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Conceptual design of a small modular natural circulation lead cooled fast reactor SNCLFR-100

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ARTICLE INFO

Article history:
Received 14 November 2015
Received in revised form
21 January 2016
Accepted 21 January 2016
Available online 26 February 2016

Keywords:
Small modular reactor
Lead-cooled fast reactor
Natural circulation
Conceptual design

ABSTRACT

SNCLFR-100, a 100 MW_{th} lead-cooled small modular reactor with a passive cooling feature to both normal and abnormal operations, was proposed by University of Science and Technology of China (USTC). The reactor is well suited as a remote power source because of its compact size, as well as because it has a refueling interval of 10 years without assembly reconfiguration. The reactor is a typical pool-type fast reactor with an array of heterogeneous square fuel assemblies loaded with MOX fuels. In this paper, the overall design and neutronics features were illustrated and evaluated. The steady state thermal-hydraulic performance, mass flow distribution characteristics and sub-channel T/H features were analyzed and discussed. Two major accident scenarios including unprotected overpower transient (UTOP) and unprotected loss of heat sink transient (ULOHS) were selected for a first evaluation of its dynamic behavior. The results show that the safety criteria are satisfied and reactor is tolerant to the UTOP and ULOHS transients. This implies that the conceptual design of SNCLFR-100 is acceptable and the reactor has excellent inherent safety characteristics.

Introduction

Small modular reactor (SMR) has attracted particular attentions in recent years due to its outstanding technical, economic and safety characteristics. Lead or Lead-Bismuth Eutectic (LBE) cooled fast reactor (LFR) technology is very promising for closing the nuclear fuel cycle. As one of the reactor types emphasized in the Gen-IV initiative, LFR should display enhanced safety performance compared to currently reactors in operation. Passive cooling small modular LFR is considered as one of the potential candidates for LFR development in order to enable its commercial application.

Due to the good natural circulation performance of lead and LBE, several small modular natural circulation Lead or LBE cooled fast reactors have been developed during the past decades. In 1990s, a natural circulation LFR was proposed by Rubbia et al. to serve as the sub-critical reactor for an Accelerator Driven System (ADS) [1]. In the beginning of the 21st century, MacDonald and Todreas carried out some research works on the natural circulation LBE cooled reactor that used for actinide burning and electricity producing with low cost

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http://dx.doi.org/10.1016/j.ijhydene.2016.01.101
0360-3199/

[2]. In the late 2000s, Sienicki et al. developed several small modular natural circulation LFR concepts, including SSTAR and SUPERSTAR [3,4]. In Korea, advanced natural circulation SMR named as PASCAR loaded with U-TRU-Zr metallic fuels and URANUS loaded with UO_2 oxide fuels have been developed [5,6]. Also, some natural circulation characteristics of lead and LBE has been researched and investigated in recent years [7–9]. In order to have a better understanding of the neutronics and thermal-hydraulics performance of LFR and accelerate the application of SMR in China, a small modular natural circulation lead-cooled fast reactor named as SNCLFR-100 is currently being developed by USTC based on the existing feasible technology and past experience.

The paper focuses on the conceptual design and neutronics characteristics analysis as well as the preliminary thermal-hydraulic performance evaluation of SNCLFR-100. The reactor neutronics characteristics were illustrated and discussed. The preliminary thermal-hydraulic design and the related steady state features calculations were performed, the assessment of reactor mass flow distribution features was conducted and sub-channel analysis was carried out for the hottest assembly. Finally, unprotected transient overpower (UTOP) and unprotected loss of heat sink transient (ULOHS) were selected to launch a first estimate of reactor thermal-hydraulic performance during transients. The results show that the conceptual design of SNCLFR-100 is acceptable and feasible, and that the reactor has excellent inherent safety characteristics.

Preliminary design of SNCLFR-100

The SNCLFR-100 is a typical pool-type fast reactor incorporating some advanced design ideas such as integral arrangement and modular design, which will help simplify the system design, improve the reactor safety performance and engineering feasibility. The overall structure design of SNCLFR-100 is shown in Fig. 1, and the main design parameters are listed in Table 1.

All the components of primary system, including core, hot pool, primary heat exchangers, cold pool and the internal wall which separates the upper plenum and the lower plenum, are arranged in the reactor vessel. Integral arrangement can simplify the primary system, eliminating penetration assemblies through the reactor vessel and thus largely reducing the occurrence possibility of loss of coolant accidents (LOCA). The primary system adopts the complete natural circulation cooling technology, thus eliminating loss of flow accidents (LOFA) induced by mechanical pump failures and improving the safety characteristics of the reactor, meanwhile avoiding construction and operation problems brought LFR mechanical pumps, and finally effectively improving economy and engineering feasibility of the reactors.

In the primary cooling system, the primary coolant lead is heated through the core. As the density of the heated primary coolant becomes smaller, the heated lead flows upward and enters the hot plenum. In the upper region of the hot pool, the primary coolant splits into four directions and flows inside the primary heat exchangers, it is cooled through these heat exchangers, and the primary coolant flows downward. The flow path of the primary coolant in the SNCLFR-100 primary cooling system is represented in Fig. 2.

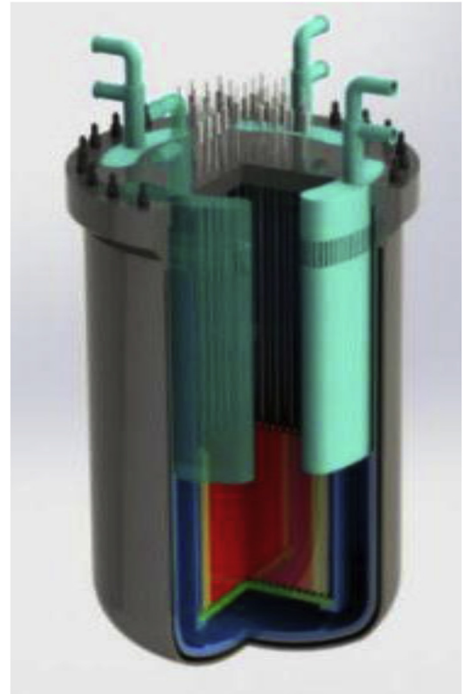

Fig. 1 – Schematic diagram of SNCLFR-100 primary cooling system.

Table 1 – Main design parameters of SNCLFR-100.

Design parameters	Values or characteristics
Thermal power	100 (MW_{th})
Refueling interval	10 (years)
Plant design lifetime	30 (years)
Primary coolant	Lead
Primary heat transport system	Compact pool type
Core configuration	Closed octahedron array
Primary normal cooling model	Fully natural circulation
Secondary normal cooling model	Water/steam forced circulation
Abnormal decay heat removal	Reactor vessel auxiliary cooling system
Fuel	MOX
Cladding	T91
Steam generators	4 modules of straight shell-tube type
Secondary water/steam cycle	Rankine cycle with superheated steam

Reactor core design

Core and assembly configurations

Owing to SNCLFR-100 is cooled completely by natural circulation for both normal and abnormal conditions. In order to reduce pressure loss in the core region, larger pitch-to-