



A Mini Review of Research Progress of Nuclear Physics and Thermal Hydraulic Characteristics of Lead-Bismuth Research Reactor in China

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The lead-bismuth research reactor is one of the most important generation-IV reactors. Currently, Chinese scholars are very enthusiastic about studying lead-bismuth research reactors. Based on the research results in the papers that have been published, research progress on lead-bismuth research reactors in some Chinese research institutes such as the Chinese Academy of Sciences, Shanghai Jiaotong University, the University of Science and Technology of China, and the Institute of Nuclear and New Energy Technology of Tsinghua University have been conducted. Firstly, Chinese academics attach great importance to the safety analysis of lead-bismuth research reactors in the event of an accident. Besides, CLEAR-I has negative reactivity coefficient feedback, which reflects its safety. The determination of the flow state of the liquid metal will be a prospect for future research. Besides, Small Modular Pb-Bi Cooled Reactor with Nitride Nuclear Fuel is easy to control during its lifetime and has inherent safety features. China lags behind its international counterparts in minor actinides transmutation. This is also an important prospect in future research. This review is expected to provide a reference for the research of lead-bismuth research reactor.

Keywords: lead-bismuth, China's research progress, generation-IV reactor, prospect, research reactor

INTRODUCTION

As one of the most important generation-IV reactors, the lead-bismuth research reactor uses lead-bismuth alloy as the coolant (Xiong and Yang, 2014). Lead-bismuth alloy has the characteristics of low melting point and high boiling point. Compared with ordinary reactors, it can greatly reduce the difficulty of design and engineering. And it also has a higher inherent safety and ability to withstand accidents. Therefore, the lead-bismuth alloy reactors have lots of advantages.

Venus III, China's first zero-probability device for a lead-bismuth research reactor manufactured by the China Institute of Atomic Energy reached its critical state for the first time on October 12, 2019. At the same time, research institutes such as the Chinese Academy of Sciences have also proposed that they will formally launch China's lead-bismuth reactor core physics experiments. This is regarded as a milestone major progress made by China in the key technology of the lead-bismuth research reactor. The success of the lead-bismuth zero reactor signifies that China will have its own set of standards and boundaries for zero-power experimental data.

Based on the research results in the papers that have been published, review and progress on lead-bismuth research reactors in some Chinese research institutes such as the Chinese Academy of Sciences, Shanghai Jiaotong University, the University of Science and Technology of China, and the Institute of Nuclear and New Energy Technology of Tsinghua University have been conducted. Prospect is given, which is expected to provide a reference for the research of lead-bismuth research reactor.

RESEARCH REVIEW

Related Research

The currently published influential China's researches on lead-bismuth research reactors are as follows. China's research on lead-bismuth research reactors started late. In 2014, Xiong and Yang of Tsinghua University conducted a physical property study and core design of an accelerator-driven subcritical system cooled by a lead-bismuth alloy with a thermal power of 800 MW and an accelerator proton energy of 600 MeV (Xiong and Yang, 2014). They used a program to study the effects of different grid-diameter ratios and the content of minor actinides (MA) on reactivity and burnup processes. Considering the factors such as safety and transmutation effect, the appropriate grid-to-diameter ratio and MA content are selected. In addition, a physically feasible subcritical scheme for driving a lead-bismuth cold accelerator is established.

In 2014, Wu et al. of the Chinese Academy of Sciences designed a Chinese lead-based research reactor called CLEAR-I under critical and subcritical conditions using lead-bismuth alloy as a coolant (Wu et al., 2014). CLEAR-I uses lead-bismuth alloy cooling and utilizes relatively mature fuel and material technologies. Different experimental goals can be achieved by automatically replacing fuel assemblies. It has good practical feasibility, safety reliability, experimental flexibility, and technical continuity.

In 2015, Mei et al. of the Chinese Academy of Sciences conducted a preliminary selection and analysis of the lead-bismuth reactor transmutation fuel (Mei et al., 2015). They proposed that separation and transmutation currently appear to be a more feasible path for the recovery and treatment of MA. In addition, by analyzing the characteristics of the lead-bismuth fast reactor/accelerator drive sub-critical system and the properties of traditional fast reactor fuel, they believe that the nitride transmutation fuel is the current preferred solution for the lead-bismuth reactor transmutation fuel. Mei et al. believe that the accelerator drive sub-critical system transmutation system being constructed by the Chinese Academy of Sciences should be considered for future tests of irradiation and transmutation performance of nitride fuels.

In 2015, Ma et al. of the University of Science and Technology of China developed a thermal calculation program for the temperature and density distribution of the core components of the subcritical system driven by lead-bismuth cooling accelerators using a single-channel model. A physical and thermal coupling calculation method was proposed (Ma et al., 2015).

In 2015, considering the weight of the lead-bismuth alloy, Zhang et al. of the University of Science and Technology of China

conducted a preliminary seismic response analysis of the CLEAR-I main vessel under the ANSYS Workbench simulation environment based on the two-way fluid-solid coupling method (Zhang et al., 2015). The calculation results show that the displacement response and equivalent stress response of the main vessel are within the allowable limits. In addition, they also found that the response of the main vessel structure is different under different fluid models. The displacement response calculated by the k-Epsilon model is smaller than that of the laminar flow model.

In 2017, Yuan et al. of Xi'an Jiaotong University preliminarily designed Small Modular Pb-Bi Cooled Reactor with Nitride Nuclear Fuel (SMPBN) and studied its physical properties (Yuan et al., 2017). SMPBN's reactivity fluctuates very little throughout its lifetime, and several important reactivity coefficients of the reactor are negative. This shows that SMPBN can be easily controlled during its lifetime and it has inherent safety features, which is consistent with the conclusion drawn by Wu et al. (2014). Yuan et al. also pointed out that the lead-bismuth research reactor driven by plutonium nitride meets the design goals of future reactors with long life, natural circulation, and passive safety characteristics.

In 2017, Wei et al. of Xi'an Jiaotong University coupled the subchannel analysis program SUBAS of the lead-bismuth alloy cooling fast reactor with the SACOL analysis program of the thermal-hydraulic system of the lead-bismuth alloy cooling fast reactor. The coupled program was used to analyze Pb-Bi cooled direct-contact-Boiling Water Fast Reactor (Wei et al., 2017).

Focusing on the analysis of unprotected transient overpower (UTOP) accidents, the thermal hydraulic characteristics of the Pb-Bi cooled direct-contact-Boiling Water Fast Reactor core sub-channel and system are obtained. The results show that the relative error of the calculation results of the SACOL program and the coupling program does not exceed 4%, which proves the correctness and rationality of the unidirectional coupling and stepwise calculation.

In 2018, Yao et al. of Shanghai Jiaotong University conducted a computational analysis of the flow blockage accident conditions under different blocking parameters of the lead-bismuth research reactor through the commercial computational fluid dynamics software STAR-CCM+ (Yao et al., 2018). They found that the maximum temperature rise of the flow blockage accident is inside the blockage. Therefore, the flow blockage accident will first threaten the integrity of the cladding. In addition, the increase in blockage area will cause a significant increase in local temperature rise.

In 2019, Yang et al. of Shanghai Jiaotong University coupled thermal engineering program COBRA-YT and physical program SKETCH-N and applied the program to the analysis of control rod lifting accidents (Yang et al., 2019). They found that after the control rod was lifted, the power of the central component increased significantly, and the main thermal parameters exceeded the safety limits. This indicates that the core should be optimized for partition layout (Yang et al., 2019). Lifting speed affects power and reactivity. The greater the speed, the greater the reactivity and peak power, thus the lifting speed should be controlled.

In 2019, Lei et al. of Xi'an Jiaotong University proposed a small transportable long-life lead-bismuth research reactor core design

TABLE 1 | Performance of the lead-based research reactor in China.

Content	Clear-I	Clear-II	Clear-III
Thermal power/ MWt	10	100	1,000
Fuel type	UO ₂	MOX	Nitride or metal
Coolant	Lead-bismuth alloy	Lead-bismuth alloy	Lead-bismuth alloy

scheme to meet the power supply needs in remote areas (Lei et al., 2019). Based on the quasi-static reactivity balance method proposed by some US research institutions, the thermal characteristics of the scheme under different kinds of unprotected accident conditions including unprotected loss-of-heat-sink, UTOP, unprotected loss-of-flow were analyzed. Among the above unprotected accident conditions, the UTOP accident has the most serious consequences. The coolant outlet temperature is 147.2°C. The maximum temperature of the coolant pipe surface under accident conditions is 595.0°C, which is still lower than the transient design limit of 650°C.

Analysis and Discussion

Prospect and underlying challenges of lead-bismuth research reactor in China are given. In the research of Xiong and Yang (2014), several factors have a great influence on the design of subcritical solutions. Thus how to weigh their weight is very important. If the gate-to-diameter ratio is too large, the reactivity change rate will be too large. The small gate-to-diameter ratio can suppress the change of reactivity, but it is also limited by the thermal properties of the lead-bismuth alloy. Therefore, this is very contradictory. How to choose the proper grid-diameter ratio is of great significance to the physical characteristics of the core. Increased MA content can improve the transmutation effect, but it will cause significant reactivity changes, which makes the fuel consumption cycle shorter and the safety performance worse. When selecting the MA content, it is necessary to comprehensively consider various factors to try to balance the contradiction between reactive changes and transmutation effects.

Performance of lead-based research reactor in China is shown in **Table 1** (Wu et al., 2014).

The CLEAR-I designed by Wu et al. (2014) is very safe because Wu et al. briefly expounded the technical route of the reactor from the aspects of core scheme, reactor body structure, thermal

engineering scheme, coolant system and safety system. And the security features were preliminary analyzed. Most importantly, CLEAR-I has negative reactivity coefficient feedback, greater thermal inertia, and passive residual heat removal capability, which reflects good safety.

Some important research institutions and research contents of MA fuel is given in **Table 2** (Mei et al., 2015).

According to Mei et al. (2015) and **Table 2**, MA fuel research mostly uses a cooperative mechanism, and the most active research institution is CEA in France (Mei et al., 2015). The most studied fuel is MA-MOX fuel, followed by MA nitride. For MA-MOX fuels, transmutation fuels with different Am, Np, Cm composition combinations and oxygen stoichiometric ratios were studied, including fuel manufacturing process, physicochemical properties, and neutron irradiation performance. For MA nitride fuels, the technology for preparing nitride fuels by carbothermal reduction was mainly studied, and a small amount of irradiation performance tests were carried out. The reactors that carry out MA fuel irradiation tests are mainly fast reactors and high-throughput reactors, especially fast reactors. Although MA fuel irradiation is researched by many institutes. At present, the research on MA transmutation fuel is extremely difficult in China, and China's research level in this respect is lower than the international advanced level. Only through extensive and in-depth cooperation will it be possible to reach the level of international peers as soon as possible.

The core component temperature and coolant flow rate obtained by this calculation method (Ma et al., 2015) meet the thermal safety limits. Nevertheless, the core radial power non-uniformity coefficient is larger, thus we hold the view that the core design needs to be further optimized.

It can be seen from Zhang et al. (2015) that the flow state of the liquid metal in the main vessel has a significant effect on the seismic response of the structure. Therefore, the determination of the flow state of the liquid metal will be a prospect for future research.

Finally, SMPBN will surely become a research hotspot and important development type for China's future nuclear reactors. The research by Yao et al. (2018) is the one of the most comprehensive researches on flow blockage accident analysis of a lead-bismuth research reactor in China. The stability and accuracy of the coupled program calculations of Yang et al. (2019) are greatly affected by the time step selected in the calculation. Stability and accuracy of this coupled program is the future research direction. The analysis by Lei et al. (2019) preliminarily proves the existence of the inherent safety characteristics of the core.

TABLE 2 | Some important research institutions and research contents of MA fuel.

Research content	Research institute
CEA, ITU	Uranium oxide or MOX fuel containing Np, Am UO ₂ , or MOX fuels containing Np and Am
CEA, ITU, etc. KTH, etc.	Homogeneous mode, MOX fuels containing Am Production of (Ce,Zr)N, (U,Zr)N, and (Pu,Zr)N pellets, thermodynamic conditions of nitride solid solutions
CEA	Comparing properties of (Pu,Am)O ₂ , (Th,Pu,Am)O ₂ , and (Pu,Am,Zr)O ₂
RIAR, IPPE, BIRF, CEA JAEA	(Pu,Am,Cm,Zr)N, pellet, and vibro-packed Irradiation behaviour of MOX fuels containing Am, including Am-MOX and Np/Am-MOX and reference MOX fuel

CONCLUSIONS AND PROSPECTS

Research on lead-bismuth research reactors in China started late. Around 2014, a preliminary feasible subcritical solution for the lead-bismuth research reactor was given. In 2015, the selection of lead-bismuth research reactors made a breakthrough. Current researches focus on the following aspects.

- (1) Researchers mostly simulate and calculate the reactivity and thermal parameters of lead-bismuth research reactors

through the coupling of nuclear physics and thermal hydraulic programs. The lead-bismuth research reactor has negative reactivity coefficient feedback, greater thermal inertness, and passive waste heat removal capability. And the fluctuation of reactivity is small, and its safety is widely recognized by Chinese research institutions.

- (2) Chinese academics attach great importance to the safety analysis of lead-bismuth research reactors in the event of an accident. Safety analysis has been studied under earthquakes, flow blockage accident, unprotected loss-of-heat-sink, UTOP, unprotected loss-of-flow, etc.
- (3) CLEAR-I has negative reactivity coefficient feedback, which reflects good safety. Flow state of the liquid metal in the main vessel has an effect on the seismic response of the structure. Therefore, the determination of the flow state of the liquid metal will be a prospect for future research. Besides, SMPBN is easy to control during its lifetime and has inherent safety features. Thus SMPBN will surely become an important development type for China's future nuclear reactors. Stability and accuracy of coupled program is weak and the study on this will be the research prospect.
- (4) When selecting the MA content, it is necessary to comprehensively consider various factors to try to balance

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the contradiction between reactive changes and transmutation effects. MA transmutation is valued, but there is currently little research in this area in China. And China lags behind its international counterparts in this technology, which is an important prospect in future research.

AUTHOR CONTRIBUTIONS

BW designed this topic. BW, BC, JW, and RT contributed to collecting related references. BW wrote most of the manuscript. The remaining authors contributed also contributed to the writing of the article.

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