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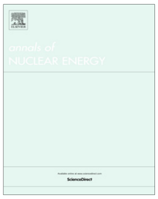

On out-of-phase higher mode oscillations with rotation and oscillation of symmetry line using an advanced integral stability methodology

A. Dokhane [*], H. Ferroukhi, A. Pautz

Paul Scherrer Institut, CH-5232 PSI-Villigen, Switzerland

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ABSTRACT

A new stability analysis methodology for the Swiss BWRs is being established at the Paul Scherrer Institute (PSI) based on the best-estimate coupled neutronic/thermal–hydraulics code, SIMULATE-3K (S3K). For each new stability investigation, the concept is to apply a systematic methodology, combining a single unique S3K vessel T/H model with a full 3-D core model directly transferred from the upstream validated core model, without any adjustments of neither circulation loop components nor fuel assembly geometries/characteristics nor calculation options (e.g. physical models). Through this, the aim is to achieve an integral methodology that can then be applied with strengthened reliability for predictions and/or interpretations of the complex non-linear and strongly coupled neutronics/dynamical phenomena characterizing BWR stability However, the methodology has so far not been validated for regional instabilities and to that aim, a special KKL cycle 07 stability test was selected. Indeed, during this test, the core not only showed growing power oscillation amplitudes in an out-of-phase regime but also an oscillating and rotating symmetry line. Thereby, it was considered highly appropriate to start the validation of the PSI S3K methodology for regional instabilities using this particular test and to gain, on that basis, more insights on the causes for oscillatory and rotational behavior of symmetry lines. The results obtained so far are presented in this paper. First, it is found that the S3K results are in good agreement with measurements both qualitatively and quantitatively, although the resonance frequency is slightly over-predicted. Secondly, the excitation of the out-of-phase mode with oscillation as well as rotation of the symmetry line is also well captured in full accordance with the experimental observations. Related to this, an in-depth analysis of LPRM signals indicates that two out-of-phase oscillation modes associated to two azimuthal neutronic modes are simultaneously excited. Furthermore, it is found that a superposition of these two modes with non-zero phase shift will trigger the symmetry line dynamics and that the behavior will be guided by the dominance ratio between these two modes. More precisely, the oscillatory behavior is due to the superposition of the two azimuthal modes but with one dominant mode. The rotational behavior is however due to the superposition of the two modes with comparable strengths. Moreover, out-of-phase higher mode oscillations are also predicted, showing time-frames when the core is divided into four and even six regions with each region oscillating out-of-phase with respect to its adjacent region. Finally, a bifurcation analysis shows that the observed limit cycle is associated to the occurrence of a supercritical Hopf bifurcation.

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1. Introduction

Boiling water reactors are found to behave as a linear system under normal operating conditions. However, several stability tests and incidents have shown that, under certain high power/low flow conditions, BWRs are susceptible to instabilities in which limit cycle power oscillations might develop. The latter is clearly an illustration of the transition from a linear regime to a nonlinear behavior. Thus, from a reactor dynamics point of view, BWR stability behavior is very complex even though extensive research has been carried out in the last decades, the phenomenon is not completely understood.

Mainly two kinds of power oscillations have been observed in BWR plants, in which a strong nonlinear coupling exists via void reactivity between the neutronic and thermal–hydraulic processes. The two types of instability are: *(a)* global, or in-phase power oscillations, where the power in fuel bundles across the whole core oscillates in phase, and *(b)* regional, e.g. out-of-phase oscillations due to the excitation of the first azimuthal mode, where half of the core behaves out of phase with respect to the other half, i.e. when the power rises in one half of the core, it falls in the other half so that the average power remains essentially constant.

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[*] Corresponding author. Tel.: +41 563104116.
E-mail address: Abdelhamid.dokhane@psi.ch (A. Dokhane).

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Recently, the development of a new methodology to predict BWR stability behavior of the Swiss reactors was initiated within the STARS project at PSI. This new methodology relies on the best-estimate coupled neutronic/thermal–hydraulics code SIMULATE-3K for coupled vessel/3-D core dynamical simulations. This methodology was in a first stage validated against the Swiss BWR Leibstadt plant (KKL) stability tests carried out during the beginning of Cycle 19 (Dokhane et al., 2013). Later on, the methodology was further validated against stability tests carried out during earlier operated cycles in KKL (Dokhane, 2011a,b). It should be emphasized that for all these tests, the core power was oscillating in an in-phase regime. And in that framework, the findings obtained at PSI were found to be well in-line with other S3K validation efforts (Grandi et al., 2011) carried out for (1) a wide range of stability tests including Ringhals-1 (cycles 14–17); Oskarshamn-3 (cycles 7–17); Olkiluoto-1 (cycles 18–26) as well as Leibstadt (Cycle 19); (2) covering thereby a wide range of BWR plant designs with internal, external, and jet pump plants from different vendors (GE, ASEA-ATOM, KWU); (3) for conditions close to, and in many cases, inside the exclusion region.

Concerning the S3K capability for regional oscillations, its assessment is much more limited and has, to the knowledge of the authors, only been reported in (Grandi and Smith, 2002). As this type of oscillations are more complex and thus more challenging to simulate, it was considered necessary to extend the PSI S3K validation to regional instabilities, noting that from a safety point of view, this stability mode is of greater concern since more difficult to detect when using only global APRMs for power monitoring purposes.

In Switzerland, one of the stability tests carried out at the KKL plant during Cycle 07, in September 1990, showed the occurrence of regional oscillations and in that context, a very interesting phenomenon was also observed. Namely, not only out-of-phase power oscillations were excited with a decay ratio equal 1 but also, the core symmetry line started to oscillate or rotate. In the past, many studies have been conducted at PSI to study this special test. For instance, the RAMONA-3 code was used in conjunction with the LAMBDA-REAC code in order to analyze the higher mode feedback reactivities (Hennig, 1998; Miro et al., 2000). These results illustrated growing amplitude out-of-phase oscillations but without a clear conclusion if such oscillations would develop asymptotically to a limit cycle or not. In addition, the rotation of the symmetry line has been reported with a mathematical demonstration that illustrates a possible rotational symmetry line if the core is assumed to have axial symmetry. In (Hennig and Aguirre, 2003), a comparative study for this stability test was conducted between RAMONA-3 and RAMONA-5. Results showed that by tuning some parameter in a small uncertainty region, the two codes can produce unstable or stable period orbits (limit cycle) of the reactor power represented by the oscillation of the azimuthal neutron flux modes. In (Dokhane et al., 2007a), the same test was studied using RAMONA-3 in conjunction with the PSI reduced order model (PSI-ROM) and using bifurcation analysis. Results showed growing amplitude out-of-phase oscillations at this operating point and pointed to the existence of a subcritical Hopf bifurcation i.e. the simultaneous existence of two solutions, i.e. a stable fixed point and an unstable limit cycle.

Hence, the main goal of this paper is to extend these previous studies with a validation of the new S3K based methodology for regional oscillations and also to verify as well as to attempt understanding, the challenging complex phenomena observed during KKL C07 stability tests regarding the rotating and oscillating symmetry line. The paper is organized as follows. Section 2 is devoted to the introduction of the current PSI stability analysis methodology with a short description of the main S3K model components and assumptions. In Section 3, a description of the stability measurements carried out during the beginning of cycle 07 is presented. In Section 4, the results of S3K model are presented, discussed and compared to the measurements. Finally, conclusions from the present work are presented in the last section.

2. PSI stability analysis methodology

The recently developed PSI stability methodology is summarized in Fig. 1 and shortly explained in the next sub-sections. Here, a particular important point to underline is that the objective at PSI is to achieve a systematic and consistent methodology to analyze all cycles of a given plant and all types of oscillation modes. Hence, the same methodology validated for global tests is applied also here without any modifications, neither to the computational route nor to the modeling options.

2.1. Core model

The starting point for the PSI-S3K stability methodology is the CMSYS platform which was established at PSI to serve as framework for the development and validation of reference steady-state core models of all the Swiss reactors including thus the KKL plant (Ferroukhi et al., 2008; Canepa, 2010). The main principle of CMSYS is that after completion of each operated cycle, a CASMO/SIMULATE-3 model is developed and a validation is performed, which for BWRs includes two main components. For the cold reference k-eff, global as well as local cold critical tests usually carried out at Beginning-of-Cycle (BOC) are analyzed. For hot full power cycle depletion conditions, a validation of the calculated 3-D reaction rates is made against TIP measurements carried out at the plant during the cycle.

Thereby, Root Mean Square (RMS) statics of the differences between calculated and measured 3-D reaction rates are estimated at the radial, axial as well as nodal level. Currently, the CMSYS core models for KKL are based on the C4E code using a 70 group library structure based on JEF-2.2. For the model, as is standard with S3K, a full core representation is applied, using a total of 648 neutronic channels, each one coupled to a single individual T-H channel and discretized into 25 axial nodes with a 1x1 radial assembly mesh. For the bypass, a common T-H channel is used to represent all leakage flows (common peripheral zone, core support plate, assembly lateral leakage) as well as water rod flows. At the radial as well as axial core periphery, explicit reflectors are used (Grandi, 2009).

The S3K core model is set-up by a static SIMULATE-3 calculation using as basis the validated reference CMSYS models of KKL (see Fig. 1). The SIMULATE-3 calculation is performed at the operating point where the stability analysis is to be conducted and requires thus a user-specification of the selected cycle, burnup and operating conditions. Thereby, the core is transferred to S3K via a restart file. It should be emphasized that, the Xenon equilibrium concentration is evaluated based on operating conditions earlier than the stability operating point.

A central aspect to note thus is that the same core spatial discretization as defined in SIMU-LATE-3 is applied in S3K. This applies to control rods, detectors and fuel assemblies. Regarding the later, this means that the S3K KKL stability analyses are made with 648 neutronic channels using one radial node and 25 axial nodes per assembly. Similarly, the assembly nuclear design (e.g. cross-sections, nodal histories) as well as the mechanical design (e.g. flow areas, pressure loss coefficients) are thus directly taken from SIMULATE-3.

However, although most core model parameters come directly from SIMULATE-3, data needed for the fuel pin conduction model must be manually specified. The reason is that while S3K solves the fuel heat conduction, SIMULATE-3 does not and relies on

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