Gas-Cooled Microreactor Direct Turbine Nuclear-Thermal Coupling Simulation

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Abstract

Gas-cooled micro-reactors represent an advanced novel reactor concept that has garnered extensive attention in recent years due to their diverse application scenarios. These prismatic reactors utilize TRISO (TRi-structural ISOtropic) fuel particles and employ a single-loop integrated helium turbine scheme for the energy conversion system. However, neither the reactor design nor the equipment utilized has accumulated sufficient operational experience, necessitating research into the operational control of gas-cooled micro-reactors. Using Modelica, a multi-physics simulation language, major systems of the gas-cooled micro-reactor were modeled, including the reactor, turbine, compressor, charging and discharging system, and residual heat removal system. The complete operational scheme from startup to shutdown was formulated, and simulation analysis of the entire operational process was conducted adopting a constant core outlet temperature control scheme. The reactor outlet temperature deviation remained within 2 ℃, the temperature change rate was below 50 K/h, and the reactor period exceeded 60 s. The results demonstrate that the gas-cooled micro-reactor 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] The core of the MGCR is a prismatic reactor using TRISO (TRistructural ISOtropic) particles as fuel, and the energy conversion system adopts a single-loop integrated helium turbine scheme. Due to the lack of operation experience, it is necessary to study the operation behavior of the MGCR. [Purpose] This study aims to simulate the behavior of the entire lifespan of the MGCR from startup to power operation to shutdown. [Methods] The main systems of the MGCR were modeled using the multi-physics simulation language Modelica, which is widely used in the field of simulation, including reactor core, turbine, compressor, regulator, heat removal system, and so on. The point reactor equation and the single channel model were adopted to simulate the reactor core. The Brayton Cycle was adopted to simulate the energy conversion system. The control system included outlet temperature control system and pressure system. The purpose of the outlet temperature control system was to keep the temperature constant, which was adjusted by the CRs (Control Rods). The purpose of the pressure control system was to follow the power changes, which was adjusted by the helium charging and discharging system. The startup and shutdown strategies were designed to meet the operation limits. All device equations, control logic, and operation strategies were modeled for the simulation. The behaviors of the entire life of the MGCR were studied, such as outlet temperature, power, pressure, turbine rotation speed, reactivity, and so on. [Results] The main parameters are stable during power operation. The outlet temperature is stable at 1000K, with a deviation of 2K. The startup and shutdown strategies were successful. The temperature change rate is below 50K/h when heating helium. The reactor period is more than 60s in the entire lifespan. The results show that the control logic and operation strategies are reasonably designed and can satisfy the system design requirements. [Conclusions] The operation plan of the MGCR is reasonable and feasible. This study also provides important reference for the design and simulation of gas-cooled reactors.

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

1. System Description of Micro Gas-Cooled Reactor

The micro gas-cooled reactor is a prismatic high-temperature gas-cooled reactor with high inherent safety and good flexibility, which can provide stable energy for special scenarios such as islands and remote areas [1]. In recent years, it has received widespread attention. The micro gas-cooled reactor uses helium as coolant and an integrated helium turbine as the energy conversion device.

Due to the large heat capacity of the micro gas-cooled reactor, the large single control rod worth, and the limited thermal shock that equipment can withstand, its processes of startup, shutdown, and power ramping differ significantly from traditional reactors. Therefore, it is necessary to conduct simulation analysis on the reactor-turbine coupling of the micro gas-cooled reactor.

This study uses the multi-physics system simulation Modelica language platform MWORKS [2][3] for simulation, models the main systems of the micro gas-cooled reactor, and performs simulation analysis on reactor startup/shutdown and power operation to verify the rationality and feasibility of the control logic, operation strategy, and overall operation scheme of the micro gas-cooled reactor.

2.1 Reactor Model

The reactor model includes a physics model and a thermal-hydraulic model. The point reactor equation [7] is used to solve the core power, assuming that the neutron flux density does not change with spatial distribution at different times.

$$\frac{dn(t)}{dt} = \frac{\rho(t) - \beta}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i c_i(t) + q$$

$$\frac{dc_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i c_i(t)$$

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

Core Thermal-Hydraulic Model

The energy conservation equation for fuel blocks is shown in Equation (2) [8][9]. The left side of the equation is the time-varying term caused by temperature change of the fuel block, while the right side represents the energy transferred into the node, including heat transferred from fuel (Q_{fuel}), heat transferred to helium flow channels (Q_{He}), and axial and radial heat conduction of the block node (Q_{axial}, Q_{radial}).

$$\rho_{i,k} V_{i,k} C_{p,i,k} \frac{dT_{block,i,k}}{dt} = Q_{fuel,i,k} - Q_{He,i,k} + Q_{axial,i,k-1} - Q_{axial,i,k+1} + Q^{N}_{radial,i,k} + Q^{NW}_{radial,i,k} + Q^{SW}_{radial,i,k} + Q^{S}_{radi}$$

The energy conservation equation for fuel rods is shown in Equations (3) and (4), where $Q_{nuclear}$ is the nuclear heating power at the fuel node, and Q_{fuel} is the heat transferred to the fuel block.

$$\rho_{fuel,i,k}V_{fuel,i,k}C_{p,fuel,i,k}\frac{dT_{fuel,i,k}}{dt} = Q_{nuclear,i,k} - Q_{fuel,i,k}$$

$$Q_{nuclear,i,k} = P_{reactor} \cdot F_{power,i,k}$$

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

2.2 Energy Conversion System

Helium turbomachinery includes two major aerodynamic components: compressors and turbines. The compressor provides gas power, converting mechanical energy into gas pressure energy. The turbine converts energy from the fluid medium into mechanical energy and outputs mechanical work.

For the aerodynamic process in the compressor, the following assumptions are made: 1) Steady flow inside the compressor; 2) The compression process is adiabatic. The pressure ratio, efficiency, and flow rate are calculated as:

$$\pi = f_1(N_{cor}, W_{cor})$$

$$\eta = f_2(N_{cor}, W_{cor})$$

where π is the pressure ratio, N is the rotational speed, η is the efficiency, W is the flow rate, subscript d represents the design point, subscript cor represents the relative value, and superscript $*$ represents the corresponding parameters on the universal characteristic curve, as shown in Figure 2 [Figure 2: see original paper].

2.2.2 Turbine

For the aerodynamic process in the turbine, the assumptions are: 1) Steady flow inside the turbine; 2) The expansion process is adiabatic. Compared with the compressor, the aerodynamic process of the turbine is relatively simple. This paper uses a similarity description for turbine flow:

$$\frac{G_T}{G_{T0}} = \frac{p^*_{in}}{p^*_{in0}}\sqrt{\frac{T^*_{in0}}{T^*_{in}}} \cdot \frac{\sqrt{1 - (\frac{p^*_{out}}{p^*_{in}})^{\frac{\gamma-1}{\gamma}}}}{1 - (\frac{p^*_{out0}}{p^*_{in0}})^{\frac{\gamma-1}{\gamma}}}$$

where G_T and G_{T0} are the actual flow rate and rated flow rate respectively, T^*_{in} and T^*_{in0} are the rated turbine inlet stagnation temperature and actual turbine inlet stagnation temperature respectively, p^*_{in} and p^*_{in0} are the rated turbine inlet stagnation pressure and actual turbine inlet stagnation pressure respectively, p^*_{out} and p^*_{out0} are the rated turbine outlet stagnation pressure and actual turbine outlet stagnation pressure respectively, and Δn and n_0 are the deviation from rated speed and rated speed value respectively.

For turbine efficiency, it is calculated using Equations (7) and (8), where n is the actual speed.

$$\eta_T = \eta_{T0} \cdot [1 - 0.4(1 - \frac{n}{n_0})^2]$$

2.3 Control Scheme

The coordinated control of the micro gas-cooled reactor mainly includes reactor core outlet temperature control and turbine speed control.

2.3.1 Outlet Temperature Control

The micro gas-cooled reactor itself has large heat capacity, resulting in slow temperature response. Meanwhile, due to the small reactor size, the number of control rod drive mechanisms is limited, and the number of control rods is small, leading to large single control rod worth and high control difficulty. Additionally, as a new reactor type, many devices have not been fully studied or tested in engineering practice, making them unable to withstand large thermal shocks, and the temperature change rate should not be too high.

Therefore, the micro gas-cooled reactor adopts a constant reactor outlet helium temperature control scheme, which can avoid the impact of outlet temperature rise on reactor structural thermal stress limits [10]. The control schematic is shown in Figure 3 [Figure 3: see original paper]. The temperature difference signal at the core coolant outlet is used as the signal to drive control rod action to adjust the control rods at different speeds.

$$L = K \cdot \frac{1}{\tau s + 1} \cdot (T_0 - T)$$

where K is the conversion system, T_0 is the outlet temperature setpoint signal, T is the outlet temperature measurement signal, τ is the integral time constant, and L is the signal driving control rod action.

2.3.2 Pressure Control

The micro gas-cooled reactor uses a battery as the energy management system at the turbine power generation backend. The battery acts as a virtual load, equivalent to adding a variable load. The turbine speed is regulated by adjusting the battery’ s power input/output through a frequency converter, which has a fast response speed. Due to the fast response of the frequency converter, the turbine speed is basically maintained constant.

Therefore, during steady-state operation, the battery' s charging/discharging is used to regulate small load changes, while when large load changes occur, the helium charging/discharging system is used to adjust the pressure in the loop. The pressure control schematic is shown in Figure 4 [Figure 4: see original paper].

3. Operation Scheme

To verify the rationality of the micro gas-cooled reactor operation scheme, the startup process [11][12][13][14], power operation process, and shutdown process of the micro gas-cooled reactor were simulated. Since this paper mainly focuses on reactor-turbine coupling analysis, the process of reaching criticality is ignored in the simulation, and the initial state is assumed to be at zero-power critical state. The parameter limits are shown in Table 1 [15].

In the initial state, a small amount of helium is charged in the loop, the helium turbine is at low speed, and the intercooler and precooler are put into operation. Then the control rods are gradually raised to increase reactor power to heat the helium in the loop, bringing the reactor to hot state. Next, the helium turbine speed is increased to rated speed. After this action is completed, the control rods are raised to gradually increase reactor power to the self-sustaining power level of the helium turbine, and the system is switched to power generation mode. The control rods are then further raised to the house load level (30% FP). Finally, through coordinated reactor-turbine control, the reactor power is increased to rated power. The shutdown process is basically the reverse of the startup process. The specific process is shown in Figure 5 [Figure 5: see original paper].

Table 1. Main Operating Parameter Limits

Parameter	Value
Reactivity	$<0.5\beta$
Temperature change rate of reactor outlet	<50 K/h
Dead zone of CRs action	>1 cm
Speed of CRs	<1 cm/s
Power change rate of reactor	<5% FP/min
Reactor period	>60 s

4. Simulation Results

Due to the small core size of the micro gas-cooled reactor, the spatial power distribution is relatively uniform. In the simulation, the influence of spatial power distribution is not considered, and the interference effect between control rods is also ignored. Meanwhile, burnable poison rods are added in the reactor design. As the reactor operates, the consumption of burnable poison basically offsets the reactor burnup effect, so the reactor burnup effect is also not considered in the simulation.

A simulation model of the micro gas-cooled reactor was built using Modelica. According to the operation scheme, simulation calculations were performed, and the main parameter results are shown in Figure 6 [Figure 6: see original paper]. In the figure, represent the startup process, represent the power operation process, represent the shutdown process, and represents the long-term cooling process.

The figure shows the variation patterns of six main parameters with the operation process: reactor outlet temperature, control rod steps, reactor inlet pressure, reactor power, turbine speed, and reactivity. Specifically:

Nuclear Heating Process: The control rods are raised to heat the helium in the loop using reactor power. At this time, the intercooler and precooler are already in operation.

Speed Raising Process: The helium turbomachinery speed is increased from low speed to rated speed, which increases helium flow rate and enhances heat removal capability, causing the average helium temperature in the reactor to decrease. Due to negative temperature feedback, reactor power increases slightly, and the core outlet temperature rises slightly.

Power Raising to House Load Level (30% FP): This process relies on raising control rods to increase power, bringing reactor power to 30% rated power while the reactor outlet temperature reaches the rated temperature. During this process, the helium turbomachinery switches from power consumption mode to power generation mode.

Power Raising Process: Through coordinated reactor-turbine control, the control rod position and helium pressure are adjusted to increase reactor power. Two intermediate power steps of 50% FP and 75% FP are set during the raising process. The reactor outlet temperature is maintained at 1000K throughout, with deviation not exceeding 2K. This temperature is also maintained during subsequent rated power operation and power reduction processes.

Rated Power Operation Process: During this stage, the reactor operates at rated power. Due to certain heat losses and xenon poisoning accumulation, the control rods are slowly raised to offset these effects and maintain constant reactor outlet temperature.

Power Reduction Process: This process is similar to the power raising process. Through coordinated reactor-turbine control, the reactor outlet temperature is maintained constant while reactor power is reduced to 30% rated power. Two intermediate power steps of 75% FP and 50% FP are also set. However, during power reduction, xenon concentration increases to some extent

[16][17], introducing negative reactivity, so the control rod insertion rate is lower than the rod withdrawal rate during power raising.

Reactor Outlet Temperature Reduction Process: In this process, the reactor outlet temperature is reduced by inserting control rods. Due to the reduction in reactor power, the helium turbomachinery switches from power generation mode to power consumption mode.

Speed Reduction Process: The helium turbomachinery speed is reduced to low speed. Due to the reduction in flow rate, the reactor inlet pressure increases slightly. During this process, the reactor remains in a critical state and can be restarted at any time.

Subcritical Process: By inserting control rods, the reactor is brought to a subcritical state. The fission power basically disappears, and the reactor outlet temperature decreases, but the reactor temperature is still relatively high, so the helium turbomachinery speed and heat sink cannot be shut down.

Reactor Shutdown Process: When the reactor parameters meet the conditions, the helium turbomachinery and heat sink are shut down, which causes the temperature to rise slightly.

Long-term Cooling Process: Due to the long-term existence of decay heat, the passive residual heat removal system continuously removes decay heat.

Through simulation of the operation strategy, the entire operation process meets the limit requirements in Table 1 . Due to the large heat capacity of the micro gas-cooled reactor, the limit of reactor outlet temperature change rate (<50°C/h) results in a lower control rod action rate and slower reactivity insertion, leading to a longer reactor period. The reactor period during the power raising stage is shown in Figure 7 [Figure 7: see original paper], meeting the requirement of >60s [18].

Figure 7. Reactor Period During Power-Up Process

The micro gas-cooled reactor, with its large heat capacity, large single control rod worth, and small temperature change limits, poses challenges for coordinated reactor-turbine operation. This paper analyzes the main systems of the micro gas-cooled reactor and establishes simulation models for major system components including the reactor, helium turbomachinery, compressor, and helium charging/discharging system. The control logic and operation strategy for the micro gas-cooled reactor were developed, and the entire process from startup to power operation to shutdown was simulated and analyzed, with the variation of main parameters in different stages examined.

The results show that the control logic and operation strategy can meet the operation requirements of the micro gas-cooled reactor. All main parameters are within operation limits. During power operation, the core outlet temperature can be maintained constant. During helium heating, the temperature change is kept below 50K/h. Control rod actions are stable with reasonable speed, and the reactor period is greater than 60s, with minimal overshoot in reactor power and temperature parameters. This study verifies that the direct turbine neutronics/thermal-hydraulics coupling control logic and operation scheme for the micro gas-cooled reactor are reasonable and feasible, providing reference for the design and simulation of control logic and operation strategies for other reactor types.

Author Contributions

Li Yunlong was responsible for system design, operation strategy and control strategy design and analysis, and reactor system model development; Zhao Yuer was responsible for thermal-hydraulic system design and model development; Pan Li was responsible for MWorks program implementation and debugging; Zhang Huimin was responsible for paper proofreading and analysis summary; Wang Jun provided technical support.

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