

RMC/ANSYS Multi-physics Coupling solutions for Heat Pipe Cooled Reactors Analyses

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ABSTRACT

The heat pipe cooled reactor is a solid-state reactor using heat pipes to passively transfer heat generated from the reactor, which is a potential and near-term space nuclear power system. This paper introduces the coupling scheme between the continuous energy Reactor Monte Carlo (RMC) code and the finite element method commercial software ANSYS. Monte Carlo method has the advantages of flexible geometry modeling and continuous-energy nuclear cross sections. ANSYS Parametric Design Language (APDL) is used to determine the detailed temperature distributions and geometric deformation. The on-the-fly temperature treatment of cross sections was adopted in RMC code to solve the memory problems and to speed up simulations. This paper proposed a geometric updating strategy and reactivity feedback methods for the geometric deformation of the solid-state core. The neutronic and thermal-mechanical coupling platform is developed to analyze and further to optimize the heat pipe cooled reactor design. The present coupling codes analyze a 2D central cross-section model for MEGAPOWERS heat pipe cooled reactor. The thermal-mechanical feedback reveals that the solid-state reactor has a negative reactivity feedback (~ 1.5 pcm/K) while it has a deterioration in heat transfer due to the expansion.

KEYWORDS: Monte Carlo methods; Finite element method; Neutronic and thermomechanical (N-T/M) coupling; Heat pipe reactor

1. INTRODUCTION

A heat pipe cooled reactor refers to a solid-state reactor that uses heat pipes to conduct heat generated from the reactor core to the secondary circuit system or thermoelectric conversion device instead of a pump-driven primary circuit system. In the 1960s, the USA and the Soviet union successively launched space nuclear power reactors suitable for the space power supply. Early space nuclear reactor power systems usually used liquid metal cooled reactor design with thermionic conversion devices. Subsequently, in order to simplify reactor design and to improve the inherent safety characteristics of space nuclear reactors, Los Alamos National Laboratory (LANL) proposed a new space nuclear reactor conceptual design with efficient heat pipe thermal conductivity elements, i.e., the heat pipe cooled reactor [1]. This modular design concept of the solid-state reactor with heat pipes, which transfers the heat effectively and passively, significantly simplifies the system and designs a much more

compact reactor. Afterward, numerous space reactor design schemes using a heat pipe reactor began to emerge at the beginning of the 21st century [2-5]. **Figure 1** shows the schematic of a typical heat pipe cooled reactor system structure, including a compact hexagonal arrangement of fuel pins and heat pipes, reactivity control drums, and outer reflecting and shielding layers. The reflector is arranged on the outer surfaces of the reactor core for better use of neutrons. The control drums are generally adopted to regulate the reactivity. **Figure 1(b)** shows the structure of the single module in a heat pipe cooled reactor, which consists the base, fuel pins, and a heat pipe.

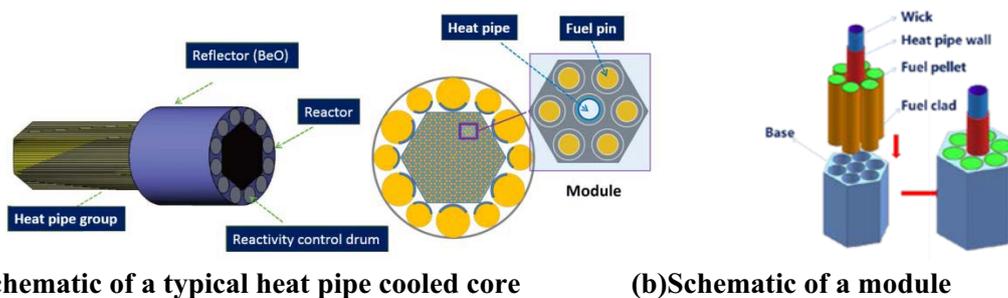


Fig. 1 Schematic of a typical heat pipe reactor system [6]

For traditional light water reactors, three kinds of reactivity feedbacks are mainly considered, including temperature, coolant density, and soluble boron density. By contrast, the reactivity feedbacks in heat pipe cooled reactors mainly consists of the micro section change caused by temperature, the density change of the fuel, monolith, and reflector, and the core size change caused by thermal expansion. Due to the considerable difference between heat pipe cooled reactor and light water reactor in the structure and design concept, the coupling solutions for light water reactor cannot be directly applied to heat pipe cooled reactor analyses.

To satisfy the urgent need for heat pipe cooled reactor engineering design for an advanced, reliable coupling program with good reusability, this paper conducted the research of neutronic/thermomechanical coupling method for heat pipe cooling reactor core's steady-state analyses. The key is to consider the neutronic and thermomechanical coupling effect caused by the solid core with high temperatures. the semi-analytical calculation is conducted with a typical MegaWatt reactor, MEGAPOWER. The Doppler effects, radial expansion, and axial expansion of fuel pellets, base and reflector are compared to demonstrate the reactivity feedback. Furthermore, based on the Monte Carlo program RMC and the finite element program ANSYS, a neutronic(N) and thermomechanical(T-M) coupling program is developed. The previous coupling program mainly adopts static geometry for multi-physics simulation. By contrast, in this paper, a method of dynamic geometry of multiple physical fields is proposed to update the model structure. MEGAPOWER heat pipe cooled reactor is analyzed by the N/T-M coupling program from three dimensions of neutron physics, thermal safety, and mechanics.

2. Coupling scheme and methods

2.1. Monte Carlo code RMC and Finite element software ANSYS

RMC (Reactor Monte Carlo code) is a new Monte Carlo neutron and photon transport code developed by the Department of Engineering Physics at Tsinghua University[7], which has been validated for criticality calculation, burn-up calculation, neutron and photon coupled transport calculation, full-core refueling simulation under multiple parallel modes [8-9].

ANSYS APDL is a general finite element analysis (FEA) software developed by ANSYS company, which is widely used in the nuclear industry for its great abilities in structure field analysis. In this paper,

ANSYS APDL 16.0 is used as the tool of FEA to accomplish parametric modeling, coupling process control, data interactions between RMC and ANSYS.

2.2 Coupling mode and mesh mapping

For the coupling code using RMC and ANSYS, the hybrid coupling model [9,10] is adopted in this paper, and RMC performs as the main program. Picard iterative method is adopted to construct the neutronic and thermal-mechanical coupling method according to the coupling framework, which is as shown in Fig.2. The RMC/ANSYS coupling program accomplishes the neutron transportation calculation. The power distribution is obtained based on the known total power and the calculated neutron flux distribution, and generates the data file. The coupling program calls ANSYS to execute the instructions compiled by APDL. After reading the power distribution, the thermal-mechanical calculation is conducted to get the core temperature distribution and the stress-strain calculation results. ANSYS transfers the calculated temperature field, density field, and structural displacement to RMC to update geometries, materials' density, and cross-sections. Finally, Calculate iteratively to convergence.

In the Coupling, The finite element analysis uses the finite element mesh, while the geometric model of RMC is defined by CSG (Constructive Solid Geometry) method, where there is no grid in the model. To implement the data transfer between neutronics and thermal-mechanics, each fuel cell is treated as an independent grid, without considering the difference of heat generation rate within the fuel cell. The monolithic core structures and the reflector's feed-backs are considered simplistically as the differences in the position distribution of the same axial position are ignored. There are two reasons for adopting this simplified method: Firstly, the uniformity of the distributions of temperature and density is good, and secondly, the thermal feedback influence is small. The feedback of deformation in the neutronic and thermomechanical coupling method is implemented by modifying the geometric boundary of cells in RMC.

For the thermal feedbacks in Monte Carlo code, whose basis is obtaining the cross-sections at different temperatures. In this paper, Target Motion Sampling (TMS) method [11] is used for the on-the-fly calculations of cross-sections. The cross-section data at any temperature are transformed from the cross-section at 0 K by the TMS method [11].

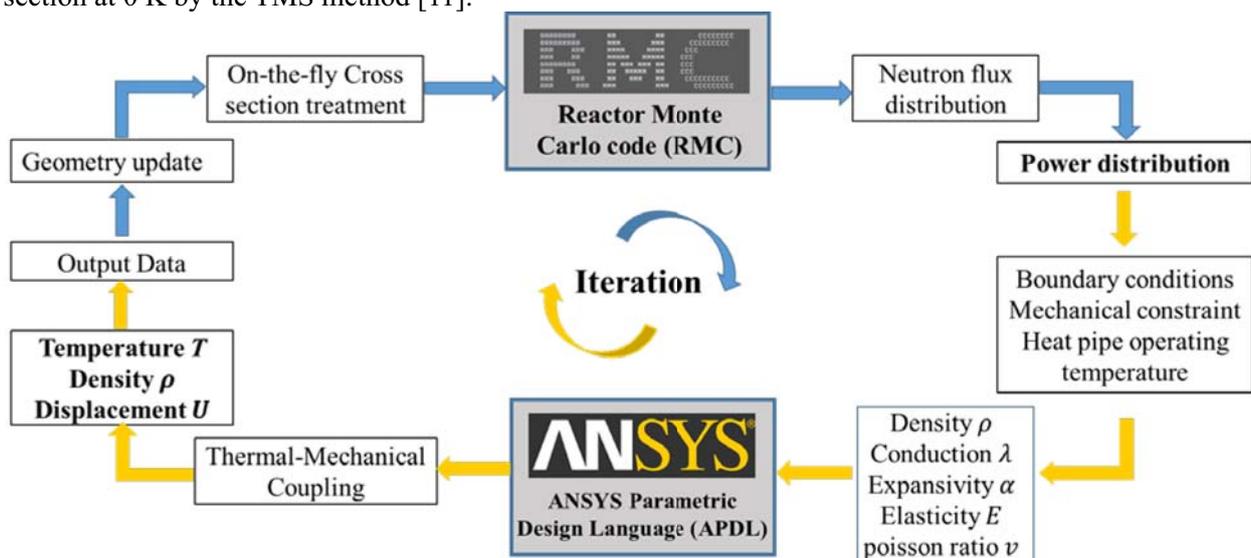


Figure 2. Coupling framework of RMC/ANSYS

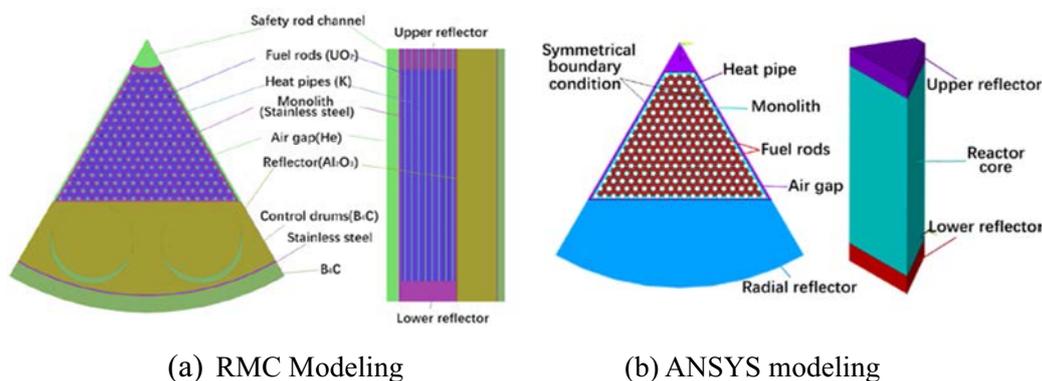
3. Modeling and verification

3.1. Modeling

The development of megawatt-power heat pipe reactors began to be the goal of the U.S. Army's nuclear energy projects in the 1950s and 1970s, to support the U.S. Army to successfully carry out military tasks in remote strategic defense sites or some mountainous areas requiring emergency rescue. In this regard, while researching space nuclear power, the Alamos National Laboratory of the United States has also proposed the design of a heat pipe reactor that can output 2WM and 5WM electric power, i.e. MEGAPOWER.

In this paper, the MEGAPOWER [5], proposed by the Alamos National Laboratory of the United States, with 5WM thermal power is selected as the research object, and its structure is shown in Fig. 3. The reactor is made up of six symmetrical 60° sectors. Each repetitive unit contains 352 fuel rods and 204 heat pipes, and six fuel rods are arranged at equal intervals around each heat pipe. There is a safety rod channel at the center of the heat pipe reactor. The outer layer is a cylindrical reflector composed of Al_2O_3 with 12 control drums in it. The working fluid in the heat pipe is metal potassium.

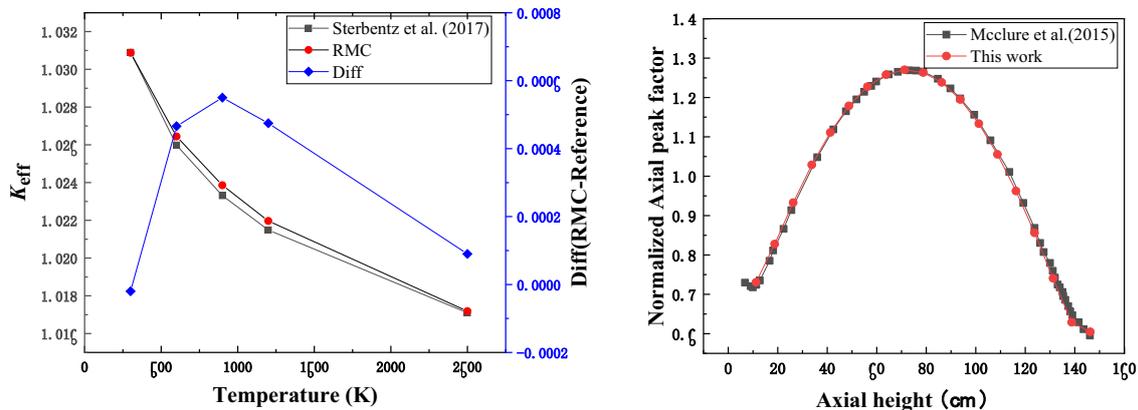
The heat pipe cooled reactor model is built by RMC and ANSYS, as shown in Fig. 3, referring to the parameters of the heat pipe reactor published by LANL [5] and INL (Idaho National Laboratory) [12].



(a) RMC Modeling (b) ANSYS modeling
Figure 3. MEGAPOWER 1/6 Symmetrical core

3.2. Model validation for Neutron Transport Calculation

The effective multiplication factor of the heat pipe reactor at different temperatures is calculated to compare with results by that of INL, as shown in Fig. 4(a). Each calculation has 500,000 particles per cycle, with 50 inactive cycles and 200 active cycles. The statistical error of the K_{eff} is less than 0.0007. The difference ranges from -0.0002 to 0.0006, which may result from the material composition differences. The axial relative power distribution is also compared, as shown in Fig. 4(b). The maximum normalized axial peak factor is 1.270 in this work, while the reference is 1.269. These results validate the neutron transport calculation in this work, which provided a solid starting point for all subsequent analyses.



(a) k_{eff} at different temperature (b) Axial relative power distribution
 Figure 4. Neutron Transport comparison and validation

3.2. Semi-quantity analysis of thermal expansion and reactivity feedback

As a solid-state reactor, the primary reactivity feedback mechanisms result from the Doppler broadening of the fuel, the thermal expansion of the fuel, the stainless steel (SS) monolith, and the reflector. For the Doppler broadening effect, as the fuel temperature increases, the neutron resonances will broaden, increasing the effective neutron absorption in the core. For the thermal expansion, the respective volumes were increased accordingly, which then resulted in a decrease in the material number density due to the mass conservation. As the fuel lengthens, the volume increases which ultimately reduces the UO₂ number density. A reduction in material density is also seen in the alumina reflector and SS cladding due to thermal expansion, which results in an increase in the leakage and parasitic absorption, respectively [13].

Table 1 lists the reactivity coefficients of various feedback effects, each of which was calculated independently from the cold state (300K) to the hot state (1200 K for fuel and 1000 K for the others). The negative feedback of UO₂ fuel doppler and UO₂ fuel axial elongation in this work is close to the LANL reference results shown in **Table 1**. Also, the present work considers more effects. The relation between the temperature and the thermal expansion is assumed to be the linear expansion. The results show that the main reactivity feedback in MEGAPOWERS are UO₂ fuel doppler (-0.95 pcm/K), fuel axial elongation (-0.33 pcm/K), SS-316 monolith radial thermal expansion (-0.33 pcm/K), and alumina reflector radial thermal expansion (-0.19 pcm/K). The thermal expansion feedback is almost equal to that of doppler effects. Therefore, thermal expansion cannot be omitted.

Table 1 Reactivity coefficients of various feedback effects

Feedback effect (cents/°C)	This work	Reference [12]
UO ₂ Fuel Doppler*	-0.95 pcm/K	-0.99 pcm/K
SS-316 Monolith Doppler*	-0.14 pcm/K	—
Alumina Reflector Doppler*	-0.02 pcm/K	—
UO ₂ Fuel Axial Elongation	-230 pcm/1%ΔH (-0.33 pcm/K, 1%ΔH~ΔT=700K)	-258 pcm/1%ΔH
Alumina Reflector Axial Thermal Expansion	-56 pcm/1%ΔH (-0.08 pcm/K, 1%ΔH~ΔT=700K)	—

SS-316 Monolith Axial Thermal Expansion	+24 pcm/1% Δ H (+0.07 pcm/K, 1% Δ H \sim Δ T=350K)	—
UO ₂ Fuel Radial Elongation	-10 pcm/1% Δ D (-0.008 pcm/k, 1% Δ D \sim Δ T=1400K)	—
Alumina Reflector Radial Thermal Expansion	-269 pcm/1% Δ D (-0.19 pcm/K, 1% Δ D \sim Δ T=1400K)	—
SS-316 Monolith Radial Thermal Expansion	-233 pcm/1% Δ D (-0.33 pcm/K, 1% Δ D \sim Δ T=700K)	—

4. Coupling results

In this section, a 2D central cross-section model for MEGAPOWER is analyzed by the neutronic and thermomechanical coupling. The modeling is the central cross section of three-dimension modeling described in Section 3.1. The average volume release rate is $1.008e7$ W/m³. Each iteration has 500,000 particles per cycle with 50 inactive cycles and 100 active cycles. Fig. 5 shows the K_{eff} variation with the iterations. The thermal-mechanical feedback leads to a change of 0.0125 in K_{eff} , i.e., 1029 pcm in reactivity. In this work, the Prediction-Correction method was used for power updates. The relaxation factor is set to be 0.5, which can effectively suppress the oscillation. Meanwhile, the N-T/M coupling tends to converge in one step in reactivity.

For the thermal/mechanical calculation, the temperature distribution is shown in Fig. 6(a). The peak temperature difference is 10K for the non-coupling and coupling cases. With the N-T/M coupling considered, the peak temperature in the MeagPower reactor is even higher than that of the non-coupling case, which is quite different from that of the typical pressurized water reactor (PWR). In PWR, the thermal/ hydraulic feedback normally leads to a flatter power distribution and thus to a decrease in the peak fuel temperature. However, in a solid-state reactor, the temperature distribution is not only affected by the power distribution change, but also the gas gap change. A small change in the gas gap may lead to a significant variation in the heat transfer. In this work, the geometry change is considered in the coupling calculations. When the reactor changes from the cold state to the hot state, the cold state static geometry expands and thus leading to an expanding trend in the gas gap. Therefore, the peak fuel temperature increases. The thermal/mechanical feedback reveals that the solid-state reactor has negative reactivity feedback while has a deterioration in heat transfer due to the expansion without constraint.

In addition, as listed in Table 2, the difference between non-coupling and coupling cases in maximum fuel temperature is -10 K while -2K for that of the monolith. The maximum monolith stress difference is -3 MPa. The coupling has a much weaker effect in thermal/mechanical performance than that of reactivity. This is mainly caused by the reactor design. In MEGAPOWER reactor, the heat pipe is designed to operate in 950K. The fuel maximum temperature is 1033K. The temperature difference between heat sink (heat pipe) and the heat source (fuel) is 83 K. Therefore, 10K is relatively significant. Meanwhile, the MEGAPOWER reactor is designed to have a steel monolith core requires drilled channels to hold UO₂ fuel pellets and to act as the in-core evaporating section of the heat pipes, where the gas gap only exit in the fuel and the monolith. The heat pipes and clads contact the monolith and upper reflector without gaps. Therefore, the geometry change in gas gaps has a much smaller affection.

The coupling calculation shows that, from a cold state to hot state, and the change of radial displacement, i.e the length of fuel pitch, is about 1.2%, as shown in Fig. 6(b). The monolith temperature over the reactor ranges from 950K to 970 K. The stress distribution shows a great symmetry, and the point with the maximum stress intensity is located at the gap between fuel and heat pipe, which is about 40MPa as shown in Fig. 6(c). The maximum monolith stress have already exceed the maximum 31 MPa ASME pressure vessel code allowable limits at 970K [13].

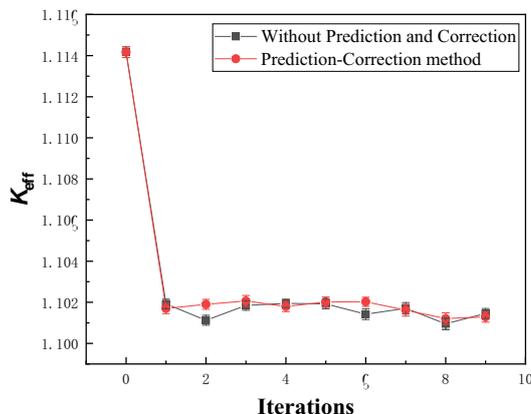


Fig. 5 K_{eff} variation with the neutronic and thermal/mechanical coupling iteration

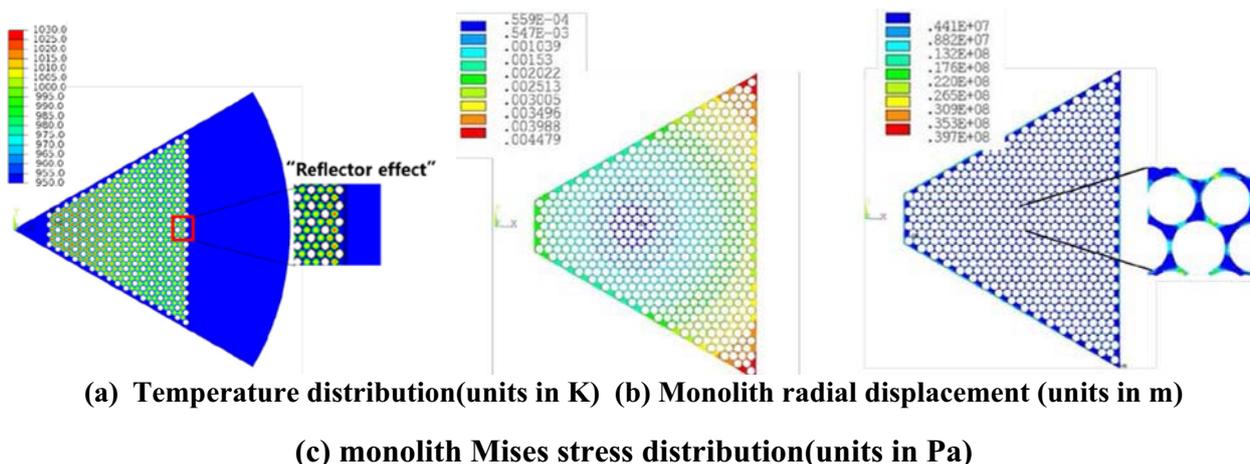


Fig. 6 MEGAPOWER temperature distribution and mechanical results after neutronic and thermal-mechanical coupling

Table 2 Temperature and stress difference between coupling and non-coupling cases

	Without N-T/M coupling	N-T/M coupling	Difference
Maxium Fuel Temperature	1023 K	1033 K	-10 K
Maximum Monolith Temperature	969 K	971 K	-2 K
Maxium Monolith Stress	37MPa	40 MPa	-3 MPa

5. CONCLUSIONS

For MEGAPOWER heat pipe cooled reactor, thermal expansion and reactivity feedback semi-analytical analysis show that the main reactivity feedbacks in MEGAPOWER are UO_2 fuel doppler (-0.95 pcm/K), fuel axial elongation (-0.33 pcm/K), SS-316 monolith radial thermal expansion (-0.33 pcm/K), and alumina reflector radial thermal expansion (-0.19 pcm/K). Therefore, the negative reactivity feedback of

thermal expansion effect is as important as the doppler effects for a solid-state reactor. Geometric deformation is the key to multi-physics coupling of heat pipe cooled reactor.

A solution for dynamic geometric feedback in multi-physics coupling was proposed, which achieves accurate feedback from mechanical effects (e.g. thermal expansion) and Doppler effect of temperature to physical calculation. The neutronic and thermomechanical coupling analyzes a 2D central cross-section model for MEGAPOWER. The thermal/mechanical feedback reveals that the solid-state reactor has negative reactivity feedback (-1029 pcm) while has a deterioration in heat transfer due to the expansion without constraint. The maximum fuel temperature increases by 10 K when thermal/mechanical feedback considered.

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