Research on Li4SiO4 Irradiation Tritium Production Device (Postprint)

Authors: ZHANG Zhihua, MI Xiangmiao, YE Mao, QIAN Dazhi, Rundong Li, FENG Qijie

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Abstract

Tritium self-sustain and circulation is the core problem to use fusion energy peacefully. As the core component of the breeder in-pile irradiation test, the irradiation tritium production device provides irradiation space for breeders' tritium production and release. We take the Li4SiO4 as the research object and design the structure of the irradiation device. We complete the physical parameters computation, the irradiation device safety analysis and the flow field analysis of the breeder refueling, realizing the adjusting of the breeder irradiation temperature and the tritium release temperature window and making the control of gas operational parameters come true. The data could provide reference for breeders' in-pile irradiation research.

Full Text

Preamble

Research of Li4SiO4 Irradiation Tritium Production Device

ZHANG Zhihua, MI Xiangmiao*, YE Mao, QIAN Dazhi, LI Rundong, FENG Qijie
Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics, Mianyang 621900, China

Abstract

Tritium self-sustainment and circulation is the core challenge for the peaceful utilization of fusion energy. As the key component of the breeder in-pile irradiation test, the irradiation tritium production device provides irradiation space for breeder tritium production and release. Taking Li4SiO4 as the research object, we designed the structure of the irradiation device, completed physical parameter computations, conducted safety analysis of the irradiation device, and performed flow field analysis of breeder refueling. This work enables adjustment of the breeder irradiation temperature and tritium release temperature window, and achieves control of gas operational parameters. The resulting data can provide reference for in-pile irradiation research of breeders.

Keywords
Li4SiO4, Breeding, Tritium Production, Irradiation Device, Design

2 Structure of Tritium Production Device

With the rapid development of society, energy issues have become a global focus. Fusion energy represents an effective solution to the energy shortage facing human society. Tritium self-sustainment and circulation is the key to achieving large-scale application of fusion energy. Currently, we lack sufficient neutron source power to accomplish tritium fusion. Establishing a tritium production line in a thermal neutron reactor and conducting irradiation experiments with breeder materials is the best approach to explore the regularity of tritium production and release.

Both Li4SiO4 and Li2TiO3 are listed as fusion reactor breeder materials. With its high lithium content, low neutron activation, and excellent tritium release performance, Li4SiO4 has become the preferred choice for tritium breeder blanket coating in both the EU and China. In this research, we take Li4SiO4 ceramic balls as the research object to design the irradiation device. The tritium production device, which provides irradiation space for Li4SiO4 breeder balls, is the key component of the tritium production line.

As the key facility of the tritium production line, the tritium production device consists of inner and outer irradiation cylinders, a conveying device, electrical heating elements, thermocouples, probes, ventilation arrangements, etc. The carrier gas enters the lower chamber through the bell mouth of the center pipe, then turns 90° in the irradiation bin and flows into the upper gas chamber, finally flowing into the collection and analysis facility through the gas exit. The area between the inner and outer cylinders is called the gas temperature adjustment area. Cooling gas enters this temperature adjustment area from the bottom and controls the irradiation temperature of the breeder. Figure 1 shows the structure of the irradiation device.

The tritium production device features a double-layer irradiation cylinder shell structure with nonlinear electric heating elements, with all parts oriented toward the central axis. We have taken irradiation heat, isothermal effects from thermal expansion and contraction, and heat compensation into consideration, resulting in evenly distributed temperature throughout the breeder. The intake pipe and drive pipe are connected to the top of the reactor, which makes the tritium production device easy to move. The pipes before and after the connecting box are separately covered with stainless steel and plastic bellows (Fig. 1).

Structural Drawing of CITP- Tritium Production Irradiation Device

(Fig. 1)
1. Switch valve; 2. Outside irradiation cylinder; 3. Inside irradiation cylinder; 4. Breeder material; 5. Electrical heating facility; 6. Thermocouple; 7. MgO core cylinder; 8. Horn mouth; 9. Carrier gas intake pipe; 10. Cooling-gas escape pipe; 11. Carrier gas escape pipe; 12. Cooling gas intake pipe; 13. Cooling gas room; 14. Center pipe.

3 Parameter Detection System

The tritium production device is equipped with a comprehensive measurement and monitoring system. The main monitoring targets include neutron flux, temperature, gas flow rate, and pressure. The primary measurement parameters are: neutron flux (2 points), inner temperature of irradiation device (7 points), carrier-gas flow (2 points), cooling-gas flow (2 points), carrier-gas pressure (4 points), cooling-gas pressure (2 points), electric heating facility current (2 points), and breeder loading height (3 points).

4 Calculation of Tritium Production Device

The physical properties, engineering performance, and tritium output capacity are influenced by the structure and materials of the tritium production device. The feasibility of tritium production depends on realizable refueling of the breeder. A series of iterative calculations covering physics, thermodynamics, and structural strength have been implemented to improve and optimize the device design.

4.1 Calculation of Physical Parameters

We established a computation model of the tritium production device based on the reactor core physical calculation model, obtaining physical parameters and their variation patterns at different positions through calculations of self-shielding factor, neutron spectrum, neutron filling rate, and tritium output distribution across different neutron energy levels. The calculation model of the tritium production device is a concentric cylinder with stainless steel coating. Other parameters are: helium as cooling gas; Li4SiO4 breeder ball diameter of 1 mm; 6Li content of 7.5%; breeder ball clearance rate of 20%; breeder loading height of 750 mm; and weight of 1132 g.

Self-shielding Factor: The self-shielding factor is influenced by the structure, materials, and location of the irradiation device. When the irradiation device is located in the active area, the thermal neutron self-shielding factors are 0.438, 0.387, and 0.393, respectively. When the irradiation device is located in the heavy water reflection area at channels 12#, 15#, 2#, and 4#, the thermal neutron factors are 0.554, 0.565, 0.538, and 0.528, respectively. The average self-shielding factor in the active area is less than that in the heavy water reflection area.

Neutron Flux: Average neutron flux is influenced by the location of the tritium production device. Two factors cause this change: first, Li4SiO4 reduces neutron flux as a neutron absorber, and second, the self-shielding of the Li4SiO4 breeder causes lower neutron flux. Table 1 shows the obvious changes in average neutron flux after loading the production device in the reactor.

Tritium Productivity: Tritium productivity is affected by the thickness of the Li4SiO4 breeder layer and the location of the irradiation device. On one hand, a thin loading layer results in low tritium productivity that cannot support online measurement and testing. On the other hand, a thick loading layer also reduces tritium productivity due to the large thermal neutron absorption cross-section of 6Li. Figure 2 shows different tritium productivities with varying breeder layer thicknesses in positions B1, H4, and G8. The tritium output varies with the thickness of the Li4SiO4 layer, and productivity differs by breeder location even at the same thickness. An optimal loading thickness exists for different locations, but if the loading thickness exceeds 2 mm, productivity does not change significantly. Increasing the 6Li content is an effective way to improve tritium productivity.

4.2 Calculation of Thermodynamics

The heat source of the tritium production device has two main components: heat released by structural materials in the n-γ radiation field and heat released by the breeder when it absorbs neutrons. With a thermal neutron flux of 6.06$×10ˆ{3}$ n/cm^{3} and Li4SiO4 weight of 1132 g, the heating efficiencies are 325 W for the outer irradiation cylinder, 325 W for the inner irradiation cylinder, and 7320 W for the Li4SiO4. There are three cooling methods for the tritium production device: (1) heat radiation from the device itself, (2) gas cooling, and (3) water cooling (6 m/s). We calculated the thermal parameters of the production device using FLUENT, obtaining data on temperature distribution gradient, hotspot temperature, limiting temperature, and non-uniformity factor. We also determined the effect of carrier gas and cooling gas on equilibrium temperature.

The vertical temperature gradient in the B1 axis direction under nuclear power is shown in Fig. 3, where the highest temperature is 751ºC and the lowest is 432ºC. The temperature distribution is influenced by neutron flux in the irradiation device, with small temperature differences in the horizontal direction. Temperature gradually decreases from the inside of the breeder area to the outside, and the non-uniformity factor is below 5%. The maximum temperature difference of 319ºC in the breeder area makes research on tritium production and release regularity very challenging. Therefore, it is necessary to install an electric heater (asymmetrical arrangement) to reduce the temperature difference in the breeder area.

There are 15 electric heating zones along the vertical height of the 750 mm breeder, which provides supplemental heat according to the heat released from the breeder and can control the non-uniformity factor to below 5%. The maximum electric power is 18 kW, which can raise the equilibrium temperature up to 800ºC.

4.3 Calculation of Flow Field Parameters

Carrier gas is the key issue for breeder replacement in the tritium production device. The pressure difference between the inlet and exit of the carrier-gas pipe produces buoyancy force on breeder spheres, and the spheres will flow out of the tritium production device with the carrier gas when buoyancy forces exceed their weight. This research simulates the flow field of the tritium production device using FLUENT, obtaining key process parameters through calculation and analysis of pressure distribution, flow field characteristics, buoyancy, and blow force.

The tritium production device has a siphon structure with a pressure difference of 2.06×10^{6} Pa between the inlet and exit. The pressure distribution around the breeder sphere in the horn mouth is shown in Fig. 4. In area 1, the carrier-gas pressure is approximately 19248 Pa. Buoyant forces act on the breeder sphere to balance the integral pressure difference between the top and bottom of the sphere.

Buoyancy force increases with the rise of pressure difference between the inlet and exit. Buoyancy force Y(N) and pressure difference X(Pa) have a linear relationship: Y=2$\times10-9-3\times10-7(1). When the pressure difference exceeds 1.5195\times10^{5}$ Pa, buoyancy force becomes larger than the sphere weight, enabling transmission of breeder spheres. When buoyancy force is 10 times larger than weight, transmission of breeder spheres becomes very easy to achieve.

5 Safety Analysis of Tritium Production Irradiation Device

Many aspects must be considered when installing the tritium production device in the reactor, including device safety in the n-γ mixed radiation field and hot environment, breeder safety in the irradiation environment, and reactor operation safety.

Structural strength characteristics of the outer and inner irradiation cylinders have been calculated using ANSYS. Device components are evaluated by stress intensity according to the Third Strength Theory. The maximum stress is 42 MPa in both normal prepared condition and hot operating condition, which is far less than the allowable stress. The tritium production device has sufficient rigidity to maintain its shape, with maximum deformation of 1.27×10^{-4} mm.

The highest temperature of Li4SiO4 spheres in operating condition has been calculated as follows: the highest temperature is 843.5ºC and the average temperature is 823.5ºC, which are far below the melting point of 1255ºC. The temperature of the outside cylinder remains below 36ºC when the hotspot reaches its maximum temperature, guaranteeing the safety of the tritium production device.

Samples and devices cannot have any negative effect on reactor safety. The influence on the reactor has been calculated when loading 1132 g of Li4SiO4 in positions B1, H4, G8 of the core area and channels 12#, 15#, 2#, 4# of the heavy water reflection area. Due to its large neutron absorption cross-section, the tritium production device will reduce reactor activity and keep ΔP in the control area. The tritium production device would not cause any vibration, explosion, or movement. In summary, irradiation tritium production devices satisfy all reactor safety requirements for in-pile irradiation.

6 Operating Parameters and Device Characteristics

Operating parameters of the tritium production device with 1132 g of Li4SiO4 in position B1 have been confirmed as follows: maximum neutron flux of 7.98$×10^{12}$ n/s·cm^3, external device diameter of 63 mm, mounting base of 76.2 mm$×76.2mm, maximumtritiumoutputof38.34Ci/d, breedercoretemperatureof7320W, electricheaterte
He(+0.1_{2}$) at 0 300 mL/min and 0 0.05 MPa, exchange gas: He with air pressure for exchange $ $0.05 MPa and emergency pressure $ $0.2 MPa, cooling gas (He, Ne, Ar) at 0.03 MPa.

The tritium production device is safe, economical, and multipurpose. It can achieve online tritium release and production with either Li4SiO4 or other breeders, while also enabling research on irradiation performance, service life, neutron activation performance, and tritium diffusivity in engineering simulation fields. It can also accomplish research on the effects of breeder temperature, gas composition, and gas flow rate on tritium release. However, practice should be conducted with online sampling, decreasing the temperature difference of the inner breeder using a nonlinear heater, which can confirm all calculation results.

7 Conclusion

The Li4SiO4 tritium production device is an advanced facility installed in a thermal reactor for research on online tritium release breeder performance and technological parameters of tritium recycling. The feasibility of the tritium production device has been confirmed through simulated operation and refueling tests with an irradiation capsule. The tritium production device will serve as an excellent platform for basic research on tritium self-sustainment and recycling in the fusion energy field.

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Note: Figure translations are in progress. See original paper for figures.