The HTR-PM Plant Full Scope Training Simulator

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Abstract – This paper describes the technical aspects of the Full Scope Training Simulator developed for HTR-PM Plant in Shidao Bay, Shandong Province, China. An overview of the HTR-PM plant and simulator structure is presented. The models developed for the simulator are discussed in detail. Some important verification tests have been conducted on the HTR-PM Plant Training Simulator.

I. INTRODUCTION

A High Temperature Gas Cooled Reactor Pebble-bed Module Demonstration Plant (HTR-PM) is under construction in Shidao Bay, and a Full Scope Simulator (FSS) is designed for simulator training of HTR-PM power plant.

I.A. High Temperature Gas Cooled Reactor Demonstration Plant

HTR-PM demonstration plant is consisted of two high temperature gas cooled reactors, two once-through steam generators, one steam turbine generator and relevant auxiliary systems. One reactor and one once-through steam generator, are disposed in a reactor building shoulder to shoulder. The two reactors with the same structure and same auxiliary system basically are independent of each other, however they shared one fuel handling system, one helium purification system and other auxiliary facilities.

Reactor pressure vessel is shaped as vertical cylindrical shell, with the inner diameter of 5700 mm and total height of 25 m. Reactor core is composed of the ceramic reactor core internals to approximate cylindrical chamber, with the core activity area equivalent height of 11.00 m, outside diameter of about 3.00m, and 420000 fuel elements in the equilibrium reactor core.

Cold helium enters the Reactor Pressure Vessel at a temperature of approximately 250°C and at a pressure of 7MPa. Then it have been heated to 750°C approximately after it flows down between the hot fuel spheres to remove the heat generated by the nuclear fission reaction. Hot helium leaves the bottom of the vessel and enters the steam generator in which the feedwater is heated to steam at a temperature of 570°C at a pressure of 13.9MPa. The significance of the high pressure and high temperature of steam into turbine lies in its superior thermal efficiency properties. A thermal efficiency (heat in, electric power out) of more than 40% is expected in the HTR-PM power plant, while a typical Pressure Water Reactor has a thermal efficiency of 33%.

The fuel element in HTR-PM reactor is spherical encapsulated with ceramic, full of graphite and coated particles of enriched uranium dioxide. The diameter of fuel spheres or pebbles is about 60 mm. The coated shell of fuel particles which can prevent release of radioactive fission product below 1620°C is the first barrier of reaction fission.

Fuel spheres are removed from the bottom of the reactor continuously and transported through the Fuel Handling and Storage System while the reactor is operated at full power. Through the Fuel Handling and Storage System, burn-up of fuel spheres is measured by burn-up and measuring devices first. If the targeted burn-up has not been reached the unburned fuel spheres will be reloaded to the reactor from the top of it to recycle, meanwhile the burnout fuel elements will be delivered to the spent fuel storage tank. When fully loaded, the core would contain approximately 450 000 fuel spheres. At full power operation under the condition of equilibrium, total of 6000 fuel elements are cycled in each reactor every day, while 400 burnout fuel spheres are
discharged to spent fuel storage tank, and the same number of the new fuel spheres are added to the reactor correspondingly every day.

Two sets of shutdown system are designed in each reactor, which are full length rod control system and absorb ball shutdown system. As the backup shutdown system, the Absorb Ball Shutdown System can reduce the temperature of cold shutdown reactor.

HTR-PM is different from the PWR and other reactors, with its inherent security features of the reactor, passive security features, and engineered safety features. Residual heat in the reactor core can be carried out by means of the move, and the temperature of coated-particle fuel sphere in reactor can be controlled under allowed limit in any case. Therefore any possibility of core melt is avoided. Even though a serious accident, radioactive dose can still be in the limited scope, without the need of emergency plan outside. This basic security feature is implemented by the inherent safety features of the reactor.

Fig. 1 shows the primary circuit system structure of one reactor.

Fig.1 the primary circuit system structure of a standard unit.

**I.B. HTR-PM Full Scope Simulator**

Full Scope Simulator is an important part of the HTR-PM demonstration power plant. It is very important to improve the safety of nuclear power plant operation by simulator training. Operator must pass the simulator training to get manipulate license.

As the first full scope simulator of HTR-PM demonstration power plant, FSS can be applied in design verification and operation procedure testing, besides the operator training. Such as:

1. Testing and verification of HMI in control room;
2. DCS verification and validation;
3. Operation procedure development and verification;

Full scope simulator covers all important systems of HTR-PM project. It includes nuclear island system, conventional island system, reactor protection system, electrical system, etc.

Full scope simulator can simulate all running mode, from the cold shutdown maintenance condition, including before the start of inspection, preheating and hot start, cold start, shutdown, initial core operation, transition reactor operation, balance reactor operation, load changing, normal condition, abnormal condition, to emergent condition.

FSS simulate about 300 system-level malfunctions of various kinds of system, including reactive control malfunction, primary circuit system malfunction, second circuit system malfunction, security system malfunction, electric system malfunction, and so on. FSS can simulator all kinds of component malfunctions (component operating failure or mistaking).

**II. DEVELOPMENT**

FSS is a complicated system based on 3KEYMaster Simulation Platform on which models are developed and VDCS, main control room operator stations are interfaced. FSS can copy the actual equipment of control room completely and accurately. In any case, normal condition and abnormal condition, operator can’t distinguish the operating difference on FSS or actual control room.

**II.A. FSS Structure**

The Full Scope Simulator System consists of the following major components, structure of which is displayed in Fig.2:
1. Main Control Room
FSS’s control room is a replica of actual control room of HTR-PM project. FSS’s control panel, control cabinet, control table and control equipment are completely same to actual control room, in terms of appearance, aspects of feeling, and operating function.

2. Virtual DCS
Virtual DCS of HTR-PM is provided by CTEC Co, which is responsible for the actual DCS also.
Virtual DCS can simulate the functions of the actual DCS system comprehensively and accurately, with system structure, control graphics configuration and logic configuration same to the actual one. The functions of Virtual DCS include:
- Consistent with the actual DCS to the greatest extent.
- Meet the need of the FSS development (Freeze/Run, fast/slow, IC snap and reset, etc.)
- The trend curve shows that meet the requirements of the simulation. This includes the freeze of trending functions when the simulator is set to Freeze mode. Trends should not continue plotting when in Freeze mode.
- Two-way communication between Virtual DCS and FSS;

3. Instructor Station
The Instructor Station is the controlling and monitoring center. The control function provided by the 3KEYMASTER IS are listed below:
- Simulator star-up/shutdown and initialize
- Initiate a snapshot, backtrack, or replay
- Simulator mode selection (run, freeze or slow)
- Initiate page select and control function table
- Select, control and initiate malfunctions (specific or combined, with or without time delay), remote function, external parameters and I/O overrides
- Parameter display, manipulation and monitoring functions
- Diagram display (simulation P&IDs and C&I, panel mimics) computer fault acknowledge, master annunciator silence
- Simulator readiness checks (including diagnostics for simulator panel-mounted equipment)
- Activation of pre-defined scenarios
- Trainee/instructor action monitoring and replay
- Trainee performance monitoring and evaluation functions

4. Engineering Stations
Five engineering stations are equipped to modify the models and maintain the FSS.

II.B. 3KeyMaster Plant Simulation Platform

Nuclear power plant FSS is a large and complicated system, and a simulation platform is necessary to support model development, running and maintenance, and includes standard FSS functions such as freeze, snapshot, reset, backtrack, replay, malfunction insertion, fast and slow time and step functions.

3KeyMaster is based on a true online, object-oriented system design, which allows the engineer to modify the model online while the model is running, including two-phase hydraulic network tool, electrical tool, and so on.

FlowBase Tool is a two-phase hydraulic network tool designed to model two-phase pressure & flow networks and typically used to simulate boiler thermal hydraulics, main steam, feedwater, and other systems dealing with steam and water flow.

Electrical Tool provides an integrated solution to the active and passive elements of an electrical system. Logic & Control Tool is used to model digital logic systems. Component Tool is used to simulate power plant components such as valves, breakers.

As the first HTR-PM FSS, new simulation tools and individual component models are specifically developed in 3KeyMaster in order to simulate some special system which is unique for HTR-PM power plant.

RCP tool is the task which is developed newly to construct Reactor Core Neutronics model. FlowBase and Heat tools are used to construct the Reactor Core Thermal-hydraulics model and steam generator model. Core metal structure, core graphite structure, core carbon brick and pebble fuel spheres are considered in Reactor Core Neutronics model and Reactor Core Thermal-hydraulics model also.

Pebble fuel tool is a new tool to simulate the refueling system.

II.C. FSS Modelling Overview

As an operator training and examination of nuclear power plant FSS, it is necessary to identify all primary and supporting systems to simulate the HTR-PM power plant. Over 70 systems, including 36 primary circuit systems, 18 secondary circuit system, and electric systems, have been identified and are in various stages of development. Among them, the most important systems developed to date are Reactor Core Neutronics Model, Reactor Core Thermal-hydraulics model, Fuel Handling and Storage System Model, steam generator model and turbine model.

1. Reactor Core Neutronics Model
The Reactor Core Neutronics is modeled using the RCP tool that is developed by INET(Institute Of Nuclear And New Energy Technology, Tsinghua University), and integrated to 3KeyMaster
simulation platform in which other model tools are working and exchanging data with RCP tool simultaneously. It makes integration easily and controllable of Reactor Core Neutronics Model with other models in 3KeyMaster platform[1].

RCP tool make use of a three-dimensional flux profile. The reactor geometry, fuel composition, level of enrichment, fuel characteristics, rod positions and fuel temperatures are also incorporated in the model. The fuel characteristics include the negative reactivity effect at high temperatures, which is one of the key safety advantages of HTR-PM. Fig.3 shows the Reactor Core Neutronics Model of one reactor new developed in 3KeyMaster used by RCP tool. Another reactor is a replica of this.

Fig.3 Reactor Core Neutron Physics Model

2、Reactor Core Thermal-hydraulics model

Reactor Core Thermal-hydraulics, which is closely coupled with the Reactor Core Neutronics model, is modeled using FlowBase and Heat tool integrated to 3KeyMaster inherently.

Reactor core fluid network is solved by FlowBase, which can calculate the nodes pressure and pipe junctions flow, and reactor thermal network is solved by Heat tool simultaneously, which can calculate all nodes temperatures of thermal network. The nodes temperature, which is calculated on next step, will impact on the resistance of pipe junctions and the pipe flow. So coupling calculation between the fluid network and thermal network is necessary. In each calculation cycle, temperature distribution calculated by Reactor Core Thermal-hydraulics model is transferred to Reactor Core Neutronics Model by interface model, and thermal power is transferred controversially.

Fig.4 shows part of Reactor Core Thermal-hydraulics model which is just one over twenty-four of all Reactor Core Thermal-hydraulics models according to the distribution of reactor core physical grid.

Steam Generator model is developed by FlowBase also. So it is easy to integrate the Reactor Core Thermal-hydraulics and Steam Generator model. This is the distinctive features of HTR-PM FSS.

Fig.4 Part of Reactor Core Thermal-hydraulics model
3. Fuel Handling and Storage System Modeling

One of the unique systems in the HTR-PM FSS design is the Fuel Handling and Storage System. This system is responsible for the operational testing, fuelling, refueling and de-fuelling of the fuel spheres from HTR-PM reactor.

The pebble fuel tool is specifically developed for modeling the movement of fuel spheres cycling through the Fuel Handling and Storage System and all components designed for the system such as fuel sphere diverter, fuel sphere stopper, counter, burnout measure locator and so on. For accurate modeling of the thermo-hydraulic properties of the working fluid in the Fuel Handling and storage System, pebble tool model is connected to a corresponding helium flow network which is calculated by FlowBase\[3]\.

Fig.5 shows the model diagram of main process in Fuel Handling and Storage System.

Fig.5 The Fuel Handling and Storage System in 3KeyMaster

4. Steam Generator, Turbine Model and Others

FlowBase, as a two phase flow model tool, provided by 3KeyMaster, is used to simulate steam generator, turbine and BOP systems of HTR-PM.

According to structure layout of HTR-PM steam generator and the flowing path of water and Helium, steam generator is simplified to 21 Helium and water/steam heat exchangers that is arranged to three groups of seven columns along the way of steam. Water/steam flow and helium flow in the steam generator, and heat exchange are calculated simultaneously in the model. The hot helium inlet and cold helium outlet are interfaced to Reactor Core Thermal-hydraulics model directly.

FlowBase flow modeling tool includes a component for modeling steam turbine. This object is used to calculate turbine power, speed and other elements such as turbine bearing vibrations, metal temperatures and expansions.

II.D. FSS Running Test and Malfunction Test

In order to test the dynamic feature of FSS models before the Virtual DCS is delivered, a simplified version of DCS control logic and MMI has been constructed in simulator platform by 3Keymaster Logic tool. A full FSS’s startup and shutdown and some important malfunctions have been tested, in the case of input power automatic control.

Malfunction Test 1: The control rods false ascension at the mode of power operation:

Assumptions:
1. Full power condition is the initial IC.
2. One rod false ascended by velocity of 5cm/s to the culmination.
3. The protection of high power range invalidation.
4. The temperature limit of Helium outlet of reactor core is 790°C.

Table 1: Procedure of rods false ascension test

<table>
<thead>
<tr>
<th>Incident</th>
<th>Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>One rod false begin to ascend by velocity of 5cm/s;</td>
<td>0.0</td>
</tr>
<tr>
<td>Power range (\geq) 300MW, shut-off signal invalid;</td>
<td>15</td>
</tr>
<tr>
<td>Power range ascending to the culmination (355MW);</td>
<td>37</td>
</tr>
<tr>
<td>One rod false ascended totally;</td>
<td>60</td>
</tr>
<tr>
<td>Temperature of hot Helium (\geq) 790°C</td>
<td>736</td>
</tr>
<tr>
<td>Rods start to drop down, vane of Helium fan closed</td>
<td>736</td>
</tr>
</tbody>
</table>

Fig.6 to Fig.7 show the curves of the power range in FSS and PSAR.

Fig.6 The curve of power range of FSS
Malfunction Test 2: The Helium Fan speed up abnormally:

Assumptions:
1. Full power condition is the initial IC.
2. The Helium Fan speed up to 110% rated speed abnormally.

Fig.8 show the curves of the reactor power range, hot helium temperature and cold helium temperature range of Helium Fan speeding up abnormally test.

As the Helium Fan speeding up abnormally, the flow of helium increases to 110% rated flow. Then hot helium temperature decrease and cold helium temperature increase at the same time. And the reactor power increase to 260MW, then to be stable gradually.

III. CONCLUSION

Test results show that, for use in operator training and examination of nuclear power plant, FSS models can simulate the normal operation and abnormal operation of HTR-PM Demonstration Power Plant. Plant system dynamics in FSS model meet the design requirements correctly.

Because virtual DCS will not be delivered till the end of 2014, the HTR-PM Operator Training Simulator System will be continually tested against operational procedures. FSS has been successfully tested by simplified DCS based on simulator platform over the past several months. As the first FSS of HTR-PM, many challenges on the model development and model parameterization, have been overcome by Engineers, but more challenges remain as the phase of FSS integration testing with Virtual DCS.

REFERENCES