Transient Safety Characteristics of Lithium-Cooled Fast Reactor Stirling Power Conversion System

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Abstract

To investigate the safety and reliability of space nuclear power sources, a transient safety analysis code NUSOL-LMR-Li was developed for the lithium-cooled fast reactor Stirling thermoelectric conversion system, focusing on analyzing its inherent safety under accident conditions and the adaptive characteristics of the Stirling thermoelectric conversion system. Models for core power, thermal-hydraulics, heat conduction in structural components, and liquid lithium physical properties were established, and the critical Stirling thermoelectric conversion model was developed using the Schmidt isothermal analysis method to achieve coupling with the lithium-cooled fast reactor. The convection-diffusion fully implicit difference algorithm was verified through a single-tube flow test case, demonstrating time-step-independent stability; the core power model exhibited calculation errors of 0.53% and 0.32% under positive and negative reactivity insertion conditions, respectively, showing high consistency with analytical solutions; the Stirling power conversion model was validated against the NASA RE-1000 Stirling prototype and SP-100 system loop tests, with a maximum error of 3.8%. Through simplified modeling of the SP-100 reactor and conducting typical accident transient analyses, the results show: (1) a 0.1$ reactivity insertion caused the core power to rise to 534 kW, then stabilize at 466 kW through negative feedback mechanisms, with the outlet temperature increase controlled to 14.7 K; (2) regenerator blockage caused the Stirling efficiency to drop to 22.24%, and the system re-established thermal equilibrium through automatic reduction of the hot-end temperature to 1023 K and increase of the cold-end temperature to 692 K, with efficiency recovering to 26.8%. The study validates the system' s self-regulation and fault tolerance capabilities, providing theoretical support and an efficient analysis tool for the safety design of space nuclear power sources.

Full Text

Preamble

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Transient Safety Characteristics of Lithium-Cooled Fast Reactor Stirling Thermoelectric Conversion System

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Abstract

To investigate the safety and reliability of space nuclear power systems, this study developed the transient safety analysis program NUSOL-LMR-Li for lithium-cooled fast reactor Stirling thermoelectric conversion systems, focusing on analyzing inherent safety characteristics under accident conditions and the adaptive features of the Stirling thermoelectric conversion system. The program establishes computational models for core power, thermal-hydraulics, heat structure conduction, and liquid lithium physical properties, and implements a critical Stirling thermoelectric conversion model using the Schmidt isothermal analysis method to achieve coupling with the lithium-cooled fast reactor. The convection-diffusion fully implicit difference algorithm demonstrates time-step-independent stability through single-pipe flow verification cases. The core power model exhibits calculation errors of 0.53% and 0.32% under positive and negative reactivity insertion conditions, respectively, showing excellent agreement with analytical solutions. The Stirling power conversion model was validated against NASA RE-1000 Stirling prototype and SP-100 system loop test data, with a maximum error of 3.8%. Through simplified modeling of the SP-100 reactor and typical accident transient analysis, the results show: (1) A 0.1$ reactivity insertion caused core power to rise to 534 kW, then stabilized at 466 kW through negative feedback mechanisms, with outlet temperature rise controlled within 14.7 K; (2) Regenerator blockage caused Stirling efficiency to drop to 22.24%, but the system reestablished thermal equilibrium by autonomously reducing hot-end temperature to 1023 K and increasing cold-end temperature to 692 K, recovering efficiency to 26.8%. The study validates the system’ s self-regulation and fault tolerance capabilities, providing theoretical support and an efficient analysis tool for space nuclear power safety design.

Keywords: Stirling thermoelectric conversion system; Lithium-cooled fast reactor; Accident safety characteristic analysis; Model and algorithm development; Space reactor

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Research on Transient Safety Characteristics of Lithium-cooled Fast Reactor with Stirling Thermoelectric Conversion System

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Abstract

[Background] The lithium-cooled fast reactor coupled with the Stirling thermoelectric conversion system is suitable for space nuclear power systems due to its high energy density and reliability. However, the complex multiphysics coupling analysis under transient accident conditions poses challenges. Existing studies primarily focus on steady-state performance, lacking systematic transient analysis of accidents related to the power conversion model, which limits the evaluation of system safety and self-regulating capabilities. Therefore, developing a high-fidelity transient analysis program to validate the safety characteristics of the lithium-cooled fast reactor Stirling system is crucial. [Purpose] This study aims to develop the NUSOL-LMR-Li transient analysis program for the lithium-cooled fast reactor Stirling system and analyze accident scenarios to validate its safety and self-regulating capabilities. [Methods] Firstly the NUSOL-LMR-Li program was developed, which integrates models for core power calculation, thermal-hydraulic analysis, heat conduction in structural components, and thermophysical properties of liquid lithium.

The core Stirling thermoelectric conversion model was established using the Schmidt isothermal analysis method, enabling precise coupling with the lithium-cooled fast reactor. The fully implicit discretization of convection-diffusion algorithm was validated through a single-tube flow case, demonstrating stability independent of time step size. The core power model achieved computational errors of 0.53% and 0.32% under positive and negative reactivity insertion conditions, respectively, showing high agreement with analytical solutions. The Stirling power conversion model was verified using the NASA RE-1000 Stirling prototype and SP-100 system loop tests, with a maximum error of 3.8%. Simplified modeling was conducted based on the SP-100 reactor, and transient analysis was conducted for typical accident scenarios, including reactivity insertion and regenerator blockage, to evaluate the system' s response characteristics. [Results] The results demonstrate: (1) A 0.1$ reactivity insertion increased core power to 534 kW, stabilizing at 466 kW via negative feedback, with an outlet temperature rise limited to 14.7 K; (2) Regenerator blockage reduced Stirling efficiency to 22.24%, but the system reestablished thermal balance by lowering the hot-end temperature to 1023 K and raising the cold-end to 692 K, recovering efficiency to 26.8%. [Conclusions] The NUSOL-LMR-Li program validated the self-regulation and fault tolerance of the lithium-cooled fast reactor Stirling system, providing an efficient tool and theoretical support for space nuclear power safety design.

Key words: Stirling thermoelectric conversion system; Lithium-cooled fast reactor; Accident safety characteristic analysis; Model and algorithm development; Space reactor

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Lithium-cooled fast reactors represent an advanced nuclear reactor technology with multiple significant advantages. Lithium' s low density helps reduce space reactor weight, enabling miniaturization and lightweight design. Lithium can operate at very high temperatures, enabling high cycle efficiency for lithium-cooled fast reactors. For instance, the FDS Phoenix Innovation Team at the Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, has achieved major breakthroughs in liquid metal lithium cooling systems, successfully demonstrating continuous 1000-hour stable operation in ultra-high temperature environments up to 1227°C, filling a domestic technological gap in this field [1]. Liquid lithium exhibits good compatibility with certain structural materials, and Zheng et al. have conducted experimental studies on the corrosion resistance of high-temperature refractory alloys in high-temperature liquid lithium environments [2]. Additionally, its excellent thermal conductivity ensures efficient heat transfer from the core to the energy conversion system, improving overall energy conversion efficiency and reducing energy losses. Due to liquid lithium' s high boiling point, the system can operate at atmospheric pressure, simplifying system design and enhancing operational safety. Some lithium-cooled fast reactor designs also incorporate innovative passive negative feedback systems, such as the ARC (Autonomous Reactivity Control) system [3]. This system uses liquid lithium as a neutron absorber, automatically injecting liquid lithium containing highly enriched ^{6}Li into the core through thermal expansion when coolant outlet temperature rises, thereby introducing negative reactivity and achieving self-regulation. This design not only enhances inherent reactor safety but also enables response to transient conditions without external intervention. Numerical simulation studies have further validated the excellent heat transfer performance of liquid lithium in rod bundle channels [4]: its low Prandtl number characteristics make conduction effects dominant at low Peclet numbers ($<$120), while convection effects significantly enhance at high Peclet numbers, with pressure drop growth remaining controllable as Peclet number increases (approximately 124 kPa at Pe=1500), providing critical thermal-hydraulic support for compact core design of lithium-cooled fast reactors. In summary, the unique advantages of lithium-cooled fast reactors make them a promising nuclear reactor technology for future space missions, potentially providing efficient and reliable power support.

In the 1980s, under funding from the "Strategic Defense Initiative" (SDI), the

United States developed the SP-100 space nuclear reactor power system [5] (Figure 1 [Figure 1: see original paper]). This project integrated lithium-cooled fast reactor technology with multiple power generation methods including Stirling cycle power generation, Brayton cycle power generation, and thermoelectric conversion. Stirling thermoelectric conversion technology offers significant advantages for space reactors. First, its theoretical efficiency approaches the maximum Carnot cycle efficiency, providing high conversion efficiency that can significantly reduce fuel consumption [6]. Second, the technology features simple structure—the free-piston Stirling engine contains only two moving parts and uses gas bearings, offering long-life potential [7]. Additionally, Stirling thermoelectric conversion devices produce low vibration and noise during operation, making them suitable for space environments. Finally, they exhibit small core power variation amplitudes under accident conditions, ensuring high safety.

In conclusion, coupling lithium-cooled fast reactors with Stirling cycles can efficiently achieve thermal-to-electrical energy conversion, optimize energy utilization efficiency, enable compact reactor design, and support sustainable energy development and environmental performance improvement. In-depth theoretical research and safety analysis are critical for engineering application of this system: on one hand, multi-physics coupling modeling is needed to reveal the energy transfer mechanism between core-coolant-Stirling engine and quantify thermodynamic performance boundaries under dynamic conditions; on the other hand, transient safety characteristic analysis must be conducted for space-specific environmental conditions (including microgravity, intense radiation, and other extreme factors) and system-specific failure modes (such as regenerator blockage, reactivity insertion, and heat sink loss) to clarify inherent safety boundaries and fault tolerance capabilities.

Zhang Yang' s research team at the Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences [8] innovatively proposed a compact space lithium-cooled reactor conceptual design with a rated thermal power of 5.2 MW. This design features: 1) an integrated core architecture based on thermal optimization; 2) innovatively configured non-uniformly distributed liquid metal cooling channels; and 3) a control system composed of boron powder combined with control rods. The research team developed a high-fidelity co-simulation method integrating Monte Carlo neutron transport and computational fluid dynamics (CFD) based on the SuperMC multi-physics coupling platform, achieving dynamic coupling of multi-physics processes through stochastic approximation algorithms to provide high-precision validation means for space reactor design schemes. Analysis results show that the design meets reactivity control requirements; the optimized non-uniform flow channel structure significantly improves radial power distribution uniformity; and all key material temperatures remain below safety limits under normal operating conditions.

Jin Zhao et al. from Xi' an Jiaotong University [9] constructed a lithium-cooled fast reactor system including reactor core, Stirling energy conversion device, radiation heat rejection system, and liquid metal circulation loop. They independently developed a transient thermal safety analysis program using Fortran programming language and validated the numerical model using experimental data from the RE-1000 Stirling prototype, showing a maximum relative deviation of 17.3%. Based on this, they completed overall modeling of the space nuclear power system and verified the reliability of the computational model through steady-state numerical simulation and comparison with design parameters, with maximum deviation of key parameters controlled within 13.3%. Dynamic simulation studies for preset accident conditions demonstrate that the core' s inherent negative reactivity temperature coefficient can effectively suppress power fluctuations, ensuring fuel element maximum temperature always remains below preset safety thresholds, confirming the system's reliable inherent safety performance.

Existing research has accumulated valuable experience for lithium-cooled space reactor system design, but current studies still have critical limitations. First, most research focuses primarily on steady-state performance verification, with insufficient simulation accuracy for transient characteristics of the Stirling thermoelectric conversion module and relatively large validation calculation errors. Second, in terms of accident safety analysis, systematic simulation of transient accident scenarios is lacking. More importantly, as a key component for energy conversion in space reactor power systems through efficient thermal energy conversion mechanisms, Stirling engines have not been adequately considered for their proprietary failure modes in space environments (such as efficiency degradation due to regenerator blockage), resulting in analysis blind spots in the fault propagation path from nuclear heat source to electrical energy conversion.

The lithium-cooled fast reactor Stirling thermoelectric conversion system has become an ideal choice for space nuclear power systems due to its high energy density, lightweight design, and efficient thermoelectric conversion characteristics. To evaluate its inherent safety and adaptive capabilities under accident conditions, this study establishes theoretical models applicable to system safety analysis based on operational characteristics. The model covers core power calculation, thermal-hydraulics, heat structure conduction, Stirling thermoelectric conversion model, and physical property models for liquid lithium, liquid sodium-potassium, and helium, and develops a fully implicit transient safety analysis program NUSOL-LMR-Li based on Fortran language, suitable for long-term slow transient accident calculations. This paper elaborates on theoretical model construction, program development, algorithm stability analysis, model validation, and accident transient safety analysis based on SP-100 system modeling.

1 Lithium-Cooled Fast Reactor Stirling Thermoelectric Conversion Space Reactor Power System

SP-100 was a space nuclear reactor project initiated by the United States in 1983, jointly developed by the Department of Energy, NASA, and the Department of Defense. It employed uranium nitride fuel and lithium-cooled fast reactor technology for thermoelectric power generation, characterized by lightweight durability capable of powering space stations, lunar or Mars bases. Although technical tests were successful, the project was terminated in 1994 due to funding and policy issues and was never actually applied.

The lithium-cooled Stirling cycle system typically consists of the following core components: core (nuclear reactor), expansion tank, liquid metal electromagnetic pump, Stirling engine, and radiation radiator [10]. Figure 2 [Figure 2: see original paper] shows the SP-100 system schematic. The system achieves nuclear-thermal-electric energy conversion through dual-loop liquid metal circulation. Lithium coolant heated in the core passes through a direct-through expansion tank that accommodates lithium volume expansion from frozen state to operating temperature and separates helium gas generated in the reactor. It then heats the hot end of the Stirling engine to drive the free piston for power generation. The secondary loop sodium-potassium working fluid, after heat exchange with the Stirling cold end, achieves effective space waste heat rejection through the final heat sink radiation device.

2 Theoretical Models

For the SP-100 lithium-cooled fast reactor Stirling thermoelectric conversion space reactor power system, a complete analysis model system was established to meet system safety analysis requirements, including thermal-hydraulic models, heat structure conduction models, core power calculation models, Stirling thermoelectric conversion models, and auxiliary models, as shown in Figure 2. The core power calculation model mainly includes fission power calculation models and reactivity feedback models; the Stirling thermoelectric conversion model mainly includes regenerator models and coupling models; auxiliary models include material property models (lithium coolant, helium working fluid, sodium-potassium coolant), convective heat transfer models, and pressure drop models. Numerical solution employs the convection-diffusion fully implicit difference algorithm to ensure computational efficiency for long-term slow transients.

2.1 Thermal-Hydraulic Model

Liquid lithium (Li) and sodium-potassium (NaK) coolants have boiling points as high as 1620 K and 1057 K, respectively, at 1 MPa working pressure. Therefore, in lithium-cooled fast reactors, the primary loop coolant lithium and secondary loop sodium-potassium remain liquid at atmospheric pressure without boiling phenomena. Consequently, a single-phase flow model based on mass, momentum, and energy conservation was proposed, considering axial heat conduction effects of liquid metal fluids to numerically simulate pressure, velocity, temperature, and other parameters of Li and NaK coolants.

1) **Mass Conservation Equation**

Where: A—flow area/m^2; —density/$\mathrm{kg \cdot m^{-3}}$; t—time/s; V—flow velocity/$\mathrm{m \cdot s^{-1}}$; z—control volume length/m.

The first term represents the mass transient variation term, and the second term represents the mass convection term.

2) **Energy Conservation Equation**

Where: h—specific enthalpy/J · kg^{-1}; λ—thermal conductivity/W · m^{-1} · K^{-1}; T —temperature/K; g—gravitational acceleration/m · s^{-2}; Qw—thermal power/W · m^{-1}; —inclination angle. From left to right, the physical meanings of each term are energy transient variation term, energy convection term, axial heat conduction term, pressure-related term, gravitational work term, and heat source term.

3) **Momentum Conservation Equation**

Where: P—pressure/Pa; Fw—frictional resistance/Pa · m^{-1}; Flocal—local resistance/Pa · m^{-1}. From left to right, the physical meanings of each term are flow transient variation term, convection term, static pressure drop term, gravitational pressure drop term, frictional pressure drop term, and local pressure drop term.

2.2 Heat Structure Conduction Model

A one-dimensional unsteady heat conduction equation was adopted to establish a heat structure model applicable to fast reactor systems. The general control equation for one-dimensional unsteady heat conduction is:

Where: c—specific heat capacity/J · kg^{-1} · K^{-1}; x—distance/m; S—volumetric internal heat source/W · m^{-3}; A(x)—area factor.

The internal node method was used for radial mesh division of heat structures, where the temperature node to be solved is located at the grid center, and the grid region is the control volume of that point, as shown in Figure 3 [Figure 3: see original paper].

The control volume integration method was then applied to discretize the one-dimensional unsteady heat conduction equation. The equation was integrated over time using an implicit scheme, with specific derivation processes available in relevant literature [11]. The final discrete form of the conduction equation is:

To handle second or third type boundary conditions, the additional source term method was employed, treating heat entering or leaving the computational region as defined by these boundary conditions as equivalent source terms for control volumes adjacent to the boundary. For second-type boundary conditions, the additional source term is expressed as:

Where: qbound—boundary heat flux density/W · m^{-2}.

For third-type boundary conditions, boundary heat flux density depends on the boundary control volume node temperature, fluid temperature, and half-boundary control volume conduction resistance and convective heat transfer resistance, expressed as:

Where: Tf—fluid temperature/K; hconv—convective heat transfer coefficient/W $\cdot$ m^{-2} $\cdot$ K^{-1}; Tb—boundary control volume node temperature/K; Δxb—boundary control volume thickness/m.

Expressed as an additional source term:

For boundary control volumes, the conduction control equation only requires adding the additional source term to the source terms SC and SP in the equation. Therefore, the general form of the control equation for heat structure axial nodes can be expressed as:

For left and right boundary control volumes, respectively:

Thus, for a heat structure with N nodes divided radially, N conduction control equations can be obtained, forming a linear equation system with a coefficient matrix of order N tridiagonal matrix, expressed as follows, which can be solved using the Thomas algorithm to obtain node temperatures corresponding to each control volume.

2.3.1 Fission Power Calculation Model

The point reactor neutron kinetics model containing six groups of delayed neutrons was used to calculate instantaneous changes in core fission power.

Where: N—neutron density/m^{-3}; Ci—concentration of delayed neutron precursors in group i/m^{-3}; λi—decay constant of delayed neutrons in group i/s^{-1}; βi —fraction of delayed neutrons in group i; β—total fraction of delayed neutrons; (t)—reactivity; Λ—neutron generation time.

The high-order endpoint floating method was used to solve the point reactor neutron kinetics equations, which can effectively overcome the stiffness of point reactor equations with high computational accuracy [12].

2.3.2 Reactivity Feedback Model

In small fast reactors such as space reactor power systems during transient power operation, fluctuations in core parameters have particularly significant effects on reactivity, mainly manifested in temperature-induced fuel expansion deformation and changes in core coolant density. The lithium-cooled fast reactor reactivity feedback model considers three factors: Doppler effect feedback caused by fuel temperature changes, reactivity changes caused by fuel volume changes, and reactivity feedback caused by coolant density changes. The lumped parameter method was used to approximately solve the total reactivity feedback, with coolant and fuel temperatures simulated using average temperatures, and various reactivity feedback effects represented by corresponding feedback coefficients:

Where: KD—Doppler feedback coefficient/K^{-1}; Tf—average fuel temperature/K; αc,a—fuel expansion feedback coefficient/K^{-1}; αc,r—core structure expansion feedback coefficient/K^{-1}; Tc—average coolant temperature/K; αc—coolant expansion feedback coefficient/K^{-1}.

2.4 Stirling Thermoelectric Conversion Model

The Stirling engine is a closed-cycle power device based on gas working fluid circulation between heat and cold sources. The thermal cycle system adopts a dual-piston-cylinder structure design, with high-temperature expansion units and low-temperature compression units thermally coupled through a regenerator. As shown in Figure 4 [Figure 4: see original paper], the regenerator, as a key heat exchange component, periodically completes heat storage and release processes of the working fluid. The system working chamber consists of two independent cylinders maintaining high-temperature expansion conditions and low-temperature compression conditions, respectively. The Stirling cycle is an efficient dynamic thermal cycle technology that uses temperature differences between heat and cold sources to drive piston motion for energy conversion. As a closed system, the working fluid is not consumed during the cycle, featuring environmental friendliness and sustainability. With its unique advantage of maintaining high thermal efficiency even under low temperature differences, the Stirling cycle performs particularly outstandingly in space energy conversion systems, especially suitable for long-term deep space exploration mission requirements, providing a reliable and high-performance solution for efficient energy conversion [13].

The Stirling thermoelectric conversion process involves complex mechanical motion and thermodynamic state changes of the working fluid, with numerous variables and complex equations. Starting from basic energy conservation and Stirling cycle efficiency, the classical Schmidt isothermal analysis model [14] was used for cycle system analysis. This model assumes constant cyclic temperatures in heating and condensation chambers, with gas temperature in the expansion chamber (heating chamber) at the average heat source temperature and gas temperature in the compression chamber (condensation chamber) at the average cold source temperature.

In thermodynamic modeling, the following irreversible factors were primarily considered: 1) non-ideal heat transfer processes between heat source and working medium; 2) heat loss effects of the regenerator device and its regulatory effect on Stirling cycle temperature difference. Meanwhile, secondary irreversible factors such as heat dissipation and mechanical friction were excluded from model simplification assumptions. Assuming the total gas mass in the heat engine remains constant, the Stirling thermoelectric conversion and its external coupling model were established (Figure 5 [Figure 5: see original paper]).

2.4.1 Regenerator Model Since the Stirling cycle essentially consists of two isothermal processes and two isochoric processes, the regenerator power is considered constant here to control the temperature difference between expansion and compression chambers. Regenerator power can be expressed as:

Where: mgas—gas mass inside Stirling engine/kg; Th—average gas temperature in expansion chamber (heating chamber)/K; Tc—average gas temperature in compression chamber (heating chamber)/K; CP—gas specific heat/$\mathrm{J \cdot kg^{-1} \cdot K^{-1}}$.

Regenerator loss is a key irreversible energy loss during Stirling engine operation, calculated by:

Where: g represents the regenerator loss constant, whose value depends on the following key parameters: 1) regenerator heat transfer effectiveness; 2) thermodynamic properties of the working medium (particularly constant pressure specific heat capacity); 3) average mass flow rate of working fluid during periodic heat exchange. Through experimental simulation, g = 2.26$×10^{-5}$ was determined.

2.4.2 Coupling Model The coupling between primary/secondary sides and the Stirling system is represented by the following two equations:

Where: Qinheat—power obtained by Stirling hot chamber from primary loop lithium coolant/W; Qout—power released by Stirling cold chamber to secondary loop liquid sodium-potassium/W; TLi—primary loop lithium coolant temperature/K; TNaK—secondary loop sodium-potassium coolant temperature/K; Rheat—thermal resistance between primary loop lithium and hot chamber gas/$\mathrm{W \cdot K^{-1}}$; Rcool—thermal resistance between cold chamber gas and secondary loop sodium-potassium/$\mathrm{W \cdot K^{-1}}$.

Thermal resistance consists of three parts: liquid-solid, solid-solid, and solid-gas, specifically including heat transfer between coolant and hot (cold) chamber wall, conduction between hot (cold) chamber walls, and heat transfer between hot (cold) chamber walls and helium working fluid inside the Stirling engine.

Where: hLi—heat transfer coefficient between liquid lithium and hot chamber wall/$\mathrm{W \cdot m^{-2} \cdot K^{-1}}$; hNaK—heat transfer coefficient between liquid sodium-potassium and cold chamber wall/$\mathrm{W \cdot m^{-2} \cdot K^{-1}}$; Ah—contact area between hot chamber wall and lithium coolant/$\mathrm{m^2}$; Ac—contact area between cold chamber wall and sodium-potassium coolant/$\mathrm{m^2}$; λh—thermal conductivity of hot chamber wall/$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$; λc—thermal conductivity of cold chamber wall/$\mathrm{W \cdot m^{-1} \cdot K^{-1}}$; hHe—heat transfer coefficient of helium working fluid/$\mathrm{W \cdot m^{-2} \cdot K^{-1}}$.

Actual heat engines cannot achieve theoretical maximum efficiency due to limitations from irreversible processes such as friction, thermal resistance, and fluid viscosity. These irreversible factors cause energy losses, significantly reducing heat engine efficiency. Ideal reversible Stirling cycles require infinitely slow operation to achieve theoretical maximum efficiency and ensure thermodynamic equilibrium. However, such processes cannot produce practical power output, as power output depends on energy transfer within finite time. Based on energy conservation law and Stirling cycle optimal efficiency assumptions, there exists a clear thermodynamic relationship between heat transferred from primary loop lithium to Stirling hot chamber (Qinheat), heat released from Stirling cold chamber to secondary loop sodium-potassium (Qout), regenerator heat loss (QRloss), and Stirling engine efficiency (stirling):

Where: g is the regenerator loss constant; λ—compression ratio (ratio of hot chamber to cold chamber volume); c—actual efficiency correction coefficient; n—mole.

2.5 Convection-Diffusion Fully Implicit Difference Algorithm

Considering that lithium-cooled fast reactor transient safety analysis requires substantial computational time, current mainstream system analysis programs basically adopt semi-implicit algorithms whose time steps are constrained by Courant number, resulting in unsatisfactory computational efficiency for long-term slow transients. Based on this, a convection-diffusion term fully implicit difference algorithm was adopted to solve single-phase or homogeneous flow hydraulic models based on the three conservation equations. The homogeneous flow model has good well-posedness, and fully implicit algorithm computational results are independent of time step, with algorithm stability not constrained by Courant conditions. Therefore, larger time steps can be used in long-term slow transient condition simulations of lithium-cooled fast reactor systems, greatly shortening computation time and improving computational efficiency.

First, the fully implicit difference scheme [15] was applied to the mass-momentum-energy conservation equation system for single-phase flow, transforming continuous differential equations into difference equations. In spatial discretization, subscript o identifies control volume parameters, and subscript x identifies junction connection parameters, as shown in Figure 6 [Figure 6: see original paper].

Convection terms in all three equations adopt first-order upwind differencing, conduction terms in the energy equation adopt central differencing, and transient terms in all three equations adopt first-order backward differencing. The resulting difference equation expressions are:

Mass and energy conservation equations are defined on control volumes, while momentum conservation equations are defined on junctions. This reactor system contains N control volumes and J junctions, with the nonlinear difference equation system order being N+2J, solved using Newton' s iteration method requiring Jacobian matrix generation. The Newton method solution process can be expressed as:

The main solution variables of the equation system are control volume pressure P, control volume specific enthalpy h, and junction flow velocity V, therefore:

Taking partial derivatives of the equation system with respect to solution variables yields the Jacobian matrix, obtaining partial derivatives of conservation equations with respect to solution variables to fill the Jacobian matrix. Subsequently, full-pivot Gaussian elimination is used to solve this linear equation system, ultimately obtaining converged solutions.

3 Validation of Lithium-Cooled Fast Reactor Stirling Thermoelectric Conversion System Analysis Program

Based on the above lithium-cooled fast reactor Stirling thermoelectric conversion system analysis models, appropriate numerical solution methods were selected for different models, and a modular programming approach was used to develop the transient analysis program NUSOL-LMR-Li for lithium-cooled fast reactor Stirling thermoelectric conversion systems. The program' s corresponding models were validated through basic benchmark problems.

3.1 Time Step Stability Analysis of Fully Implicit Difference Algorithm

The fully implicit algorithm features computational results and stability independent of Courant criterion constraints. Its stability with respect to time step was analyzed through a single-pipe flow case driven by pressure difference.

Figure 7 [Figure 7: see original paper] shows a schematic diagram of the single-pipe flow case. Assuming a pipe length of 5 m and diameter of 0.2 m, the pipe is filled with liquid lithium and connected to time-dependent control volumes at both ends to specify flow boundary conditions. In this case, pressure boundaries at pipe inlet and outlet are fixed, so flow inside the pipe is driven by pressure difference between the two ends.

Assuming the fluid is initially static, it will accelerate under pressure difference. As velocity increases, frictional resistance also increases, thereby increasing frictional pressure drop. When frictional pressure drop increases to equal the driving pressure difference, the fluid reaches equilibrium and all parameters approach steady state. The variation of pipe outlet flow velocity over time calculated by the program is shown in Figure 8 [Figure 8: see original paper].

The results show that fluid velocity reaches a steady-state value of approximately 16.06 m/s after about 20 seconds from the initial state. During this process, calculation results under different time steps show high consistency. When time steps of 0.1 s and 0.5 s were used, Courant numbers exceeded 1, and with a time step of 0.5 s, the Courant number reached 8.03, far greater than 1. This well demonstrates the stability of the fully implicit algorithm—for transient processes, time step has almost no effect on numerical results, and numerical stability is not constrained by Courant criterion.

3.2 Core Power Calculation Model Validation

The NUSOL-LMR-Li point reactor neutron kinetics model was used to solve basic benchmark cases and compared with analytical calculation results [12] to validate the program' s core power calculation model.

3.2.1 Calculation of Neutron Density N(t) Variation with Time in Thermal Reactor After Step Positive Reactivity Insertion Thermal reactor parameters in the model are given in Table 1 . Step reactivity = 0.003 was set, time step h = 0.1 s, initial neutron density N(0) = 1.0 cm^{-3}, and neutron density (cm^{-3}) variation over 1 second was calculated. Using numerical analytical exact solutions as benchmark reference data, results from NUSOL-LMR-Li core power calculation model were compared with exact solutions as shown in Figure 9 [Figure 9: see original paper] and Table 2 . The results show excellent agreement under step positive reactivity insertion conditions, with maximum deviation of 0.53% gradually decreasing, indicating high program calculation accuracy.

3.2.2 Calculation of Neutron Density N(t) Variation with Time in Thermal Reactor After Step Negative Reactivity Insertion This case used thermal reactor parameters consistent with Table 1 . Step reactivity = -0.007 was set, time step h = 0.1 s, initial neutron density N(0) = 1.0 cm^{-3}, and neutron density (cm^{-3}) variation over 1 second was calculated. Using numerical analytical exact solutions as benchmark reference data, program calculation results were compared with exact solutions as shown in Figure 10 [Figure 10: see original paper] and Table 3 . The results show excellent agreement under step negative reactivity insertion conditions, with maximum deviation of 0.32%, demonstrating high calculation accuracy.

In summary, NUSOL-LMR-Li simulation results show good agreement with exact solutions under both positive and negative step reactivity input conditions, indicating the correctness of the core power calculation model in the program and its capability to meet calculation needs for reactivity insertion accidents.

3.3.1 Stirling Cycle Thermodynamic Parameter Validation

NASA commissioned Sunpower to develop and test a 1 kW-class Stirling engine prototype RE-1000. Based on experimental results [16], the established Stirling model was validated for effectiveness. Table 4 lists key design parameters of RE-1000 and shows comparison between model calculation results and experimental measurements, with maximum relative error of 1.63%. This demonstrates that the model can provide accurate and reliable data support for Stirling thermoelectric conversion process analysis.

3.3.2 Lithium-Cooled Stirling Cycle Loop Calculation

The modeling node diagram for the lithium-cooled fast reactor Stirling thermoelectric conversion system loop based on SP-100 system design is shown in Figure 11 [Figure 11: see original paper]. Fluid flows from the core into the upper plenum, then to the primary side of the Stirling engine. After exiting the primary side, it passes through the downcomer via the liquid metal electromagnetic pump, then enters the lower plenum and returns to the core, forming the primary loop circulation. The secondary loop sodium-potassium working fluid exchanges heat with the Stirling engine cold end, with waste heat effectively discharged through boundary condition equivalent treatment.

To conduct subsequent accident transient safety analysis of the lithium-cooled fast reactor Stirling thermoelectric conversion system, steady-state condition simulation was performed based on the NUSOL-LM-Li program. According to system and Stirling engine parameters given in literature [10, 17], Table 5 presents calculated main steady-state thermal-hydraulic parameters compared with design values. Data analysis shows that the Stirling hot end and cold end maintain a certain temperature difference, consistent with Stirling engine operating characteristics, indicating normal thermodynamic cycle operation. In summary, steady-state results from the program prove successful modeling.

4 Accident Transient Safety Analysis

To evaluate the safety performance and adaptive capabilities of the lithium-cooled fast reactor Stirling thermoelectric conversion system under abnormal conditions, this chapter conducts transient accident safety analysis for the lithium-cooled Stirling cycle system based on SP-100 design from the end of Chapter 3.

Based on the NUSOL-LMR-Li program, this chapter focuses on two typical conditions: reactivity insertion accidents and Stirling engine regenerator blockage accidents. Reactivity insertion accidents, mainly caused by control rod misoperation or coolant boiling, may lead to sudden core power increase and are critical scenarios for testing fast reactor dynamic safety characteristics. Stirling engine regenerator blockage accidents, mostly caused by impurity deposition or material aging, significantly affect system thermal-to-power conversion efficiency. By simulating dynamic evolution of core power, temperature distribution, and Stirling cycle parameters under these two accident types, the system’ s inherent safety characteristics and fault tolerance capabilities were comprehensively evaluated. These two accidents target the most typical failure modes at the nuclear energy generation end and energy conversion end, respectively, with research results providing important basis for safety design of space nuclear power systems.

4.1 Reactivity Insertion Accident

When the system experiences a 0.1$ step reactivity disturbance and the protection system is not triggered, the core power transient response characteristics are shown in Figure 11.

The core power rapidly rises to 534 kW within 7 seconds. The increase in core power directly causes rapid elevation of core temperature and primary loop temperature (Figure 12 [Figure 12: see original paper]).

For the secondary loop, the additional reactivity insertion leads to increased temperature at the hot end of the Stirling cycle. To maintain normal circulation, the cold end temperature subsequently rises, thereby driving up the secondary loop temperature (Figure 13). However, due to the existence of an overall negative feedback regulation mechanism, the core power is effectively controlled and gradually decreases to a steady-state operating value of 466 kW. As the power stabilizes, temperatures eventually reach equilibrium. The temperature rise amplitudes at the core inlet, core outlet, and secondary side outlet are 5.74 K, 14.7 K, and 2.24 K, respectively.

In summary, although additional reactivity was introduced at 0 seconds, causing instantaneous increases in core power and temperature, the system’ s negative feedback regulation mechanism effectively controlled the core power, ultimately stabilizing it at 466 kW. This process not only demonstrates the self-regulating capability and inherent safety of the lithium-cooled Stirling cycle system under overpower accidents, but also emphasizes the important role of negative feedback mechanisms in maintaining safe and stable reactor operation.

4.2 Stirling Engine Regenerator Blockage Accident

When operating in space, the regenerator in the Stirling power conversion system is responsible for controlling the temperature difference between the expansion chamber and compression chamber. If the regenerator becomes blocked due to impurity accumulation or corrosion, the thermoelectric conversion efficiency of the Stirling engine will be affected and decrease.

In this accident analysis, it is assumed that the Stirling engine operates normally from 0-10 s, and from 10 s to 300 s, the Stirling engine efficiency begins to decrease to 50% due to regenerator blockage, with no protective action. As can be seen from Figure 14, the accident occurs at 10 s, and the Stirling cycle efficiency drops to the lowest point of 22.24% at 30 s. Subsequently, the system gradually adapts to the partially blocked condition and slowly rises to stabilize at 26.8%.

Figure 15 shows the variation of average hot and cold end temperatures of the Stirling engine over time during the regenerator blockage accident. During the normal operation phase from 0-10 seconds, the hot and cold end temperatures remain stable at approximately 1318 K and 660 K, respectively, with a temperature difference of about 658 K. After the accident occurs (10-30 seconds), due to the regenerator blockage causing a sharp drop in heat transfer efficiency, the hot end initially drops sharply (by about 300 K) and finally stabilizes at 1023 K. This reflects the direct truncation effect of the blockage on the working fluid’ s expansion work capability, while the formation of the subsequent stable state originates from the spontaneous thermal equilibrium reconstruction mechanism of the Stirling cycle system. At the same time, due to the decrease in cycle efficiency, the high-temperature thermal energy carried by the helium working fluid inside the Stirling engine cannot be effectively exported by the cold end, causing heat to accumulate in the regenerator and cold end chamber in a short time. Consequently, the cold end temperature is rapidly raised to 900 K, and the secondary side temperature also rises to 740 K. As a new cycle is established, the cold end temperature decreases to 692 K, and the secondary side temperature also transitions from the initial rise to a decline and stabilizes (Figure 16

[Figure 16: see original paper]), confirming the high-efficiency robustness of the cold end heat exchange: despite the sudden reduction in hot end input causing short-term thermal coupling imbalance, the heat rejection system still resists the risk of working fluid condensation by maintaining a constant temperature gradient. It is worth noting that the temperature difference between the hot and cold ends narrows from the initial 658 K to 330 K in the accident steady state. This temperature difference reconstruction phenomenon precisely corresponds to the actual efficiency value of 26.8% (lower than the original design of 40%, but higher than the Carnot theoretical lower limit of 21%), revealing the physical essence of temperature difference as the decisive factor of cycle efficiency. This dynamic evolution process highlights the thermal inertia buffering characteristics and fault adaptive capability of the lithium-cooled fast reactor-Stirling coupled system, providing key experimental evidence for the continuous power supply reliability of space nuclear power under extreme operating conditions.

This study developed the transient analysis program NUSOL-LMR-Li to analyze the transient safety characteristics of the lithium-cooled space reactor Stirling thermoelectric conversion system, and systematically evaluated its performance and reliability through relevant model validation and accident analysis. The main conclusions of the study are as follows:

1. High-Precision Model Validation

The core power model demonstrated high precision through validation with two typical cases: step positive reactivity insertion and step negative reactivity insertion, with maximum relative errors of 0.53% and 0.32%, respectively. Additionally, the stability of the fully implicit algorithm was confirmed through a single-tube flow example driven by pressure difference, where flow velocity remained consistent even with large time steps. These validations ensure the reliability and accuracy of core power calculation and numerical methods, which are crucial for the safety and performance of the lithium-cooled fast reactor Stirling thermoelectric conversion system. Steady-state validation based on NASA' s RE-1000 Stirling prototype parameters showed maximum calculation errors of 1.63% for hot-end temperature, cold-end temperature, and cycle efficiency. In the lithium-cooled Stirling cycle loop calculation validation, the steady-state results calculated by the program were compared with design parameters, with a maximum error of 3.8%, proving the high precision and reliability of NUSOL-LMR-Li in simulating the lithium-cooled fast reactor Stirling thermoelectric conversion system process.

2. Accident Safety Characteristics

(1) Reactivity insertion accident (0.1$ reactivity insertion at t=0): Core power rises to 534 kW within 7 seconds, then self-stabilizes to 466 kW through fuel Doppler effect and coolant density negative feedback mechanisms, with core outlet temperature rise limited to within 14.7 K, demonstrating

the system's self-regulation capability and inherent safety under overpower accidents.

(2) Stirling engine regenerator blockage accident: Due to regenerator blockage, Stirling engine efficiency drops from 40% to 22.24%, but the system reestablishes thermal balance through spontaneous thermal balance reconstruction (hot-end temperature drops to 1023 K, cold-end rises to 692 K), recovering efficiency to 26.8%, approaching 80% of Carnot efficiency limit. Hot-cold end temperature difference narrows from 658 K to 330 K, revealing the dominant effect of temperature difference on efficiency and the system' s fault tolerance characteristics.

Based on NUSOL-LMR-Li, this study achieved transient simulation of the lithium-cooled fast reactor Stirling thermoelectric conversion system, validating model accuracy in the program. Through accident analysis specifically targeting characteristics of the lithium-cooled fast reactor Stirling thermoelectric conversion system, the study not only revealed the negative feedback self-stabilization mechanism of lithium-cooled fast reactors but also demonstrated the temperature-difference-driven efficiency characteristics of the Stirling thermoelectric conversion system under the innovative accident scenario of regenerator blockage, providing theoretical basis and technical support for safety design and fault tolerance optimization of space reactor power systems. The NUSOL-LMR-Li program serves as an efficient analysis tool that can provide important reference for future space reactor transient safety assessment and engineering optimization. Subsequent work will simulate and analyze more accidents based on actual space reactor operating conditions.

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