INVESTIGATION ON THE SELF-START-STOP FUNCTIONALITY FOR SMALL SODIUM COOLED FAST REACTOR NUCLEAR POWER SYSTEMS

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INTRODUCTION: Small sodium-cooled fast reactor nuclear power sources are widely applicable to various regions with stable power supply demands, such as isolated islands and remote mountainous areas, due to their flexibility and high degree of modularity. The targeted demand users of nuclear power sources are located in remote areas far from the external power grid. Therefore, it is very necessary to carry out design research related to the self- start-stop function for this demand. This project is based on the test data of the non-nuclear integrated test device of the small loop-type sodium cooled fast reactor nuclear power source self-developed by the China Institute of Atomic Energy (CIAE), and conducts analysis on the start-up and shutdown logic of small sodium reactor in combination with the application scenarios of small sodium cooled fast reactor nuclear power source. The project focuses on the power consumption of key equipment during the start-up and shutdown processes and provides design schemes for energy storage modules suitable for small sodium cooled fast reactor nuclear power source of different size levels. A well-performing and efficient energy storage module combined with reasonable start-up and shutdown logic can effectively ensure the applicability of small sodium cooled fast reactor nuclear power source under various conditions, and at the same time promote their future engineering application and promotion.

1. 1. OVERVIEW

As a kind of clean energy, nuclear energy has the advantages of high energy density, not relying on oxygen environment and long service life. With the accumulation of experience in nuclear reactor operation and the progress of related technologies, the application scenarios of nuclear energy are more and more extensive. Various countries have put forward a variety of new reactor concepts. Among them, small modular reactors (SMRs) are the hot research field at home and abroad. In the 1950s, many countries have designed a variety of small reactors, and most of the well-known small reactor design schemes refer to the design and test experience of early small reactors. A single small reactor unit re-duces costs through modular design and standardized production, its initial investment is much lower than that of a large reactor, and flexible expansion is carried out through module combination and other ways. Small modular reactors have great advantages in safety, economy and constructability, and many countries (regions) such as the United States, Russia, the European Union and Japan attach great im-portance to the research, engineering development and application of small modular reactors [1].

Through the co-production model, SMRs can provide a variety of non-power products such as heat, desalinated water, industrial steam, and so on, which greatly improves its competitive strength. From the current development status, the application of SMRs is mainly concentrated in remote mountainous areas, isolated areas, remote islands and reefs that do not require high-power generation, floating power stations for power supply and heating near port cities or islands and reefs, and offshore platforms, and in the field of seawater desalination [2-4]. These target users have the characteristics of remote locations and far away from the external power grid. Therefore, assembly flexibility and autonomous start-stop are important parts of SMRs R&D technology.

Years of research and development and operation experience show that the sodium-cooled fast reactor is easy to miniaturize and has mature control experience. However, due to the chemical activity of sodium, it is easy to react with water and air. In particular, the sodium-water reaction is violent and highly destructive, and special systems need to be configured to prevent the harm of sodium-water reaction. The existence of this system increases the number of auxiliary systems. In order to solve the industrial problem of sodium water reaction, it is considered to optimize the loop system, establish a new cycle and change the intermediate heat transfer medium.

Because of its heat transfer medium, Stirling cycle can avoid violent chemical reaction with high temperature liquid metal, which fundamentally solves the harm of sodium-water reaction. On the other hand, the Stirling cycle can be completed directly by a single multi-cylinder Stirling engine, and the Stirling generator is simple to start, which is more suitable for the autonomous start-stop and control of small modular reactors. Combining the characteristics of miniaturization and intelligence, the small modular reactor using sodium-cooled fast reactor combined with Stirling engine technology is more suitable for the requirements.

The economic competitiveness of SMRs has always been an important factor to promote its development, and its capital cost consists of two parts: the initial investment cost of unit construction and the daily operation and management cost. The upfront investment costs are mainly for design, manufacturing, transportation, installation and commissioning. These capital costs are relatively fixed and difficult to reduce, and reducing costs by changing existing design and manufacturing techniques takes time and requires additional capital investment. The daily operation and management cost mainly comes from the daily operation and maintenance of the human cost, the current nuclear power plant operation and maintenance (O&M) personnel is composed of multiple shift operator teams, each team involves a great deal of technicians and experts. If the SMRs still uses this mode to ensure that there are enough people to make decisions and operate under transient and accident conditions, the operating cost will increase greatly. This mode will reduce the economy of SMRs and even cause SMRs to lose economic advantages. The reason for the current situation is that the current degree of automation and intelligence of nuclear power plants is not high enough. SMRs is mostly deployed in remote areas. In order to achieve flexible layout and high economy, the automation degree of the control system should be improved as much as possible, the scale of operation and maintenance personnel should be reduced, and the overall design should be developed in the direction of fewer people on duty and independent control.

Based on the sodium-cooled fast reactor combined with Stirling engine technology, this paper focus-es on the design and verification of the start-stop function of small sodium reactor. By building a non-nuclear integrated test device for small sodium reactor and combining with the characteristics of Stirling engine equipment, this project carried out several verification and analysis works such as reactor start-stop test, and obtained an energy storage module design scheme suitable for SMRs combined with the auxiliary system power consumption.

2. SMALL SODIUM REACTOR MODULAR NUCLEAR POWER SUPPLY DESIGN

China is a vast country, and the use of small piles varies according to the geographical conditions of different provinces. Coastal provinces mainly use small reactors for desalination. The South China Sea islands and reefs mainly use small reactors for seawater desalination and cogeneration. High latitude provinces mainly use small reactors for heating. Due to the lack of coal and other fossil energy in inland provinces, resulting in unbalanced power development, small reactors can be considered for regional power supply and grid-connected power supply.

For the demand of electricity, it is planned to develop MW modular small sodium reactor. Based on the design of traditional large sodium-cooled fast reactor, except the necessary reactor body and thermoelectric conversion system, only the necessary auxiliary system is retained. The retained systems include sodium charging and purification system, residual heat removal system, argon vacuum pumping system, instrument controlled electrical system and waste heat removal system. The overall design scheme is shown in Fig 1, and the designed rated electric power is 2.4MW. Small sodium reactor adopts double loop design, sodium as the primary working medium, with Stirling generator set for thermoelectric conversion. Considering the different use scenarios, the final cold trap can choose one of the two forms of air cooling and water cooling.

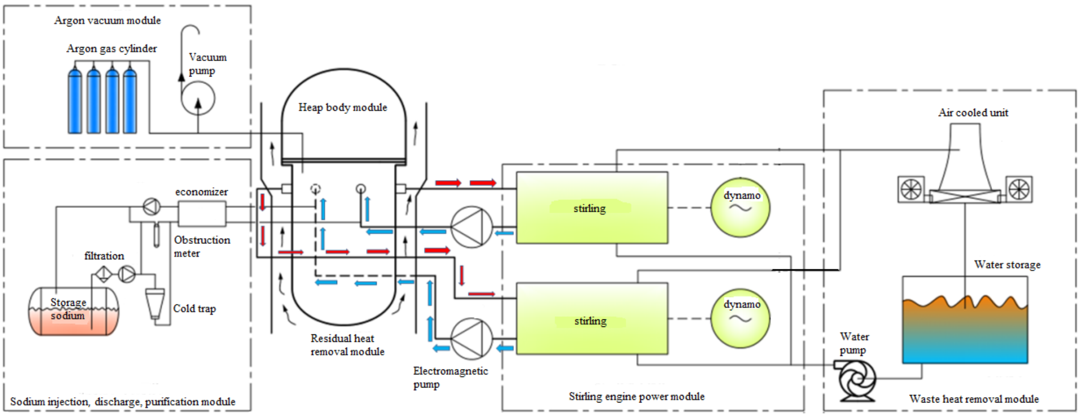

FIG. 1. Overall design diagram of small sodium reactor (courtesy of Mr Qian, CIAE).

The design of the non-nuclear integrated test device is consistent with the overall design scheme of the small sodium reactor. It scales overall to 3% of the nuclear power supply. The non-nuclear integrated test unit has a rated thermal power of 315kW and an electrical power of 72kW. The thermoelectric conversion system uses Stirling engine as the main equipment. The non-nuclear device uses an electrically heated core to simulate the reactor body, which also has various auxiliary systems as shown in Fig 1. During the test, liquid metal sodium enters the heat pipe section of Stirling machine after being heated by electric heating core. The high-temperature sodium transfers heat to helium gas in Stirling machine, and the cooled sodium is transported back to the electric heating core by electromagnetic pump to complete the coolant circulation in the whole main loop. After the helium in the Stirling machine obtains the reactor heat, the helium expands to push the piston to do work, and then cooled by the water to complete the Stirling cycle. The Stirling piston drives the generator to output electrical energy to the load, completing the conversion of thermal energy to electrical energy.

3. AUTOMATIC START-STOP DESIGN AND VERIFICATION

Aiming at the design goal of low or even unattended attendance brought by high economy of SMRs, this paper designs the control strategy of autonomous start-up and shutdown for non-nuclear integrated test equipment. On the other hand, in order to realize the automatic function of the small sodium reactor power supply, it is necessary to analyse the conditions and ways of starting and shutting down the reactor.

This chapter will subsequently analyse the compatibility of different start-up control strategies with small modular sodium-cooled fast reactor core power supply. The main text content will present the start-up and shutdown control strategies. The main analytical work is to verify the rationality of the start-up and shutdown strategies using the non-nuclear integrated test device and provide the variation graph of the test data results.

4. ENERGY STORAGE MODULE DESIGN

During the test, the electricity required for the equipment to start is provided by the external power grid of the factory building. However, in actual use of the SMR, there is a high probability that there will be no available external power grid. On the other hand, the power supply for multiple auxiliary systems and the power supply for preheating the working medium are also necessary. In response to this situation, an energy storage module is added to the scheme design of the small sodium reactor core power supply. The energy storage module can store the excess electricity when the load of the small sodium stack is low, replenish the electricity when the load is too high, and at the same time serve as the power source during the start-up process. It can provide a reliable power supply in the event of an accident at the nuclear power source and ensure the power supply for key equipment and instruments within a certain period of time.

Low-carbon, environmentally friendly energy storage technologies have gained increasing attention from various nations, including hydrogen energy storage, carbon dioxide energy storage, flywheel energy storage, and liquid metal energy storage. To address the self-start-stop power supply requirements of small sodium-cooled reactor nuclear power systems, this paper focuses on analysing the power consumption of critical equipment and procedures during these operational phases. By evaluating the applicability of different energy storage technologies and integrating experimental data analysis, this chapter proposes design solutions for energy storage modules tailored to small-scale nuclear power systems of varying capacities.

5. CONCLUSION

Small modular reactor using sodium-cooled fast reactor combined with Stirling engine technology solution can successfully achieve MW nuclear power supply design. The redundant systems in large sodium-cooled fast reactor power plants can be simplified and only the necessary auxiliary systems can be retained to meet the design requirements.

Experimental verification revealed that the Stirling engine exhibits an extremely short start-up response time, achieving positive net electrical power output within 100 s under low-power and low-pressure start-up conditions.

The experimental results indicate that the startup phase requires high power input but has a short duration, with the Stirling engine's power generation rapidly meeting the electricity demand of auxiliary systems. In contrast, the shutdown phase demands lower power; however, due to the extended duration of residual heat removal, its total energy consumption remains significant. Current analyses for MW-level and hundred-kW-level small modular reactor units operating in islanded conditions suggest energy storage module design capacities of 4,000 Ah and 250 Ah respectively.

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