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Impact of the KRUSTY Reactor Core Insulation Layer on Power

Authors: Zhang Jie, Liu Fudong, Wang Kunpeng

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Abstract

Small modular reactors feature simple structures, convenient construction, and easy deployment. Heat pipe reactors belong to the category of small modular reactors and operate in load-following mode. KRUSTY (Kilowatt Reactor Using Stirling TechnologY), as the prototype of the Kilopower heat pipe reactor, has undergone relevant testing and achieved satisfactory results. To further optimize the structure of KRUSTY, deepen the understanding of insulation layer effects on the reactor, and enhance the efficiency of reactor energy output, this study was conducted. Using multiphysics software Simscape, KRUSTY was modeled and subjected to varying degrees of modification (Schemes 1~6), with the reactor behavior of each scheme calculated under conditions of 0.6 $ reactivity startup, ±40 pcm reactivity insertion, and ±50% load change. Among these, Scheme 6 achieved the highest energy output efficiency, reaching 79.71%. The results demonstrate that increasing the number of gaps between structures such as the core, vacuum vessel, and reflector, while incorporating a thicker insulation layer inside the vacuum vessel, yields higher efficiency in reactor energy extraction.

Full Text

Preamble

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Impact of KRUSTY Reactor Core Insulation Layer on Power Output

ZHANG Jie[1,2,3], LIU Fudong[1,2], WANG Kunpeng[1,2]

[1](Nuclear and Radiation Safety Center, Ministry of Ecology and Environment, Beijing 102401, China)

[2](State Environmental Protection Key Laboratory of Nuclear and Radiation Safety Review Simulation Analysis and Verification, Beijing 102401, China)

[3](School of Mechanical Engineering, Shanghai Jiao Tong University, Shanghai 200240, China)

Abstract

[Background]: Small modular reactors (SMRs) feature simple structures, convenient construction, and easy deployment. Heat pipe reactors, which operate in load-following mode, represent a class of SMRs. KRUSTY (Kilowatt Reactor Using Stirling TechnologY), the prototype for the Kilopower heat pipe reactor, has undergone successful testing with satisfactory results. [Purpose]: This study aims to optimize the KRUSTY design, understand how insulation layers affect reactor performance, and improve energy extraction efficiency. [Methods]: Using the multi-physics software Simscape as the system analysis tool, reactor power calculation modules, heat pipe modules, and other components were added to simulate the heat pipe reactor. Taking KRUSTY as the research object, system models for different insulation thickness schemes (Case 1–Case 6) were built. Reactor behavior was calculated under conditions of 0.6 $ reactivity startup, ±40 pcm reactivity insertion, and ±50% load change. [Results]: Case 6 achieved the highest energy output efficiency, reaching 79.71%. Moreover, each working condition had minimal influence on the energy output efficiency of Case 6. [Conclusions]: The results show that reactor energy extraction efficiency is higher when the number of gaps is increased between structures such as the core, vacuum vessel, and reflector, and when the vacuum vessel contains a thick insulation layer.

Keywords: Simscape, KRUSTY, insulation layer, heat pipe cooled reactor, transient analysis

Introduction

As reactors develop toward miniaturization, the research and development of small modular reactors (SMRs) has significantly expanded. For scenarios with low power demands, SMRs can not only provide energy but also offer greater economy, safety, and ease of construction compared to full-scale light water reactors. Microreactors, being even smaller, can be built in factory environments, facilitating deployment and transportation, and have diverse application scenarios—for example, powering remote areas, islands, and planetary surface bases.

A typical example of a microreactor is the Kilopower proposed by the National Aeronautics and Space Administration (NASA)[1-2]. This reactor aims to provide 1 to 10 kilowatts of electrical power for spacecraft or landers. Its prototype is named KRUSTY. KRUSTY, representing the 5 kW thermal Kilopower space reactor, had a design, development, manufacturing, and testing cost of less than $20 million, with final testing completed in March 2018[3].

The heat pipe reactor type adopted by KRUSTY features many designs distinct from traditional reactors[4-6]. This paper takes KRUSTY as the research object to investigate the significance of the core insulation layer and its impact on reactor power[7].

1 Significance of the Insulation Layer

In traditional reactors, multiple heat removal systems are often required to reduce core temperature after shutdown and avoid the impact of decay heat on reactor safety. However, in KRUSTY or any low-power high-temperature reactor, this heat dissipation phenomenon should be minimized. The reasons are: the heat transfer process from the reactor to the external environment at high temperatures wastes significant thermal energy, and the lost heat severely affects reactor thermal efficiency, thereby impacting overall reactor performance. Meanwhile, the lower power makes the impact of core decay heat very weak, and does not pose a serious threat to reactor safety[6,8].

To reduce heat loss, two aspects of work need to be combined. One is maintaining a vacuum environment around the core, thereby reducing the effects of heat conduction and convection. The other is using insulation materials to construct an outer insulation layer for the core, making it difficult for thermal energy acquired by structural materials like the core reflector to further diffuse into the external environment.

In space, the vacuum environment for space reactors is relatively easy to obtain. However, the requirements for insulation materials are extremely stringent. Traditional insulation materials are not only heavy, making them unsuitable for space reactors; more importantly, greater thickness also increases neutron absorption, thereby affecting core reactivity.

For this reason, the use of multilayer insulation (MLI) has become the preferred solution because it is compact and lightweight, and has multiple radiation gaps that can greatly reduce material thermal conductivity.

In KRUSTY, MLI consists of molybdenum foils separated by fused quartz braided wires. Molybdenum has characteristics such as low emissivity, high temperature resistance, and acceptable neutron absorption. Fused quartz braided wires have characteristics such as high temperature resistance and low thermal conductivity. This composition scheme limits potential contact between molybdenum foils, thereby reducing thermal conductivity and making it an ideal choice for MLI.

2 Research Methods

By simulating reactor states under different core insulation layer configurations, this study obtains the significance of the insulation layer for KRUSTY and further optimization recommendations.

2.1 Simulation Tool

Simscape is a multi-domain physical system modeling and simulation tool. It runs in the Simulink environment, allowing convenient and rapid creation of physical system models. This paper adopts Simscape and uses MATLAB-based Simscape language to create custom component models such as point reactor and heat pipe.

Using Simscape, a physically-connected thermal-hydraulic component model of the heat pipe reactor is built, and system analysis is conducted.

2.2 Models

2.2.1 Neutron Physics Model The point reactor neutron kinetics equation with 6 groups of delayed neutrons is used to handle reactor power transient characteristics:

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

$$\frac{dC_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i C_i \quad (i = 1, 2, \dots, 6)$$

where $n(t)$ is neutron density (power level), m^{-3}; $\rho(t)$ is total reactivity; β_i is the fraction of delayed neutrons in group i; β is the total fraction of delayed neutrons; C_i is the concentration of delayed neutron precursors in group i, m^{-3}; λ_i is the decay constant of this group, s^{-1}; Λ is the neutron generation time, s.

The total reactivity is calculated as:

$$\rho(t) = \rho_{ext}(t) + \sum_{j} \rho_{j,e}(t)$$

where

$$\rho_{j,e}(t) = \alpha_{j,e}(T_j(t) - T_{j,0})$$

where $\rho_{ext}(t)$ is externally introduced reactivity; $\rho_{j,e}(t)$ is reactivity introduced by temperature changes in region j; $\alpha_{j,e}$ is the temperature reactivity feedback coefficient for region j, K^{-1}; $T_j(t)$ is the average temperature of region j, K; $T_{j,0}$ is the initial temperature of region j, K.

2.2.2 Heat Pipe Model An improved thermal resistance network method is used to simulate heat pipes (as shown in Figure 1 [Figure 1: see original paper]). Based on the traditional thermal resistance network method[9-11], it divides more nodes[12-13] and considers vapor thermal resistance.

Figure 1 Heat pipe nodalization method

The radial heat transfer resistance of the pipe wall and wick ($K \cdot W^{-1}$) is:

$$R_{radial} = \frac{\ln(r_o/r_i)}{2\pi l \lambda}$$

The axial heat transfer resistance of the pipe wall and wick ($K \cdot W^{-1}$) is:

$$R_{axial} = \frac{l}{\pi(r_o^2 - r_i^2)\lambda}$$

where r_o and r_i are the outer and inner diameters of the heat pipe wall (or wick) corresponding to the divided node, m; l is the length of the heat pipe region corresponding to the divided node, m; λ is the thermal conductivity of the node, $W \cdot (m \cdot K)^{-1}$.

The liquid-vapor interface resistance ($K \cdot W^{-1}$) is:

$$R_{lv} = \frac{R_0 T_v^2}{h_{fg}^2 P_v} \sqrt{\frac{2\pi R_0 T_v}{\mu_v}}$$

The vapor heat transfer resistance ($K \cdot W^{-1}$) is:

$$R_v = \frac{8\mu_v l}{\pi r_v^4 \rho_v h_{fg}}$$

where R_{lv} is the liquid-vapor interface resistance, $K \cdot W^{-1}$; R_v is the vapor heat transfer resistance, $K \cdot W^{-1}$; R_0 is the gas constant of the working fluid, $J \cdot (kg \cdot K)^{-1}$; T_v is the vapor temperature, K; P_v is the (saturated) vapor pressure, Pa; h_{fg} is the latent heat of vaporization of the working fluid, $J \cdot kg^{-1}$; r_v is the vapor cavity radius, m; l is the axial length of the vapor cavity in the calculation region, m; μ_v is the dynamic viscosity, $Pa \cdot s$; ρ_v is the (saturated) vapor density, $kg \cdot m^{-3}$.

Additionally, the vapor heat transfer portion must consider the effect of heat transfer limits. When the heat transfer exceeds the maximum heat transfer at that temperature, the vapor heat transfer resistance changes accordingly, making the heat transfer equal to the maximum heat transfer at that temperature.

2.3 System Model

The KRUSTY model[14] is established, with its nodalization method shown in Figure 2 [Figure 2: see original paper], where the outermost layers of the reflector or shield exchange heat with the external environment through thermal radiation. The core cross-section schematic is shown in Figure 3 [Figure 3: see original paper].

Figure 2 KRUSTY nodal diagram

Figure 3 Core schematic

For research convenience, the condenser sections of all heat pipes use nitrogen cooling—i.e., the simulator cooling scheme adopted in the KRUSTY experiment, rather than the Stirling engine scheme.

To investigate the impact of MLI insulation and vacuum isolation between components on core power, the following cases are simulated and calculation results compared[15-17]:

1. No MLI insulation, core, vacuum vessel, and reflector in direct contact
2. No MLI insulation, core, vacuum vessel, and reflector not in direct contact
3. With MLI insulation, core, vacuum vessel, and reflector in direct contact
4. With MLI insulation, core, vacuum vessel, and reflector not in direct contact
5. Same as 4, MLI thickness is 0.5 times the original
6. Same as 4, MLI thickness is 2 times the original

Among them, Case 4 is the scheme adopted by KRUSTY. Its specific configuration is: 8 layers of MLI between the fuel/clamp and vacuum vessel, and 4 layers of MLI between the fuel and axial reflector.

3 Calculation Results

Using the reactivity insertion method of Case 4 as the standard, Cases 1, 2, and 3 were simulated with identical reactivity insertions at the same time, yielding the results shown in Figure 4 [Figure 4: see original paper]. As illustrated in Figure 4a, under the same reactivity insertion, Case 1 exhibits the largest power variation, eventually stabilizing near 16,700 W. Case 3 shows a moderate power increase, stabilizing around 2,150 W. Cases 2 and 4 demonstrate the smallest power fluctuations, oscillating near 500 W.

Examining the model structures reveals that Case 1 lacks sufficient thermal insulation, allowing core heat to readily diffuse into the reflector and raise its temperature. Since the reflector has a positive temperature reactivity coefficient, this temperature rise further drives up core power, ultimately maintaining the reactor at a significantly higher power level than other configurations. In Case 3, the presence of multilayer insulation (MLI) partially impedes heat transfer from the core to the reflector, resulting in core power only slightly higher than Case 4 and far below Case 1. Case 2 shows minimal power difference from

Case 4, demonstrating that vacuum insulation is far more effective than MLI insulation. However, MLI is necessary to prevent component contact during accident conditions, which would otherwise produce Case 1 behavior. Moreover, insufficient vacuum quality would also lead to Case 1-like conditions.

Figure 4b shows that Cases 2 and 4 export the most energy through heat pipes, reaching a peak of approximately 730 W and stabilizing around 300 W. Case 3 exports about 130 W, while Case 1 exports nearly zero energy. These results underscore the significance of Case 4: it enables greater energy extraction at lower reactor power levels. Figures 4c and 4d indicate that core temperature differences among the cases are relatively small, except for Case 1, whose minimum core temperature is approximately 160°C lower than the others.

A comparative analysis of Cases 1–6 under 0.6 $ reactivity startup, ±40 pcm reactivity introduction, and ±50% load change conditions reveals that direct contact between components (core, vacuum vessel, reflector, etc.) has the greatest impact on total reactor power and energy exported through heat pipes. The presence and thickness of insulation layers within the vacuum vessel also affect these parameters. For instance, Case 6 achieves at least 1% efficiency improvement across all conditions compared to the original design (Case 4). Additionally, increasing system load to raise total reactor power can effectively improve energy extraction efficiency by approximately 4%. Therefore, at 3 kW steady-state power, appropriately increasing the number of gaps between the core and external components, thickening insulation layers, and elevating load levels—all while satisfying neutronic and structural mechanics requirements—positively impact reactor energy extraction efficiency.

[**Results**]: Among them, the energy output efficiency of Case 6 is the highest, reaching 79.71%. Moreover, the influence of each working condition on the energy output efficiency of Case 6 is also minimal.

[**Conclusions**]: The results show that the efficiency of the reactor's energy output is higher when the number of gaps is increased between the core, the vacuum tank, the neutron reflector and other structures, and the vacuum tank contains a thick insulation layer.

Author Contributions

ZHANG Jie was responsible for designing simulation schemes, performing calculations, organizing data, and drafting the manuscript. LIU Fudong provided technical guidance. WANG Kunpeng assisted in analyzing and interpreting the results.

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