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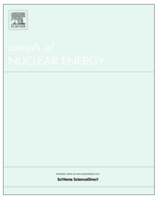

Experimental studies in water for safety grade decay heat removal of prototype fast breeder reactor

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ABSTRACT

Decay heat removal is an important safety feature of any nuclear reactor. Prototype Fast Breeder Reactor (PFBR) is sodium cooled pool type reactor under construction at Kalpakkam, India. PFBR consists of two decay heat removal systems i.e. Operational Grade Decay Heat Removal (OGDHR) system and Safety Grade Decay Heat Removal (SGDHR) system. SGDHR system is a passive decay heat removal system based on natural circulation. Heat removal by natural convection is governed by many factors such as reactor configuration, and operating conditions. Hence it is essential to understand the thermal hydraulics of decay heat removal by natural circulation. In this regard experimental studies were carried out in 1/4th scale model of the reactor primary circuit using water as simulant to demonstrate the effectiveness of the Decay Heat Exchangers (DHX) on core cooling by establishment of the natural circulation in the model. This will help to understand decay heat removal by natural circulation and temperature pattern in the reactor during decay heat removal operation. Heat removal by inter wrapper flow is very effective during SGDHR operation. System is able to achieve steady state with only two DHX in operation at elevated temperature. Temperature pattern in the hot pool is lesser stratified with only two DHX operation. This paper discusses about similarity criteria followed, details of the experimental model, description of the instrumentation and experimental methodology and the experimental results.

1. Introduction

Decay heat removal system is an important system of any nuclear reactor. Decay heat generated in the core after shutdown of the reactor should be removed to limit the temperature rise within safety limits and thereby for safety of the core components. PFBR is sodium cooled fast reactor under advanced stage of construction at Kalpakkam, India. It is a pool type reactor with two secondary sodium loops. Thermal power capacity of the PFBR is 1250 MWt. Heat generated inside the core due to nuclear fission is transferred to the primary sodium which in turn transfers the heat to the secondary sodium through Intermediate Heat Exchangers (IHX). Finally, the heat is transferred to the steam in the steam generator for driving the turbine to generate electricity. Schematic of the heat transport path in the PFBR is shown in Fig. 1. Heat is generated inside the core due to decay of fission products even after shut down of the reactor and is termed as decay heat. It is very important to remove decay heat in order to limit the temperature rise inside the core within safety limits to maintain structural integrity of the core components for assuring safety of the reactor. OGDHR system is utilized for removal of decay heat generated inside the core after shut down of the reactor. This OGDHR system consists of Intermediate Heat Exchangers (IHX), intermediate secondary sodium loop and steam water circuit. All the components of the normal heat transport path of the reactor should be available for OGDHR operation. However in case of non availability of the normal heat transport path such as during station black out, this OGDHR system is unavailable. Hence, addition to OGDHR system, one more completely passive decay heat removal system has been provided for PFBR. This system is termed as Safety Grade Decay Heat Removal (SGDHR) system as shown in Fig. 1. Whole SGDHR system works on the principle of the natural circulation for removing decay heat generated inside the core. This passive feature of the SGDHR system makes it an important safety system in case of station black out and when normal heat transport path is unavailable (Athmalingam et al., 2002).

SGDHR system consists of four independent natural circulation loops for heat removal. Each loop consists of sodium to sodium DHX of 8 MWt capacity, intermediate sodium loop, sodium to Air Heat Exchanger (AHX) of 8 MWt and chimney of 30 m height. All the four DHXs are kept immersed in the hot pool of the reactor. During SGDHR operation, cold sodium exiting out of the DHX primary outlet penetrates into Inter Wrapper Spaces (IWS) of the subassembly (SA) in outer core region. This cold sodium in the outer core region and hot sodium in the vicinity of fuel SAs set up the

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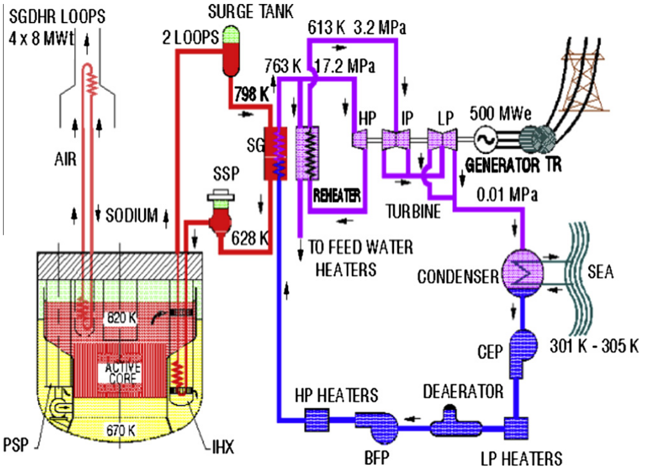

Fig. 1. Heat transport path in the PFBR.

natural circulation path through these Inter Wrapper Spaces (IWS). This natural circulation flow established in the SA gap regions is known as Inter Wrapper Flow (IWF) and has a major role to play in the cooling of the reactor core during SGDHR operation (Kamide et al., 1998). During decay heat removal process natural circulation paths are also established through core via Intermediate Heat Exchanger (IHX) and reverse flow through blanket and reflector SAs. Thus the decay heat removal process by SGDHR system is quite complicated specifically due to involvement of complex phenomenon such as IWF. The system is also quite susceptible to the various conditions prevailing in the reactor during reactor operation. Hence demonstration of the heat removal by natural circulation is important to ensure higher reliability of the whole SGDHR system. Experimental and theoretical studies are essential for detailed understanding of the heat removal by SGDHR system. It is extremely difficult and unviable option to simulate complete SGDHR system with sodium coolant. Therefore, these studies were split into (a) core–hot pool–cold pool interaction studies and (b) intermediate loop – AHX interaction studies. It is easy to handle intermediate loop experiments with sodium as the simulant due to lesser inventory of sodium. Hence experiments were carried out with sodium as the simulant in intermediate loop (Vinod et al., 2011). Water experimental models are preferable for primary pool thermal hydraulic studies due to easier instrumentation and possibility to carry out different parametric studies. Hence primary pool thermal hydraulic studies were carried out using water model to investigate core–hot pool–cold pool interaction during SGDHR condition.

Several experimental studies have been performed worldwide for evaluation of the Decay Heat Removal (DHR) system. Most of the pool related natural circulation studies were conducted in water experimental models as in case of SPX and SNR (Astegiano and Martin, 1980; Rust et al., 1995). Water experimental studies have been carried out to assess the performance of the DHR system in European Fast Reactor (EFR) (Weinberg et al., 1995a,b). Mainly pool related studies are performed in smaller scale experimental models i.e. RAMONA and NEPTUN. RAMONA is 1:20 scaled model of EFR. This model is mainly used for demonstration of decay heat removal by natural convection and generating database for code validation. Steady and transient decay heat removal conditions of the reactor were studied in this model. Transient studies mainly focus upon transition from forced circulation to natural circulation during decay heat removal condition (Hoffmann et al., 1995). NEPTUN is 1:5 scaled model of the EFR and this experimental facility has also been used for evaluating decay heat removal by natural convection and data generation for code validation. Simulation of the IWS geometry was possible in this model due to larger scale size. Steady and transient decay heat removal conditions of the reactor were studied in this model also. Experimental results of NEPTUN model proves that IWF plays vital role in passive decay heat removal (Weinberg et al., 1995a,b). IWF studies were also conducted in 90° sector and 0.48 scaled model of the EFR (HIPPO Model). In this experimental program interface between hot and cold liquid is studied with water (Betts et al., 1991). GODOM is 90° sector model of the SPX 2 hot pool and it has been utilized to understand the interaction of the core and DHX flows under natural convection decay heat removal (Hoffmann et al., 1993). For understanding flow characteristics and thermal stratification in hot pool during decay heat removal condition, experimental studies were conducted in 1:20 scaled model of SPX.

It is evident from the above discussions that scaled down water models are used to understand the decay heat removal process in reactor hot pool by natural convection. Temperature and flow pattern in the model were measured during the decay heat removal condition to generate experimental database that are needed for validation of numerical codes. In line with this, present work is carried out in a 1/4 scale water model of PFBR primary circuit (SAMRAT) to assess the performance of DHR system on core coolability. It is possible to maintain geometrical similarity in miniscule details owing to large size of the model. Immersion type rod heaters were fixed inside the fuel subassemblies and storage subassemblies to represent the generation of decay heat inside the core and DHX are immersed in the hot pool of the model. This paper details about similarity criteria followed for the studies, details of the model, instrumentation details, experimental methodology, results and conclusion.

2. Similarity criteria

Decay heat generated in the reactor decreases with respect to time. Just after shut down of the reactor the thermal power inside the core is approximately 21% of the total thermal power. Approximately after 2700 s it reduces to 24 MWt which is approximately 2% of the nominal thermal power of the reactor. During this fast transient period, various factors such as forced flow due to pump inertia, and thermal inertia of large quantity of sodium in the pool, are able to keep the temperature inside the core within safe limit. After this time period, the rate of decay heat generation reduces slowly and a steady decay heat generation of 24 MWt can be assumed thereafter for a long duration. It is essential to remove this decay heat for safety of the reactor. Therefore, in this present work, experimental studies are conducted with simulation of steady state decay heat generation.

Decay heat removal during SGDHR operation establishes through three main flow paths as shown in Fig. 2.

Path-A indicates natural circulation within the core–hot pool–IHX-Grid box-core.

Path-B shows reverse flow circulation within the lesser heat generating SAs (Blanket SA).

Path-C is the Inter Wrapper Flow (IWF) path.

Therefore it is very much essential to simulate these flow paths in the model geometry. Hence geometrical similitude is maintained in the model for main primary circuit components. Dynamic similitude is also very important and it is achieved by maintaining the governing non dimensional numbers. Non dimensional numbers can be derived from the normalized governing differential equations representing SGDHR operating condition of the reactor (Eguchi et al., 1997; Ushakov and Sorokin, 1998).

The non-dimensional numbers that are required to be simulated in present case of steady state decay heat removal operation from the primary pool are as follows;