Introduction to LOFA

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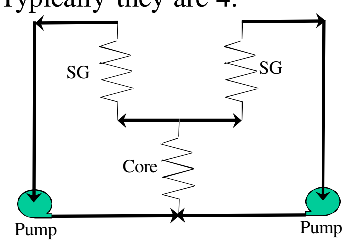
Introduction

- Nuclear power plants have multiple pumps and steam generators
- Part of the reason to split them is to allow part load operation even if one of the pump fails
- Between the full power state and part power state, the system goes through a transient
- Throughout this transient the fuel temperature has to be kept under control to prevent overheating and damage
- When the station loses all external power such as station blackout, then all pumps fail and the system goes through a transient to eventually have natural circulation, should such a mode be possible

All Loops Intact Case-I

- We shall restrict to PHWR and PWR, wherein the flow is single-phase and the schematic view is as sketched
- While we have shown two loops, there may be more than 2. Typically they are 4.



All Loops Intact Case-II

Mass Balance

- At steady state in each leg the mass flow rate is constant and in each junction the sum of all mass flow rate shall be zero, if we assign opposite signs for coming into and leaving the junction

$$\Sigma \dot{m}_{in} = \Sigma \dot{m}_{out}$$

- If there were N loops, then we can say

$$\dot{m}_C = N\dot{m}_L \quad (1)$$

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Momentum Balance

- From earlier part of the course, if the density variation is small, we can conclude that an integration around the loop shall lead to

$$\Sigma \Delta p_A = 0 \qquad \Sigma \Delta p_G = 0$$

- The frictional pressure drop can be written as

$$-\Delta p_{F\text{-}core} = \frac{fl_C}{d_C}\frac{\dot{m}_C^2}{2\rho A_C^2}$$

- If f varies as Re^{-n}, then we can write

$$-\Delta p_{F\text{-}core} = K_C \dot{m}_C^{2-n} \quad \text{Where,} \quad K_C = \frac{l_C}{d_C^{1+n}}\frac{\mu^n}{2\rho A_C^{2-n}}$$

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- Similarly for the loop component other than core, we can write

$$-\Delta p_{F\text{-}loop} = K_L \dot{m}_L^{2-n} \quad \text{Where,} \quad K_L = \frac{l_L}{d_L^{1+n}}\frac{\mu^n}{2\rho A_L^{2-n}}$$

- Integrating around the core and the loop to form a cyclic path, we can write

$$\sum_{cyclic} \Delta p_F = 0$$

$$\Rightarrow \rho g H_P(\dot{m}_L) - K_C \dot{m}_C^{2-n} - K_L \dot{m}_L^{2-n} = 0$$

- Using Eq.(1) that relates the core and loop flow rates, we can write,

$$\Rightarrow \rho g H_P(\dot{m}_C / N) - K_C \dot{m}_C^{2-n} - K_L \dot{m}_C^{2-n} / N^{2-n} = 0 \qquad 2$$

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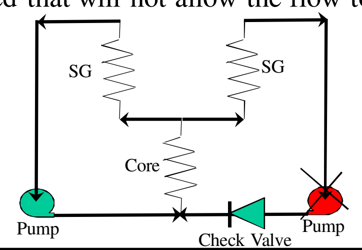
- If an expression is available for the pump characteristics, that is usually supplied the manufacturer, Eq.(2) is a non-linear equation for the single unknown, viz., core flow rate.
- Now let us look at what happens when one pump fails
- Flow shall reverse in the broken loop, unless check valve is provided that will not allow the flow to reverse.



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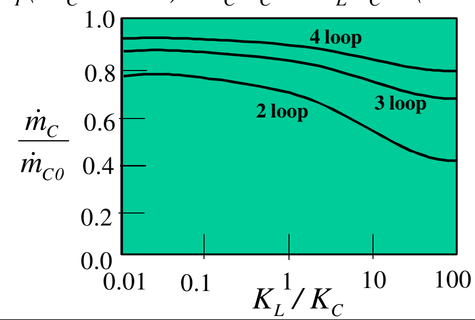
- If the flow does not reverse, then the situation is similar to the case where we have N-1 intact loops. The core mass flow rate in this can be obtained by solving Eq.(2) with N in Eq. (1) to be replaced with N-1

$$\Rightarrow \rho g H_P(\dot{m}_C / N-1) - K_C \dot{m}_C^{2-n} - K_L \dot{m}_C^{2-n} / (N-1)^{2-n} = 0 \qquad 3$$



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Pump Failure with Check Valve-II

- Larger the number of loops, smaller is the fractional loss in core flow.
- For large K_L/K_C, the core pressure drop is small implying the operating point in the loop is determined by loop pressure loss.
- Thus flow from each operating pump shall remain same implying 50 % loss for a 2 loop, 33% for a 3 loop and 25% for a four loop plant
- At lower K_L/K_C, the reduction of core flow is lesser
- Now let us analyse the case when the check valve does not exist or fails to function

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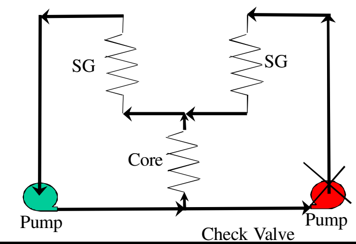
Pump Failure with No Check Valve-I

- As analysed previously the modifed mass flow rate in the core will be connected to the pressure drop as given by,

$$-\Delta p_{F\text{-}core} = K_C \dot{m}_{C*}^{2-n}$$

- Similarly, we can write for the intact and broken loops;

$$-\Delta p_{F\text{-}LI} = K_L \dot{m}_{LI}^{2-n}$$



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Pump Failure with No Check Valve-II

$$-\Delta p_{F\text{-}LB} = K_L \dot{m} \left|\dot{m}_{LB}\right|^{1-n}$$

- The reason for splitting the mass flow rate is to ensure that no problem is caused while programming to evaluate power of a negative number
- Integrating around the intact loop would lead to

$$\Rightarrow \rho g H_P(\dot{m}_{LI}) - K_C \dot{m}_{C*}^{2-n} - K_L \dot{m}_{LI}^{2-n} = 0 \quad (4)$$

- Similarly, integrating around the broken loop would lead to

$$-K_C \dot{m}_{C*}^{2-n} - K_L \dot{m}_{LB} \left|\dot{m}_{LB}\right|^{1-n} = 0$$

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Pump Failure with No Check Valve-III

- Knowing that the mass flow rate is negative in the broken loop, we can rewrite the previous equation such that the solution will give the absolute or the positive value
$$K_C \dot{m}_{C*}^{2-n} = K_L \dot{m}_{LB}^{\;2-n} \quad (5)$$
- The mass balance at the junction of loops at the entrance of the core would imply. Note that $\dot{m}_{LB}$ is positive number
$$\dot{m}_{C*} = (N-1)\dot{m}_{LI} - \dot{m}_{LB} \quad (6)$$
- Equations 4, 5 and 6 are used to solve for $\dot{m}_{C*}, \dot{m}_{LI}$ and $\dot{m}_{LB}$
- We can rewrite Eq. (5) as $\dot{m}_{LB} = \left\langle \dfrac{K_C}{K_L} \right\rangle^{\frac{1}{2-n}} \dot{m}_{C*}$ (7)

Pump Failure with No Check Valve-IV

- Eqs. (6) and (7) imply

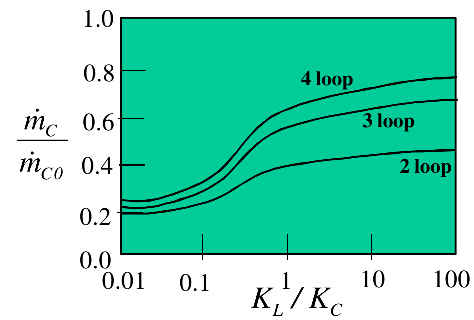
$$\dot{m}_{C*} = (\,N - 1\,)\dot{m}_{LI} - \left\langle \frac{K_C}{K_L} \right\rangle^{\frac{1}{2-n}} \dot{m}_{C*}$$

$$\Rightarrow \dot{m}_{LI} = \frac{\dot{m}_{C*}}{(\,N - 1\,)} \left\langle 1 + \left\langle \frac{K_C}{K_L} \right\rangle^{\frac{1}{2-n}} \right\rangle \qquad 8$$

- Substitution of Eqs. (7) and (8) in Eq. (4) would lead to a non-linear equation in modified core flow rate and can be solved for.

Pump Failure with No Check Valve-IV

- Higher K_L/K_C implies more loop resistance, less bypass and hence has less loss in core flow.
- Trends are opposite for the case with check valve



Analysis of All Pumps Failing

- When a reactor has tripped, and also loses grid power, all the pumps will fail.
- If we can assume that all the loops are symmetric, we need to analyse only one loop.
- Usually pumps are provided with flywheel to keep them rotating for a longer time
- Following the analysis that we have carried out earlier, we can integrate over the loop and can write

$$\Rightarrow \frac{L_C}{A_C}\frac{d\dot{m}_C}{dt} + K_C\dot{m}_C^{2-n} + \frac{L_L}{A_L}\frac{d\dot{m}_L}{dt} + K_L\dot{m}_L^{2-n} - \rho g H_P(\,\dot{m}_L\,) = 0 \qquad 9$$

- Mass balance implies $\dot{m}_C = N\dot{m}_L$ 10

- Eqs. (9) and (10) would imply

$$\Rightarrow \frac{L_C}{A_C} N \frac{d\dot{m}_L}{dt} + K_C N^{2-n}\dot{m}_L^{2-n} + \frac{L_L}{A_L}\frac{d\dot{m}_L}{dt} + K_L\dot{m}_L^{2-n} - \rho g H_P(\,\dot{m}_L\,) = 0$$

- The above equation can be written as

$$\Rightarrow \left\langle \frac{L}{A} \right\rangle_{Eq} \frac{d\dot{m}_L}{dt} + K_{Eq}\dot{m}_L^{2-n} - \rho g H_P(\,\dot{m}_L\,) = 0 \qquad 11$$

Where, $\left\langle \frac{L}{A} \right\rangle_{Eq} = N\frac{L_C}{A_C} + \frac{L_L}{A_L}$ and $K_{Eq} = K_L + K_C N^{2-n}$ 12

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- As the power is lost, the pumps will begin slowing down and hence developed head by the pump will decrease.
- Using the characteristics of the centrifugal pump, the head developed ( ) depends on the angular velocity ω as,

$$\frac{H_P}{\omega^2} = \frac{H_{P0}}{\omega_0^{\,2}} \qquad \Rightarrow H_P = \frac{H_{P0}}{\omega_0^{\,2}}\omega^2 \qquad (13)$$

- When a pump starts rotating at speeds less than the rated speed, the friction in the pump increases. The torque necessary to drive the pump can be written as

$$I\frac{d\omega}{dt} = -C\omega^2 \qquad (14)$$

I is the mass moment of inertia of the pump, C is called windage coefficient

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- Separating the variables and Integration of Eq. (14) gives

$$\left.\frac{d\omega}{\omega^2}\right|_{\omega_0}^{\omega} = -\frac{C}{I}dt\Big|_0^t \qquad \Rightarrow \left.\frac{-1}{\omega}\right|_{\omega_0}^{\omega} = -\frac{C}{I}t\Big|_0^t$$

$$\Rightarrow \frac{1}{\omega_0} - \frac{1}{\omega} = -\frac{C}{I}t \qquad \Rightarrow \omega \frac{\omega_0}{1+\dfrac{C\omega_0}{I}t}$$

$$\Rightarrow \frac{\omega}{\omega_0} = \frac{1}{1+\dfrac{t}{T_P}} \text{ Where, } \quad T_P = \frac{I}{C\omega_0}$$

- T_P is called the pump half time.

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- Substituting the solution of ω in Eq. (11) and utilising Eq. (13) gives

$$\left\langle\frac{L}{A}\right\rangle_{Eq}\frac{d\dot{m}_L}{dt} + K_{Eq}\dot{m}_L^{2-n} - \rho g\frac{H_{P0}}{\omega_0^{\,2}}\frac{\omega_0^{\,2}}{(1+t/T_P)^2} = 0$$

$$\Rightarrow \left\langle\frac{L}{A}\right\rangle_{Eq}\frac{d\dot{m}_L}{dt} + K_{Eq}\dot{m}_L^{2-n} - \rho g\frac{H_{P0}}{(1+t/T_P)^2} = 0$$

- The above is a first order ODE and can be integrated numerically.