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Experimental investigation of weir instability in main vessel cooling system of 1/4 FBR model

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ABSTRACT

The 500 MWe Prototype Fast Breeder Reactor (PFBR) is under construction at Kalpakkam, India. The main vessel of this pool type reactor acts as the primary containment in the reactor assembly. In order to keep the main vessel temperature below creep range and to reduce high temperature embrittlement and also to ensure its healthiness for 40 years of reactor life, a small fraction of core flow (0.5 m^3/s) is sent through an annular space formed between the main vessel and a cylindrical baffle (primary thermal baffle) to cool the vessel. The sodium after cooling the main vessel overflows the primary baffle (weir shell) and falls into another concentric pool of sodium separated from the cold pool by the secondary thermal baffle and then returned to cold pool. The weir shell, where the overflow of liquid sodium takes place, is a thin shell prone to flow induced vibrations due to instability caused by sloshing and fluid–structure interaction. A similar vibration phenomenon was first observed during the commissioning of Super-Phenix reactor. In order to understand the phenomenon and provide necessary experimental back up to validate the analytical models, weir instability experiments were conducted in a 1:4 scale stainless steel (SS) model installed in a water loop. The experiments were conducted with flow rate and fall height as the varying parameters. The experimental results showed that the instability of the weir shell was caused due to fluid structure interaction. This paper discusses the details of the model, the modeling laws, similitude criteria adopted, analytical prediction, the experimental results and conclusion.

1. Introduction

Prototype Fast Breeder Reactor (PFBR) is liquid metal sodium cooled pool type 500 MWe reactor currently under construction phase at Kalpakkam, India. The PFBR core is surrounded by thin axisymmetrical shells which separate sodium flow volumes and avoid thermal problems (Fig. 1).

The shells are concentric thin walled structures (thickness–diameter ratio: $t/D \sim 1/650$ and height–diameter ratio: $h/d \sim 1$), each separated by thin annulus of liquid sodium (annulus gap–diameter ratio: $w/D \sim 1/100$). These geometrical arrangements with interconnected liquid columns may respond to flow fluctuations which leads to vibration during reactor operation. Another special feature is the existence of free fluid surfaces which is the source of sloshing phenomenon.

The main vessel of this pool type reactor carries about 2000 tonnes of weight and operates with reactor outlet temperature of 547 °C. In order to keep the main vessel temperature below creep range (<420 °C) and to reduce high temperature embrittlement and to ensure its healthiness for 40 years of reactor life, a small fraction of core flow (0.5 m^3/s) is sent through an annular space formed between the main vessel and a cylindrical baffle (outer baffle) to cool the vessel. A part of the reactor sodium flow (≈5%) in the grid plate leaks out at the foot of the subassemblies through specially designed labyrinths collected in a chamber below and directed to the annular space indicated above, through 24 circumferentially spaced pipes (Fig. 2).

Sodium then overflows the top of the primary thermal baffle (weir shell) and falls into the annular pool of sodium separated from the cold pool by the inner shell. The weir shell, where the overflow of liquid sodium takes place, is a thin shell prone to flow induced vibrations (Jalaldeen et al., 1991) due to liquid sloshing and fluid–structure interaction (FSI). This vibration phenomenon was first observed during the commissioning of French Super-Phenix reactor (Aita et al., 1986), which has a similar main vessel cooling arrangement. Weir instability studies were carried out earlier in house in a 1:16 scale model using aluminum and SS thermal baffles, simulating geometrically the design of PFBR. In the 1:16 scale aluminum baffle model, sloshing driven type of instability was observed (Jason Premnath et al., 1993) whereas in the 1:16 scale SS baffles model, no instability was observed. This could be

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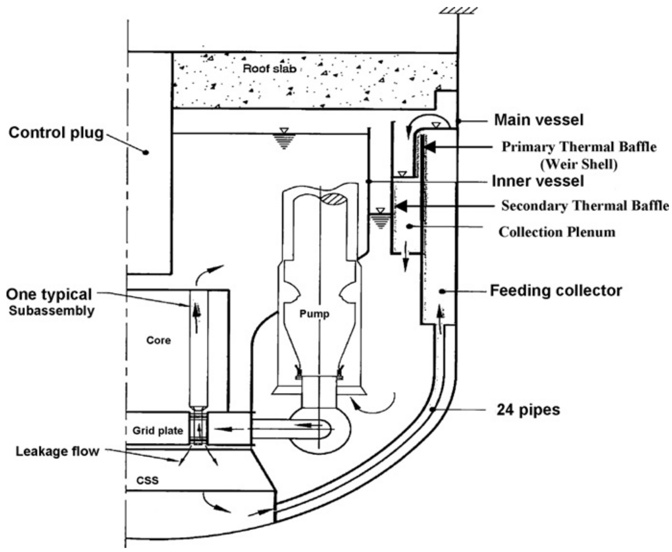

Fig. 1. PFBR weir arrangement.

attributed to stainless steel baffles being quite rigid and this could have prevented the build-up of instability. The same observation was reported by Eguchi et al. (1991) for the same shell thickness, sloshing type of instability was observed when the end condition was changed from bolted support to elastic rubber attachment. Hence it is clear that stiffness of a baffle needs to be simulated properly. Moreover, many experiments were carried out world wide to understand the phenomenon using cylindrical tanks and baffles and only a few literatures are available related to pool type fast reactor by simulating all primary components inside the main vessel. In order to understand the phenomenon and also to provide necessary experimental back up to validate the analytical predictions, experiments were carried out on a 1/4 scale SS model installed in a water test loop. Experiments were conducted over a wide range of flow rates and fall heights to establish the instability chart, thereby to predict the safe operating zone. This paper discusses the details of the model, the modeling laws, similitude criteria adopted, analytical prediction, the experimental results and conclusion.

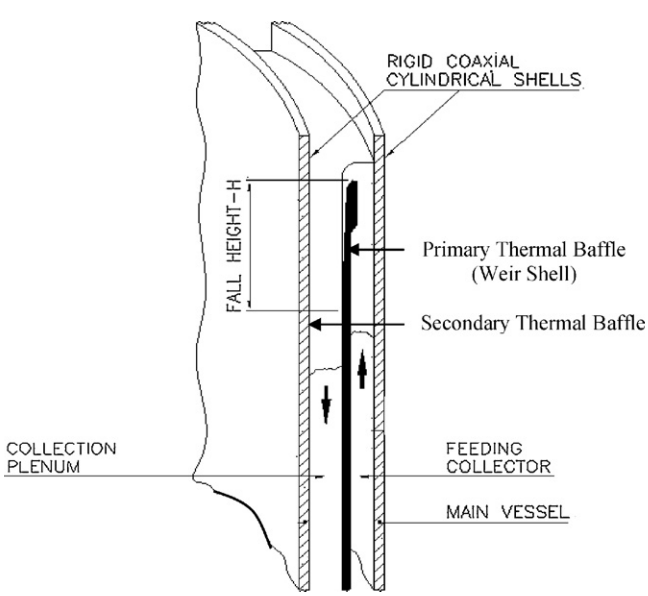

Fig. 2. Weir cooling system.

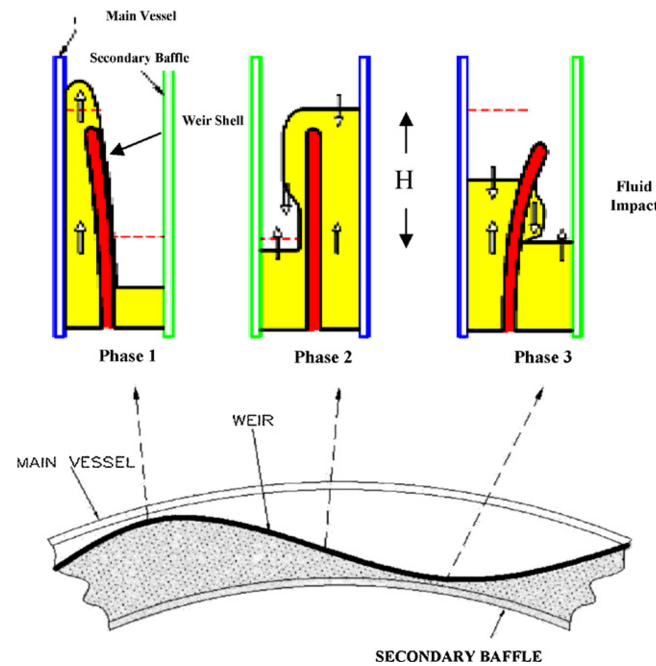

Fig. 3. Fluid elastic instability.

2. Excitation mechanisms

The two important mechanisms identified for instability of the weir cooling system is sloshing and fluid elastic instability. These mechanisms are explained below.

2.1. Sloshing (Type I)

Surface wave oscillation will be produced in a liquid filled container/tank when it is excited with an external force. In case of weir systems, the pressure pulsations due to the falling liquid over the free surface could be the source of excitation. When this exciting frequency coincides with system natural frequency, resonance like condition can occur which leads to very large surface liquid motion and vibration of the container.

This is governed by the equation

$$\omega^2 = n\frac{g}{D}\tan h\left(\frac{nh}{D}\right)$$

where n is the constant dependent on mode shape; ω = sloshing natural frequency; h is the height of the tank; D is the characteristic length; (for cylindrical tank 'D' is the diameter of the tank).

It is reported that, this kind of instability occurs in the system at very low flow rates and fall heights.

2.2. Fluid elastic instability (Type II)

If the weir shell is disturbed from its equilibrium position, it naturally vibrates with a particular wave number n. For the stable flow configuration, the vibration decays exponentially to zero. On the contrary, the shell vibrates with exponentially increasing amplitudes for the unstable system. If the dynamic fluid forces causing vibration are developed from the shell displacements, then the resulting unstable vibration is termed as fluid elastic instability.

The fluid elastic instability which affects the weir shell is mainly due to the sloshing of the liquid free levels that is associated with the feeding and collection plenums. The mechanism is illustrated schematically in Fig. 3. If the kinetic energy imparted by the liquid falling from the weir crest and the free surface of the restitution