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Modelling of a self-sustained density wave oscillation and its neutronic response in a three-dimensional heterogeneous system

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ABSTRACT

The main types of instabilities encountered in commercial Boiling Water Reactors (BWRs) are global and/or regional oscillations. In addition to those, pure Density Wave Oscillations (DWOs) have also been observed in some operating BWRs. These oscillations are particularly challenging from a modelling viewpoint because of the radially strongly localized character of the perturbation and of the corresponding neutronic response. In this paper, the features of a recently developed numerical tool, named CORE SIM, are taken advantage of. More specifically, this tool has the ability to estimate in the frequency domain the spatial and energy distribution of the stationary fluctuations of the neutron flux in any three-dimensional heterogeneous system. The perturbations should be directly defined in terms of fluctuations of the macroscopic cross-sections. In this study, the fluctuations in the macroscopic cross-sections are obtained by first modelling a boiling channel exhibiting a DWO with the US NRC RELAP5 code, and by thereafter converting the fluctuations of the coolant density along the channel into fluctuations of the macroscopic cross-sections using the Studsvik Scandpower CASMO-4E code. The RELAP5 and CASMO-4 models are representative of a typical BWR fuel assembly. The conditions modelled in RELAP5 were adjusted in order to obtain self-sustained DWOs. The axial distribution of the amplitude and phase of the fluctuations observed in the coolant density from the RELAP5 simulations are thus converted into fluctuations of the macroscopic cross-sections via CASMO-4E, and fed into a CORE SIM model representative of a heterogeneous BWR. The CORE SIM simulations in turn allow estimating the three-dimensional effects of a self-sustained DWO in a BWR core. More specifically, the axially dependent amplitude and phase of the variation of the coolant flow are properly accounted for, and the properties of the relative induced neutron fluctuations throughout the core are assessed.

1. Introduction

One of the important safety issues in operating commercial Boiling Water Reactors (BWRs) is the possible instabilities that can arise in the reactor core and lead to unplanned reactor shutdowns. These instabilities can be due to several reasons, such as the interplay between coolant/moderator conditions and neutron density, pure thermal–hydraulics effects in two-phase flow, and malfunctions in the plant control system (March-Leuba and Rey, 1993). In particular, the nature of coupled neutronic/thermal–hydraulic instabilities in a BWR can be global, regional, and/or local. As regards global instabilities, the reactor core oscillates in-phase, i.e. the fundamental mode of the core is excited and the core behaves as a whole. In the case of regional instabilities, the azimuthal modes of the core are affected and the reactor oscillates out-of-phase: the two halves of the core can then show an opposite behavior with respect to a symmetry line in the cross-sectional plane. In addition to those two types of instabilities, the core can become unstable because of local effects, e.g. pure thermal–hydraulic Density Wave Oscillations (DWOs) propagating axially in one or several core channels can bring local oscillations of the reactor power.

Density wave oscillations in heated channels have been widely studied (e.g., Yadigaroglu and Bergles, 1972; Rizwan-Uddin, 1994), and reviewed together with other thermal–hydraulic instabilities by several authors (e.g., Bouré et al., 1973; Kakaç and Bon, 2008). A simplified description of DWOs can be provided as follows. Given a boiling channel with an imposed constant external pressure drop, at constant power, and an inlet sub-cooled flow, two axial regions in the channel can be identified: a lower single-phase region and an upper two-phase region, and they are ideally divided by the so-called boiling boundary. The external pressure drop is the sum between the single-phase pressure drop (i.e., the pressure difference between the boiling boundary and the system inlet) and the two-phase pressure drop (i.e., the pressure difference between the outlet and the boiling boundary). Under proper system conditions, the axial phase shift related to the travelling time of possible

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flow perturbations through the channel can support self-sustained oscillations of the fluid density. Accordingly, if a decrease of mass flow is supposed at the inlet of the system, an increase of the single-phase pressure drop occurs. As a consequence of the constant total pressure drop, the two-phase pressure drop decreases. Since the mass flow is reduced and the input power is constant, the specific enthalpy rises in the single-phase region, and the boiling can begin at a lower position in the channel. The downward movement of the boiling boundary makes the void fraction and the two-phase pressure drop increase. This increase of the two-phase pressure drop causes an opposite change of the pressure drop of the single-phase region (again, the pressure boundary condition is constant), and the latter reverses the initial negative change of the mass flow, starting an opposite cycle along the channel. Therefore, a stationary oscillating behavior of the flow is established.

An example of local instabilities most likely due to DWOs is the irregular oscillation pattern that was observed in Unit 1 of the Swedish Nuclear Power Plant (NPP) at Forsmark after the annual outage in 1996. In this event local oscillations were superimposed on the oscillations of the core fundamental/azimuthal modes, and they were measured in the position of unseated fuel assemblies. As explained by Analytis et al. (2001), the mass flow through the unseated fuel assembly may have been reduced whereas the by-pass mass flow increased. In these conditions DWOs can then be developed according to the mechanism discussed above, and perturb the neutron flux in the unseated channel via moderator density reactivity feedback. This variation of neutron flux can finally impact the neutron flux in the surroundings, where the strength of the effect decays with increasing distance from the unseated bundles.

Research on BWR local instabilities has been extensively carried out in the past years (e.g., Oguma, 1997; Analytis et al., 2001; Demazière and Pázsit, 2001, 2005; Oguma and Bergdahl, 2005a,b; Lange et al., 2012; Dykin et al., 2013). However, the dependence of the three-dimensional neutronic response of a BWR-type system on the axial properties of a self-sustained DWO propagating in one core channel has not been analyzed in details in any previous work. Thus, the aim of the current paper is to emphasize the relevance of this dependence and to provide further insights on how the neutron flux in a BWR can be influenced by DWOs. For this purpose, the neutronic core simulator CORE SIM was used (Demazière, 2011). This tool has the ability to estimate, among other things, the spatial and energy distribution of the stationary fluctuations of the neutron flux (the so-called neutron noise) in the frequency domain. The fluctuations of the neutron flux are calculated by varying the macroscopic cross-sections consistently with an assumed perturbation, also called noise source. In this case the noise source is chosen to be a DWO in one of the core fuel assemblies. To model appropriate changes in the macroscopic cross-sections, a DWO in a standalone BWR fuel assembly was simulated with the U.S. NRC thermal–hydraulic system code RELAP5 (RELAP5, 2003). The characteristics of the thermal–hydraulic perturbation (i.e. amplitude, frequency and phase of the DWO) were estimated from the RELAP5 simulation by making use of a Fast Fourier Transform (FFT) algorithm. The generation of the macroscopic cross-sections with respect to the variations of the flow conditions was performed with the Studsvik Scandpower lattice code CASMO-4E (CASMO-4E, 2009). Finally, these macroscopic cross-sections were used in CORE SIM, and the corresponding spatial distribution of the neutron noise was estimated. It must be pointed out that the approach followed in the analysis is based on some approximations. In fact no power feedback to the thermal–hydraulics of the channels and no Doppler feedback have been included in the analysis. Besides, it was assumed that the oscillating bundle does not influence the thermal–hydraulics of the other core channels.

Table 1
System conditions.

Inlet pressure (MPa)	7.1
Outlet pressure (MPa)	7.05
Inlet temperature (K)	501.5
Power (MW)	6.45
Power axial profile	Uniform

The paper is structured as follow: in Section 2 the thermal–hydraulic simulation of a DWO in a BWR fuel assembly is discussed; in Section 3 the preparation of the macroscopic neutron cross-sections is explained; in Section 4 the calculation of the neutron noise in a BWR-type system, with one channel oscillating because of the DWO, is presented; in Section 5 the work is summarized and conclusions are drawn.

2. Thermal–hydraulic simulation of a self-sustained DWO

As mentioned in the introduction, a DWO in a typical BWR bundle was simulated with the thermal–hydraulic system code RELAP5. The capability of RELAP5 to simulate thermal–hydraulic instabilities along heated tubes has been already assessed in other works (e.g., Ambrosini and Ferreri, 2006).

Fig. 1 shows the nodalization developed for the Westinghouse SVEA-96 BWR bundle (Helmersson et al., 1989). The hydrodynamic flow of the heated channel is modelled as a RELAP5 pipe with 24 axial nodes, whereas the total heat flux from the fuel rods is given by a RELAP5 heat structure coupled to the pipe. The inlet temperature and the inlet pressure are specified with a RELAP5 time-dependent volume that is connected to the inlet of the pipe with a RELAP5 single junction. The outlet pressure is fixed with a second

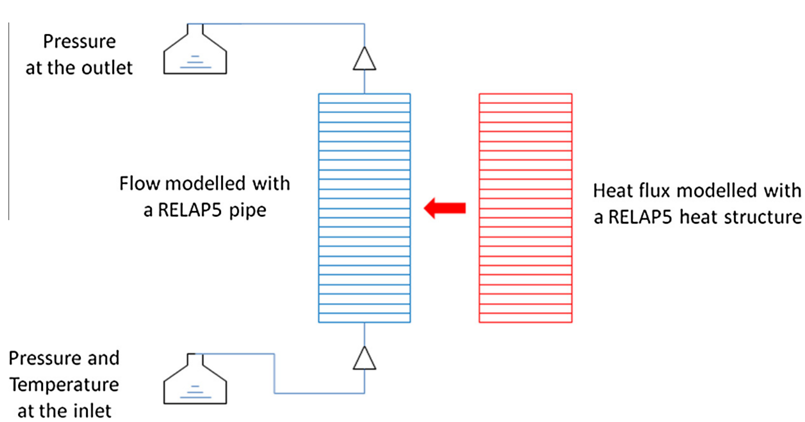

Fig. 1. Schematics of the RELAP5 input model of the SVEA-96 BWR bundle.