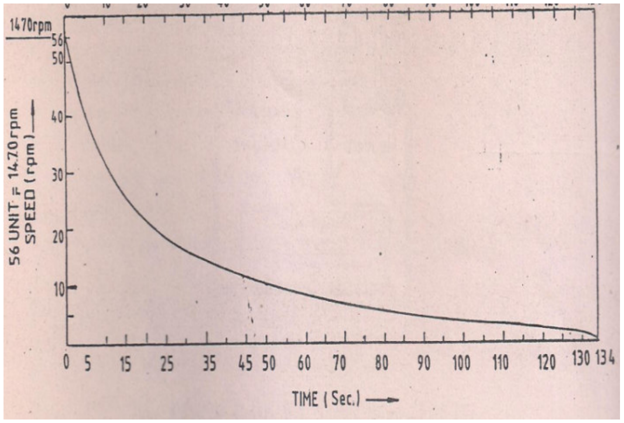
- Since ρ is a function of p and T

$$d\rho = \left(\frac{\partial \rho}{\partial p}\right)_T dp + \left(\frac{\partial \rho}{\partial T}\right)_p dT \text{ or } \frac{d\rho}{dt} = \left\{\frac{\partial (1/v)}{\partial p}\right\}_T \frac{dp}{dt} + \left\{\frac{\partial (1/v)}{\partial T}\right\}_p \frac{dT}{dt}$$

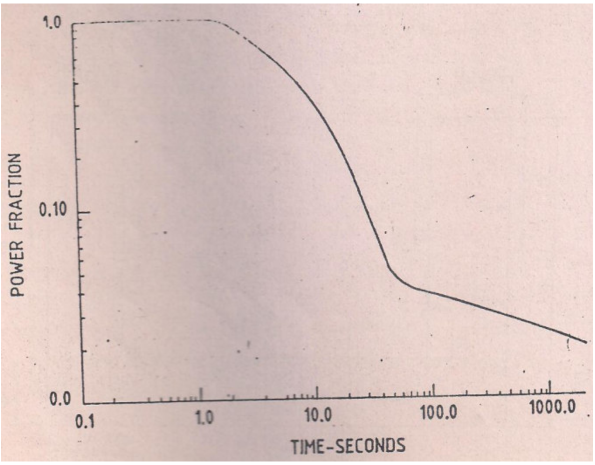
$$\frac{d\rho}{dt} = -\frac{1}{v}\left(\frac{1}{v}\left[\frac{\partial v}{\partial p}\right]_T\right)\frac{dp}{dt} - \frac{1}{v}\left\{\frac{1}{v}\left(\frac{\partial v}{\partial T}\right)_p\right\}\frac{dT}{dt} = -\frac{\alpha}{v}\frac{dp}{dt} - \frac{\beta}{v}\frac{dT}{dt}$$

Using (1) $\dfrac{dp}{dt} = \dfrac{-v}{V_l \alpha}\dfrac{dm}{dt} + \dfrac{\beta}{\alpha}\dfrac{dT}{dt}$ where

$\dfrac{dT}{dt}$ *is obained from the energy equation* & $\dfrac{dm}{dt}$ *is PHT inventory change*



NAPP PHT pump coastdown at 249 ^{0}C from 1470 rpm



Variation of reactor power with time

Transition from Pumped to Natural Circulation – Contd.

- **PHT bleed flow modeling**: Whenever PHT system pressure exceeds 86.3 bar, the bleed valves open and the bleed flow rate is obtained by

$$m_b = 0.023494(P - 86.3) + 5.22241$$

- The feed pump is on class-IV, hence feed flow rate was not modelled. The mechanical seal cooling flow rate was not simulated.
- **SG model**: Enables calculation of SG secondary pressure & temperature variation with time. The mass inventory in the SG is obtained as

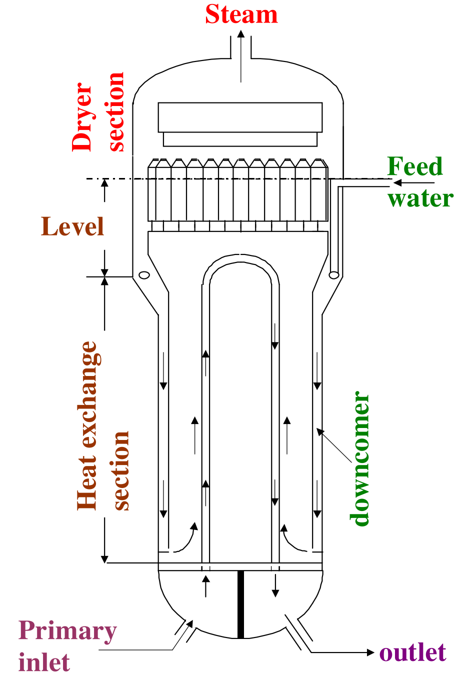
$$\frac{dm}{dt} = m_i - m_o \quad \& \text{ the enthalpy change is obtained as}$$

$$m\frac{dh}{dt} = m_i h_i - m_o h_o + \Delta Q \text{ where } \Delta Q = U_o A_0 (T - T_{sat})$$

- The above equations enable calculation of v_m & h_m

$$\text{The saturation pressure } p_{sat} = f(v_m, h_m)$$

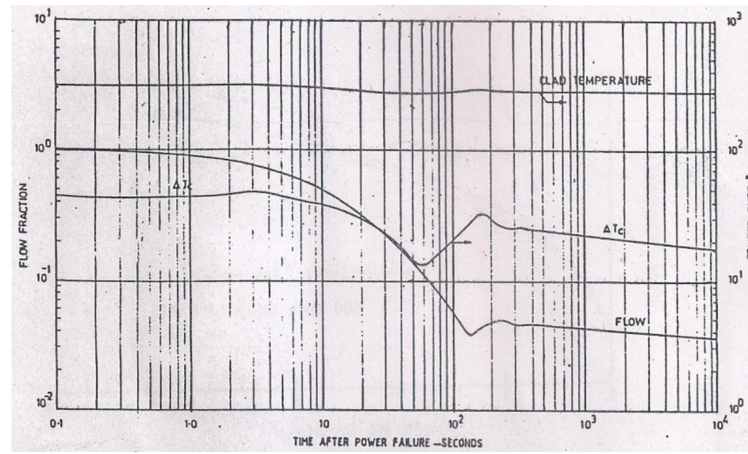
The SG temperature is taken as the corresponding saturation value. The ASDV opening and closing was also modelled.



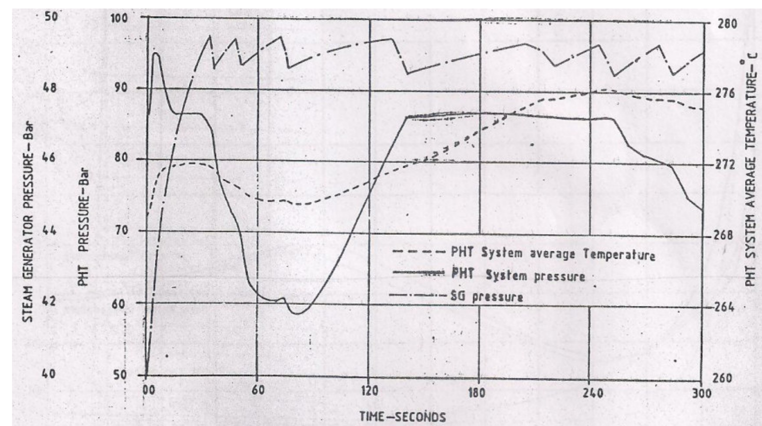
NC SG

Typical Results

- Successfully predicted the primary side and secondary side transient following power failure.
- Flow percent was always more than the power percent.
- Bleed valve limits the primary pressure below the IRV set point
- The ASDV is able to maintain the secondary side pressure below 50 bar.



Transient behaviour of primary flow, core ΔT & clad temperature following power failure at 100%FP



Predicted transient following power failure at 100% FP in NAPP

Problem Assignment

- Compute the transition from Pumped to NC in PHWR-540
- Compute the transition from pumped to natural circulation in VVER

Transient behaviour of ventilation system

- **Problem:** Following a LOCA, the particulate radioactivity released into the containment is detained in the HEPA filter of the containment ventillation system (see figure). Subsequently, the failure of the fan is a concern as it can lead to heating of the HEPA filter due to the heat generated by the absorbed radioactivity. The maximum allowable temperature of the HEPA filter is 300 ^{0}C. Calculate the transient behavior of the temperatures in the filter medium following the fan failure if the total heat generation rate is 2 kW. If the heat transfer coefficient at the filter medium is 70 W/m^{2}K what is the maximum surface temperature achieved? The air mass flow rate with the fan running is 0.04 kg/s. The reference temperature for air property calculation can be taken as 20^{0}C. Boussinesq approximation may be assumed to be valid. The perimeter of the filter can be taken as 1.225 m and its cross sectional area is 90 cm^2. The coastdown time of the fan can be neglected in comparison with the transient time

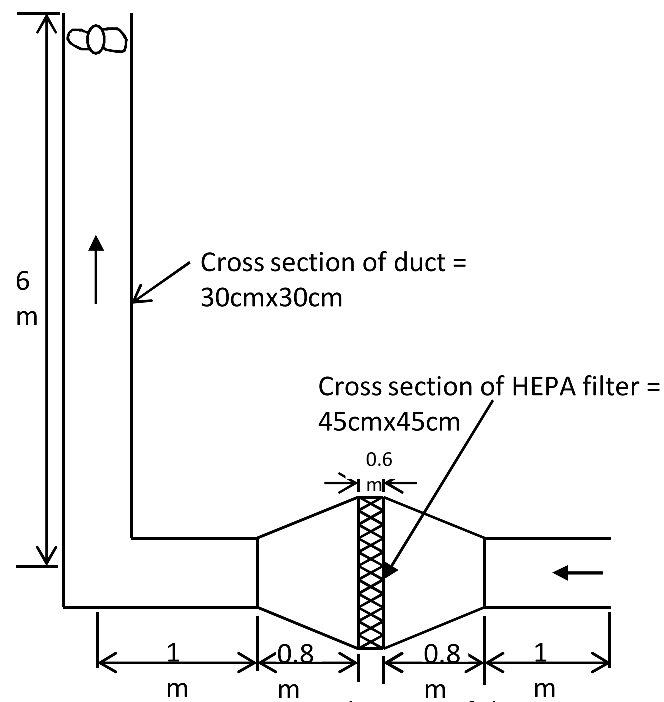


Fig. 2.5.7: Schematic of the ventillation duct

Ventilation system

- **Solution:** The governing equations can be expressed as

$$\frac{1}{A}\frac{dW}{dt} = -\frac{dP}{ds} + \frac{\tau_w \xi}{A} + \rho g \sin\theta$$

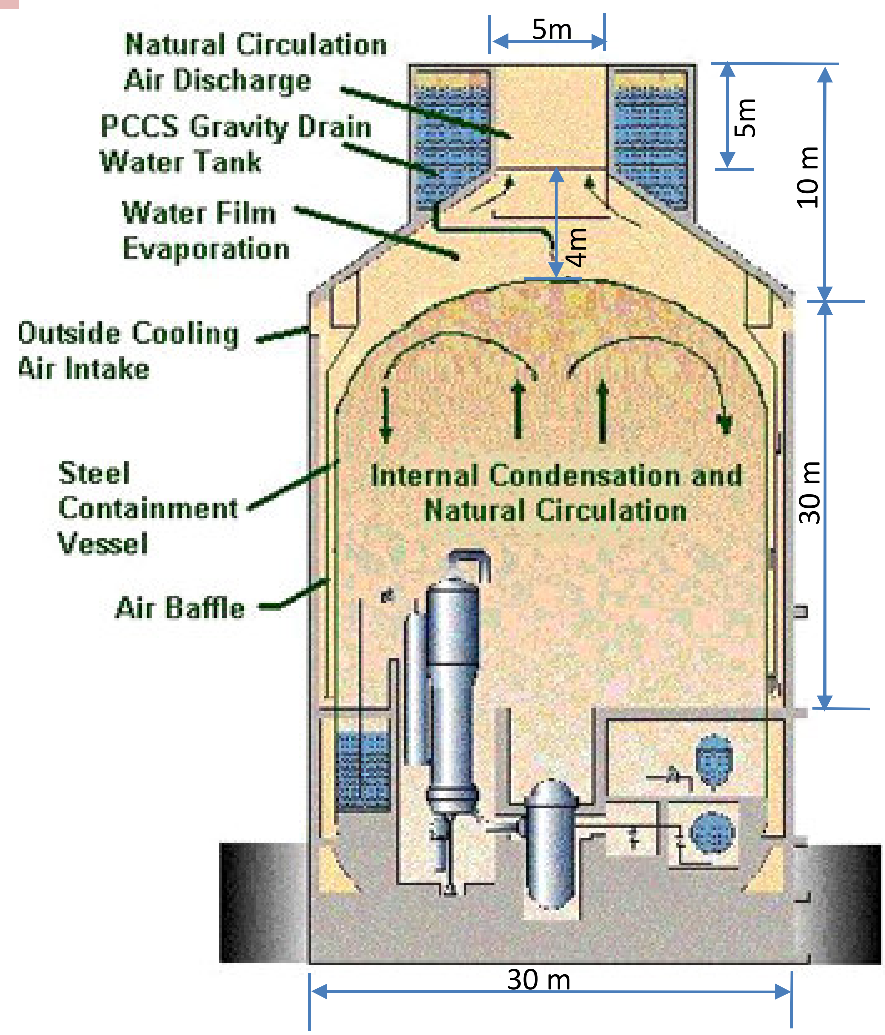
- where θ is the angle with the horizontal in the direction of flow. The energy equation can be written as

$$\frac{\partial T}{\partial t} + \frac{W}{A\rho}\frac{Cp}{Cv}\frac{\partial T}{\partial s} = \begin{Bmatrix} \frac{h\xi_h}{A\rho Cv}\left(T_f - T\right) & filter \\ 0 & unheated\ ducts \end{Bmatrix}$$

- Where T is the air temperature and T_f is the filter temperature. Where ξh is the wetted perimeter of the heater.

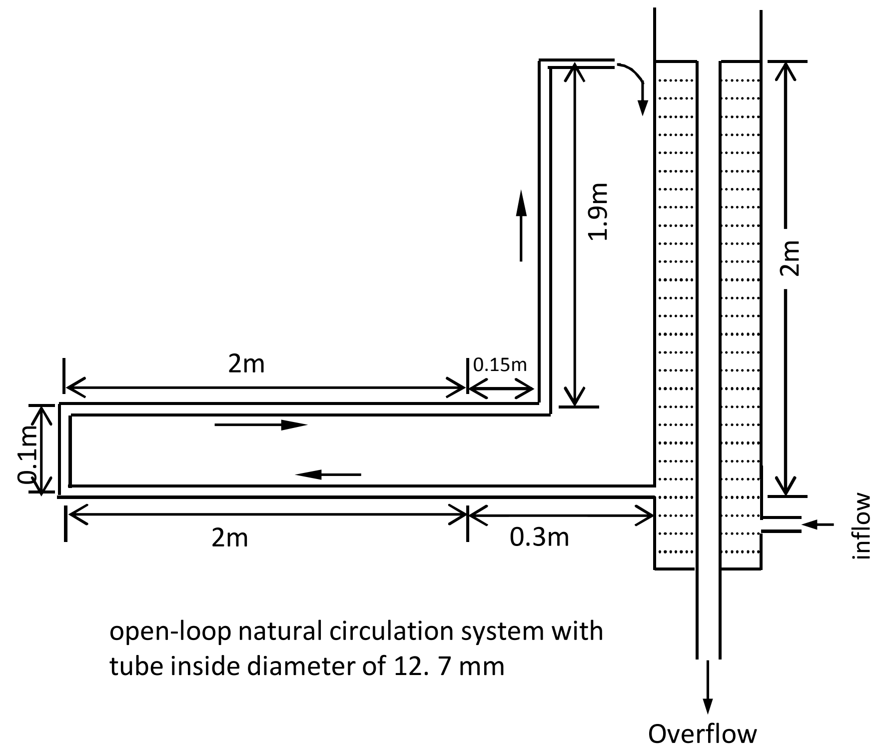
Containment NC Performance

- Calculate the transient air flow rate if the outer surface of the steel primary containment is suddenly brought from ambient temperature of 40 ^{0}C to 110 ^{0}C following a LOCA. The air baffle is dividing the 1m annulus into two halves of width 0.5 m each. The outer diameter of the steel shell is 28m. Other required dimensions are shown in the figure.
- What is the effect of bringing down the outside air intake to the bottom of the secondary containment eliminating the air baffle?
- Repeat the calculations for constant steel outer surface temperature between 60 to 110 ^{0}C?



Open loop natural circulation

- Calculate the transient behaviour in the open loop shown if the heater power is suddenly raised from 100 W to 300 W. The heater portion is 4.1 m long.



open-loop natural circulation system with tube inside diameter of 12. 7 mm

Concluding Remarks

- Methodology described to predict the transient behaviour of single-phase NCS
- Flow initiation from rest and step change in power can be obtained in this way.
- Other transients like sudden change in secondary flow rate, sudden change in the secondary side inlet temperature can also be solved with the methodology described.
- Effect of heat losses can be accounted by solving the wall conduction equation.
- Transition from pumped to natural circulation in reactors can be calculated.
- The technique can also be applied to systems of interest to nuclear reactors


Thanks for Your Attention
Every word against nuclear energy is spoken
with energy derived from nuclear