HYDRAULIC DESIGN AND DEVELOPMENT OF PASSIVE SAFETY SHUTDOWN SYSTEM OF INDIAN SFR

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INTRODUCTION: In Indian Sodium-cooled Fast Reactors (SFRs), a passive shutdown system is planned to introduced to address the Unprotected Loss of Flow (ULOF) event. This will ensure shutdown of reactor in case of any loss of coolant through the core. The mobile neutron absorber rod of the passive shutdown system will be suspended in its top seat, above the active core region, due to the drag forces generated by the flowing sodium. When the coolant mass flow rate goes below a specified value of the nominal mass flow rate, the mobile rod will descend by gravity into the core active region, thereby shutting down the reactor by absorbing neutrons. This paper brings out hydraulic design & developments of passive shutdown system in details.

1. OVERVIEW

A passive reactor shutdown device is designed to shut down the reactor if the coolant flow drops below a certain fraction of the nominal mass flow rate. The new passive shut down system has been introduced as per safety design guidelines for Gen IV sodium cooled fast reactors [1]. The schematic of the passive shutdown system in normal operating and deposited conditions during reactor shutdown is shown in Figure-1. The mobile rod, which consists of B_4C pellets enriched with B-10, is raised to its operating position manually using the drive mechanism. Once the nominal mass flow rate is established across the subassembly, the drive mechanism detaches, and the mobile assembly remains suspended from its top seat due to the drag forces generated by the flowing sodium. Presently in Indian FBR, a 50% reduction in the nominal mass flow rate is the trigger condition for release of the mobile rod from its suspended condition. This means, if the coolant mass flow rate falls below 50% of the nominal rate, the mobile rod will descend by gravity into its subassembly sheath within the core. At the end of its free fall, the mobile rod is decelerated by a sodium dashpot and brought to rest. This system will serve as an auxiliary shutdown mechanism, addressing the event of an Unprotected Loss of Flow Accident (ULOFA) when both primary shutdown systems (CSR and DSR) fail to shut down the reactor. It ensures the reactor is in a safe state and maintains the temperature below the boiling point of the coolant. Given that the void coefficient of Indian SFRs is positive and they are not operating at the most reactive configuration, the importance of the passive shutdown system is further emphasized to prevent sodium boiling in the reactor. This system will significantly reduce the probability of a Core Disruptive Accident (CDA) and enhance the safety level of the nuclear reactor.

2. DESIGN CRITERIA

The following hydraulic design criteria has been set as functional requirements for the development of passive safety shut down system

(i) The passive shutdown system shall be actuated as per the specified designed flow rate within a margin of ± 3%.
(ii) Once mobile absorber rod of passive shut down system is deposited in the reactor core, it shall not come out from the core by itself even at 110% of nominal flow rate condition.
(iii) The time taken for the shutdown system from its actuation to deposition in the core shall be as minimum as possible.

3. HYDRAULIC DESIGN & DEVELOPMENTAL ACTIVITIES

The hydraulic design & developmental activities involve

(i) Development of pressure drop device to achieve required drag force to keep the mobile rod in suspended condition at 50% of the nominal flow rate.
(ii) Development of seating interface between mobile rod head and SA top.
(iii) Demonstration of the functionality of the system.

These are briefly described in the following paragraphs.

3.1 Design & development of pressure drop device

The pressure drop device was initially designed using empirical corelation for the mobile assembly. This device is designed to generate sufficient drag, ensuring that the mobile assembly remains suspended from its seat until a specific flow rate is achieved. The pressure drop device based on Multiple Orifices Plates (MOP) is provided in the mobile assembly head to balance the apparent weight of the mobile rod at 50% of the nominal flow rate. In case the coolant flow, reduced less than 50% of the nominal mass flow rate through the passive shutdown subassembly, it falls into the core by its own weight, leading to shutdown of the reactor. The individual orifice plate is arranged in staggered manner with respect to the adjacent plates for effective utilization of the MOP and due to space constraint. Further numerical analysis of MOP was carried out using numerical tools to fine tune the design. The development was an iterative process, which involves both CFD & experimental studies. Cavitation free performance of MOP was checked by model experiments in water medium for each iterative stage to achieve the final design.

Pressure drop vs volumetric flow rate for the final design of MOP as obtained from experiment is plotted in Figure 2 and ‘k vs Re’ is plotted in Figure 3. The flow resistance ‘k’ is a function of Reynolds number (Re) and relative surface roughness. The relative roughness however was maintained in 1:1 scale model fabricated exactly in the same way as in prototype. It can be seen that the change in ‘k’ with increase in ‘Re’ is negligible for wide range, which include the range of interest. The experimental data is extrapolated for the reactor conditions. The pressure drop at different volumetric flow rate for sodium at reactor conditions is plotted in Figure 4. It can be seen that the pressure drop for sodium at 400^{o}C and nominal mass flow rate of 3.87 kg/s is 141 kPa (extrapolated from experimental results) compared to the numerically estimated value of 145 kPa and empirically calculated value of 126kPa. Hence, the design of pressure drop device with four plate assembly has been validated.

Further it is also found from water model testing that the designed pressure drop device will perform cavitation free operation up to a minimum of 110% of nominal mass flow rate of sodium at 400^{o}C.

3.2 Development and experimental testing of seating interface

The coolant enters into the passive shutdown system subassembly through grid plate sleeve. Later coolant is bifurcated into two parallel paths as shown in Figure 1. One path is leakage through the seating interface between mobile rod head and outer hexagonal sheath seat. The other flow path is through the pressure drop device inside the mobile rod. Major portion of the coolant shall pass through the mobile rod to generate the sufficient differential pressure. The leakage through the seating interface shall be minimized in order to provide sufficient pressure drag to keep the HSR mobile assembly in suspended condition at 50% of the nominal flow rate. After testing of seating interface in water it was found that leakage through seat is < 0.1% of nominal flow rate, which is very well acceptable.

3.3 Demonstration of the functionality of the system

The functionality of the system demonstrated in two steps.

3.3.1 Functionality Test

The experimental study was conducted in flowing water, using 1:1 scale model of passive shutdown dummy subassembly with reproducing all features as in prototype. The apparent weight of the mobile rod was simulated. The mobile rod was raised manually using a rope with relatively negligible weight and pulley arrangement to its top position and engaged with the seat. Once the volumetric flow rate of water equivalent to

100% nominal sodium mass flow rate at 400°C was developed, the rope completely loosened for the mobile rod. The pressure drop across the top seating interface and across the total passive shutdown subassembly was recorded continuously. Now the volumetric flow rate of water reduced slowly using VFD driven pump motor set. After attaining a certain volumetric flow rate the mobile rod detached from its top seat and fall freely by gravity. The mobile rod finally depositing into the dashpot of the sheath of passive shutdown subassembly. Once the mobile rod is deposited into the dashpot it is not coming out even at 150% of nominal flow rate due to its hydraulic resistance characteristics.

It has been assumed that the flow resistance in model is equal to flow resistance of prototype, since as discussed earlier in Para 3.1 and shown in Fig. 3 that the 'k' is almost independent of Re for the operative range of flow rate.

$$k_m = k_p \qquad (2)$$

**The subscript 'm' is used for model and 'p' is used for prototype.*

The required flow rate in testing was estimated based on pressure drop simulation

$$\Delta P_m = \Delta P_p, \quad \text{or} \quad k_m \times \rho_m \times V_m^2 = k_p \times \rho_p \times V_p^2$$

Hence for 1:1 geometry the required flow rate of water can be find out as

$$Q_m = Q_p \sqrt{\frac{\rho_p}{\rho_m}} \qquad (3)$$

The testing was repeated 100 times to reduce the uncertainty in the results. After extrapolating the results for reactor condition the mobile rod in sodium at 400°C, will release from its seat at 49.10% ± 2% of nominal mass flow rate at differential pressure of 35.26 ± 3.1% kPa with 99.7% confidence level on spread of data.

3.3.2 Measurement of Drop Time

The experimental study was conducted in flowing water using a 1:1 scale model of the passive shutdown dummy subassembly. The procedure for conducting the experiment has been outlined in the previous section. Dynamic Pressure Sensors (DPS) were positioned near the top seating interface of the mobile head and the dashpot seating to capture variations in static pressure. Additionally, a charge-type accelerometer was installed on the outer hexagonal sheath of the dashpot to detect any noise generated by the mobile rod striking or rubbing against the dashpot. The readings from all instruments, namely the flow meter, Differential Pressure Transducers (DPTs), DPS, and accelerometer were recorded simultaneously. A representative time-travel plot for the free fall of the mobile rod, showing its release from the top seating (detected by DPS) and its arrival at the bottom seat in the dashpot (detected by sound signals via the accelerometer), is presented in Figure 5. The results indicate that the total travel time of the mobile rod from the top seat to its final position in the bottom dashpot seat is 1.5 seconds, with a variation of ±3.771% at a 99.7% confidence level.

4. SUMMARY

In Indian advanced sodium fast reactors, a passive shutdown system based on the principle of hydraulic suspension of absorber rods has been proposed as a backup shutdown mechanism. This system is designed to shut down the reactor in the event that both primary shutdown systems fail to operate and the coolant flow rate through the core decreases below a specific percentage of the nominal flow rate. The mobile rod, containing neutron absorber material, is suspended above the reactor core from its top seat using the differential pressure generated across a pressure drop device. The pressure drop device has been meticulously designed and validated through experimental measurements. Furthermore, the seating interface between the mobile rod and its top seat has been developed and rigorously tested. A full-scale dummy subassembly of the passive shutdown system has been fabricated, demonstrating that the mobile rod successfully released at 49.1% of the nominal flow rate under reactor conditions. Once the mobile rod is positioned within the reactor core, it remains securely in place, even at 150% of the nominal flow rate. The drop time of the mobile rod has been measured and found to be less than 1.5 seconds. Hence, the hydraulic design of the passive shutdown system is validated.

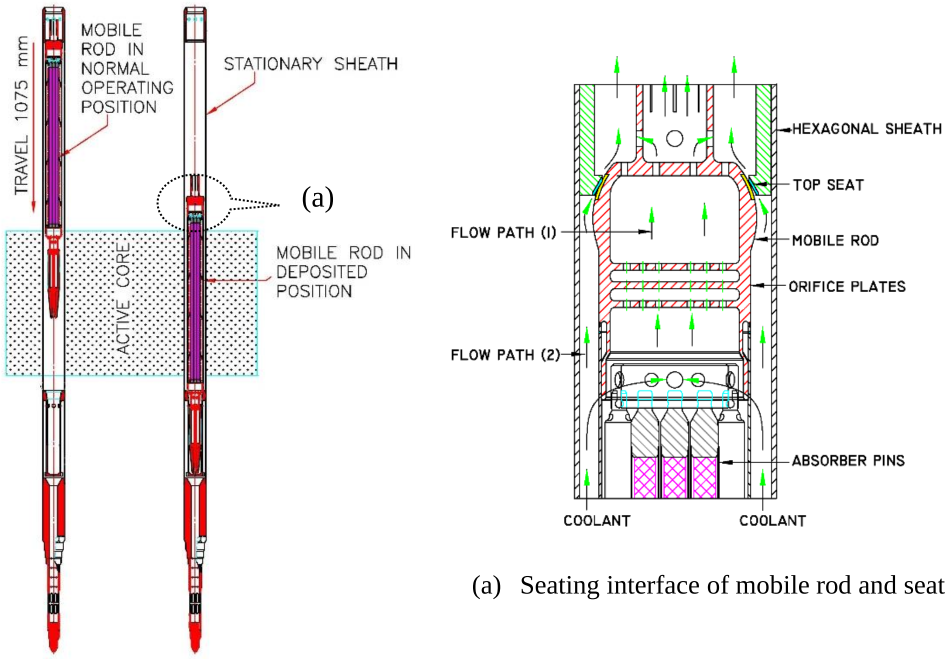

FIG. 1. Schematic of HSAR while dropped condition and suspended condition

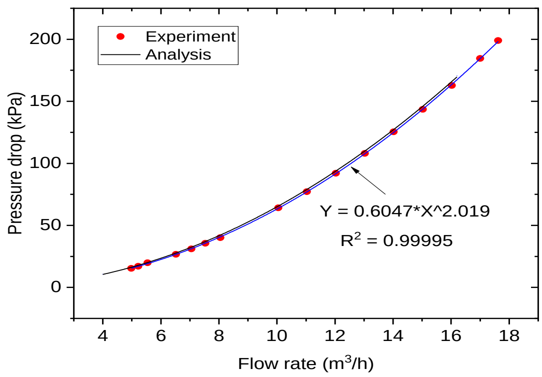

FIG. 2. Pressure drop vs flow rate for model

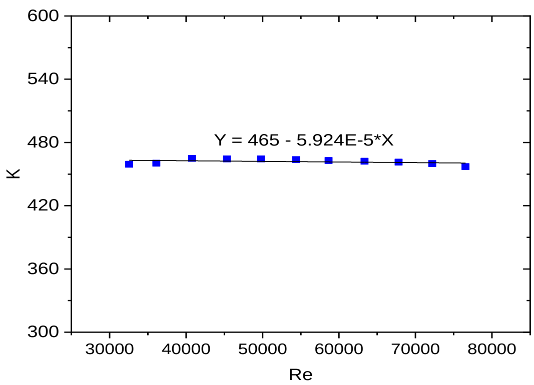

FIG. 3. K vs Re plot in pressure drop device

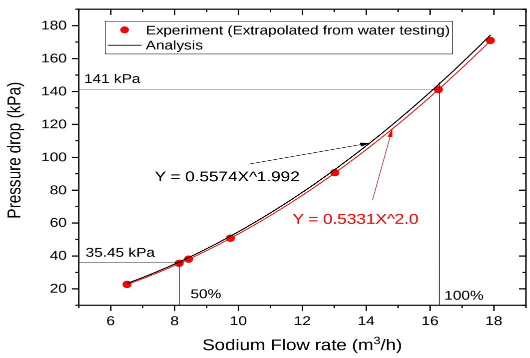

FIG. 4. Pressure drop vs flow rate for reactor

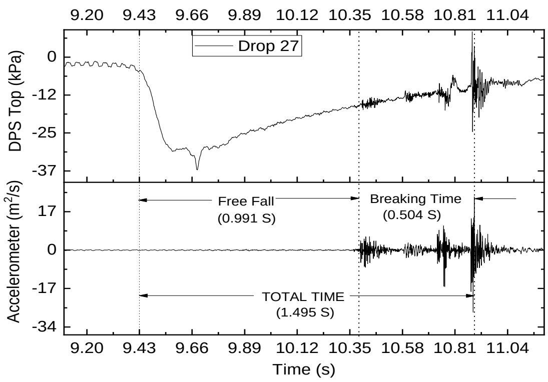

FIG. 5. Falling of mobile rod on time scale

REFERENCES

[1] Safety design guidelines on safety approach and design conditions for Gen IV sodium cooled Fast Reactor Systems, SDC-TF/2016/01.