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Challenges in Thermal Hydraulic Design of Indian Prototype Fast Breeder Reactor

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Summary

Prototype fast breeder reactor (PFBR) marks the 2^{nd} stage of Indian nuclear power programme. PFBR is a pool type liquid sodium cooled nuclear reactor, wherein the entire primary circuit consisting of reactor core, control plug, intermediate heat exchangers (IHX), decay heat exchangers, primary sodium pumps, grid plate, core support structure etc. are immersed in a pool of liquid sodium (Fig. 1). The grid plate is a high pressure plenum which feeds cold primary sodium to various subassemblies of the core. Sodium, having a very high heat transfer coefficient is essential to remove very high heat flux values encountered in the core. Since the boiling point of sodium very high the systems need not be pressurized to achieve high temperature. Hence, the main load on the structures is the thermal load arising out of high operating temperature, large temperature gradient and large number of cyclic variations in temperature due to various incidents taking place in the plant. High thermal expansion coefficient and low thermal diffusivity of austenitic stainless steel enhance the severity of the thermal transients. Hence, a detailed knowledge of temperature distributions prevailing in the structures is essential for computing the stress and for life prediction of the structures. The main drawback of sodium is its violent chemical reaction with air and water. Hence, in all the sodium systems inert argon gas is maintained above the sodium free surfaces to avoid sodium-air contact and to accommodate volume change of sodium resulting from various operating temperatures.

Thermal hydraulic characteristics of PFBR pose considerable challenges to the analyst. Large buoyancy force arising out of temperature difference between various sodium streams leads to Richardson number in the pools is of the order of unity and phenomenon known as thermal stratification where a large temperature change occurs over a short height. The unstable stratification interface leads to low frequency temperature oscillations of large amplitude in the pool. Since the heat transfer coefficient of sodium is very large, the fluid temperature fluctuations are transmitted to the adjoining structures with minimum attenuation. Similarly, the mixing interface of sodium jets issuing out of various subassemblies that constitute the core is unstable and it leads to temperature oscillations in the structures, known as thermal striping. For thin structures of PFBR, the Biot number is of the order of unity, indicating the conductive and convective resistances are of similar

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order. This suggests that a multidimensional conjugate convection-conduction heat transfer analysis is required for the estimation of structural temperatures.

The free surface of sodium pool is not static and it fluctuates when the sodium circulatory pumps are in operation. The fluctuating sodium free level leads to high cycle thermal fatigue in structures which are partly immersed in sodium and partly in cover gas. If the free level sodium velocity is sufficiently large, flowing sodium can entrain droplets of argon cover gas. Entrainment of gas in sodium and its subsequent passage through the core leads to reactivity perturbations. Hence it is essential to have a free surface with low velocities. In the narrow component penetrations in the topshield, cellular convection of argon takes place, which leads to circumferential temperature variation in the structures.

To understand the above complex thermal hydraulics phenomena, a judicious combination of experimental and numerical approaches has been adopted, by performing many large scale water experiments and limited sodium experiments to validate computer codes and then using these validated computer codes for numerical prediction of sodium flow and temperature distributions in the reactor.

The full paper would cover the thermal hydraulic features of PFBR, challenges in the computational prediction of special phenomena, experiments performed for validation of the computer codes etc. in detail.