Annals of Nuclear Energy 90 (2016) 26–31

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Fuel-steel mixing and radial mesh effects in power excursion simulations

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ARTICLE INFO

Article history:
Received 20 May 2015
Accepted 30 November 2015
Available online 18 December 2015

Keywords:
Sodium cooled fast reactor
SIMMER-III code
Power excursion simulation
Fuel-steel mixing effect
Mesh size effect

ABSTRACT

This paper deals with SIMMER-III once-through simulations of the earliest power excursion initiated by an unprotected loss of flow (ULOF) in the Working Horse design of the European Sodium Cooled Fast Reactor (ESFR). Since the sodium void effect is strictly positive in this core and dominant in the transient, a power excursion is initiated by sodium boiling in the ULOF case. Two major effects, namely (1) reactivity effects due to fuel-steel mixing after melting and (2) the radial mesh size, which were not considered originally in SIMMER simulations for ESFR, are studied. The first effect concerns the reactivity difference between the heterogeneous fuel/clad/wrapper configuration and the homogeneous mixture of steel and fuel. The full core homogenization (due to melting) effect is −2 $, though a smaller effect takes place in case of partial core melting. The second effect is due to the SIMMER sub-assembly (SA) coarse mesh treatment, where a simultaneous sodium boiling onset in all SAs belonging to one ring leads to an overestimated reactivity ramp. For investigating the influence of fuel/steel mixing effects, a lumped "homogenization" reactivity feedback has been introduced, being proportional to the molten steel mass. For improving the coarse mesh treatment, we employ finer radial meshes to take the subchannel effects into account, where the side and interior channels have different coolant velocities and temperatures. The simulation results show that these two effects have significant impacts on the earliest power excursion after the sodium boiling.

1. Introduction

In the 7th FP EURATOM CP-ESFR project KIT simulated an unprotected loss of flow (ULOF) in the Working Horse (WH) design of the European Sodium Cooled Fast Reactor (ESFR) with the SIMMER-III code (Maschek et al., 2012; Rineiski et al., 2011). For the major computation route, SIMMER was employed after pin-failure onset, while another code was used for the initial phase. In parallel, KIT performed core optimization studies for which SIMMER was employed starting from nominal conditions. Since the void worth in the active core is positive and quite large (about +4 $) and is therefore dominant in this transient, i.e. larger than other negative feedbacks, e.g. Doppler, fuel and steel thermal expansions, a power excursion is initiated by sodium boiling. A natural question is: are there any other significant reactivity effects to counteract the positive coolant void worth?

Two major reactivity effects were recognized by us, which are not taken into account originally in the usual SIMMER treatments: (1) reactivity effects due to fuel-steel mixing in computational cells after melting were assumed to be negligible and (2) a rather coarse radial mesh related to sub-assembly (SA) rings was assumed to be appropriate. Due to the first assumption, a negative reactivity insertion in the transition from heterogeneous to homogeneous fuel/clad arrangement (homogeneity effect) is neglected. According to our evaluations, the double heterogeneity effect in the fuel SA (Maschek et al., 2012; Nakagawa and Inoue, 1983) does introduce about −1.7 $ based on β = 390 pcm as the whole active core melts, or say physically homogenized. The heterogeneity effect on the reactivity has been well understood and studied in detail in Gabrielli (2011). Due to the second assumption, a simultaneous sodium boiling onset in all SAs belonging to the "boiling" ring leads to a large reactivity insertion within a short time instead of several smaller insertions in delayed time steps. That would be observed, if several finer radial meshes were employed and the different types of subchannels were considered. This problem has been recognized and studied independently by CEA and noted as "coherency effects" (Guyot et al., 2014). On the other hand the finer mesh modeling of pin bundle flow was developed for the SIMMER code at KIT and successfully applied for a heavy liquid metal cooled reactor (Chen et al., 2015a). For other new developments and applications of SIMMER and other CFD codes for gas and heavy liquid metal

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http://dx.doi.org/10.1016/j.anucene.2015.11.041
0306-4549/

cooled reactors we refer readers to our recent papers published in ANE (Chen et al., 2015b; Li et al., 2015; Chen et al., 2015).

In the following the problems will be studied in detail and methods to overcome these two drawbacks will be described.

2. Problem studies and solutions

2.1. Neutronic calculations and double heterogeneity

The neutronic stand-alone calculations for the CP-ESFR Working Horse core have been performed with ERANOS (Rimpault et al., 2002) and reported in Maschek et al. (2012). Additionally to Doppler constant and coolant void worth, the homogeneity effect has been evaluated. The following table summarizes the results.

The Doppler constant K_D, which is almost not affected by the heterogeneity, is calculated as −1234 pcm and the coolant void worth, which is slightly affected by the heterogeneity, is +1532 pcm and +1659 pcm for the heterogeneous and homogeneous states, respectively. Table 1 shows as well the homogeneity effects. It is −641 pcm in the no void case and −514 pcm in the void case. Herewith we should distinguish "double" and "single" heterogeneities. The double heterogeneity is concerning the fuel pellet with respect to clad and wrapper, while the single heterogeneity the fuel pellet only to the clad (Nakagawa and Inoue, 1983). Since we apply SA coarse meshes here, we consider, as a first step, only the double heterogeneity effect that is suitable for the coarse mesh model.

2.2. SIMMER ESFR coarse mesh modeling and fuel-steel mixing effect modeling

The CP-ESFR WH core was modeled with SA coarse meshes and simulated (Rineiski et al., 2011). Details are not repeated here. Only the radial SA mesh arrangement is shown in Fig. 1 and the power distribution in Fig. 2. There are 8 inner fuel SA rings and 3 outer fuel SA rings, which can be identified in Fig. 2 as well. The highest power density is located at the innermost ring of the outer core under the beginning of life (BOL) condition. In the design there is flow gauging, so that the core outlet temperature is quite uniform. The steady state calculation results reproduce design conditions very well (Maschek et al., 2012).

SIMMER feedback coefficients are quite similar to ERANOS ones. The Doppler constant and the core void worth are −1224 pcm and +1377 pcm, respectively. The delayed neutron fraction β, which is slightly smaller than the ERANOS value, is about 340 pcm. The implemented thermal expansion model has been applied here. However after the first cell melting, it is shut off, meaning its reactivity components do not change any more.

The unprotected loss of flow considered for CP-ESFR WH reactor is defined as the coolant mass flow halving time constant of 10 s. In order to produce an input for SIMMER calculations, the following scheme of pump pressure head is prepared for ULOF calculation:

$$\Delta p = \Delta p_0 \frac{1}{\left(1+\frac{t}{10}\right)^2} \quad (1)$$

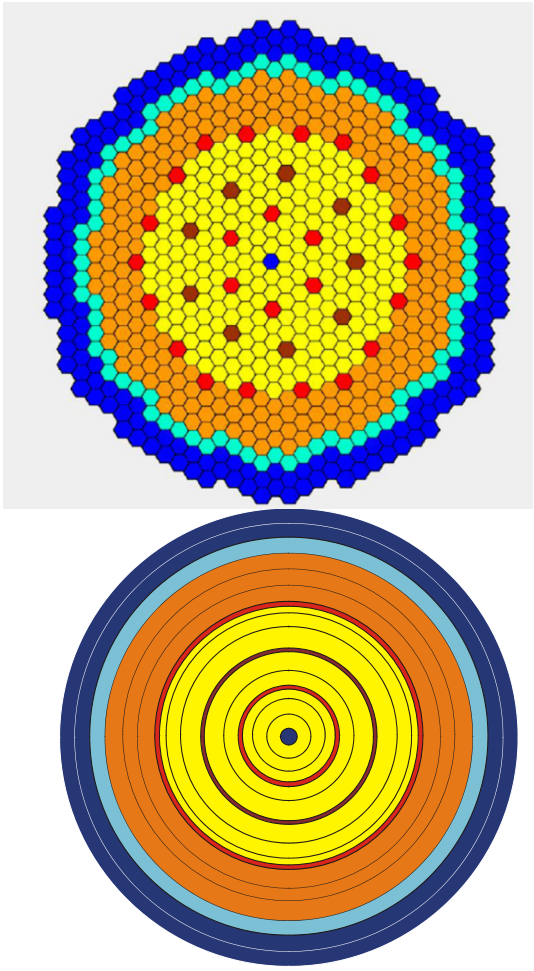

Fig. 1. CP-ESFR WH core (upper) and SIMMER radial SA-coarse mesh ringwise model (lower).

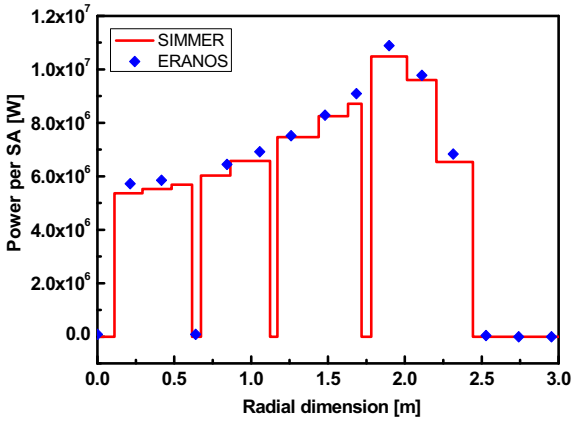

Fig. 2. Power density distributions at BOL condition: SIMMER vs. ERANOS.

Table 1
ERANOS k_{eff} results at different core conditions.

Fuel T (K)	Sodium void (%)	Heterog.	Homog.	Homogeneity effect (pcm)
1500	0	1.00930	1.00281	−641
2500	0	1.00292	0.99651	−641
1500	100	1.02515	1.01978	−514

Table 2
Reactivity change from heterogeneity to homogeneity; where the reality closing case is highlighted by boldface.

Solid steel nuclear density reduction factor	SIMMER III SA-ring mesh k_{eff}	Equivalent homogeneity effect (pcm)
1.00	1.01205	−0
0.90	1.01745	−524
0.87	**1.01906**	**−680**
0.80	1.02279	−1038
0.70	1.02800	−1533
0.60	1.03296	−1999