CONCEPTUAL DESIGN OF A MICRO NUCLEAR ENERGY SYSTEM WITH INTEGRATED HEAT PIPE COOLED REACTOR AND MOLTEN SALT HEAT STORAGE

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INTRODUCTION: Micro nuclear energy systems offer promising application prospects due to their low cost and deployment flexibility. These compact systems operate in closer proximity to populated areas, necessitating higher safety performance. The paper proposes a new conceptual design of a micro nuclear energy system with high thermal inertia. It is based on a heat pipe cooled reactor and an integrated heat storage system along with a Supercritical Carbon Dioxide (SCO_2) Brayton cycle. The system can achieve 34.45% energy conversion efficiency and 1.2MW(e). A heat pipe cooled reactor with UO_2 fuel and sodium heat pipe was designed. It was connected by the condensation section of heat pipes to a molten salt heat storage system. The SCO_2 Brayton cycle was used to ensure a compact system layout. Three transient conditions including the load reduction, reactivity insertion, and loss of heat sink were discussed in the paper. The results indicate that, with the intermediate heat storage, the micro nuclear energy system has better tolerance of the transient thermal shocks. The peak temperature in the core is reduced for all conditions. Particularly in the process of loss of heat sink, the peak temperature in the core can be reduced by more than 70 K.

1. OVERVIEW

Micro reactors are compact and transportable in standard shipping containers [1], enabling flexible deployment. Compared to traditional nuclear plants, the micro nuclear energy systems are closer to the users and requires higher safety performance. However, their tightly coupled reactor-energy conversion systems heighten thermal shock risks. Besides, most microreactors feature fast neutron spectra with weak negative reactivity feedback, which is not conducive to suppressing temperature fluctuations and increasing the risk of core damage.

Larger thermal capacity and thermal inertia in a nuclear energy system has better thermal shock tolerance. Increasing heat storage is a way to improve the thermal inertia of the whole system. Westinghouse proposed a concrete energy storage system for light water reactors [2]. This system operates independently of the secondary loop and does not directly participate in heat exchange between the primary and secondary loop. Federal University of Santa Catarina developed a combined system of SCO_2 Brayton cycle and independent heat storage [3], ensuring that the system's output aligns with the load demand.

The paper presents a new conceptual design of micro nuclear energy system, which is based on a heat pipe cooled reactor and an integrated heat storage system. The proposed system was designed to operate at full power of 3.5MW(th) and achieve 34.4% energy conversion efficiency. A heat storage system is embedded between the reactor and the secondary loop to enhance the thermal inertia of the overall energy system, enabling it to withstand thermal transients and mitigate thermal shock effects.

2. OVERALL SYSTEM DESIGN

The micro nuclear energy system proposed in the paper is illustrated in FIG. 1. The system comprises three primary subsystems: the nuclear reactor system, the heat storage system, and the energy conversion system. The reactor uses sodium heat pipe heat transfer to improve the reliability of core cooling. The heat storage system adopts Phase Change Material (PCM) for their large latent heat of phase change. The PCM in the system is composed of 78.7LiOH-21.3LiF with 700 K melting temperature. It is integrated into the heat exchanger. Heat from the heat pipe's condenser section is transferred to the PCM, then to the secondary circuit's working fluid through the PCM-mediated. The energy conversion system employs the SCO_2 Brayton cycle. Such system presents distinct advantages due to its compact configuration, reduced equipment dimensions, and high cycle efficiency. The system adopts the atmosphere as the ultimate heat sink.

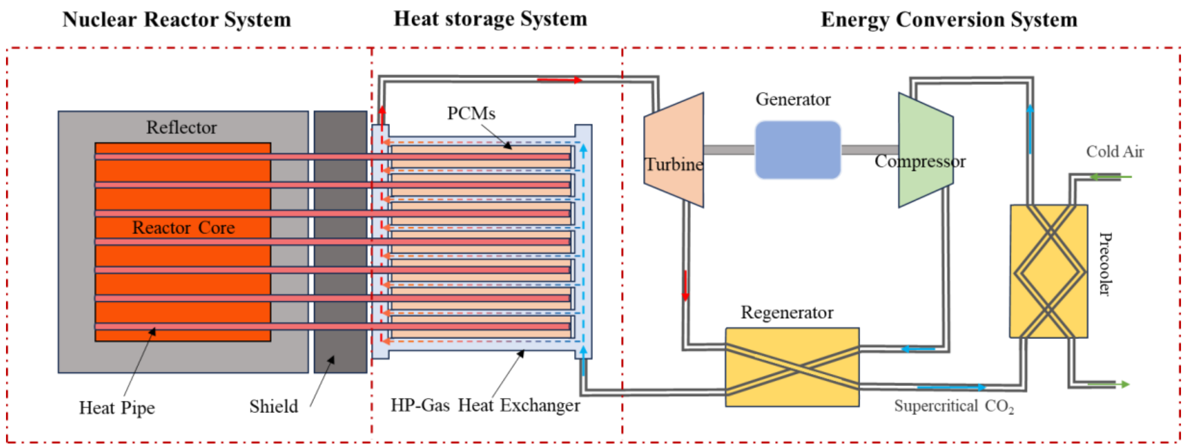

FIG. 1. Schematic diagram of the micro nuclear energy system.

3. EVALUATION OF THE SYSTEM PERFORMANCE

To model and simulate the system performance, a new simulation platform named DAISYSYS was developed. It integrates the point kinetics model [4] and a series of lumped parameter methods to simulate the transient behavior of the entire system. The dynamic parameters and feedback coefficients of the reactor, obtained by using the SARAX code system [5]. Besides the proposed system, a contradistinction system was established with an only difference of removing the heat storage materials. This approach allows for a comparative analysis of the system performances with and without heat storage. The three transient conditions of load reduction, reactivity insertion and loss of heat sink are calculated, and the changes of the core are mainly concerned.

3.1. Load reduction

This case simulated the system behavior under a load reduction condition. This condition considered a 10% step decrease in load at 1000 seconds during the 100% full power operation. The responses of key parameters of the system were analysed during 8,000 seconds, with the results presented in FIG. 2 and FIG. 3.

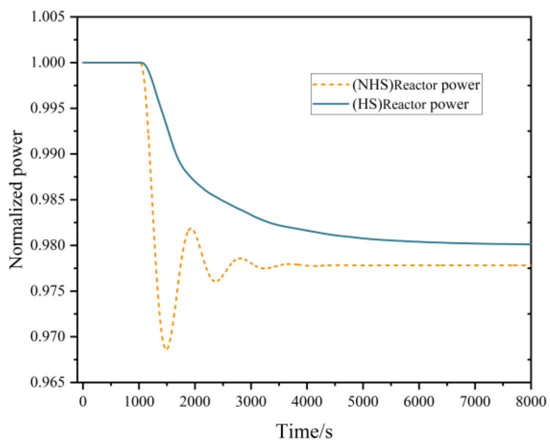

FIG. 2. Reactor power (load reduction).

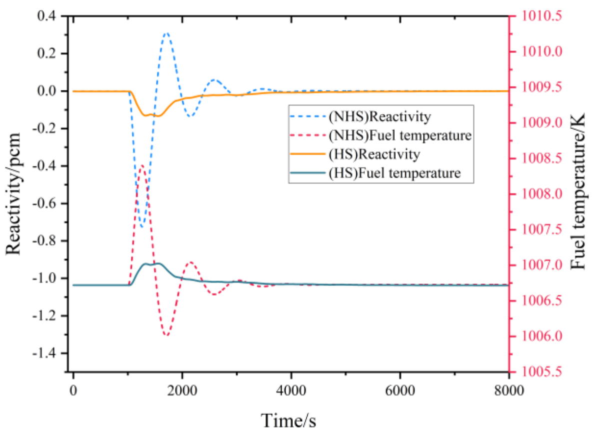

FIG. 3. Reactivity and fuel temperature (load reduction).

For simplification, the term "HS" in the figure denotes heat storage, whereas "NHS" means the absence of heat storage. As shown in FIG. 2 and 3, load reduction triggers temperature and power variations in the core. Without heat storage, load reduction causes core heat accumulation, elevating fuel temperature. It triggers negative reactivity, reducing the power until a new equilibrium is reached at 97.7% of the initial power, with 2.5 K maximum temperature fluctuations. With heat storage, the influence of the secondary loop is alleviated, the power is gradually reduced to 98 % of the initial power, and the core temperature change is suppressed within 0.3 K.

3.2. Reactivity insertion

This case simulated the transient with 50 pcm positive reactivity insertion at 1000 seconds during the 100% full power operation. The simulated results of the system during 4500 seconds are presented in FIG. 4 and 5, illustrating core power, reactivity feedback, and fuel temperature variations. Without heat storage, positive reactivity insertion triggers rapid core power escalation (peaking at 210% full power), elevating fuel temperature from 1006 K to 1179 K. Rising temperature induces negative feedback, which overcomes the initial reactivity insertion, causing power decline. The system stabilizes at 110% full power after 3500 s. When heat storage is integrated, core power initially rises before gradually decreasing, peaking at 221% of rated power. The temperature reaches a peak of 1138 K, with a restrained final temperature rise of 132 K. Power oscillations are significantly damped. This phenomenon can be attributed to the substantial heat capacity of the heat storage system, which effectively absorbs the thermal shocks from the core.

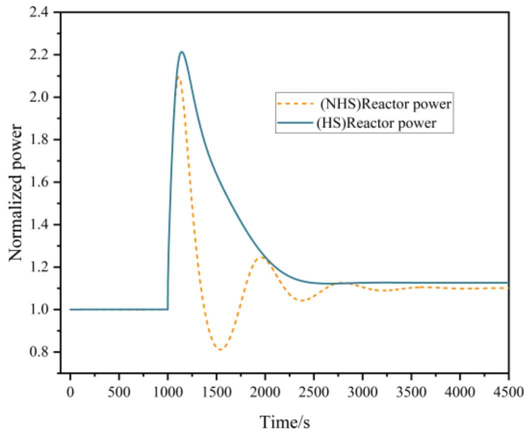

FIG. 4. Reactor power (reactivity insertion).

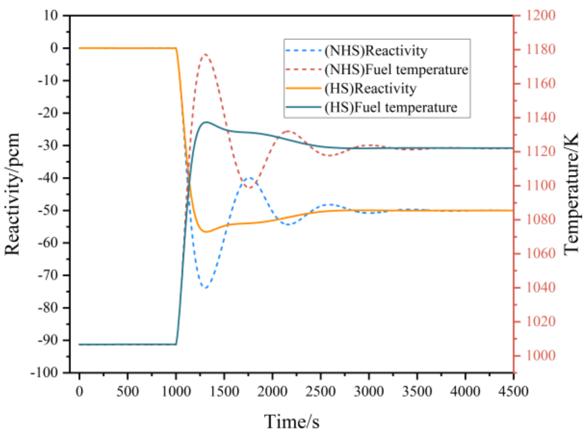

FIG. 5. Reactivity and fuel temperature (reactivity insertion).

3.3. Loss of heat sink

This case simulated a scenario in which a fault in the energy conversion system happened. The surface of heat exchanger suddenly changes to an adiabatic boundary at 1000 seconds during the 100% full power operation. Then, the energy conversion system stopped working. The process was simulated during 5000 seconds, with the results presented in FIG. 6 and 7.

In the absence of heat storage, the temperature increases rapidly due to the loss of heat sink. However, the temperature increase introduces negative reactivity into the core and results in the gradual decrease of core power. Without the heat storage, the temperature rises from 1006 K to 1150 K during 500 seconds. Conversely, when the heat storage works, the PCMs in the heat exchange units serves as a temporary heat sink, enabling it to absorb a portion of heat released from the core. This mechanism significantly delays the rise of temperature. The temperature rises from 1006 K to 1078 K during over 1500 seconds.

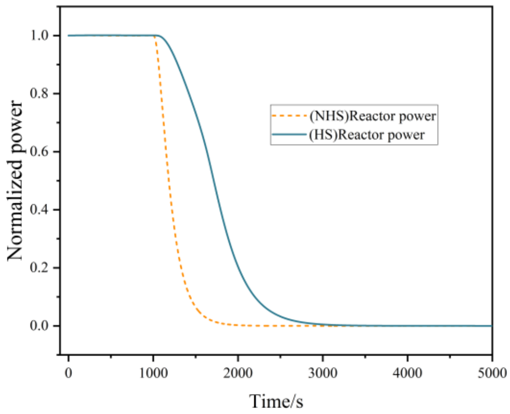

FIG. 6. Reactor power (loss of heat sink).

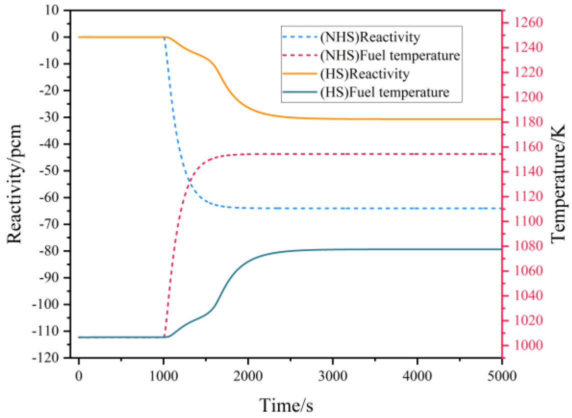

FIG. 7. Reactivity and fuel temperature (loss of heat sink).

4. CONCLUSION

The paper proposes a new conceptual design for a micro nuclear energy system, which consists of a heat pipe cooled reactor, a combined heat storage system and a SCO_2 Brayton cycle system. The PCMs in the heat storage system significantly enhances the thermal inertia of the whole system, thereby improving its capacity to respond to the temperature shocks and providing an additional safety margin of the nuclear energy system. Benefiting from the presence of heat storage, the new system has better safety performance in the predictable transients of reactor with thermal shock.

ACKNOWLEDGEMENTS

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