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Modelling and Simulation of Decay Heat Removal using Steam Water Circuit for PFBR Operator Training Simulator

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***Abstract*— In nuclear power plants decay heat removal systems play a critical role in ensuring the safety of the reactor. These systems continuously remove the post shutdown decay heat from the core. This should be done in order to ensure the temperatures of reactor components and core subassemblies within design safety limits. In Prototype fast breeder reactor (PFBR) an active decay heat removal system called operation grade decay heat removal system (OGDHR) is envisaged to achieve some design and operational constraints. Owing to uniqueness in design, operation and safety critical nature of Operation grade decay heat removal system, training plant operators on this system is mandatory. The Real time Computer based modelling and simulation is one of the best available cost effective strategies to imitate such first of its kind and computationally complex systems in real time. This paper presents some of the aspects of process modelling and simulation of OGHDR in the context of PFBR operator training simulator.

***Index Terms*—Decay heat, Simulator, Modelling, Condenser and steam separator..**

I. Introduction

Decay heat is generated in the core due to energetic beta emissions from radioactive fission by products. The primary function of decay heat removal systems is to remove the decay heat generated in the core following a reactor shutdown. The reliability in performance of decay heat removal system is one of the major safety concerns in nuclear power plants. Most of the major nuclear power plant accidents occurred due to failure of decay heat removal systems. For instance the failure of decay heat removal systems due to non availability of onsite, offsite and emergency power supply was the reason behind Fukushima accident. In case of Three Mile Island accident equipment malfunctions, design related problems and operator errors were the reasons for the failure of decay heat removal from the core. In fact after the accident at the Three Mile Island nuclear power plant, the international body for Nuclear Power Reactors has decided to incorporate the new methodology for training the nuclear power plant operators using process simulators.

Real time Computer based operator training simulators are widely acknowledged to improve the reliability and safety of power plants. They perfectly suit the purpose of providing a live and immersive control room environment for the simulation of normal and abnormal conditions in the plant. Through computer based operator training simulator the best possible training can be imparted to operators, in view of the flexibilities and functionalities they provide. Training the operators in anticipated and unforeseen emergencies in the plant helps in enhancing the reflexes of plant operators and reduces the plant outage. The simulator based operator training strategy is perfectly suits for first of its kind, critical and complex real world equipment. Also high fidelity simulators can be used to get the feedback on reliability, feasibility and flexibility in the design, operation and maintenance of a plant. The cost incurred in setting up the simulator is justified in terms of reduced economic losses due to reduced plant down time and improvement in the life of the plant. On the same note in India as per Atomic Energy Regulatory Body (AERB) guidelines a full scope replica type operator training simulator has been developed for PFBR at computer division, IGCAR to impart training to PFBR plant operators in all the reactor subsystems starting from nuclear island to Power Island [1].

II. Description of PFBR Simulator

A. *PFBR Plant Description*

The PFBR stands for Prototype Fast Breeder Reactor, the first of its kind Indian commercial pool type liquid metal fast breeder reactor indigenously designed by IGCAR, Kalpakkam. The PFBR consists of three coupled heat transport circuits primary sodium, secondary sodium and steam generator circuits [2].

The steam water system of PFBR uses regenerative reheat rankine cycle for thermal to mechanical energy conversion. The plant is rated for 1250 Mwt with 40% thermal to electric energy conversion efficiency. The flow sheet of PFBR is shown in Fig. 1[3].

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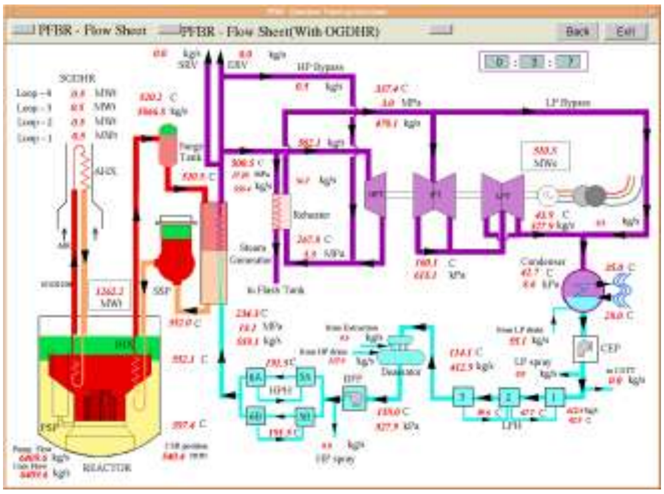

Fig 1. PFBR Flow Sheet

B. *PFBR Operator Training Simulator*

The PFBR operator training simulator (OTS) is a full scope simulator with the capability of imitating all the reactor subsystems in real time. The simulator control room is an exact one to one replica of real plant control room. The simulator's computer system comprises of simulation server and I/O computers.

C. *Simulator Configuration*

The simulator configuration and signal flow is shown in Fig 2.

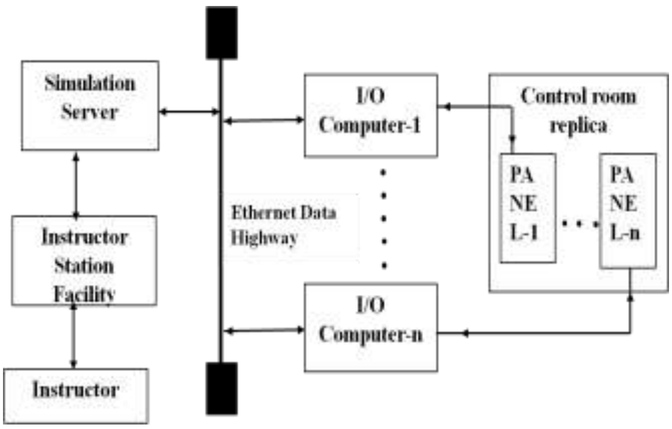

Fig 2. Simulator Configuration

The I/O computers sends/receives the data to simulation server though LAN network. The simulation server executes all the models in real time according to the inputs from control/console panels and sends the required plant data to I/O computers through LAN network. The I/O computers receive and process the data from simulation server for display on control/console panels. The Instructor Station consists of a Computer System with a CRT display, keyboard and mouse. The instructor's console provides menu for the selection of mode of operation of the simulator, malfunction selection and monitoring of plant variables. It also provides controls for the initialization and monitoring of simulator runs. The Instructor can pause at any stage of a simulation and continue or back track up to a number of time units. The Instructor station also includes recording facility for audio and video to monitor the operator's response including trainee's reflexes [4].

The simulation software comprises of three main default interlinked modules a) process modelling module for process model development b) logic modelling module for emulating the plant logic c) virtual panel modelling module for developing soft control/console panels of the plant which will be useful in development phase of simulator and in the development of plant control screens. The simulation software also supports development and integration of external model with default simulation environment through common shared memory [5]. The PFBR Full Scope Replica Simulator follows ANSI standard ANSI/ANS-3.5-1998, IAEA – TECDOC – 995 and IAEA – TECDOC – 1411 for operator training and examination [6].

III. OGDHR System Description

In PFBR there are two diverse paths for decay heat removal a) passive safety grade decay heat removal system and b) active OGDHR system [2]. The process schematic of OGHDR system is shown in the Fig 3.

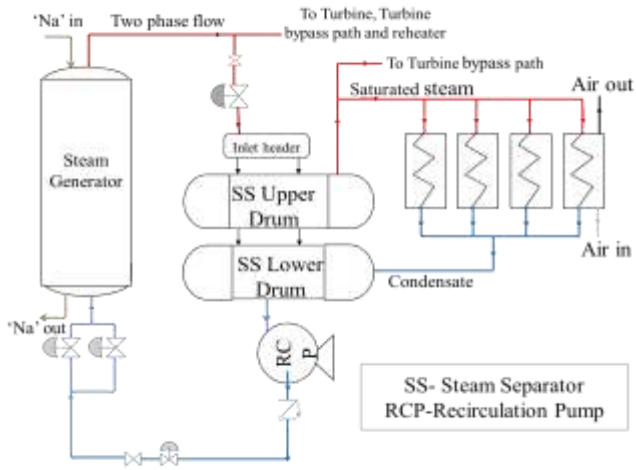

Fig 3. Process Schematic of OGDHR System

The OGDHR operation utilizes the same heat transport circuits used while the reactor is in operation except for a specialized circuit on the steam water system called as OGDHR system. Being an active system the healthiness of secondary and tertiary heat transport systems is mandatory to carry out decay heat removal operation through OGDHR System [7]. In OGHDR operation the decay heat generated in the core is rejected to atmosphere through air cooled condensers via secondary heat transport circuit and steam generator (SG). In order to handle this SG outlet two phase flow a cyclone steam separator is placed at the outlet of SG which separates steam and water from SG outlet two phase flow. The separated water is collected in lower and upper drum of steam separator from which decay heat pumps take suction to pump feed water to SG during OGDHR operation. The separated steam is sent to air cooled condensers. The air is blown through the shell side of condensers using variable speed fans. By controlling the speed of these fans the air flow and thus the heat removed from the core can be controlled. The condensate from outlet of air cooled condensers joins the bottom of separator storage tank thus completing the cycle [7]. The OGHDR system is used intermittently once the plant reaches cold shutdown condition.

IV. OGDHR SYSTEM MODELLING

In PFBR there are two diverse paths for decay heat removal a) passive safety grade decay heat removal system and b) active OGDHR system [2]. The process schematic of OGHDR system is shown in the Fig 4.

A. *Process Modelling*

The process modelling tool is used to model conventional power plant components like pipes, valves, pumps, electric drives e.t.c. The tool provides a library of GUI based generic configurable components and devices. These models are configured as per plant data obtained through thorough study and analysis of design reports, Operation notes, isometrics and piping and instrumentation diagrams. The exchange of data between different models of simulator is established by configuring software stubs defined for each component by developer. This is done by identifying the inputs and outputs of each and every model in the system. As per the scope of simulation simplified simulator flow sheets are drawn. The configured models are interconnected in the same order as that in simulator flow sheets by filling configuration tables. Most of the networks for steam and water systems are developed using these models. The flow rates, pressure drops and temperature variations across the network are calculated using the network solvers and model specific component code. In special cases where the library models are not accurate enough to represent a specific component dynamics, user defined models are developed. These models are developed from the scratch using the model template available in the process modelling tool. Specific to OGDHR system steam separator and air cooled condenser models are developed in consultation with the plant designers. The details of the modelling of these components are given below:

B. *Steam Separator Model*

The steam separator used in PFBR has inlet header where separation takes place, upper and lower drums to collect the separated saturated liquid droplets. In modelling the steam separator, the separator efficiency is assumed to be unity at all operating conditions and no separated steam enters the collection drums. The saturated vapor and water correlations used in the modelling of steam separator are taken from the reference [8] [9].The separator upper and lower drum levels are curve fitted against the volume of liquid water to reduce the model execution time. The fundamental mass balance, thermal balance equations along with the constraint of constant total volume occupied by steam and water were used in evaluating steam separator dynamics which are as follows

$$dN_s/dt = \sum N_{s,in} - \sum N_{s,out}$$

$$dN_w/dt = \sum N_{w,\,in} - \sum N_{w,out}$$

$$dE_s/dt = W_v*h_g - W_c*h_f + \sum E_{s,\,in} - \sum E_{s,out}$$

$$dE_w/dt = -W_v*h_g + W_c*h_f + \sum E_{in} - \sum E_{out}$$

$$d(M_s*v_s + M_w*v_w) = 0$$

Where subscript S corresponds to steam, subscript w corresponds to water, E refers to energy content for example E_w is total energy content in the collected liquid water in separator tanks, N is number of moles, v is specific volume, W_v is vaporization flow rate, W_c is condensation flow rate, H_f is specific enthalpy of liquid water and H_g is specific enthalpy of saturated steam inside separator tank.

C. *Air Cooled Condenser Model*

The air cooled condensers used in PFBR are of finned tube type with saturated steam on the tube side and air is blown on the shell side using air blowers provided with variable speed drives. The variation of air flow rate with fan speed is modeled using affinity law (Air flow rate directly proportional to fan speed). The air cooled condensers are modelled using the design procedure as given in ESDU 80622 for high-fin staggered tube banks [10] [9]. The effect of fouling on the performance of the condenser is neglected in the modeling. The Logarithmic mean temperature difference method (LMTD) is used to estimate the outlet temperatures and heat removed by the condensers. The equations so obtained are solved iteratively at each time step of 200 ms to calculate the heat removed by condenser, outlet temperatures of air and condensate. Following were the equations obtained and solved

$$Q = U*A*LMTD = m_{dot,\,air}*C_{pm,\,air}*(T_{out,\,air} - T_{in,\,air}) = m_{dot,\,steam}*\{L*(1-X) + q*(H_{fsat} - H_f(T_{cond}))\}$$

Where Q is heat removal rate, U is overall heat transfer coefficient, LMTD is logarithmic mean temperature difference, $m_{dot,\,air}$ is mass flow rate of air, $C_{pm,\,air}$ is mean specific heat of air, $T_{out,\,air}$ is outlet temperature of air, $T_{in,\,air}$ is inlet temperature of air, $m_{dot,\,steam}$ is the mass flow rate of steam, L is latent heat of vaporization of liquid water function of inlet steam temperature, X is steam quality, q is a factor either 1 or 0 based on whether the outlet fluid on tube side is in two phase or sub cooled or saturated state, H_{fsat} is specific enthalpy of saturated water, H_f is specific enthalpy of sub cooled condensate and T_{cond} is temperature of condensate.

D. *Plant control logic and Virtual panel modeling*

The control logic associated with the OGDHR system is entirely done using logic modeling tool. The Logic modeling tool provides a menu of logic gates and comparators along with an editor to draw logic sheets. It also provides a feature to debug, compile and convert the logic sheet into a C code. Also Graphical user interfaces are developed using virtual panel modeling tool for display and control. These soft screens are used during development phase to emulate the functionality of control and console panels.

E. *Plant integration and Testing*

Integration and Testing is an important phase in the system modeling as it brings out the adequacies that are ignored during the modeling phase. The process networks of all the subsystems are interconnected and tested in standalone mode. The process models are tested against a predefined input data sequence obtained from designers. The satisfactory performance of process models is followed by integration of process with logic and virtual panel models. All these are tested in integrated mode for discrepancies. Once the simulation performance is found to be satisfactory it is demonstrated to verification and validation committee for approval. The results of the simulation are given below to demonstrate the performance of simulation.

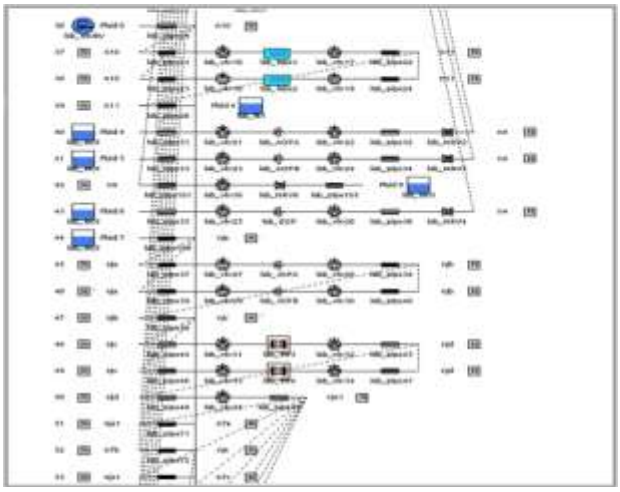

Fig 4 Sample process network developed

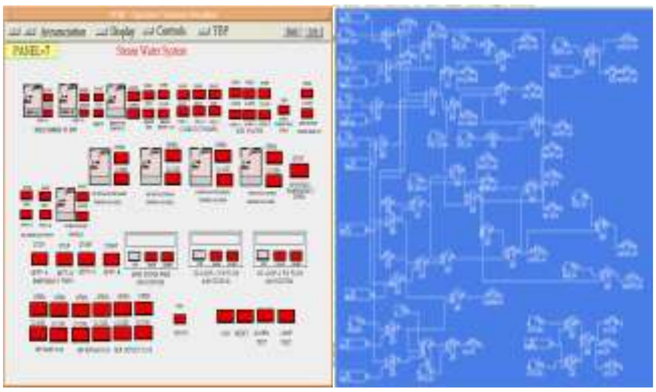

Fig. 5 Sample virtual panel, logic sheet developed

V. VERIFICATION AND VALIDATION

Verification and validation is the most critical phase in simulator development. It ensures the correctness of developed product and is fit for use by end user. Verification and validation was carried out by an independent group of process domain experts. The Entire OGHDR system simulation comprising of process, logic and virtual panel model in integrated mode was demonstrated to verification and validation (V&V) committee. During the process of V&V, first the system was tested for normal operating procedures then the system was subjected to event based testing by initiating a transient or malfunction in the OGDHR system. The system dynamics were captured, plotted and compared with the design and event analysis reports. The performance of the system was found to satisfactory.

VI. RESULTS

The results of OGDHR operation and a transient involving abrupt fan speed reduction due to the malfunction of variable speed drives during OGDHR operation are presented to illustrate the performance of OGDHR system

A. *OGDHR Operation*

The procedure adopted to perform OGDHR operation was as follows: Prior to OGDHR operation the separator drums were filled sufficiently with saturated water collected during separation phase. Once the water volume reaches a certain threshold recirculation pumps were started to feed steam generators and simultaneously boiler feed pumps were tripped. The saturated steam from steam separator was sent to air cooled condensers. The condensate from air cooled condensate will be joining the bottom of separator tank there by completing the cycle. The fan speed was kept constant throughout the entire operation.

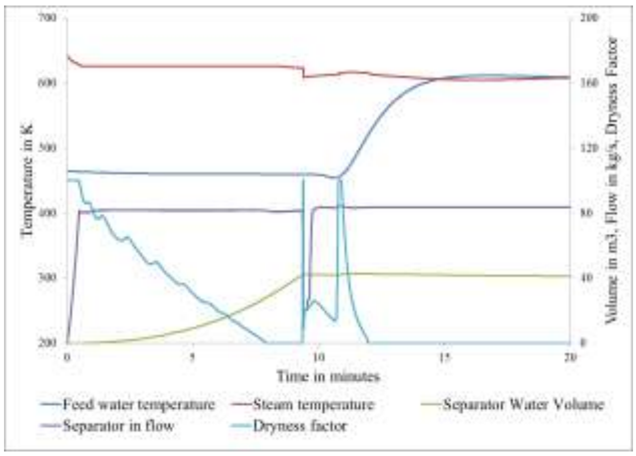

Fig 6. Profiles of parameters during OGDHR operation

The profiles of Feed water temperature, steam temperature at outlet of SG, Volume of collected water in Separator tanks, SG outlet flow to separator header, SG outlet wet steam dryness factor from the instant at which steam separator is brought into operation till the instant where OGDHR system was deployed and operated for 20 minutes are shown in the Fig 6. The steam separator is deployed at the onset of two phase at SG outlet. The collection of saturated water from SG outlet continues till the volume reaches a predefined collection threshold. The separator feed to SG was maintained constant during the entire OGDHR operation. The feed water temperature rises from that of deaerator water temperature of 155^0C to separator water temperature of around 350^{0}C after the deployment of OGDHR System. The slight decrease in separator water volume is due to increase in the density of water due to decrease in the temperature of water in separator tank.

B. Transient involving failure of Variable Speed Drives

In OGDHR system each air cooled condenser is provided with two variable speed fans. The speed of these fans is manually controlled by operator to control the heat removal rate across the condenser. The trends of Feed water temperature, Steam flow to air cooled condensers and air flow rate when the transient involving reduction of fan speed from 500 rpm to 40 rpm is initiated during OGDHR operation is shown in the Fig 7.

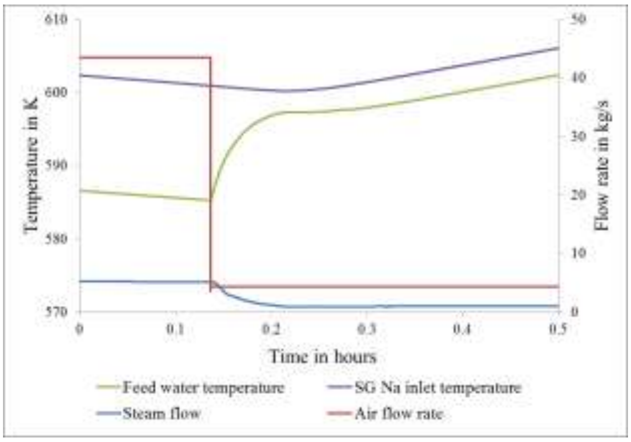

Fig 7. Profiles parameters during a transient in OGDHR operation

All the coolant temperatures in primary sodium, secondary sodium and steam generator circuits will increase as there is no effective heat sink to carry away the decay heat generated in the core. This transient is initiated at around 12 minutes from the reference time shown in Fig 6. All the fan speeds are simultaneously forced to reduce from 500 rpm to a minimum value of 40 rpm and the malfunction is allowed to persist for a longer time. When the OGHDR fails, the standby Safety Grade Decay Heat Removal System automatically takes over when the primary coolant temperature crosses the predefined threshold.

VII. CONCLUSION

The Process, logic and virtual panel models of OGDHR system are developed, integrated and tested on PFBR operator training simulator platform. The performance of the simulation is verified and validated by design experts. The system has been qualified by Verification and validation committee and operators are trained on the system. The performance of the OGHDR system simulation is found to be satisfactory. The real time process simulation of such systems is one of the most vital tools in carving efficient operators for next generation nuclear power plants with enhanced safety and reliability

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