Conceptual Design of Uranium-Zirconium Hydride Microreactor Cooled by Supercritical CO_2

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1. Introduction

To combat climate change and achieve carbon neutrality, nuclear energy emerges as a pivotal player in the realm of clean energy transition. In the forthcoming era, a paramount contribution is anticipated to emanate from the advent of smaller and more compact micro-reactors.

Microreactors are one of the emerging nuclear energy technologies with the potential to provide low-carbon energy. These are extremely small reactors with expected power levels typically ranging from less than 1 MW (electric) to 20 MW (electric), and a maximum of 50 MW (electric).

Given that micro-reactors are typically deployed in remote regions and operate autonomously, their inherent safety is of paramount significance. The objective of this article is to design a micro-reactor utilizing uranium-zirconium hydride fuel and supercritical carbon dioxide for cooling.

1.1 Uranium-Zirconium Hydride Fuel

A uranium—zirconium hydride reactor employs UZrH as fuel, where metallic uranium is uniformly blended with the primary moderator hydrogenated zirconium (ZrH). This configuration grants it a substantial negative prompt temperature coefficient, enabling both steady-state and pulsatile operation. Its applications are diverse, costs are economical, and it is recognized for its safety and reliability.

In conventional reactors, the fuel and moderator are separate, resulting in a smaller negative temperature coefficient that is gradual in nature. In uranium-hydrogen-zirconium components benefit from the uniform dispersion of uranium and hydrogenated zirconium. This not only facilitates effective moderation for a compact reactor design but also leads to an adiabatic and simultaneous temperature increase of the fuel and moderator hydrogenated zirconium. As the temperature rises, reactivity increases, causing an immediate temperature rise in the hydrogenated zirconium, generating a significant negative reactivity temperature coefficient (approximately 1×10^{-4}/°C). This inherent safety feature contributes to the uranium-hydrogen-zirconium reactor's overall stability.

1.2 Supercritical CO2

Once carbon dioxide reaches its critical temperature of 30.98°C and pressure of 73.78 bar, it transforms into a supercritical fluid known as supercritical carbon dioxide (SCO2). Supercritical carbon dioxide exhibits physical and chemical properties that fall between those of liquids and gases. It is neither strictly a liquid nor a gas. Its density is similar to that of a liquid, yet its low viscosity and high diffusion coefficient are comparable to those of a gas, endowing it with excellent flow and transport characteristics. Additionally, it possesses advantages such as safety, ease of availability, and cost-effectiveness.

Based on these characteristics, sCO2 can serve as both an energy conversion medium and a coolant, enabling the integration of the reactor core and the circulation loop within a single container. This allows for the creation of a compact and modular microreactor design.

2.Conceptual Design of the reactor

The core section is composed of 36 identical fuel rods arranged in a regular hexagonal pattern. The side reflector is a stack of beryllium oxide that moderates and reflects neutrons back into the active core. The beryllium oxide side reflector also houses the four rotating CDs.

The coolant in the microreactor is sCO_2， distributed in the gaps of the fuel. Reactivity control in the microreactor is provided by four control drums.

The two-dimensional radial geometry of the MARVEL microreactor for the quarter-core is shown in Figure 1. The inner core of the MARVEL microreactor is shown in Figure 2. The specific dimensions of the microreactor is shown in Table 1.

Table 1: Microreactor Model Dimensions

Parameter	Dimension(cm)
Fuel Rod Radius	1.679
Fuel Pin Pitch	3.50
Core Outer Radius	12.8
BeO Radius	32.41
B4C Radius	54.80
Outer Steel Shield	59.52

Fuel Height	51
Total Height	67

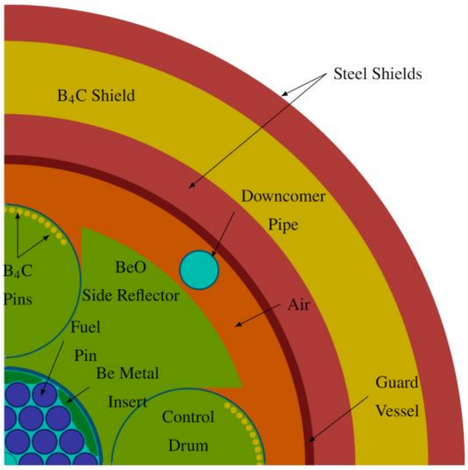

Fig.1. Two-Dimensional Microreactor Model

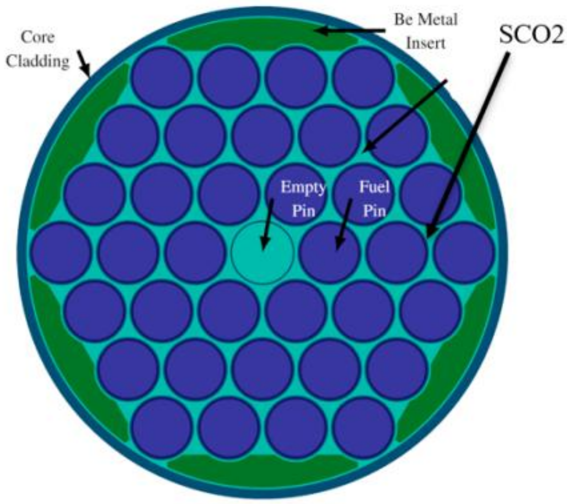

Fig.2. Inner core region

The electric power output target is set to 100KW and top pressure and turbine inlet temperature is selected to be 20MPa , 500℃.

3.Caculation and Analysis of the Core

This study uses the RMC (Reactor Monte Carlo code) for calculation and analysis.

3.1 K_{eff}

The calculation method is to make the four control drums rotate the same degree together and record the Keff at different degrees. The RMC program is set with an initial source of 100,000 and a total iteration count of 1,000, with skipping 100 iterations. The relationship between the rotation degree of the control drums and Keff is shown in the graph Figure 3.

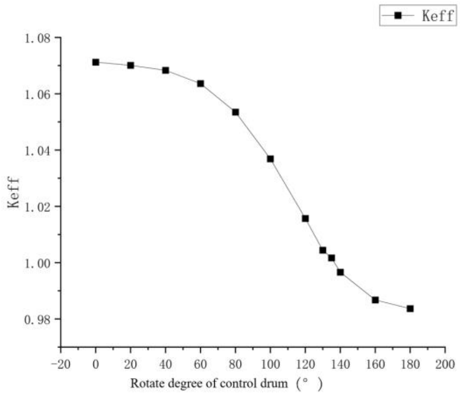

Fig.3. The relationship between the rotation degree of the control drums and Keff

When the control drum rotates 0 degrees, Keff is equal to 1.07121. When the control drum rotates 180 degrees, Keff is equal to 0.98366. After inserting the central control plate, Keff becomes 0.88445. When the control drum rotates 135 degrees, Keff is equal to 1.00168, which meets the criticality requirements of the reactor.

3.2 The Core Power Distribution

During the operation of an actual reactor, the power distribution within the core is non-uniform. In reactor research and design, the concept of "power peaking factor" is commonly used to indicate the degree of uniformity in power distribution.

The overhead view and 3D view of the full power distribution of the core stack are shown in the Figure.4 and Figure.5

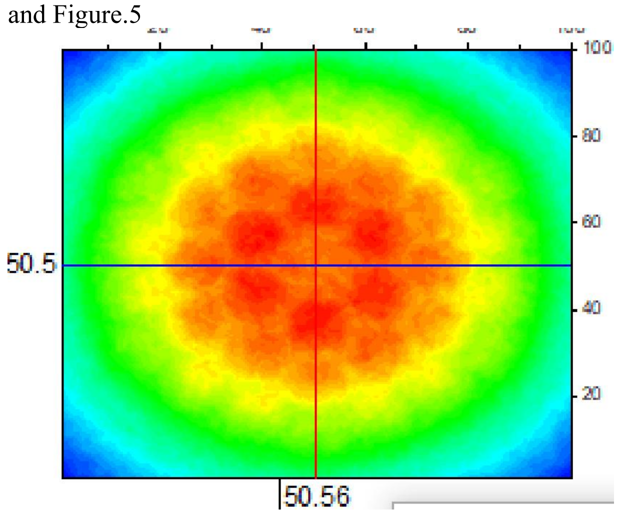

Fig.4 overhead view of power distribution

It can be seen from Figure 4 and Figure 5 that the overall power distribution in the core tends to be smooth and relatively flat. The power distribution across the entire core is quite uniform.The power peaking factor, obtained by dividing the maximum power by the average power, is 1.29. This power peaking factor is within a reasonable range. This indicates that the power distribution in the core changes relatively smoothly, and the overall power distribution in the core is relatively flat and stable.

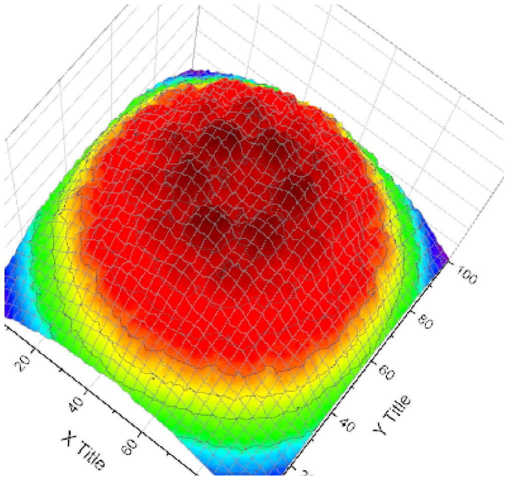

Fig.5 3D view of power distribution

3.3 Temperature Feedback Effect of sCO₂

When the temperature of the sCO_2 coolant changes, the density of sCO_2 changes. The change of sCO_2 density will affects neutron leakage, which mainly affects the reactivity.

Table 2: Relationship between Keff and density of sCO2

Pressure/MPa	Temperature /K	Density/g/cm^3	K_{eff}
10	650	0.082	0.98981
10	850	0.061	0.98906
100	650	0.601	0.99861
100	850	0.468	0.99574

Calculating temperatures specified at 650K and 850K serves two purposes. Firstly, it covers the temperature range of the reactor coolant. Secondly, it allows for significant variations in reactivity, avoiding the impact of statistical errors on the results. The calculation is performed by altering the density of the coolant. At 10MPa, the temperature feedback coefficient of CO_2 is -0.375pcm/K, while at 100MPa, it is -1.435pcm/K.

4. Simulation of sCO2 Brayton cycle based on Flownex

In this study, Flownex SE was used to design S-CO2 Brayton cycles.Flownex SE simultaneously solves mass, momentum and energy in conjunction with two-phase fluid properties for system models. This makes it ideal for modelling supercritical CO2 cycles where key design parameters can be analyzed and optimized.

Figure.6 shows the sCO_2 recompressing Brayton cycle model.As a part of ongoing research of conceptual design of microreactor, preliminary design of power generation cycle was performed in this study.

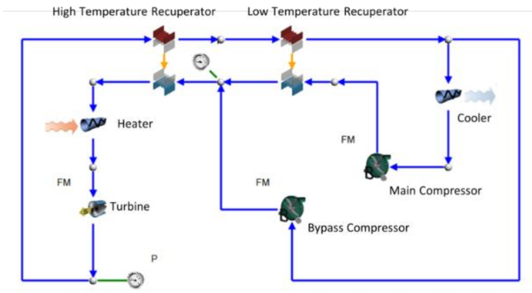

Fig.6. sCO_2 RCBC model built in Flownex

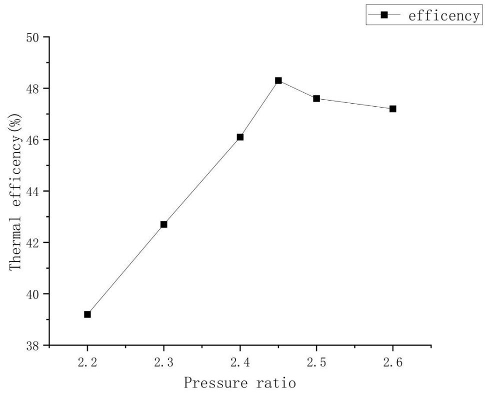

Fig.7. Thermal efficiency with respect to ratio

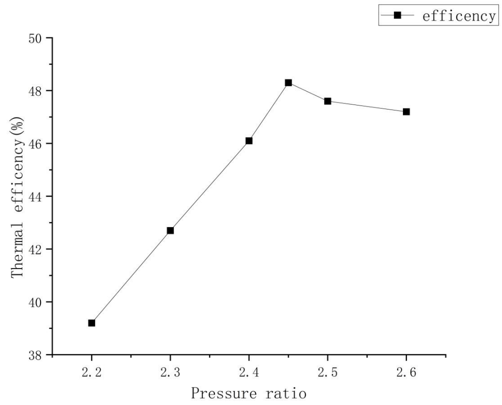

Fig.8. Thermal efficiency with respect to temperature

Since the targets of microreactor are full modularization of a reactor system with S-CO2 coolant, authors selected a recompressing SCO2 Brayton cycle as a power conversion system. The size of components of the S-CO2 cycle is much smaller than existing helium Brayton cycle and steam Rankine cycle, and whole power conversion system can be contained with core and safety system in one containment vessel.

5.Conclusion

A concept design of a microreactor utilizing UZrH fuel and a direct cooling cycle with sCO_2 has been proposed.Through core physics calculations and sCO2 cycle simulations, the reactor meets the design requirements, and further thermodynamic research will be conducted. The RMC code is used to establish core models for fuel elements, coolant, and reflector layers, and to perform physics calculations such as Keff, power distribution, and reactivity coefficients. The Flownex simulation is used to simulate the supercritical CO2 recompression Brayton cycle. The research shows that the core can reach criticality, the power distribution in the core is flat, and the efficiency of the sCO2 direct cooling cycle is high, which effectively improves the utilization efficiency of nuclear energy. Meanwhile, through the analysis of reactivity coefficients, the core structure can be further optimized to improve the safety performance of nuclear reactors. In conclusion, the research on fuel elements and the sCO2 recompression Brayton cycle using RMC code and Flownex simulation technique provides an effective method and tool for design optimization and performance improvement in the field of nuclear energy.

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