# Heat transfer studies with steam generator and decay heat removal system for FBRs

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**Abstract**

The Prototype Fast Breeder Reactor (PFBR) in Kalpakkam, India, has two major heat transport paths, one for normal heat power transport through secondary sodium system, which transport heat from primary sodium pool to steam generators and second a dedicated decay heat removal system which transport heat from primary sodium pool to atmosphere on demand. Steam generator is the critical component in the main heat transport system where sodium is pumped by secondary sodium pump. Experiments were conducted to characterize the heat transfer through steam generator and its operational stability. These experiments were conducted in a dedicated Steam Generator Test Facility. Safety Grade Decay Heat Removal (SGDHR) system in PFBR is a natural circulation driven system, keeping at poised state during the normal plant operation and operated on demand. A dedicated experimental facility called SADHANA was built to demonstrate and characterize the operation of passive decay heat removal system. This paper brings out the details of the experimental facility and heat transfer experiments carried out for normal heat transport path and safety grade heat transport path of PFBR.

Key words;

Steam Generator, Heat transfer in sodium, Decay heat removal system, Prototype Fast Breeder Reactor, Flow instability.

1. **INTRODUCTION**

Safe and reliable operation of steam generator is a key factor for the plant availability of sodium cooled fast reactors. Hence to validate the design of 157 MWt steam generator module for PFBR, a model of steam generator was tested in Steam Generator Test Facility (SGTF). Thermal hydraulic studies were carried out with the 19 tube once through sodium heated steam generator model to characterize the heat transfer and stability behavior of once through steam generator used in PFBR. The model steam generator is with same tube dimensions and tube material as in the PFBR steam generator. It is designed to operate with the same process conditions but with a nominal heat transfer rating of 5.5MWt. Nominal sodium inlet temperature to the steam generator is 525°C and it is intended to produce steam at 493°C temperature and 17.2Mpa pressure. A fossil fuel heated sodium heater delivers the power to heat sodium from 355°C to 525°C and an Annular lenier Induction Pump (ALIP) circulates the sodium through the closed heat transport system of the facility. A condenser operating at 1 bar pressure receives the steam produced from the steam generator through three stages of depressurinsing and desuper heating stations and rejecting the heat to atmosphere [1].

Table 1: Comparison of parameters in prototype and model systems

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| Parameters | SGDHR of PFBR | SADHANA |
| Working fluid | Sodium | Sodium |
| Nominal heat removal capacity | 8 MW | 355 kW |
| Design basis hot and cold leg temperatures | 495°C /302°C | 495°C /302°C |
| Height between thermal centers | 41m | 19.5m |
| Inside diameter of intermediate loop pipe | 200 mm | 52.48mm |
| Richardson number, Ri | 15.66 | 16.67 |
| Euler’s number, Eu | 14.13 | 15.36 |
| Reynolds’s number, Re | 7.34 x 105 | 125 x 105 |
| Sodium velocity | 1.2m/s | 0.78m/s |
| Sodium mass flow rate | 32.42 kg/s | 1.45kg/s |

SGDHR system is a dedicated passive decay heat removal system of PFBR. The SGDHR system consist four independent loops with individual heat removal capacity of 8MWt. Each loop consists of one sodium to sodium heat exchanger (DHX) immersed in the hot pool of reactor, one sodium to air heat exchanger (AHX) positioned at elevated height from the DHX, associated piping and auxiliary components. SADHANA facility is 1:22 scaled down in terms of nominal power transfer capability. Scaling of the system was performed based on the philosophy of Richardson number similitude table 1 give the comparison of operating parameters of SADHANA facility and prototype reactor system. A model DHX, receive heat from a hot sodium pool contained in tank of diameter 1.0m, which simulates the reactor hot pool in the experimental facility. Hot sodium at the exit of DHX rises due to its lower density and reaches to a model AHX were it releases its heat to atmosphere while passing through the finned tubes. Cold sodium comes down due to its higher density and completes the circuit. Elevation difference between the thermal centers of DHX and AHX in SADHANA facility is 19.5m where as the height difference in the SGDHR system of PFBR is 41.0m. DHX and AHX are scaled hown by the length and number of heat transfer tubes by keeping the tube size and geometry same. Interconnecting piping is of inside diameter 52.0 mm. A chimney of 0.68m diameter and 20m heigh above the outlet of AHX produces the natural drauft required for the airflow through AHX. Operating temperatures of prototype system and model were kept same [2].

The steady state characteristic of a buoyancy driven closed loop system is determined by the balance of buoyancy forces, inertial forces and viscus forces. The non dimensional groups which is characterising the behavior of the natural circulation loop at steady state is Richardson number (Ri) and Euler’s number (Eu). Other important non dimensional numbers to be considered while simulating the steady state heat transfer and transport phenomenon are Peclet number (Pe) and Reynolds Number (Re). Peclet number characterises the heat transfer inside the heat exchangers and Reynolds number characterises the heat and momentum transport in the system. While scaling down the Prototype system to the experimental facility the ratio of Ri and Eu in the prototype and model is maintained as unity. The ratio of Pe and Re in the model is maintained in same order as in the prototype system. This philosaphy will satisfy most of the steady state simulation requirements to characterize the SGDHR system.

1. **EXPERIMENTS WITH STEAM GENERATOR**

Steady state heat transfer experiments and two phase flow instability studies were conducted with the model steam generator. Schematic of the steam generator test facility is shown in figure 1 and crosectional view of model SG is shown in figure 2. Heat transport capacity of system was experimentally demonstrated. From the experiments, it was found that, rate of steam produced at nominal conditions were 7.7% more than the nominal steam mass flow rate. It is also estimated that the actual heat transfer in the single phase regions of the steam generator is 3% more than the theoretical estimation where as the same is 23.5% less in two phase regions. The testing revealed the adequacy of heat transfer capability of the steam generator to transfer the intended power. The model steam generator was subjected to different design basis simulated plant transients and the thermal loading on the thick tube sheets were evaluated. Results of these experiments where in expected lines. Thermal baffles provided above the bottom tube sheet is successful to attenuate the thermal transient produced by a feed water loss incident to about one third of its original peak gradient.

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| Fig.1: schematic of steam generator test facility | Fig.2: Cross sectional view of model steam generators |



Fig. 3: Sodium side and water side temperatures during the SG startup with 61.1% of the rated sodium flow rate

Experiments verified that the steam outlet temperature from the representative steam generator tube are free from fluctuations during the full power conditions and all anticipated partial load conditions. Mass flow rate of feed water through sream generator is manipulated with respect to sodium outlet temperature form steam generator and steam pressure at steam generator outlet is maintained at 17.2 MPa. However, the steam outlet temperature from the individual tubes were fluctuating with large amplitudes as shown in figure 3 during certain steam generator startup conditions when the thermodynamic quality of the steam was around one, even though the overall steam outlet temperature is more or less steady. On attaining sufficient superheat, these oscilations were vanished. These instabilities are identified as compound type pressure drop instabilities and the same has been verified by establishing pressure drop charactristics of the steam generator tubes at similar conditions.

1. **EXPERIMENTS WITH PASSIVE DECAY HEAT REMOVAL SYSTEMS**

Among the three mutually coupled natural convection loops in SGDHR system as shown in figure 4(a), the natural convection in the intermediate circuit is more influencial and hence important in the reliability and performance of SGDHR system. From the steady state experiments, it was established that, heat transported by the system under nominal pool operating temperature was 19.4% higher than the nominal heat transport capacity. The sodium flow rate in the intermediate circuit and heat removal rate by the system were steady without any perturbations. Thus the effectiveness of heat exchangers and the system was proven and the design is validated. If the velocity of sodium in the intermediate loop is in non favourable direction,that is the flow direction is opposite to the normal direction from, the heat transport capability of the system deteriorates by 45% compare to its capability when the sodium velocity is in favourable direction. This is mainly due to the reduction in the heat transfer capacity of heat exchangers when it is in parallel flow condition. When sodium flow in the normal direction sodium velocity is in upword direction through DHX tubes and downwards through AHX tubes.

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| (a) | NCSL PIPING - 3D - North West VIEW - op1-Model.jpg  (b) |

Fig.4: (a) Schematic and (b) configurationof passive decay heat removal system for experimental studies



Fig. 5: Development of sodium mass flow followed by the AHX inlet dampers opened.

During normal operation of reactor, the SGDHR system is in poised condition by keeping the air dampers in crack opened condition. On demand, the dampers of SGDHR system are actuated to open by reduntant systems. Each air damper is provided with two parallel louvers actuated by electrical and pneumatic actuators. The response of the system during sudden opening of damper was experimently evaluated and found that, the mass flow rate of sodium and heat power transfer are reached maximum value in 500 second as shown in figure 5. Time required to achieve steady state is independent of pool temperature and initial condition. Experiments shows that the system can remove decay heat at the rate of 90% of its nominal capacity even one louver is struck to open and other louver is opened partially with 50% of its angular travel.

Primary sodium enters to the shell side of the DHX through small perforations, which are distributed almost top 50% of it heat transfer length. Due to this feature the heat transfer through the DHX is ensured even after a sodium level reduction in the reactor vessel. Experiments revealed that the reduction in heat transfer is only 5% of its nominal value, when the sodium level reduced to an extend, which oncovered 88% of its inlet region.

1. **CONCLUSSION**

In sodium Experiments were conducted to validate the design of two major heat transport sysems of Prototype Fast Breeder Reactor. These experiments validated the design of the system and components and characterised it operational performance during normal operation and various upset conditions.

References

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