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Natural circulation characteristics analysis of a small modular natural circulation lead–bismuth eutectic cooled fast reactor

Pengcheng Zhao, Shuzhou Li, Zhao Chen, Jie Zheng, Hongli Chen*

School of Nuclear Science and Technology, University of Science and Technology of China, Hefei, Anhui 230027, China

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A B S T R A C T

Small modular reactors (SMRs) have attracted particular attentions in recent years, and small modular natural circulation lead or lead–alloy cooled fast reactor (LFR) is one of the potential candidates for SMRs development. In the small modular natural circulation LFR, the natural circulation characteristics of primary cooling system is a coupled thermal-hydraulic problem of the core, hot and cold plenums, reactor internal parts and heat sink. Therefore, in order to study the thermal-hydraulic performance and safety features of the reactor, the understanding of natural circulation characteristics of primary cooling system is very important. In this work, a CFD simulation was conducted to analyze the natural circulation characteristics of LFR-10 primary cooling system during nominal condition, the velocity and temperature distribution of the reactor pool were illustrated and discussed, the core flow distribution behavior was evaluated. The simulation results show that, a stable natural circulation can be established in the primary cooling system, the current thermal-hydraulic design scheme is feasible, some design features of the cold pool are found that need some reconsideration. The coolant was distributed automatically at the core inlet region, the mass flow rate gradually decreased along the core radial direction, but the mass flow share of each core layer is inconsistent with its power share, the current core flow distribution design of LFR-10 need further analysis, Finally, a correlation was proposed to predict the relationship between the core mass flow rate and the core power under different conditions based on theoretical deduction and simulation results, which can be used to evaluate the heat remove capacity and the primary system natural circulation characteristics for LFR-10 under different operating conditions quickly.

1. Introduction

Recently, research about the development and application of small modular reactors (SMRs) has rapidly increased. These reactors can reduce capital costs and to provide power away from grid systems, which are most suitable for deployment in the developing countries with low electrical grid capacity and in countries with low electricity demand projections. SMRs can be widely used in the generation of electricity, desalination of seawater, district heating, hydrogen production and other process heat applications (IAEA, 2004). Lead and lead–bismuth eutectic are potential candidate coolants for SMRs due to their good neutronic and thermal physical properties such as being chemical inert, in comparison with sodium which has been used as coolant in FBRs. Owing to having a high atomic number, LBE can well suited as a spallation target for accelerator –driven systems (ADS). In addition, due to its large thermal expansion coefficient and low kinetic viscosity, the Lead or LBE-cooled reactors can achieve good natural circulation capability (Cheng et al., 2004).

Motived by above good properties of SMRs, Lead and LBE coolant, some small- and medium sized lead or LBE cooled fast reactors (LFR) are ongoing design (OECD/NEA, 2002; Abu-Khader, 2009; Takahashi et al., 2011), and small modular natural circulation LBE cooled fast reactor is one of the most important direction of LFR development since it can further increase the inherent safety and economic performance of LFR (IAEA, 2007). Several small modular natural circulation LFR concepts have been proposed and some of them are under study at different development stage in many countries. In Europe, a natural circulation LFR named Energy Amplifier (EA) had been developed to severe as the sub critical reactor of ADS (Rubbia et al., 1995), and the European Lead Cooled Training Reactor (ELECTRA) is promoted by the Royal Institute of Technology (KTH), which is a lower power natural circulation fast reactor intended for research, education, training and technology

* Corresponding author. Tel./fax: +86 0551 63607931.
E-mail address: hlchen1@ustc.edu.cn (H. Chen).

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demonstration purposes (Wallenius et al., 2012). In Japan, a Pb–Bi-cooled direct contact boiling water fast reactor (PBWFR) is capable of eliminating components of the cooling system as primary pumps and steam generators has been developed by the Tokyo Institute of Technology (Takahashi et al., 2008). In the United States, the natural circulation LFR actinide burner reactor (ABR) was designed for producing low-cost electricity as well as actinide burning (Davis and Kim, 2002). Several Natural Circulation, Lead cooled, small modular fast reactors such as STAR-LM, SSTAR and SUPERSTAR have been developed for international Deployment (Sienicki et al., 2007, 2011; Smith et al., 2008). In China, a small modular natural circulation lead–bismuth eutectic cooled fast reactor-10MW$_{th}$ (LFR-10) is under design by the University of Science and Technology of China (USTC) (Chen et al., 2012).

Thermal-hydraulics is recognized as one of the key scientific subjects in the design and construction of LFR (Cheng et al., 2006), and different approaches have been used to solve thermal-hydraulics issues. Such analysis has been mainly done by modifying the nuclear thermal-hydraulic codes, such as RELAP (Bandini et al., 2006) or TRACE (Ma et al., 2006), and then these modified codes are used to analyze the heavy liquid metal phenomenon. These codes frequently use a one-dimension lumped-parameter method to model real reactor systems. Another approach is the application of Computational Fluid Dynamics (CFD) codes, with the rapid development of high performance computer technology and CFD models, the CFD techniques are becoming more and more integrated in the daily practice of the LFR researchers and designers. Vanderhaegena et al. (2011) carried out a CFD analysis to study the thermal-hydraulic characteristics of MYRRHA under the nominal state and an accident condition. Abánades et al. (2009) studied the free convection cooling mode characteristics of one of the reference ADS design using the CFD code FLUENT. Chen et al. (2014a, b) analyzed the core flow distribution with CFD code for a small-sized LFR, and compared the results with the system code. Since the typical LFR is usually a pool-type reactor, and there are many multi-dimensional thermal-hydraulic phenomenon exist in the primary cooling system, which cannot be predicted by using traditional one-dimension system codes (IAEA, 2003). With the developments of mesh generation tools, compute technology and CFD models, the complex multi-dimension thermal-hydraulic issues can be modeled precisely with CFD codes. The CFD codes will be more and more widely used in the design and safety analysis of LFR in the future based on above advantages.

Unlike the pump-forced reactor, the coolant mass flow rate of natural circulation LFR is determined by the balance between the driving force and resistance force. For this reason, the natural circulation of reactor primary cooling system is a coupling of thermal-hydraulic problems of the core, the upper and lower plenums of the reactor, reactor internal parts and so on. Therefore, the understanding of the natural circulation characteristics of LFR-10 is very important from the view of improving the safety features of the reactor. Which is extremely useful to evaluate the current thermal-hydraulic scheme is reasonable or not, reveal the natural circulation reactor flow distribution characteristics. The LFR-10 is a typical LBE cooled pool type fast reactor, the conclusions drawn from this work can provide some suggestions about thermal-hydraulic and structural design to similar natural circulation LFR.

In this work, a CFD model of LFR-10 primary cooling system with all their components was established based some reasonable assumptions and simplifications, an analysis of the steady state operation was conducted by using the CFD code FLUENT. The temperature and velocity distribution characteristics in the reactor pool were illustrated and discussed. The core flow distribution behavior at the core inlet region was investigated to study the characteristics of the coolant automatic distribution phenomenon. The simulation results show that the current thermal-hydraulic design of LFR-10 is feasible, some design features of the cold pool are found that might need some reconsideration, and the coolant flow distribution scheme needs further analysis. Finally, a correlation was proposed to predict the relationship between the core mass flow rate and the core power under different conditions based on computational results and theoretical deduction.

2. LFR-10 design description

The schematic of the LFR-10 is depicted in Fig. 1 and the main parameters of LFR-10 are shown in Table 1 (Chen et al., 2014a, b). LBE is selected as the coolant for LFR-10 primary system, and the primary cooling system is driven by natural circulation based on making full use of the LBE good natural circulation capacity. The primary cooling system is divided into hot pool and cold pool by a heat barrier, and four primary heat exchangers (PHX) are located in the reactor main vessel. The cold LBE from the lower plenum is heated in the core region and driven by the natural circulation, which is caused by the coolant density difference between the hot pool and cold pool, the heated LBE collected and mixed in the hot pool. Then the hot LBE flows to the PHX where it is cooled by the secondary system and then enter the cold pool once again through the outlet of PHX (Zhao et al., 2013). There are 84 fuel assemblies in the core, each fuel assembly contain 61 fuel roads. The length and diameter of the LFR-10 active core is 0.8 m and 2.0 m respectively.

3. Calculation model description

Since the layout of the internal structures has a great influence on the establishment of natural circulation in the primary cooling system, so it impractical to model the entire LFR-10 primary system geometry and the internal parts arrangement. As it is presently not possible to run a CFD model, that is able to simulate the complete primary circuit in detail, so in order to achieve practical simulation results, some simplifications are needed to be done.

The simulation was done in a 2D axisymmetric geometry, as shown in Fig. 2 with a model nearly 120,000 cells. The CFD model

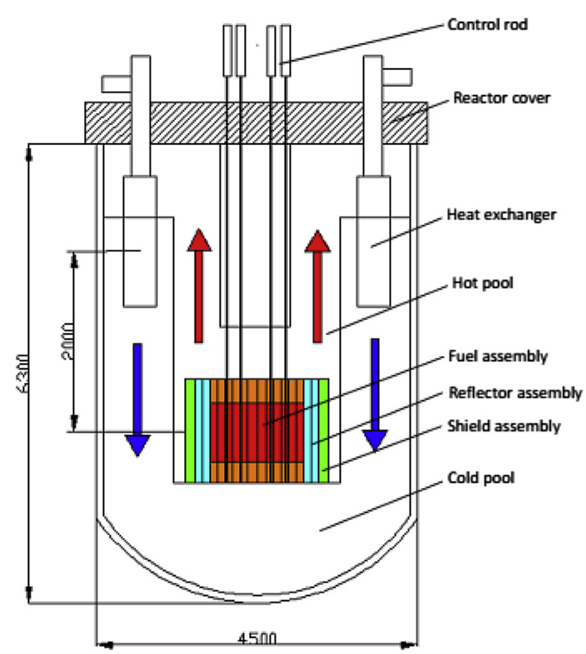

Fig. 1. Primary cooling system of LFR-10.