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Dimensionally adaptive dynamic switching and adjoint sensitivity analysis: new features of the RELAP5/PANBOX/COBRA code system for reactor safety transients

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Professor H.-H. Hennies on the occasion of his 65th birthday.

Abstract

This paper highlights two novel features that have been implemented into the coupled RELAP5/PANBOX2/COBRA3 (R/P/C) code system. On the one hand, the R/P/C code system has been extended to include a dimensionally adaptive algorithm that uses the underlying physical phenomena to switch dynamically between three-dimensional (3D), one-dimensional (1D), and point-kinetics models, thereby reducing computational times up to a factor of five while preserving the accuracy, within user-defined error criteria, of the 3D reference calculation. On the other hand, the R/P/C system has also been extended to include the Adjoint Sensitivity Analysis Procedure (ASAP) for the RELAP5/MOD3.2 two-fluid model with non-condensables, thus enabling the efficient calculation of local sensitivities of RELAP5 results to various parameters in the RELAP5 code.

1. Introduction

The coupled RELAP5/PANBOX2/COBRA3 (R/P/C) code system (Knoll and Müller, 1994) is used for detailed numerical simulations and analyses of light-water reactor (LWR) plant transients, both for normal operating conditions and for postulated accident scenarios. Within the R/P/C code system, the RELAP5 (Ransom et al., 1987) code simulates the thermal-hydraulic characteristics of LWRs by using a non-equilibrium, non-homogeneous two-phase flow model together with conservation equations for boron concentration and non-condensable gases; the PANBOX code solves the diffusion-theory-based neutron kinetics equations in three-, one-, or zero (point)-dimensions using the nodal expansion method; the COBRA code computes the flow and enthalpy in the sub-channels of rod bundles for boiling and non-boiling conditions.

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On the one hand, the coupling of three-dimensional (3D) neutron kinetics models with system thermal-hydraulics codes leads to a very high computational overhead, which prohibits their routine use. On the other hand, most of the postulated accident scenarios are characterized by relatively large time intervals during which a point-kinetics (PK) or a one-dimensional (1D) neutron kinetics model would suffice. Thus, an efficient code system would activate the 3D neutron kinetics model only when called for by the physical phenomena occurring in the respective portions of the transient, but would use a correspondingly lower dimensional model at other times. The R/P/C code system has been recently extended (Jackson et al., 1999a,b) to include a dimensionally adaptive, automatic algorithm that switches dynamically, using the underlying physical phenomena, between the 3D, 1D, and PK models, as required by the physical phenomena underlying the transient scenario under investigation. This algorithm is described qualitatively in Section 2; specifically, Section 2.1 highlights the criteria for dynamic switching from lower-to-higher dimensional neutron kinetics models, while Section 2.2 highlights the criteria for dynamic switching from higher-to-lower dimensional neutron kinetics models. Section 2.3 presents illustrative results for the dimensionally adaptive calculation of the Control Rod Ejection NSC Benchmark Problem (Finnemann et al., 1993; Fraikin, 1996).

The implementation of efficient methods to analyze the sensitivity of results (responses) calculated with the R/P/C code system would represent a major development towards establishing a general-purpose code system for the analysis of postulated accident scenarios. As an important first step in this direction, work is currently in progress (Cacuci and Ionescu-Bujor, 2000; Ionescu-Bujor and Cacuci, 1999, 2000) to implement the Adjoint Sensitivity Analysis Procedure (ASAP) for Nonlinear Systems, originally developed by Cacuci et al. (1980), Cacuci (1981a,b), into the RELAP5/MOD3.2 code. The salient features of this work are briefly described in Section 3. Finally, Section 4 summarizes the results obtained thus far and outlines developments aimed at establishing a multipurpose code for comprehensive analyses of reactor plant transients.

2. Dimensionally adaptive automatic selection of neutron kinetics models in RELAP5/PANBOX/COBRA

Within the RELAP5/PANBOX/COBRA (R/P/C) code system, the coupling between the RELAP5 thermal-hydraulics code system and the PANBOX neutron kinetics code system is achieved by replacing the simple neutron PK model in RELAP by the PANBOX system, which comprises 3D, 1D, and consistently-derived PK models. The coupling between RELAP5 and PANBOX is provided by the interface EUMOD (Rothe, 1992). Due to the structure of EUMOD, the coupling between RELAP5 and PANBOX is performed explicitly. This means that PANBOX is called at the end of every RELAP5 time step; no iterations are performed between the RELAP5 and PANBOX solutions for a given time step. For all problems analyzed so far, this coupling procedure has proven to be stable.

Core thermal-hydraulics can be calculated using either RELAP5 or COBRA, with a one-channel-per-fuel-assembly grid. Plant transients and postulated accident scenarios can be calculated using PANBOX, with either the 3D neutron kinetics model, or the 1D or the PK models with parameters generated automatically from the 3D solution and cross-section data base.

2.1. Dynamic adaptive switching from higher- to lower-dimensional neutron kinetics models

Although it is possible, in principle, to consider three ways of switching from a higher to a lower dimensional kinetics model (i.e., 3D → 1D, 3D → PK, 1D → PK), the switch 3D → PK is not implemented in practice because it is more efficient to use the (combined) route 3D → 1D followed immediately by 1D → PK rather than to calculate the two additional switching criteria that would be needed if the 3D → PK switch were implemented. The criteria for switching from higher to lower dimensional kinetics models are