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Mathematical modelling of performance of safety rod and its drive mechanism in sodium cooled fast reactor during scram action

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HIGHLIGHTS

- Mathematical modelling of dynamic behaviour of safety rod during scram action in fast reactor.
- Effects of hydraulics, structural interaction and geometry on drop time of safety rod are understood.
- Using simplified model, drop time can be assessed replacing detailed CFD analysis.
- Sensitivities of the related parameters on drop time are understood.
- Experimental validation qualifies the modelling and computer software developed.

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ABSTRACT

Performance of safety rod and its drive mechanism which are parts of shutdown systems in sodium cooled fast reactor (SFR) plays a major role in ensuring safe operation of the plant during all the design basis events. The safety rods are to be inserted into the core within a stipulated time during off-normal conditions of the reactor. Mathematical modelling of dynamic behaviour of a safety rod and its drive mechanism in a typical 500 MWe SFR during scram action is considered in the present study. A full-scale prototype system has undergone qualification tests in air, water and in sodium simulating the operating conditions in the reactor. In this paper, the salient features of the safety rod and its mechanism, details related to mathematical modelling and sensitivity of the parameters having influence on drop time are presented. The outcomes of the numerical analysis are compared with the experimental results. In this process, the mathematical model and the computer software developed are validated.

1. Introduction

The main safety objectives in the design and operation of nuclear power plants are

(a) Control of reactivity (i.e., ability to control neutron flux in reactor core),
(b) Maintenance of core cooling (i.e., maintaining adequate supply of coolant to the core region along with a provision of backup supply) and
(c) Provision of several barriers against release of radioactivity to the public (i.e., fuel cladding, reactor vessel and containment building system).

Safety of the reactor during normal and off-normal conditions is achieved by prompt control of reactivity using engineered safeguard shutdown systems, which consist of neutron absorber rods and their drive mechanisms operating in fail-safe mode and having very high reliability. Provision of redundancy and diversity in design, manufacture and operation ensures that the failure probability of the shutdown systems is less than 10^{-6} per reactor-year so that the targeted reliability can be achieved.

In sodium cooled fast reactor, the safety rods containing neutron absorber elements are evenly placed in reactor core which consists of fuel, blanket, reflector and shielding subassemblies. They are totally immersed in sodium pool and their drive mechanisms hanging from top shield are partially immersed in hot pool liquid sodium. During off-normal conditions, the safety rods are to be inserted into the reactor core within a stipulated time by scram action before the plant parameters exceed the design safety limits. The gravity assisted free fall of the mobile assembly of the safety rod and its drive mechanism during scram action is opposed by the forces due to fluid drag, buoyancy, pressure and mechanical contact friction. This causes reduction in effective acceleration and increase in drop time of the safety rod. The opposing forces are

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Nomenclature

A	sectional area of flow path
C_n	arbitrary constants ('n' varying from 0 to 7)
CSR	control and safety rod
CSRDM	control and safety rod drive mechanism
D	hydraulic diameter
$\frac{dy(t)}{dt}$, V	instantaneous velocity of mobile assembly of CSR and CSRDM (downward movement is positive)
$\frac{d^2y(t)}{dt^2}$	instantaneous acceleration of mobile assembly of CSR and CSRDM
EM	electromagnet
f	friction coefficient
F	functional equation
$F_{\text{friction}}(y)$	displacement dependent frictional force
$F_{\text{press}}(t), F_{\text{buoy}}(t)$ and $F_{\text{drag}}(t)$	time dependent hydraulic forces (due to pressure, buoyancy and drag respectively).
F_{seal}	seal frictional force
F_{vis}	force due to viscous friction
g	acceleration due to gravity
L	length of flow path
$m[i]$	mass flow rate of fluid in path no. 'i'
M	mass flow rate of fluid considered in governing equations
M_{MA}	Mass of mobile assembly of CSR and CSRDM
PFBR	prototype fast breeder reactor
P_{I}	inlet pressure at foot of CSR subassembly
P_{O}	outlet pressure at head of CSR subassembly
$R_{11}, \ldots R_{31}$	arbitrary constants
SFR	sodium cooled fast reactor
t	time
u	velocity of fluid in flow path (upward movement is positive)
U	relative velocity of fluid with respect to the contact surface of flow path
$y(t)$	displacement of mobile assembly as a function of time

Greek symbols

ρ	density of fluid
$\Delta m[k]$	mass flow rate of displaced fluid at region 'k'
ΔP	pressure difference across CSR subassembly
ΔP_i	differential pressure across ith flow path
ΔP_{vis}	frictional pressure drop
ΔP_h	pressure difference due to elevation

inter-related and coupled and vary with respect to time as a function of travel distance and velocity of the mobile assembly. They are due to sodium pressure build-up inside the safety rod subassembly, volume of mobile assembly immersed in the pool and mechanical contact reactions at the guides.

Donis and Goller (1972) presented the details of mathematical model for the control rod drop in a pressurised water reactor and its experimental verification. Borquin and Berney (1975) presented the theoretical prediction of scram time and experimental verification in fast flux test facility. Taliyan and Roy (1994) presented the details of theoretical modelling and the studies carried out to predict the drop characteristics of shut-off rod and its experimental verification in pressurised heavy water reactors. Andriambololona et al. (2006) formulated a methodology for a numerical simulation of an insertion or a drop of the rod cluster control assembly into its guide in a pressurised water reactor. Hanliang et al. (2000, 2002) developed hydraulic control rod drive mechanism for the nuclear heating reactor and analysed its performance theoretically and experimentally. Hofmann et al. (2000) made a numerical study of the influence of the pressure forces applied to control rods and flow circulation through the guide tube in pressurised water reactor.

It is understood from all these studies that the flow characteristics and rod drop behaviour of the shutdown system during scram action are totally influenced by the reactor configuration, geometry of core, safety rod and its drive mechanism, physical properties of coolant and mechanical and fluid-structure interactions. Hence the characteristic movement of the safety rod during scram action is reactor specific. So the theoretical as well as experimental characterisation is a must for each system with a particular design configuration.

In this context, the performance of the safety rod during scram action should be thoroughly investigated using numerical modelling and the design should be fine tuned to establish the desired characteristics. Further, the numerical model has to be validated with the experimental simulations.

In the present study, control and safety rod (CSR) and its drive mechanism (CSRDM) of first shutdown system in Prototype Fast Breeder Reactor (PFBR) are considered for characterisation. PFBR is a typical 500 MWe power, (U-Pu)O_2 fuelled, sodium cooled, pool type fast reactor. Chetal et al. (2006) detailed out the design features of PFBR and Rajan Babu et al. (1995, 2010) detailed out the features of shutdown systems and CSR and CSRDM in PFBR.

Since CSR and CSRDM are constituents of plant protection safety system, high quality has been ensured during design, modelling, analysis, development, manufacture, testing and qualification. Mechanical design and manufacture of the system were done as per the guidelines given in RCC-MR (French Design and Construction Code). The individual component and the system as a whole were qualified based on the well-defined procedure to ensure the performance of the system at all operating conditions of the reactor.

In the context of characterisation, CSRDM and CSR having many paths for sodium flow and the dynamic pressure and opposing forces developed were mathematically formulated. In the present study, simple 1D mathematical modelling of the safety rod and its drive mechanism has been done considering all the performance related parameters which influence the drop time of the safety rod during scram action. Based on that, well versed computer software using C^{++} language was developed to study the steady state flow characteristics of sodium inside the CSR subassembly and to analyse the dynamic behaviour of the system as a whole during scram action. In the next stage, full scale prototype CSR and CSRDM were manufactured and tested in air, water and sodium, simulating the operating conditions to qualify them for use in the reactor. A systematic approach has been followed during qualification of the system (Rajan Babu et al., 2010). The theoretical behaviour was compared with the experimental results. It is proved that the results from theoretical modelling well match with that from qualification tests carried out systematically, one after the other, in air, in water and then in sodium at various operating temperatures. The parameters sensitive to the characteristic behaviour were identified and the possible deviations in the drop time of the CSR during operation of the reactor were derived.

This paper details out the features of the CSR and CSRDM, design requirements, mathematical modelling of the system, special purpose computer software developed, theoretical and experimental characterisation and their comparison.

2. Features of safety rod and drive mechanism

In PFBR, there are two independent fast acting diverse shutdown systems consisting of sensors, logic circuit, drive mechanisms