Progress in Nuclear Energy 90 (2016) 11–18

Contents lists available at ScienceDirect

Progress in Nuclear Energy

journal homepage: www.elsevier.com/locate/pnucene

Natural circulation characteristics of lead-based reactor under long-term decay heat removal

Xiaojuan Wang, Ming Jin, Guowei Wu, Yong Song, Yazhou Li, Yunqing Bai*

Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China

ARTICLE INFO

Article history:
Received 29 September 2015
Received in revised form
5 February 2016
Accepted 9 February 2016
Available online 5 March 2016

Keywords:
China Lead-based Research Reactor (CLEAR-I)
RVACS
Primary heat exchangers (PHXs) cooling system
Natural circulation

ABSTRACT

The natural circulation of primary coolant plays an important role in removing the decay heat in Station-Black-out (SBO) accident from reactor core to decay heat removal systems, such as RVACS and PHXS cooling, for lead-based reactor. In order to study the natural circulation characteristics of primary coolant under Reactor Vessel Air Cooling System (RVACS) and primary heat exchangers (PHXs) cooling, which are crucial to the safety of lead-based reactors. A three-dimensional CFD model for the China Lead-based Research Reactor (CLEAR-I) has been built to analyze the thermal-hydraulics characteristics of primary coolant system and the cooling capability of the two systems. The abilities of the two cooling systems with different decay heat powers were discussed as well. The results demonstrated that the decay heat could be removed effectively only relying on either of the two systems. However, RVACS appeared the obvious thermal stratification phenomenon in the cold pool. Besides, with the increase in decay heat power, the natural circulation capacity of primary coolant between the two systems had a significant difference. The PHXs cooling system was stronger than the RVACS, with respect to the mass flow of primary coolant and the average temperature difference between cold pool and hot pool.

1. Introduction

As a fast reactor system, the Lead-based reactors are particularly effective in fuel utilization as well as for burning long-life actinide components of high-level waste, that have accumulated from past and ongoing Generation I through III nuclear fuel cycles (Wu, 2006, 2009a; Wu et al., 1999). Motived by above good properties of Lead-based reactors, a great deal of interests have been displayed in Lead or LBE cooled fast reactors (Wu et al., 2008; Huang et al., 2004, 2009a). Chinese Academy of Sciences (CAS) launched an engineering project to develop Accelerator Driven System (ADS) for nuclear waste transmutation since 2011 (Wu et al., 2002; Wu, 2009b). China Lead-based Research Reactor (CLEAR-I) proposed by Institute of Nuclear Energy Safety Technology (INEST) was selected as the reference reactor in this ADS project (Huang et al., 2009b, 2013; Wu et al., 2015a; Song et al., 2014).

The Reactor Vessel Air Cooling System (RVACS) that removing the decay heat in the typical Station-Black-out (SBO) accident is one of the most important approaches to increase the safety of Lead-based reactors. Many countries applied this system for their lead or lead–alloy cooled fast reactor (LFR), such as MYRRHA, SSTAR and SVBR (Song et al., 2014), etc. Meanwhile, the primary heat exchangers (PHXs) cooling system as one of passive decay heat system could remove the decay heat when primary coolant flowed through the PHXs where pressurized water in secondary loops was heated into vapor without the power supply. The Belgian Nuclear Research Center (SCK-CEN) has applied the passive PHXs cooling system in the MYRRHA (Maes, 2006). CLEAR-I adopted the two varieties of passive decay heat removal systems, which are RVACS and PHXs cooling.

In this paper, a three-dimensional model based on CLEAR-I was established, and the velocity and temperature distribution of primary coolant under long-term decay heat removal condition was simulated. One of the objectives of this work was the study on the natural circulation characteristics of primary coolant in which the RVACS and PHXs cooling system was initiated, during the SBO accident without using any external power supply, respectively. Meanwhile, the capacity of two systems was compared based on different decay heat powers.

* Corresponding author.
E-mail address: yunqing.bai@fds.org.cn (Y. Bai).

http://dx.doi.org/10.1016/j.pnucene.2016.02.009
0149-1970/

2. CLEAR-I design description

The CLEAR-I is a pool type reactor which was proposed by FDS team for Accelerator Driven Subcritical System (Wu et al., 2016). It is an experimental reactor for thermal-hydraulics, neutronics and safety analysis. The lead-bismuth eutectic which flows through the core, hot pool, cold pool, four PHXs and two pumps consist of the primary coolant system. A heat barrier separates hot pool and cold pool. The cold pool incorporates two primary pumps which drive the fluid flow the core when the reactor is in normal operation. The RVACS placed outside of the reactor safety vessel. The configuration of the CLEAR-I has shown in Fig. 1, the main design parameters presented in Table 1, furthermore, the thermal power of the CLEAR-I is 10 MW and average inlet and outlet temperature of the core is 300 °C and 385 °C respectively (Wu et al., 2015b; Sheng et al., 2014).

3. Calculation model

3.1. Geometry model

A simplified model of CLEAR-I which the height and diameter is 6.8 m and 4.6 m respectively has been established, as shown in Fig. 2. Since the layout of the internal structures in the reactor is complicated, especially the construction of core, it is impractical to model the all subassemblies arrangement. Some simplifications are needed to be done as follows: firstly, the model assumed a cylinder for core in place of 86 fuel assemblies with different enrichment zones; then the four PHXs are simulated as annular model and the secondary side tubes are neglected; additionally, fuel handling machine located in the cold pool has small influence in the study, therefore, it can be neglected as well. The simplified geometry model has been meshed following a block-structured strategy, and the quantity of blocks are 2892.

3.2. Grid sensitivity analysis

In this paper investigated the effect of grid sensitivity analysis based on different mesh levels to the coolant flow in the above-mentioned model. This grid sensitivity analysis was performed based on three different grids: a finer grid, a coarser grid and a reference grid. The different temperature output of core outlet for different mesh value with the same boundary conditions are extracted and plotted in the Fig. 3. It indicates that both the values of 3 million and 5 million mesh sizes were consistent. Obliviously, the 2 million mesh was not in accordance with the two other. However, in consideration of the computational time and the performance of computers, the 3.271128 million mesh was selected.

1. Safety vessel
2. Manifold
3. Reactor core
4. Primary pump
5. Control rod driven system
6. PHXs
7. RVACS
8. Cover

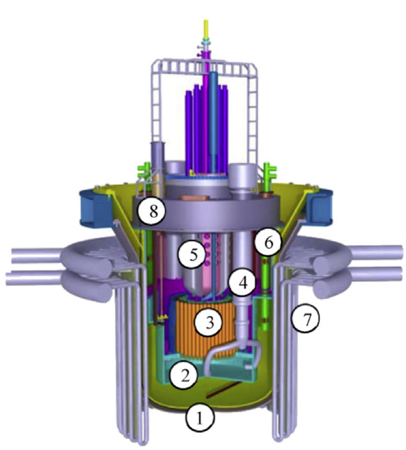

Fig. 1. The configuration of the CLEAR-I.

Table 1
CLEAR-I main parameters.

Parameters	Value
Thermal power (MW)	10
Core inlet/outlet temperature (°C)	300/385
Primary coolant mass flow rate (kg/s)	811.67
Total LBE coolant(t)	~600
Fuel assembly	86

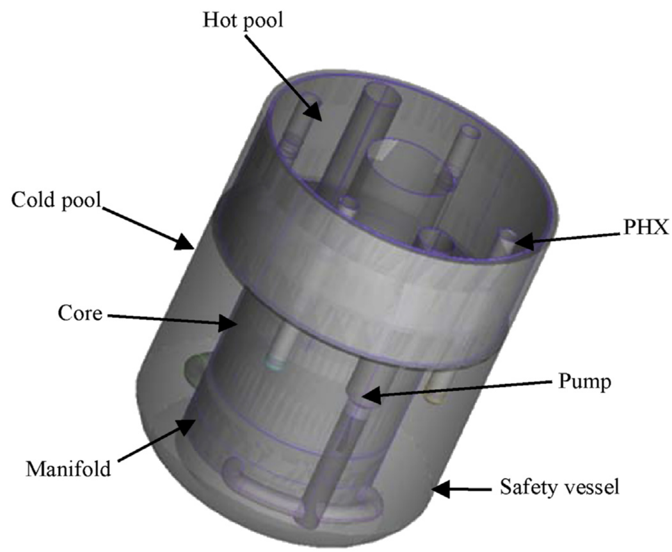

Fig. 2. The simplified geometry model of CLEAR-I.

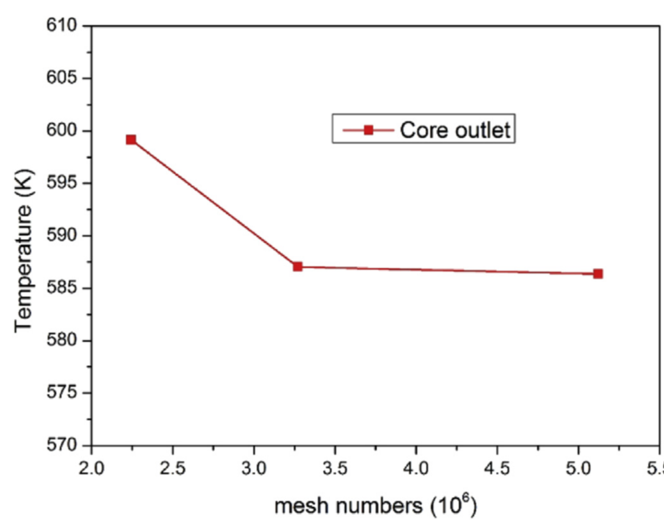

Fig. 3. The core outlet temperature for different mesh levels.

3.3. Porous medium approach

In the geometry model, the configurations of core and PHXs have been simplified while the two parts implies a significant effect on the pressure loss of primary coolant. Therefore, porous medium model has been applied to realize the same pressure drop as the real flow. The pressure drop was modeled by the porous medium