Direct Turbine Nuclear-Thermal Coupling Simulation for Gas-Cooled Microreactors

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Abstract

Gas-cooled microreactors are an advanced novel reactor type that has attracted widespread attention in recent years due to their diverse application scenarios. These prismatic reactors utilize TRISO fuel particles, and their energy conversion system adopts a single-loop integrated helium turbine scheme. Since neither the reactor design nor the employed equipment has accumulated sufficient operational experience, research on the operational control of gas-cooled microreactors is required. Using the multi-physics simulation program Modelica, models were established for the main systems of the gas-cooled microreactor, including the reactor, turbine, compressor, charging and discharging system, and residual heat removal system. The entire operational scheme from startup to shutdown was formulated, and simulation analysis of the complete operational process was conducted employing a constant core outlet temperature control scheme. The reactor outlet temperature deviation remained within 2℃, the temperature change rate was below 50℃/h, and the reactor period exceeded 60s. The results demonstrate that the gas-cooled microreactor can achieve its operational objectives, with all parameters remaining within limits throughout the operational process, thereby validating the reasonableness and feasibility of the nuclear-thermal coupling operational scheme. This study provides valuable reference for control logic, operational scheme design, and simulation analysis of other gas-cooled reactor types.

Full Text

Preamble

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Neutronics/Thermal-hydraulics Coupling Simulation of Direct Turbine Micro Gas-Cooled Reactor

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Abstract

[Background] Micro gas-cooled reactor (MGCR) is a new type of advanced reactor that has attracted widespread attention in recent years due to its diverse application scenarios. The MGCR features a prismatic core using TRISO particles as fuel, with a single-loop integrated helium turbine as its energy conversion system. Since neither the reactor design nor the equipment has accumulated sufficient operational experience, it is necessary to investigate the operational behavior of MGCRs. [Purpose] This study aims to simulate the entire lifespan of an MGCR from startup to power operation to shutdown. [Methods] The main systems of the MGCR were modeled using the multi-physics simulation language Modelica, including the reactor core, turbine, compressor, pressure regulation system, and residual heat removal system. An entire lifespan operation plan was formulated from startup through power operation to shutdown. The constant outlet temperature control scheme was adopted for simulation, with main reactor process parameters such as outlet temperature, power, pressure, turbine rotation speed, and reactivity being simulated. [Results] The MGCR operated successfully. The outlet temperature deviation remained within 2°C, the temperature change rate was below 50°C/h, and the reactor period exceeded 60s. The results demonstrate that the MGCR can achieve its operational objectives, with all parameters remaining within limit values throughout the entire process. [Conclusions] The operation plan for the MGCR is reasonable and feasible. This study also provides an important reference for the design of control logic, operational strategies, and simulation analysis for other gas-cooled reactor types.

Keywords: Micro gas-cooled reactor; Neutronics/thermal-hydraulics coupling; Reactor operation; System simulation; Modelica

Introduction

Micro gas-cooled reactors are prismatic high-temperature gas-cooled reactors with high inherent safety and flexibility, capable of providing stable energy for special scenarios such as islands and remote areas, and have received extensive attention in recent years. MGCRs use helium as coolant and an integrated helium turbine as the energy conversion device. Due to their large thermal capacity, high single control rod worth, and limited thermal shock tolerance of equipment, their startup, shutdown, and power ramping processes differ significantly from those of conventional reactors, necessitating simulation analysis of the reactor-turbine coupling.

This study employs the MWORKS platform for multi-physics system simulation using the Modelica language to model the main systems of an MGCR and simulate reactor startup, shutdown, and power operation, thereby verifying the rationality and feasibility of the control logic, operational strategy, and overall operation plan.

1 System Description of Micro Gas-Cooled Reactor

The MGCR fuel employs TRISO-coated particle fuel that can effectively contain fission products, with graphite serving as the moderator. The overall core power and power density are relatively low. Reactivity is controlled by withdrawal-type control rods located in the reflector, with helium used as the coolant.

The energy conversion system adopts a direct turbine helium Brayton cycle. Major equipment includes a helium turbine, regenerator, precooler, low-pressure compressor, high-pressure compressor, intercooler, helium charge/discharge system, and passive residual heat removal system, as shown in Figure 1 [Figure 1: see original paper]. The helium turbine, low-pressure compressor, and high-pressure compressor are integrated coaxial devices.

2 Reactor Model

2.1 Point Reactor Model

The point reactor equations are used to solve for core power, assuming that the neutron flux density distribution does not change with space at different times. The equations are:

where $n(t)$ is neutron density (cm^{-3}), $c\ (t)$ is the concentration of delayed neutron precursors of group i (cm^{-3}), Λ is neutron generation time (s), q is external neutron source strength (s^{-1}), β is the delayed neutron fraction of group i, λ is the decay constant of delayed neutron precursors of group i, and β is the total delayed neutron fraction.

2.2 Core Thermal-Hydraulic Model

The energy conservation equation for fuel assemblies is given by Equation (2). The left side represents the time-dependent term due to temperature changes in the fuel assembly, while the right side represents energy transferred into the node, including heat from fuel Q fuel , heat transferred to the helium channel Q He , and axial and radial heat conduction Q axial and Q radial .

The energy conservation equations for fuel rods are given by Equations (3) and (4), where Q nuclear is the nuclear heating power at the fuel node and Q fuel is the energy transferred to the fuel assembly.

where is density, V is volume, C is specific heat capacity, and K is heat transfer coefficient. Helium is heated through convective heat transfer with the fuel graphite matrix. The flow and heat transfer in helium channels are simulated using pipe models.

3 Energy Conversion System

Helium turbomachinery includes two major aerodynamic components: compressors and turbines. Compressors provide gas motive power, converting mechanical energy into gas pressure energy, while turbines convert energy from the fluid medium into mechanical energy output.

3.1 Compressor

The following assumptions are made for the aerodynamic process within the compressor: (1) steady flow inside the compressor; (2) adiabatic compression process. The pressure ratio, efficiency, and flow rate are respectively:

where π is pressure ratio, N is rotational speed, β is operating point position, is efficiency, W is flow rate, subscript d denotes design point, subscript cor denotes relative value, and superscript * indicates corresponding parameters from the general characteristic curve, as shown in Figure 2 [Figure 2: see original paper].

For compressor efficiency, calculations are performed using Equations (7) and (8), which account for speed deviation.

3.2 Turbine

For the aerodynamic process in the turbine, the following assumptions are made: (1) steady flow inside the turbine; (2) adiabatic process. Compared with compressors, the aerodynamic process of turbine turbomachinery is relatively simple. This study employs a similarity description for turbine flow:

where G and G_0 are actual and rated flow rates respectively, T^* and T_0^* are rated and actual turbine inlet stagnation temperatures respectively, P^* and P_0^* are rated and actual turbine inlet stagnation pressures respectively, and P^* and P_0^* are rated and actual turbine outlet stagnation pressures respectively, with n being the actual rotational speed.

4 Control Scheme Overview

The coordinated control of the MGCR is primarily divided into reactor core outlet temperature control and turbine speed control.

4.1 Outlet Temperature Control

MGCRs inherently possess large thermal capacity, resulting in slow temperature response. Meanwhile, due to the small reactor volume, the number of control rod drive mechanisms that can be installed is limited, leading to fewer control rods with higher individual worth and increased control difficulty. Additionally, as a new reactor type, many equipment components have not been sufficiently studied or tested in engineering practice, making them unable to withstand large thermal shocks, thus temperature change rates must be limited.

Therefore, MGCRs adopt a constant reactor outlet helium temperature control scheme, which avoids the impact of outlet temperature rise on reactor structural thermal stress limits, as shown in Figure 3 [Figure 3: see original paper]. The temperature difference signal from the core coolant outlet is used to drive control rod movement, adjusting the rods at different speeds.

where L is the control rod drive signal, K is the conversion system, T is the outlet temperature setpoint signal, T is the outlet temperature measurement signal, and τ is the integral time constant.

4.2 Pressure Control

The MGCR employs a battery as the energy management system at the turbine power generation backend. The battery acts as a virtual load, effectively adding a variable load. By adjusting the battery’ s power input/output through a frequency converter, turbine speed can be regulated with fast response. Due to the rapid response of the frequency converter, turbine speed is essentially maintained constant.

Therefore, during steady-state operation, the battery’ s charge/discharge regulates minor load variations, while larger load changes are accommodated by adjusting pressure in the loop through the helium charge/discharge system, as shown in Figure 4 [Figure 4: see original paper].

5 Operation Plan

To verify the rationality of the MGCR operation plan, the startup process, power operation process, and shutdown process were simulated. Since this study focuses on reactor-turbine coupling analysis, the process of reaching criticality is ignored in the simulation, with the initial state assumed to be at zero-power criticality. Parameter limits are listed in Table 1 .

In the initial state, a small amount of helium is charged in the loop, with the helium turbine at low speed, intercooler and precooler already in service. Control rods are gradually raised to increase reactor power, heating the helium in the loop and bringing the reactor to hot standby condition. The helium turbine speed is then increased to rated speed. After this action is completed, control rods are further raised to bring reactor power to the helium turbine self-sustaining power level, switching to power generation mode. Control rods continue to be raised to the house load level (30% FP). Finally, through coordinated reactor-turbine control, reactor power is increased to rated power. The shutdown process is essentially the reverse of the startup process. The specific procedure is shown in Figure 5 [Figure 5: see original paper].

6 Simulation Results

Due to the small core size of the MGCR, the spatial power distribution is relatively uniform. The simulation does not consider the effect of spatial power distribution and also ignores interference effects between control rods. Additionally, burnable poison rods are incorporated in the reactor design, and the consumption of burnable poison during operation essentially offsets the burnup effect, so reactor burnup effects are also not considered in the simulation.

A simulation model of the MGCR was built using Modelica, and calculations were performed according to the operation plan. The main parameter results are shown in Figure 6 [Figure 6: see original paper], where represent the startup process, represent power operation, represent shutdown, and represents long-term cooling. The figure illustrates the variation patterns of six main parameters—reactor outlet temperature, control rod steps, reactor inlet pressure, reactor power, turbine speed, and reactivity—throughout the operation process.

Nuclear heating process: Control rods are raised to heat the helium in the loop using reactor power, with the intercooler and precooler already in service.
Speed raising process: Increasing helium turbomachinery speed from low to rated speed enhances helium flow and heat removal capacity, reducing average helium temperature. Due to negative temperature feedback, reactor power increases slightly and core outlet temperature rises modestly.
Power raising to house load (30% FP): This process raises reactor power to 30% rated power by raising control rods, bringing reactor outlet temperature to the rated value. During this process, the helium turbomachinery switches from motor mode to generator mode.
Power escalation process: This process employs constant core outlet temperature control through coordinated reactor-turbine control, adjusting control rod position and helium pressure to increase reactor power. Two intermediate power steps are set at 50% FP and 75% FP.
Rated power operation: The reactor maintains rated power operation. Due to heat losses and xenon poisoning accumulation, control rods are slowly raised to offset these effects and maintain constant reactor outlet temperature.
Power reduction process: Similar to power escalation, this process uses coordinated control to maintain constant outlet temperature while reducing reactor power to 30% rated power, also with intermediate steps at 75% FP and 50% FP. However, xenon concentration increases during power reduction, introducing negative reactivity, so the rod withdrawal rate is lower than during power escalation.
Core outlet temperature reduction: Control rods are lowered to reduce reactor outlet temperature. Due to reduced reactor power, the helium turbomachinery switches from generator mode to motor mode.
Speed reduction process: Helium turbomachinery speed is reduced to low speed. Due to decreased flow, reactor inlet pressure increases slightly. The reactor remains critical during this process and can be restarted at any time.
Subcritical process: Control rods are lowered to bring the reactor to a subcritical state, where fission power essentially disappears and reactor outlet temperature drops, but helium turbomachinery speed and heat sink cannot be shut down as the reactor temperature remains high.

Reactor shutdown: When reactor parameters meet conditions, the helium turbomachinery and heat sink are shut down, causing a slight temperature rise.
Long-term cooling: Due to the long-term presence of decay heat, passive residual heat removal systems continuously remove decay heat.

Simulation of the operation strategy demonstrates that the entire process satisfies the limit requirements in Table 3 . Due to the large thermal capacity of the MGCR, the limit on core outlet temperature change rate (<50°C/h) results in low control rod movement rates and slow reactivity insertion, yielding long reactor periods. The reactor period during power escalation is shown in Figure 7 [Figure 7: see original paper], meeting the >60s requirement.

The large thermal capacity, high single rod worth, and small temperature change limits of MGCRs pose challenges for coordinated reactor-turbine operation. This study established simulation models for major MGCR systems including the reactor, helium turbomachinery, compressors, and helium charge/discharge system. Control logic and operational strategies were developed, and the entire process from startup through power operation to shutdown was simulated. The results demonstrate that the control logic and operational strategy can meet MGCR operational requirements, with all main parameters remaining within operational limits. This study verifies the rationality and feasibility of the direct turbine neutronics/thermal-hydraulics coupling operation plan for MGCRs and provides a reference for control logic design, operational strategy development, and simulation analysis for other reactor types.

References

1. Su Yihui, Zhang Ganghe, Yi Ke, et al. Analysis of operational scenarios for micro gas-cooled reactor[J]. Science & Technology Vision, 2024, 17: 54-56.

2. Chen Liping, Zhou Fanli, Ding Jianwan, et al. The unified multi-domain physical modeling language Modelica and systems modeling application with Mwork[M]. Wuhan: Huazhong Science Technology University Press, 2019.

3. Zhou Fanli. Study on compilation mapping and simulation solution of unified model in multiple fields engineering system[D]. Wuhan: Huazhong University of Science and Technology, 2011.

4. Zhang Chenglong, Liu Guoming, He Kai, et al. Research on influence of neutronics characteristics in fuel design of micro gas-cooled reactor[J]. Atomic Energy Science and Technology, 2021, 55(11): 2060-2069.

5. Xie Zhongsheng. Analysis nuclear reactor physics[M]. Xian: Xian Jiaotong University Press, 2003.

6. Zhang H, Li Y, Zhao Y, Wang J, Du S and Ma W(2023). Modeling and simulation of a micro gas-cooled nuclear reactor using Modelica. Fron.

Energy Res. 11:1206755. doi: 10.3389/fenrg.2023.1206755.

7. Zhang Jianmin. Control of nuclear reactor[M]. Xian: Xian Jiaotong University Press, 2002.
8. Liu Dan, Sun Jun, Xu Xiaolin, et al. Simulation and analysis of start-up process of high temperature gas-cooled reactor[J]. Atomic Energy Science and Technology, 2014, 45(sup): 594-598.
9. Si Tianqi, Du Yu, Yi Ke, et al. Study on automatic plant startup and shut down operation scheme for gas-cooled micro reactor[J]. Nuclear Power Engineering, 2024, 45(S1): 58-62.
10. Zhou Bo, Yan Rui, Zou Yang, et al. Analysis of xenon dynamic characteristics in primary loop system of MSR[J]. Nuclear Power Engineering, 2018, 39(5): 15-20.
11. Zuo Yanci, Li Jianlong, Wang Yulin, et al. The evaluation of the calculation method about Idoine pit reactivity on research reactor[J]. Nuclear Electronics & Detection Technology, 2020, 40(3): 443-447.