

Research on MBSE-based Design Method for S-CO₂ Micro-Nuclear Reactor Energy Conversion Systems

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Abstract

To address the limitations of traditional supercritical carbon dioxide Brayton cycle design methods in system layout and multi-parameter coupling impact analysis, as well as the difficulty in achieving collaborative optimization from the overall system to subsystems, this study introduces a model-based systems engineering method. Taking the land-based mobile multi-mode micro nuclear reactor power source designed by University of South China as the object, a systematic model from top-level requirements to the equipment level is constructed through a forward design process of “Requirement-Function-Logical Architecture.” This method effectively improves issues in traditional design such as inconsistent information transmission, insufficient traceability, and the lack of forward guidance in verification stages. Requirement analysis based on requirement diagrams and use case diagrams can clearly express the mapping relationship between top-level requirements, subsystem requirements, and functions; the energy conversion system activity diagram under power operation conditions constructed during the functional analysis stage can form a system functional model and support preliminary verification; logical architecture analysis achieves standardized design of the system architecture through internal block diagrams; the indicator system diagram established during the indicator decomposition stage achieves top-down indicator allocation. The model-based systems engineering modeling method for the supercritical carbon dioxide Brayton cycle significantly enhances the standardization, consistency, and traceability of the full-process design, improving efficiency while reducing design risks and costs.

Full Text

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1. Introduction

Micro-nuclear reactors have emerged as a pivotal technology in the modern energy landscape, offering decentralized, reliable, and high-energy-density power solutions for remote regions, military bases, and space exploration. Unlike large-scale commercial nuclear power plants, micro-reactors prioritize modularity, transportability, and autonomous operation. A critical component in achieving these objectives is the energy conversion system (ECS), which dictates the overall efficiency, footprint, and thermal management requirements of the reactor unit.

The design of an ECS for micro-reactors presents unique challenges. These systems must operate under stringent constraints, including limited volume, mass limitations, and the need for high reliability with minimal maintenance. Traditional Rankine cycles, while efficient for large-scale applications, often prove too complex and bulky for micro-scale integration. Consequently, research has shifted toward alternative cycles, such as the supercritical carbon dioxide (sCO_2) Brayton cycle and the closed-loop Brayton cycle using noble gases, which offer higher power densities and simplified configurations.

2. Design Methodology and System Architecture

The design process for a micro-nuclear reactor energy conversion system requires a multi-physics approach that couples neutronics, thermal-hydraulics, and structural mechanics. The primary objective is to optimize the thermodynamic cycle to match the reactor's thermal output while ensuring that the core temperature remains within safety limits.

[Figure 1: see original paper]

As shown in [Figure 1: see original paper], the integrated design framework begins with the definition of boundary conditions, such as the reactor's rated thermal power and the ambient cooling environment. The selection of the working fluid is a decisive factor; for instance, sCO_2 is favored for its high density near the critical point, which significantly reduces the size of turbomachinery. The system architecture typically involves a primary heat exchanger (recuperator), a precooler, and the power conversion unit consisting of a turbine and compressor.

3. Thermodynamic Modeling and Optimization

To evaluate the performance of the ECS, a comprehensive thermodynamic model is established. The efficiency of the cycle, η_{th} , is defined by the ratio of the net

work output to the thermal energy supplied by the reactor core. For a closed Brayton cycle, the relationship can be expressed as:

$$\eta_{th} = \frac{W_{turb} - W_{comp}}{Q_{in}}$$

Abstract

The design methodology for Supercritical Carbon Dioxide (sCO_2) Brayton cycles currently faces limitations regarding system layout configurations and the analysis of multi-parameter coupling effects. These constraints make it difficult to achieve collaborative optimization across the spectrum from the overall system to individual subsystems. To address these challenges, this study introduces a forward design approach based on Model-Based Systems Engineering (MBSE), constructing a systematic model that spans from top-level requirements down to the equipment level.

This methodology effectively mitigates common issues in traditional design processes, such as inconsistent information transfer, insufficient traceability, and the lack of forward guidance during the verification phase. The research results demonstrate that requirement analysis using requirement diagrams and use case diagrams can clearly articulate the relationships between top-level requirements, subsystem requirements, and system functions. During the functional analysis phase, the construction of activity diagrams for the energy conversion system under power-operating conditions enables the formation of a system functional model and supports preliminary verification. Furthermore, logical architecture analysis achieves a standardized design of the system architecture through internal block diagrams (IBDs). During the index decomposition phase, the established index system diagram facilitates top-down allocation of performance metrics.

The application of MBSE to sCO_2 Brayton cycle modeling significantly enhances the standardization, consistency, and traceability of the entire design process. By reducing design risks and costs while simultaneously improving efficiency, this study provides a novel framework and methodology for the optimized design of sCO_2 Brayton cycle systems.

Keywords: Supercritical carbon dioxide; Brayton cycle; Model-Based Systems Engineering; Design requirements; Architecture design

1. Introduction

Nuclear energy, characterized by its high energy density, long refueling cycles, and significant potential for miniaturization, has become a primary candidate for addressing diversified global energy demands in both military and civilian

sectors [?]. It is a critical component for many nations striving to achieve sustainable development [?]. Currently, nuclear reactors are evolving toward technical directions such as miniaturization and modularization. The Land-based Mobile Multi-mode Micro-nuclear Reactor (NSCAR) is a new type of supercritical carbon dioxide (sCO_2) reactor power source independently developed by the University of South China. It possesses unique advantages, including high energy density, long operational life, a high power-to-weight ratio, and excellent environmental adaptability. However, due to the complexity of the system and the multiplicity of design indicators, there is an urgent need for a development methodology that ensures both standardization and indicator traceability.

The design of Brayton cycle energy conversion systems has traditionally relied on document-driven development models. However, because of the complex system structures and strong parameter correlations, this mode faces several challenges: 1) When design changes occur, the workload for updating technical documents and drawings is immense, leading to resource waste; 2) Parameter adjustments can trigger chain reactions, causing technical indicators to deviate from requirements or even preventing the design scheme from converging; 3) The lack of synergy in evaluation and optimization across different disciplines and stages often leads to inconsistencies between design parameters and system requirements. To address these issues, the International Council on Systems Engineering (INCOSE) proposed the Model-Based Systems Engineering (MBSE) methodology. By utilizing formal modeling languages such as SysML, MBSE enables the layer-by-layer decomposition of requirements, functions, and parameters. This establishes a traceable system architecture model that supports design, verification, and optimization throughout the entire lifecycle. This method has gained widespread application across various fields, with theoretical exploration and engineering practice maturing over time [?].

2. Modeling Methodology and Research Object

Micro-reactors are characterized by their compact structure, high energy density, high system pressure, tight physical coupling between subsystems, and stringent safety and reliability requirements. Consequently, traditional document-driven systems engineering methods face potential challenges regarding efficiency and consistency in areas such as requirement tracing, interface coordination, change propagation, and design optimization.

2.1 Research Object

The land-based mobile multi-mode micro nuclear reactor power source, NSCAR, is an independently developed nuclear power system capable of both steady-state power operation and pulsed operation. It is characterized by its mobility, multimodal operational capabilities, and high level of safety. Focusing on land-based application scenarios, the system is designed to provide reliable energy solutions for power supply in remote areas and electric vehicle support.

The overall design of the NSCAR nuclear reactor power source is shown in [Figure 1: see original paper], which includes the subcritical module, coupling adjustment device, reactor main body, structural frame, and generator. The NSCAR energy conversion system is established based on the Brayton cycle. In this process, the working fluid is pressurized at the compressor outlet, flows to the low-temperature side of the recuperator for preheating, and then enters the reactor to absorb heat before directly entering the turbine to perform work.

2.2 Modeling Method

To address the deficiencies of document-based modeling, this study utilizes the Systems Modeling Language (SysML) and integrates the forward design process of the Harmony-SE methodology. The modeling process focuses on four core stages: requirements analysis, functional analysis, logical architecture analysis, and indicator decomposition.

For a given control volume, the energy balance equation can be expressed as:

$$\frac{dE_{sys}}{dt} = \dot{Q} - \dot{W} + \sum \dot{m}_{in} h_{in} - \sum \dot{m}_{out} h_{out}$$

In this expression, E_{sys} represents the total energy within the system, \dot{Q} and \dot{W} denote the heat transfer rate and work transfer rate respectively, while \dot{m} and h represent the mass flow rate and specific enthalpy at the inlets and outlets.

2.3 Requirements Analysis

Requirements analysis constitutes the foundational step. The top-level requirement—“Power supply under specified design and operating conditions”—is systematically decomposed into seven categories of sub-requirements for various application scenarios, such as remote area power supply and disaster emergency response. These are further refined into specific performance indicators, including power capacity, dimensions, and weight.

The system achieves high-efficiency energy conversion, with a comprehensive thermal efficiency of $\geq 35\%$. For the NSCAR project, the thermal power and steady-state electric power are defined within the 3 MWth range. The core outlet temperature is maintained at ≤ 650 °C, and the reactivity swing throughout the core lifetime is $\leq 1,000$ pcm. The system weight is constrained to ≤ 49 t to ensure mobility within a standard Type 1AAA container.

2.4 Functional Analysis

During the functional analysis phase, the requirement models are transformed into executable models. Activity diagrams are utilized to represent system functions under two modes: power operation mode and pulse operation mode.

In pulse operation mode, the process is subdivided into the ejection of pulse control elements, which triggers a surge in core power, followed by the re-insertion of elements to return the core to a subcritical state. The dynamics of such a surge are modeled using the point kinetics equations:

$$\begin{aligned}\frac{dN(t)}{dt} &= \frac{\rho(t) - \beta}{\Lambda} N(t) + \sum_{i=1}^6 \lambda_i C_i(t) \\ \frac{dC_i(t)}{dt} &= \frac{\beta_i}{\Lambda} N(t) - \lambda_i C_i(t)\end{aligned}$$

2.5 Logical Architecture Analysis

The logical architecture modeling phase defines functional modules and their interaction interfaces. The energy conversion system is divided into five core components: the compressor, turbine, recuperator, precooler, and reactor. Block Definition Diagrams (BDD) define the structural hierarchy, while Internal Block Diagrams (IBD) specify the internal connections and data/energy flows between specific modules.

2.6 Indicator Decomposition

The top-level indicators are decomposed into specific technical parameters for each subsystem. For example, turbine technical specifications include operating temperature, speed range, output power range, mass flow rate, and efficiency. This hierarchical decomposition establishes the design benchmarks necessary for equipment selection and detailed design.

3. Conclusion

The design of the NSCAR reactor energy conversion system demonstrates that the MBSE approach enhances design standardization, consistency, and traceability. The research results indicate that requirement diagrams and use case diagrams provide a definitive baseline for system design. Activity diagrams precisely characterize the dynamic behavior under different operational modes, and the established indicator system ensures that top-level constraints are traceably allocated to specific equipment. This study provides a robust methodological framework for the optimized development of advanced micro-reactor power systems.

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

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