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WEIR INSTABILITY ANALYSIS OF FBR COOLING CIRCUIT

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ABSTRACT

The main vessel (MV) is the most critical component in the reactor assembly. An important feature is that MV temperature is maintained below creep and embitterment regime (<700 K) under all prolonged operating conditions to. This is achieved by incorporating a cooling system which consists of two thermal baffles viz. outer baffle (OB) and inner baffle (IB) positioned in the annular space close to the main vessel. Twenty four cooling pipes facilitate the flow of a fraction (about 3 % ~ 200 kg/s) at cold pool sodium to the baffles. The steady flow of cold sodium over the inner surface of MV protects it against the radial heat flux from hot pool, there by maintaining temperature less than 700 K. With the overflow system, the level fluctuations which in turn cause temperature fluctuations normally encountered in the large pool surfaces are eliminated; thereby the MV is protected against high cycle fatigue damage. The OB and IB form feeding and restitution collectors respectively. The sodium from feeding collector flows over the OB and falls through a height of 0.3 m before impacting on the free surface of restitution collector. The fall of sodium may become a source of vibration of the baffles. Such vibrations have been already noted in case of Superphenix-1 during its commissioning stage. This paper deals with the vibration mechanisms in the MV cooling system and theoretical model to obtain the stability chart (relationship between the operating parameters) for avoiding such vibration. Methodology was developed for the weir instability analysis of main vessel cooling circuit. From literature Aita's stability criterion is adopted. The criterion is improved by eliminating few assumptions for the Type-1 stability criterion. For the fall height of 0.3 m, the present cooling system is stable based on Type-1 and Type-2 criterion of instability. However the system is more critical based on Type-2 stability criterion.

INTRODUCTION

The main vessel is the most critical component in the reactor assembly, since its failure has got significant impact on safety. Hence, it is designed by incorporating many features which provide high reliability. An important feature is that MV temperature is maintained below creep and embitterment regime (<700 K) under all prolonged operating conditions to. This is achieved by incorporating a cooling system which consists of 2 thermal baffles (TB) viz. outer baffle (OB) and inner baffle (lB) positioned in the annular space between the main vessel (MV) & inner vessel (IV) and 24 cooling pipes to facilitate the flow of a fraction (about 3 % ~ 200 kg/s) at cold pool sodium from the grid plate (CSS) plenum. The steady flow of cold sodium over the inner surface of MV protects it against the radial heat flux from hot pool, there by maintaining temperature less than 700 K. With the overflow system, the level fluctuations which in turn cause temperature fluctuations normally encountered in the large pool surfaces are eliminated; thereby the MV is protected against high cycle fatigue damage. The schematic of TB is shown in Fig.1.

The OB and IB form feeding and restitution collectors respectively. The sodium from feeding collector flows over the OB and falls through a height of 0.3 m before impacting on the free surface of restitution collector. The fall of sodium may become a source of vibration of the baffles. The vibration mechanisms in the MV cooling system are studied. Theoretical model to obtain the stability chart (relationship between the operating parameters) for avoiding such vibration are presented.

TYPES OF MECHANISMS

There are two types of mechanisms involved in the instability of weir system.

Type 1

This mechanism is purely a sloshing type and is due to strong coupling between two thin collectors (feeding and restitution) because of very flexible shell in between them. There exist two types slosing modes (in phase and out of phase) wherein the movements of free surfaces of feeding and restitution collectors are 'in phase' and 'out of phase' respectively. The 'out of phase' mode induces pressure variation along the circumference which in turn causes vibration of the shell, whereas the 'in phase' mode does not produce any pressure variation along the circumference. When the frequencies of these two modes are very close the effect of 'out of phase' mode is dominated by the effect of 'in phase' mode thus the vibration of the shell is more improbable and vice versa.
Moreover, the damping of the structure is also a controlling parameter in this type of mechanism. The more the damping value, the less is the risk of vibration. This mechanism is very much controlled by the risk of vibration. This mechanism is very much controlled by the ratio of damping factor and relative resonance frequency difference between the two sloshing modes (ε / Δf). This mechanism will occur at low frequency. The amplitude of surface motion of sodium is less compared to that of shell.

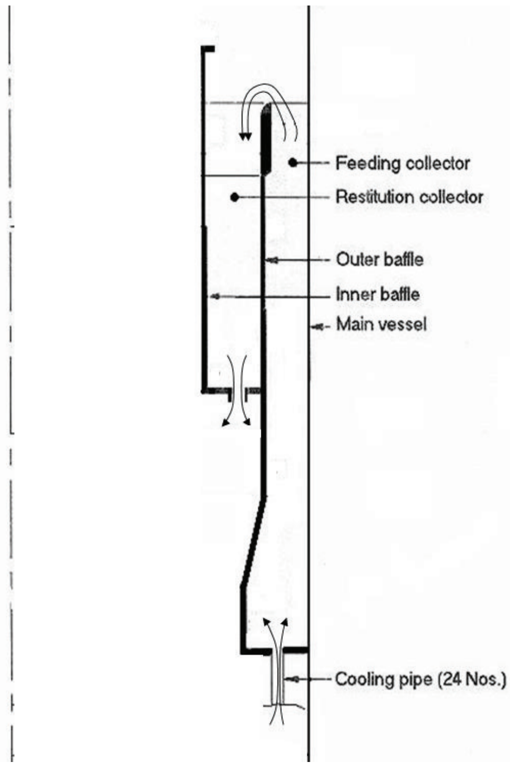

Figure. 1 Schematic of thermal baffle

Type 2

This mechanism is mainly due to the fluid – structure interaction. This occurs at high flow-rate and fall

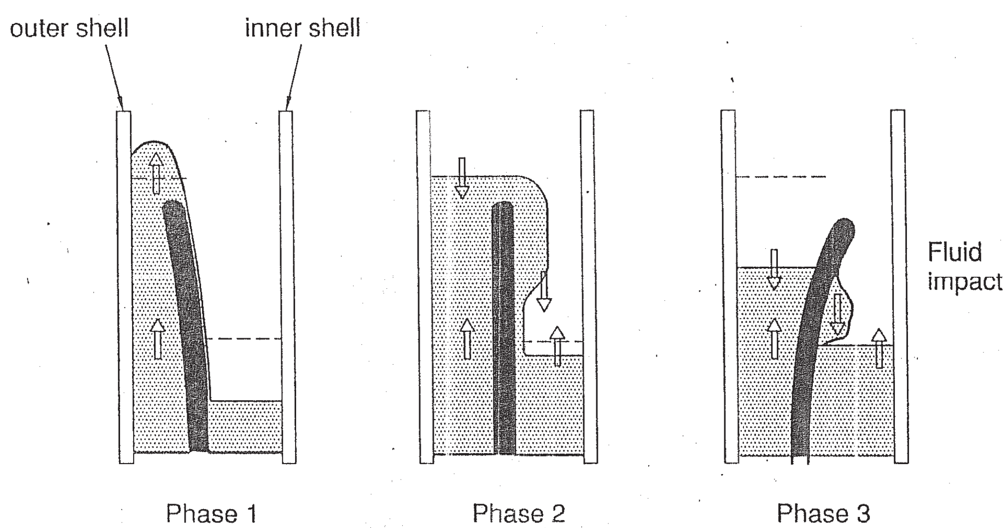

Figure. 2 Schematic of 'out of phase' instability

heights. The frequency corresponding to this mechanism is much higher than those that of Type 1 mechanism. This type of mechanism is pictorially represented in Fig. 2.
Inside movement of the outer baffle reduces pressure on the feeding collector and increases pressure on the restitution collector, which will move the baffle outside again, thereby the shell gets the self excitation due to its own movement itself. This mechanism is very much controlled by the ratio of the sodium free surface amplitudes of the two collectors (feeding to restitution) of a particular fluid-structure mode. For a given fluid–structure mode the ratio is always negative.

THEORETICAL MODEL

Though the governing equations controlling this instability phenomenon are nothing but the equilibrium equations for the given fluid–structure system, the identification and derivation of the exciting forces are important and essential step in the theoretical formulation. The governing forces are due to effect of free surface oscillations, discharge flow rate from feeding to restitution collectors and friction on associated shell surfaces. The theoretical model is adopted from (Aita, et. al. 1986).

Effect of free surface

Gravity effects on fluid free surfaces are modulated as

$$P_i = \rho_f\, g\, h_i \tag{1}$$

i = 1, 2 corresponding to feeding and restitution collectors
P_i = pressure at mean surface level
g = gravitational acceleration
ρ_f = density of fluid

Effect of discharge on feeding collector

The discharge flow rate from feeding collector is

$$q_d = K\sqrt{g}\, h_1^{3/2} \qquad h_1 > 0$$
$$q_d = 0 \qquad h_1 \le 0 \tag{2}$$

Where, h_1 = height of fluid surface from weir shell edge
K = weir constant.

Since flow is going out of feeding collector, let us introduce a negative "flow rate source" as

$$\Delta q_1 = -\, q_d(t, \theta) = -K\sqrt{g}\, h_1^{3/2}(t, \theta) \tag{3}$$

Where, t = time
θ = circumferential angular position

The volume conservation at any moment be verified by

$$\int_0^{2\pi} (\rho_f e_1 \frac{\partial h_1}{\partial t} + q_d)\, d\theta = 2\pi q_0 \tag{4}$$

Where e_1 = width of feeding collector
q_0 = mean feeding mass flow rate per unit length of weir edge

Effect of discharge on restitution collector

The discharged fluid reaches the restitution collector after a delay time τ corresponding to fall time.

$$\Delta q_2 = q_d(t - \tau, \theta) \tag{5}$$

The fluid arrives the restitution free surface with a velocity of V_f. The momentum equation integrates in a small fluid volume (height Δz) near the free surface.

$$\int_0^{2\pi} (\rho_f e_1 \frac{\partial h_1}{\partial t} + q_d) d\theta = 2\pi q_0 \tag{6}$$

P_2 = pressure at the level Δz below free surface
e_2 = width of restitution collector

The first part of equation (6) is similar to the equation (1). The other part is equivalent to introduce at free surface level, a force per unit length

$$f(t,\theta) = - p_f \;\; q_d\,(t-\tau,\theta) V_f \tag{7}$$

Friction effect on falling film

To estimate the delay time τ and film velocity V_f, we must consider the friction effect along the weir shell. The weir flow is similar to open channel flow, hence Moody type equation can be used to determine friction co-efficient. For higher Renold's number ($R_e > 10^6$), Manning type correlation can be used. By effect of friction, the weir flow reaches a limit velocity V_l so that pressure drop dH_f over a fall height dz is

$$dH_f = f \frac{1}{D_h} \frac{V_l^2}{2g} dz \tag{8}$$

If it is a free fall then the velocity of fluid is $V_g = \sqrt{2gH}$

The equilibrium equations of the system, projected on the χ_{nm}, can be written as:

$$M_{nm}\left(\ddot{\alpha}_{nm} + 2\varepsilon_{nm}\omega_{nm}\dot{\alpha}_{nm} + \omega_{nm}^2 \alpha_{nm} \right) = \left(\chi_{nm}, \Delta q_1\right) + \left(\chi_{nm}, \Delta q_2\right) + \left(\chi_{nm}, F\right) \tag{9}$$

Where, ω_{nm} = resonance pulsation
ε_{nm} = modal damping
χ_{nm} = "fluid-structure" mode shape
M_{nm} = generalized mass

Let us consider the system of equations formed by (9), (3), (5) and (7). The free surface heights can be written as

$$h_i(t,\theta) = h_{0i} + \sum_{nm} d_{nm}(t) Z_{nm}^{(i)}(Q) \tag{10}$$

h_{0i} = the free surface height over reference level in permanent stable situation
Z^i_{nm} = the component of χ_{nm} corresponding to collector free surface vertical motion

Using the expressions 1-10, the governing equation is written in the following non-dimensional form

$$\left(\Omega_{nm}^2 - \Omega^2 + Zi\varepsilon_{nm}\Omega_{nm}\Omega\right)\alpha_{nm} + \lambda_{nm}\left(i\frac{\Omega}{\Omega_{nm}^2} Z_{nm}^{(1)} - i\frac{\Omega}{\Omega_{nm}^2} Z_{nm}^{(2)} e^{-i\beta\Omega} + UZ_{nm}^{(2)} e^{-i\beta\Omega} \right)\left(\sum_{nm} Z_{nm}^{(1)} \alpha_{nm} \right) = 0 \tag{11}$$

Here, Ω_{nm} = Non dimensional modal pulsation = ω_{nm} / ω_0
Ω = ω / ω_0
ω_0 = characteristic sloshing pulsation = $\sqrt{(g / L)}$
β = non dimensional delay = $\omega_0 \tau$
U = non dimensional impact velocity = $V_f / V_0 = q_0 / eV_0$
V_0 = $\sqrt{(gL)}$
e = width of collectors = $e_1 = e_2$

$$\lambda = \frac{3}{2}\frac{U^{1/3}}{M_{nm}}\left(\frac{e}{L}\right)^{-2/3}$$

M_{nm}	= non dimensional modal mass m_{nm} / m_0	
m_0	= characteristic mass	$= \pi \rho_f LRe$
L	= characteristic length	= R / n
n	= circumferential wave number	

The above non-linear equations can be solved for the responses. However the present scope is limited to obtaining the conditions for instability from the above equation.

AITA'S SIMPLIFIED CRITERIA

The first order development of the above equation leads to two simplified instability criteria. One is for coupled sloshing modes and the other is for fluid structure interaction mode.

Case of a couple of close resonance frequencies (sloshing mode

It concerns with sloshing modes of the free surfaces of the feeding and restitution collectors. The simplified instability criteria can be written as:

$$\sin\ \beta - U\ \cos\ \beta < \frac{\varepsilon}{\Delta\Omega_0} \tag{12}$$

ε = global modal damping coefficient
Δf = relative resonance frequency difference between the coupled sloshing modes.

The first member of the instability criteria is a function of non-dimensional delay β and the non-dimensional impact velocity U. If free fall considerations are assumed, this function can be plotted as in Fig. 5. It reaches a first maximal value of π. The delay limit, and corresponding fall height limit of instability can be calculated from (12) as a function of $(\varepsilon/\Delta\Omega_0)$. If friction of the falling fluid is considered, instability potentiality will be decreased and fall height limits will depend upon flow rate. Then equation (12) gives us a stability domain in the fall height v/s flow rate diagram.
The above criterion is refined to get following relation (Jaladeen, S et. al. 2013). In the AITA'S criteria, the following assumptions are made:

$$MG_1 = MG_2$$

Where $MG_{1,2}$ generalized mass of mode (1) and mode (2).

$$Z_1^1 = Z_1^2\ ; Z_2^1 = Z_2^2$$

Where $Z_{1,2}^{1,2}$ modal shape of free surface of feeding and restitution collectors

The above assumptions made in AITA'S criteria are applicable to very specific case. In more general cases, the following assumptions are very much suitable and they are:

$$\frac{MG_1}{MG_2} = M$$

(Ratio of generalized masses of mode (1) and mode (2))

$$Z_1^1 \neq Z_1^2\ ;\ Z_2^1 \neq Z_2^2$$

Based on this refined assumptions, the simplified criteria is obtained as follows for Type-1 instability (sloshing modes):

$$Sin\ \beta - U\ Cos\ \beta < \frac{\varepsilon\left[(K_1 Z_1^1 + K_2 Z_2^1\right] - (Cos\ \beta + U\ Sin\ \beta)\,(K_1 Z_1^2 + K_2 Z_2^2)}{\Delta\,\Omega_0\left[K_2 Z_2^2 \text{ - } \mathrm{K}_1 Z_1^2\right]} \tag{13}$$

Where : $K_1 = M_1 Z_1^1$, $K_2 = M_2 Z_2^1$

Case of an isolated resonance frequency (FSI mode)

It concerns with the fluid shell modes where gravity has very little influence. The instability criteria can be written as:

$$\cos \beta \Omega_{nm} + U\Omega_{nm} \sin \beta \Omega_{nm} > \frac{Z_{nm}^{(1)}}{Z_{nm}^{(2)}} \tag{14}$$

For concerned modes, ($Z^{(1)}_{nm}/Z^{(2)}_{nm}$) is always negative. The LHS of (14) is again a function of β and U which can be plotted assuming a free fluid fall. It reaches a first maximal value of ($-3\pi/2$). If absolute value of ($Z^{(1)}_{nm}/Z^{(2)}_{nm}$) > $3\pi/2$, no instability can occur. Friction will also reduce instability potentiality and fall height limits. Then another stability domain is obtained from relation (14) in fall height v/s flow rate diagram.

ANALYSIS FOR FBR TB

Axi-symmetric model of the TB along with MV consist of 2 noded axi-symmetric shell element is used for the analysis with CASTEM FE software. Sodium is modeled as four nodded liquid element. The connection between the structure and liquid is modeled by the fluid-structure interaction element. The free surfaces are modeled using surface elements.
The analysis is carried out for the axi-symmetric geometry with Fourier decomposition to account for the circumferential variations of load flow. Figure 3 shows the ‘in phase’and ‘out of phase’ modes of sloshing. Damping coefficient at normal condition is taken as 6% to 8%. Roughness at normal condition is assumed to be 0.00075 to 0.0015. Flow rate is varied from 0.0 to1.0 m^3/s (nominal flow rate is ~0.23 m^3/s) and fall height is varied from 0.0 to 1.0 m (nominal fall height is 0.3 m).

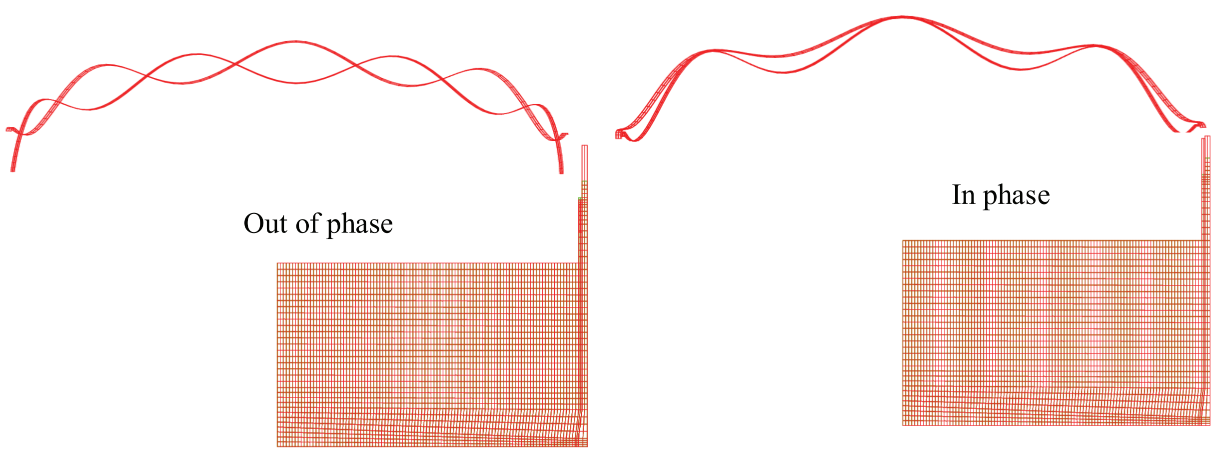

Figure 3. Coupled modes of sloshing

Sloshing as well as structural mode shapes are extracted for various azimuthal numbers (n = 1 to 10). Knowing the mode shapes the relative difference (Δf) between sloshing frequencies for all ‘n’, thefirst structural frequency and the modal displacement for the free surface are found out. The delay time τ and impact velocity V_f and from which non-dimensional delay time β and non dimensional impact velocity U for a given height of fall considering the friction of the surface are determined. Based on the stability criterion stability chart is obtained in the flow rate and fall height region. The stability charts are shown in Figure 4 and 5 for Type 1 and Type 2 instability respectively.

Table 1 – Parameters for Type 1 (old as well as improved criteria) criterion

F N	f_1 (Hz)	f_2 (Hz)	$\Delta\xi$	Mass (kg)		Normalised displacements			
				m_1	m_2	z_{11}	z_{12}	z_{21}	z_{22}
1	0.1483	0.1688	0.1297	108	224	0.0095	-1.0000	-1.0000	-0.0198
2	0.2617	0.2768	0.0561	338	605	0.0277	-1.0000	-1.0000	-0.0496
3	0.3412	0.3470	0.0169	592	979	0.1228	-1.0000	-1.0000	-0.2032
4	0.3987	0.4017	0.0075	1804	1446	0.8822	-1.0000	-0.7071	-1.0000
5	0.4428	0.4497	0.0155	2112	1329	-1.0000	0.6991	-0.4411	-1.0000
6	0.4810	0.4931	0.0248	2763	1742	-1.0000	0.8171	-0.5175	-1.0000
7	0.5189	0.5341	0.0289	3032	1703	1.0000	-0.9477	0.6012	1.0000
8	0.5593	0.5731	0.0243	2611	1497	1.0000	-0.9719	0.6169	1.0000
9	0.5994	0.6097	0.0171	2076	1228	1.0000	-0.8830	0.5605	1.0000
10	0.6366	0.6442	0.0119	1608	972	1.0000	-0.7182	0.4558	1.0000
11	0.6707	0.6768	0.0091	1275	780	1.0000	-0.5315	0.3372	1.0000
12	0.7023	0.7078	0.0078	1067	655	1.0000	-0.3706	0.2351	1.0000

Table 2 – Parameters for Type 2 criterion

Fourior No.	Frequency (Hz)	z_1	z_2
3	2.7733	1.0000	-0.5132
4	2.3282	0.9930	-0.5044
5	1.9867	0.9933	-0.5884
6	1.8031	0.9940	-0.8119
7	1.8033	-0.9349	0.9596
8	2.0075	-0.8353	0.9530
9	2.3962	-0.8145	0.9212
10	2.8741	1.0000	-0.0106
11	2.8753	-0.9924	0.0009
12	2.8759	-0.9919	0.0004

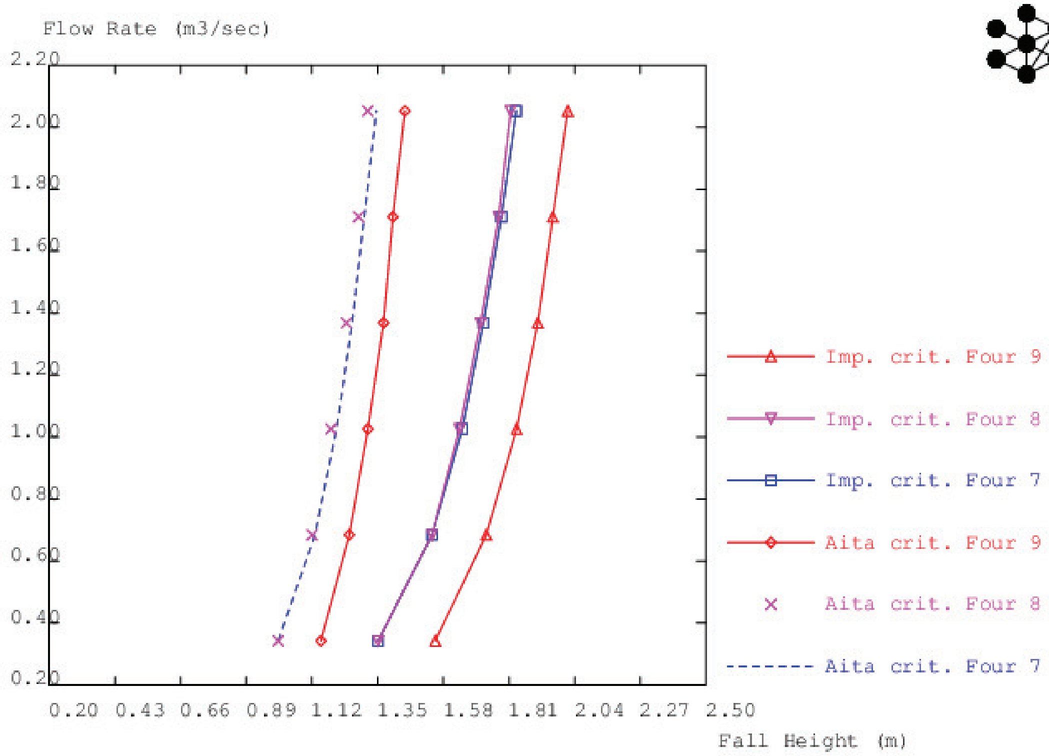

Fig. 4 Weir stability Type-1 chart for thermal baffle

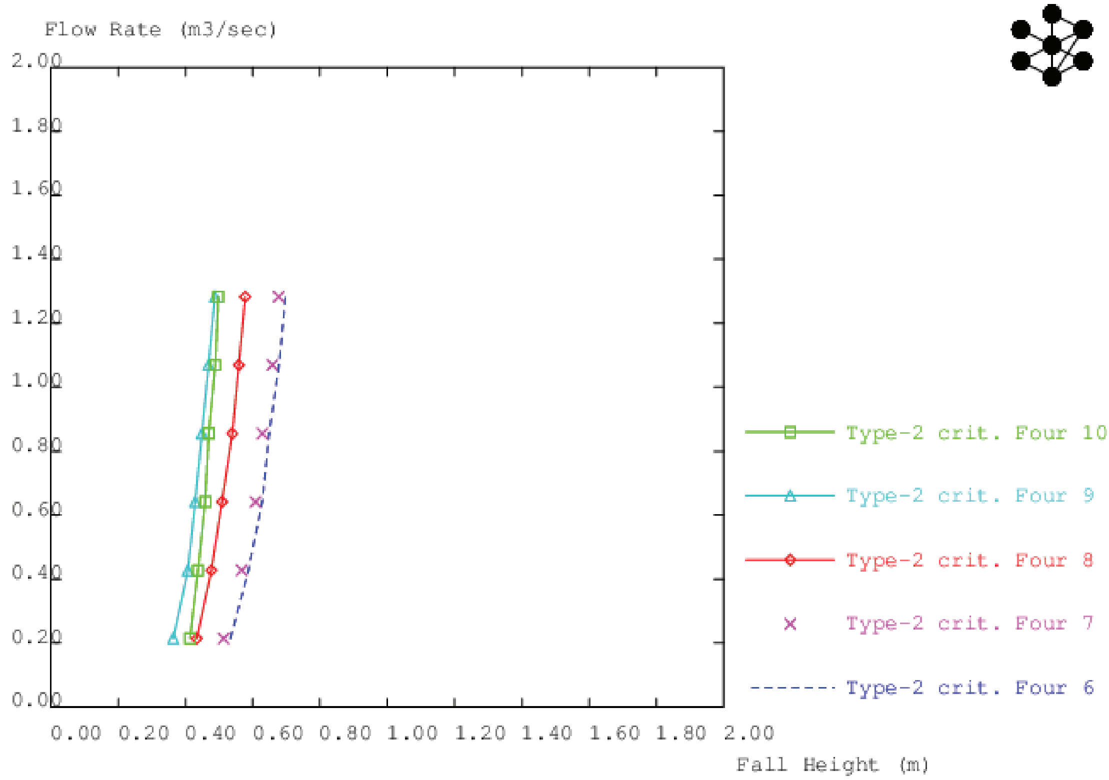

Fig. 5 Weir stability Type-2 chart for thermal baffle

CONCLUSION

Methodology was developed for the weir instability analysis of main vessel cooling circuit of FBR. From literature Aita's stability criterion and its improved form are adopted. The original criterion is improved by eliminating few assumptions for the Type-1 stability criterion. It is clear from the stability charts that higher flow rate is more stable for a given height or for a given flow rate lower fall height is more stable. For a flow rate of 0.2m^3/s the cooling system is stable for a fall height of 0.9 m as per Aita's simplified criterion and 1.2 m as per improved criterion. The improved criterion is less conservative. Fall height of 0.3 m for the present cooling system is stable for a flow rate of 0.50 m^3/s and 0.25 m^3/s based on Type-1 and Type-2 criterion respectively. Therefore the system is stable. However the system is more critical based on Type-2 stability criterion. The sloshing modes shape for the thermal baffle system is obtained using CASTEM FE code.

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