Progress in Nuclear Energy 81 (2015) 60–66

Contents lists available at ScienceDirect

Progress in Nuclear Energy

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

Transient analyses on loss of heat sink and overpower transient of natural circulation LBE-cooled fast reactor

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ARTICLE INFO

Article history:
Received 27 August 2014
Received in revised form
5 December 2014
Accepted 5 January 2015
Available online

Keywords:
NTC-2D
Natural circulation
Loss of heat sink
Overpower transient
Safety analysis

ABSTRACT

Two transient analyses on a natural circulation LBE-cooled fast reactor were performed by using a Neutronics and Thermal-hydraulics Coupled Simulation Program NTC-2D. The two transients were unprotected loss of heat sink (ULOHS) and unprotected overpower transient (UTOP). For ULOHS, as the reactor is driven by natural circulation, the coolant mass flow rate decreased, but the simulation results showed that the reactor shutdown by itself and the peak temperatures of fuel and cladding were far smaller than the safety limits. For UTOP, the results showed that the coolant, cladding and fuel temperatures in the reactor increased and the more heat was taken away by the increase of the coolant mass flow rate. Finally, a new steady state was re-established by natural circulation.

1. Introduction

The lead- or LBE-cooled fast reactor has good thermal-hydraulics and neutronics characteristics. It plays an important role in the sustainable development of nuclear energy, reprocessing of spent nuclear fuel and nuclear safety (Liang and Tang, 2003; Wu, 2011).

The study on lead- or LBE-cooled fast reactor has been carried out in several countries. In Europe, a European Lead-cooled System (ELSY) project, which aimed at accomplishing a conceptual design of a 600 MWe industrial size plant, was initiated in 2006 (Cinotti et al., 2008, 2011). Based on the previous studies and experience, a new project, Lead-cooled European Advanced Demonstration Reactor (LEADER) project was started in European within the 7th Framework Programme. During this project, the developments of a European Lead-cooled fast reactor (ELFR) and an Advanced Lead-cooled Fast Reactor European Demonstrator were underway (Alemberti and Frogheri, 2013). A small-scale modular LBE-cooled fast reactor SVBR and a lead-cooled fast reactor BREST were developed by Russia (Zrodnikov et al., 2006, 2011). On account of the nice natural circulation performances of lead or LBE, some natural circulation lead- or LBE-cooled fast reactors have been researched and developed. In United States, several natural circulation lead-cooled fast reactors were developed in Argonne National Laboratory (ANL), such as SSTAR (Smith et al., 2008), SUPERSTAR (Bortot et al., 2011). In China, based on the past research and development work in advanced nuclear energy system (Wu et al., 1999, 2002, 2011; Wu and FDS Team, 2006, 2007, 2008, 2009; Qiu et al., 2000; Wu, 2007), FDS team developed a natural circulation LBE-cooled fast reactor.

In natural circulation fast reactor, on the one hand, it is designed to have a good inherent safety feature, such as the strong negative feedback. However, on the other hand, with no pumps in this type of reactor, the coolant mass flow rate is determined by the heat sink and the reactor power. Thus, the transient safety analyses for this kind of reactor are very significant and necessary.

To investigate the safety behaviors of the lead- or LBE-cooled fast reactor, several studies have been carried out (Wang et al., 2008; Tucek et al., 2006). In this paper, to investigate the transient characteristics of this 10 MW_{th} natural circulation LBE-cooled fast reactor, two transients which were unprotected loss of heat sink (ULOHS) and unprotected overpower transient (UTOP), were

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http://dx.doi.org/10.1016/j.pnucene.2015.01.010

simulated by a Neutronics and Thermal-hydraulics Coupled Simulation Program NTC-2D.

2. Computational code NTC-2D

2.1. Outline of NTC-2D

NTC-2D is a transient analysis code for the advanced reactor especially Liquid Metal cooled Fast Reactor (LMFR) developed by the FDS Team. NTC-2D is a two-dimensional thermal-hydraulics codes based on multi-phase, multi-component, multi-velocity model coupled with neutronics codes based on a two-dimensional time-, space- and energy-dependent neutron kinetic model. The verification and validation (V&V) work of NTC-2D is on process, which is carried out by the benchmark work and verification experiments for NTC-2D and the results are presented in the related literature (Wang et al., 2015).

2.2. Neutronics model in NTC-2D

NTC-2D employs a time-, space- and energy-dependent neutron transport model solved by an improved quasi-static method. For this method, the space and time dependent neutron transport equation is factorized into two equations, which are shape function equations as shown in Eqs. (1) and (2) and amplitude equations as shown in Eqs. (3) and (4). Here the delayed neutron effect is considered. NTC-2D contains two cross section data bases, which are infinite dilute microscopic cross section and self-shielding factor. The parameters used in the following four equations are given below.

$$\frac{1}{v}\frac{\partial\varphi(r,t)}{\partial t}+\frac{1}{vN}\frac{\mathrm{d}N}{\mathrm{d}t}\varphi(r,t)+M\varphi(r,t) = (1-\beta)\chi_p F\varphi(r,t)+\frac{1}{N}\chi_d\lambda C(r,t)+\frac{1}{N}S(r,t) \tag{1}$$

$$\frac{\partial C(r,t)}{\partial t}=N\beta F\varphi(r,t)-\lambda C(r,t) \tag{2}$$

$$\frac{\mathrm{d}N(t)}{\mathrm{d}t}=\left(\frac{\rho}{\Lambda}-\frac{\beta_{eff}}{\Lambda}\right)N(t)+\lambda C^*(t)+S^*(t) \tag{3}$$

$$\frac{\partial C^*(t)}{\partial t}=\frac{\beta_{eff}}{\Lambda}-\lambda C^*(t) \tag{4}$$

v velocity of neutron
φ shape function
N amplitude function
M mathematical operator for the disappearance terms of neutron
F mathematical operator for the generation terms of neutron
β delayed neutron fraction
β_{eff} effective delayed neutron fraction
χ_p fission spectrum of prompt neutron
χ_d fission spectrum of delayed neutron
λ decay constant of delayed neutron precursor
C concentration of delayed neutron precursor
S source term of neutron
ρ reactivity
Λ neutron generation time

2.3. Thermal-hydraulics model in NTC-2D

Mass, momentum and energy conservation equations constitute the governing equations for the thermal-hydraulics model. They are shown in equations (5)–(7) respectively. An EOS (Equations Of State) model has been developed to close the three equations. The parameters used in the following three equations are given below.

$$\frac{\partial\rho_i}{\partial t}+\nabla\cdot(\rho_i v_j)=S_{\rho i} \tag{5}$$

$$\frac{\partial(\rho_j v_j)}{\partial t}+\sum_{i\in j}\nabla\cdot(\rho_i v_j v_j)+\alpha_j\nabla p-\rho_j g+f_{jst}v_j+\sum_{j'}f_{jj'}(v_j-v_{j'})=S_{vj} \tag{6}$$

$$\frac{\partial(\rho e_k)}{\partial t}+\sum_{i\in k}\nabla\cdot(\rho_i e_k v_j)+p\left[\frac{\partial\alpha_k}{\partial t}+\nabla\cdot(\alpha_k v_j)\right] -\sum_{j'}f'_{j'j}(v_j-v_{j'})(v_j-v_{j'j})+f'_{jst}v_j(v_j-v_{jst})=S_{ek} \tag{7}$$

i mass component
j velocity field
k energy component
ρ macroscopic density
v velocity
S_ρ source term of mass
α volume fraction
p pressure
g acceleration of gravity
f_{jst} momentum exchange function between structure and fluid
$f_{jj'}$ momentum exchange function between fluids
S_v source term of momentum
e internal energy
S_e source term of internal energy

In the thermal-hydraulics calculation, the four governing equations are calculated by a four-step algorithm, in which the intra-cell transfers (mass, momentum and energy transfers) are calculated with ignoring the inter-cell convection terms. The first step solves Eqs. (5)–(7) for intra-cell transfers ignoring the inter-

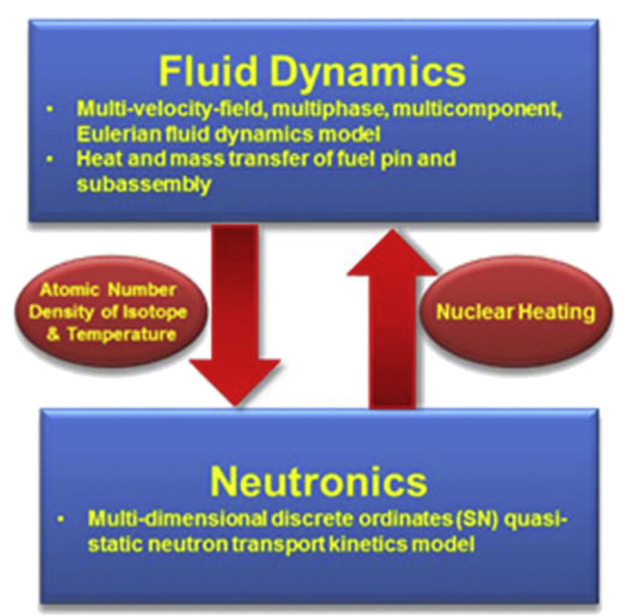

Fig. 1. Coupling process in NTC-2D.