Nuclear Engineering and Design 338 (2018) 16–22

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Dynamic behavior in fast burst reactor with three-dimensional coupled multiphysics method

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ARTICLE INFO

Keywords:
Fast burst reactor
Prompt supercritical
Multiphysics models
Coupled calculation

ABSTRACT

In this paper, the neutronic and thermoelastic behaviors of prompt supercritical bursts in the fast burst reactor are numerically studied by developing a 3D coupled multiphysics FEM (finite element method) code FBR-MPC based on the neutron transport theory for neutronics, thermal conduction equation for temperature and thermoelastic equations for displacement/stress. Because the feedback effect of core expansion on the neutronics can be accurately modeled by reforming the discretized element and changing the material density, the developed code is expected to be applicable for simulating the dynamic behaviors of all the bursts under controlled condition. To validate the developed code and obtain precise pictures of the dynamic behaviors, the slow, medium and fast bursts in the Godiva I reactor are investigated. The results show that the developed code can provide accurate results for all the three selected bursts. For the medium and fast bursts where the inertia effect is generated, the fission rate oscillation caused by the core vibration, which cannot be reproduced with the simplified models in early works, is first observed by using the developed FBR-MPC code. Due to the small core expansion and short burst time, the point kinetic and adiabatic approximations are suitable for the neutronic and temperature calculations for all the three selected bursts. At the time of displacement wave crest, the stress concentration in the core central regions becomes more significant for faster bursts.

1. Introduction

The fast burst reactors (FBRs), a kind of nuclear assemblies mainly fabricated from Highly Enriched Uranium, are designed for studying the neutron behavior in the prompt supercritical state. The injection of a certain amount of reactivity in the core leads to the transition of FBR from the sub-delayed-critical to super-prompt-critical state. Once the burst is triggered, the intensive excursion of fission rate causes the fast temperature rise and hence the quick core expansion, the induced larger neutron leakage and smaller macro cross sections in turns results in the decrease of fission rate, i.e. the thermal expansion extinction effect (He and Deng, 2012). Following this short burst (the duration time is usually less than 100 microseconds), the fission rate drops to the low-amplitude plateau sustained by the delayed neutrons and the burst operation is finally terminated upon automatic scramming of the assembly (Wimett, 1956; Shabalin, 1979).

Although the dynamic behaviors of burst in FBR have been studied for decades since the first FBR Godiva I was built at Los Alamos National Laboratory (LANL) in 1953 (Wimett, 1956), the main efforts were devoted to the experimental researches on various assemblies such as Godiva I, Godiva IV and HPRR in America (Shabalin, 1979), CFBR-II in China (Yang et al., 1995), Caliban in France and BIGR in Russia (Khariton, 1994). In order to make better explanation of the experimental data or to get deeper understanding of the dynamic behavior, coupled theoretical models considering the temporal variations and spatial distributions of neutron flux (fission rate), temperature and displacement/stress should be calculated. Most of such works were made in early decades based on simplified models (Wimett, 1956; Shabalin, 1979), in which the point kinetic approximation was applied for neutronics and the adiabatic approximation for temperature, the displacement was obtained by calculating the elastic wave equation or just assumed as a linear function of fission yield. These three models were coupled together by introducing the reactivity feedback model (Chen et al., 2007; He and Deng, 2012).

In recent years, more accurate models have been adopted to study this dynamic behavior, because the preconditions of the simplified models used in early works cannot be well satisfied in many cases. For instance, the point kinetic approximation is unsuitable for FBRs

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https://doi.org/10.1016/j.nucengdes.2018.07.026
Received 28 April 2018; Received in revised form 18 July 2018; Accepted 23 July 2018
0029-5493/

surrounded by reflectors; the assumption of linear relation between displacement and fission yield is applicable only when the core expansion can accommodate the temperature rise, whereas in the large power excursion case, there is a lag between the core expansion and temperature rise, a portion of thermal energy is converted to the kinetic energy, producing vibrational displacements and potentially large dynamic stresses, i.e. the inertia effect (Canaan, 2000); the heat transfer effect should be considered when the time of heat balance is comparable with that of power excursion.

Grove et al. (2008) developed the enhanced MRKJ code to simulate the dynamic behavior in a 1D (one-dimensional) spherical FBR model with the coupled neutronic-thermoelastic method, in which the neutronic component was calculated with the neutral particle transport code PARTISN (Alcouffe et al., 2005), the thermoelastic displacement equation and a finite difference heat transfer technique were utilized to calculate the internal displacement and heat transfer between coarse regions. Kadioglu and Knoll (2009) coupled the calculations of neutron diffusion equation and elastic wave equation for 1D spherical case, with the adiabatic approximation for temperature calculation. Fiorina et al. (2014) developed an OpenFOAM-based discrete ordinates solver for neutron transport and then coupled it with other thermal-mechanics solver. Although these codes can be used to simulate the dynamic behavior, they were developed for the simplified 1D case or consisted of individual codes for different component and coupled them by exchanging the most relevant information through passage interfaces. It is clear that the 1D approximation is improper for FBRs with unsymmetrical geometry or inhomogeneous material distribution, and exchanging information among different codes may bring extra calculation error because the spatial and temporal discretization schemes used in each code may be different, the interpolation or fitting process should be performed to make the data generated in one code usable in the others.

To overcome these disadvantages, this paper developed a 3D FEM (finite element method) code FBR-MPC (Fast Burst Reactor-MultiPhysics Coupling) by coupling the neutron diffusion theory for neutronics, thermal conduction equation for temperature and thermoelastic equations consisted of the equilibrium equation, strain–displacement equation and constitutive equation for displacement/stress. To validate the FBR-MPC code and get deeper insight of the dynamic behavior, the slow, medium and fast bursts in the Godiva I reactor were simulated. The structure of this paper is as following. At the beginning, the Godiva I configuration was briefly introduced. Next, the theoretical models for neutronics, temperature and thermoelastics were established and all the governing equations were discretized with FEM for space-dependent terms and the implicit scheme for time-dependent terms. The discretized equations were then numerically calculated with the FBR-MPC code. Finally, the code validation was presented and the results were discussed in details.

2. FBR system description

In this work, the FBR Godiva I is selected partly because there are a plenty of experimental data which can be used as benchmark to validate the FBR-MPC code, and partly because China CFBR-II reactor has the similar structure as that of Godiva I, the results are thus expected to be useful for analyzing the dynamic behavior of CFBR-II.

The Godiva I reactor is built in 1953 at LANL and constituted by a sphere of Highly Enriched Uranium. It is fabricated in three sections that go to together to form a sphere, as shown in Fig. 1. The completed assembly has Uranium enriched to ~90 percent isotopic abundance in ^{235}U. Similar to previous works, a spherical model of Godiva I reactor is adopted in this paper and the detailed parameters are listed in Table 1 (Fiorina et al., 2014).

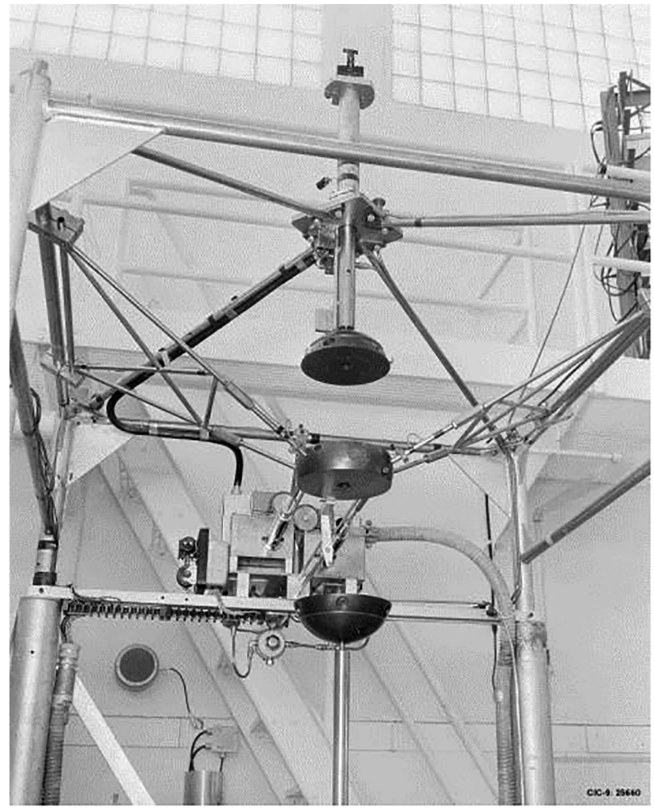

Fig. 1. Configuration of unassembled Godiva I experiment.

Table 1
Main parameters for Godiva reactor at room temperature.

Parameter [unit]	Value used
Radius [cm]	8.7407
Young's Modulus [GPa]	208
Poisson Ratio	0.23
Linear thermal expansion coefficient [1/K]	1.39E−5
Thermal conduction ratio [W/(cm K)]	0.275
Specific heat capacity [J/(g K)]	0.1177
Heat released per fission [J]	2.848E−11
Yield strength [MPa]	200

3. Theoretical models

3.1. Neutronics

Previous works on the neutron burst were mainly based on simplified methods such as the point kinetic approximation (Wimett, 1956; Shabalin, 1979) and the neutron diffusion theory (Kadioglu and Knoll, 2009). These simplified methods have high calculation efficiency and can provide basic understanding of the dynamic behavior, whereas the point kinetic approximation is improper for FBRs surrounded by reflectors; the neutron diffusion theory is inaccurate in the regions few neutron diffusion lengths near the boundary, this inaccuracy is expected to be more prominent for FBRs because the core size is usually in centimeters. Thus to obtain the accurate spatial distribution and temporal variation of neutron flux (fission rate) or to specify the applicability of simplified methods, the neutron transport theory should be adopted. The neutron transport equation and the balance equation for delayed neutron precursors read as (He and Deng, 2012):