SPACE-DEPENDENT DYNAMICS OF PWR

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Abstract

The azimuthal dependent reactor dynamics coupled to thermohydraulics are studied by using the neutron-flux and coolant temperature signals measured at an actual PWR. The second azimuthal mode of neutron-flux fluctuation was found, and the coupling of the mode to thermohydraulics of the coolant was suggested. The coherent coolant flow in the reactor core seems to sustain this spatial oscillation mode.

Introduction

When pressurised water reactor (PWR) dynamics are modelled for some purposes, the azimuthal dependence is often ignored by adopting a model with single flow-channel [1,2]. This model includes most of the physical processes in the reactor, and it is true that this simplification is adequate for many engineering requirements saving time and cost. The model, however, ignores the interaction between neighbouring flow channels, although it always exists. In other words, this simplification is based on the idea that the net neutron and heat flows through boundaries between neighbouring channels is constantly negligibly small.

Assume that a spontaneous and small neutron-flux fluctuation appears due to the fission or heat exchange process between the fuel and coolant and dies at random in the reactor. As long as each fluctuation is isolated from any others, the reactor dynamics can be regarded as a pure stochastic process, and represented by an averaged value over space and time; the single flow-channel model is valid in this case. If the fluctuations are so populated (or long-lived) that each is overlapped with another in space and time, the system forms some co-operative motions which are sometimes space-dependent. Then the dynamics are no longer represented by the summation of isolated fluctuations, because of the onset of the non-linear interaction between the fluctuations. Note that the neutron dynamics is coupled to the highly non-linear thermohydraulics. This is the scenario when the reactor dynamics become non-linear and space-dependent. Obviously, the single flow-channel model is no longer valid in this regime.

The spatial oscillations observed in some boiling water reactors (BWRs) [3,4] cannot be simulated by the single flow-channel model for example. In the case of PWRs, the neutronic-thermohydraulic coupling is not as strong as that of BWR because the main cause of the coupling for BWR, i.e. void in the coolant, is missing. Therefore the neutron-flux fluctuation in PWRs tends to be small in comparison to that of BWR, since the remaining source of the fluctuation is fairly small. This is why the neutron-flux fluctuation in a thermohydraulic-relevant frequency range in PWRs, has not been of great interest to nuclear engineers, as compared to the frequency range of mechanical vibrations such as core barrel motion or the vibration of the in-core instrumentation channels [5].

Recently however, powerful PWR-type plants of 1300 MW or more have been built. Generally, the more power generated from the reactor, the more intensively do the neutronics and thermohydraulics interact to keep the fuel rod assemblies cool; moreover, in large PWRs the coolant flow through the core is much higher, therefore the greater fluctuation is expected. Eventually it is more likely to cause the space-dependent neutron-flux fluctuation, although this is not predicted in reactor modelling and designing. This fluctuation is occasionally so large that the power is reduced by the automatic control system [6]. It is, therefore, important to study characteristics of the fluctuation, but such detailed analysis has, to our knowledge, rarely been carried out.

The aim of this paper is to examine the neutron-flux and thermocouple signals measured in an actual PWR, in order to manifest the interaction between neutron-flux and thermohydraulics fluctuation, with a particular focus on azimuthal dependent dynamics. After a brief description of the reactor and its measurement instrumentation in the section entitled *The reactor and signals used for analyses*, the correlation between ex-core neutron-flux signals located at different azimuthal positions are analysed. In this section, *Space dependence of neutron-flux fluctuation*, the purpose is to observe space-dependent fluctuations. The relation of these to thermohydraulic variables is studied in *Correlation between core-exit thermocouple signals and ex-core neutron detectors signals*. This allows an understanding of how the neutronics and thermohydraulics are coupled in the co-operative fluctuation regime. Conclusions are given in the final section.

The reactor and signals used for analyses

All data-analyses conducted in this paper are based on the operation signals measured at the Borssele nuclear power plant (NPP) in the Netherlands, a PWR-type nuclear reactor built in 1974 by KWU; it has two coolant loop systems and generates a nominal electrical power of 477 MW, which is much smaller than that of recent models. The magnitude of neutron-flux fluctuation is also smaller, and fluctuation has hardly disturbed operations so far. We expect the mode of fluctuation to be similar to recent plants, and could suggest how to cope with, or to subdue, a larger fluctuation.

Figure 1 is a horizontal cross section of the reactor core, showing neutron detector positions indicated by D8, D6, D7 and D5. Each azimuthal angular between neighbouring detectors deviates from the next by 90°. The origin of the angular is defined as seen in Figure 1, and according to this, the four detectors, i.e. D8, D6, D7 and D5 are located at 50°, 140°, 230° and 320°, respectively. Figure 1 also shows the position of six core-exit thermocouples, T1–T6. These thermocouples are located above the core top deviating by 33.4 cm.

Analyses in the following sections were repeated for other burnup conditions and other fuel cycles, and time-invariance of the results was confirmed.

Space dependence of neutron-flux fluctuation

The coherences and phase relations between each pair of neutron detectors are expected to disclose the azimuthal dependence of neutron-flux fluctuation, and signal analyses were carried out for the low frequency range of 0–0.5 Hz. Figure 2 depicts the correlation between an ex-core neutron detector signal, D8 and the remaining D6, D7 and D5.

Because the detail of each coherence curve is too complicated, the more easily examined phase curves were first analysed. Each phase is almost 0° for ~0.1 Hz and more than 0.2 Hz, hence the fluctuations in these frequency ranges are core-wide (or in-phase). The coherences at these frequency ranges have a relatively higher value than those in other ranges. Consequently, the core-wide motions observed here seem to have a close relation to coherence. Of course this is not surprising, because unless the two signals are correlated, the core-wide motion would not be observed. Other pairs; D6-D7, D7-D5 and D5-D6, give similar results for coherence and phase relations, that is, core-wide motion at ~0.1 Hz and more than 0.2 Hz with high azimuthal correlation. The power spectral densities (PSDs) of four ex-core neutron detector signals are shown in Figure 3. Each graph resembles the coherence curves in Figure 2 except that the PSD's curves have a basic decreasing trend, probably due to the fundamental character of the coolant

Figure 1. Horizontal cross section of the Borssele reactor showing the location of the ex-core neutron detectors D5–D8 and the core-exit thermocouples T1–T6

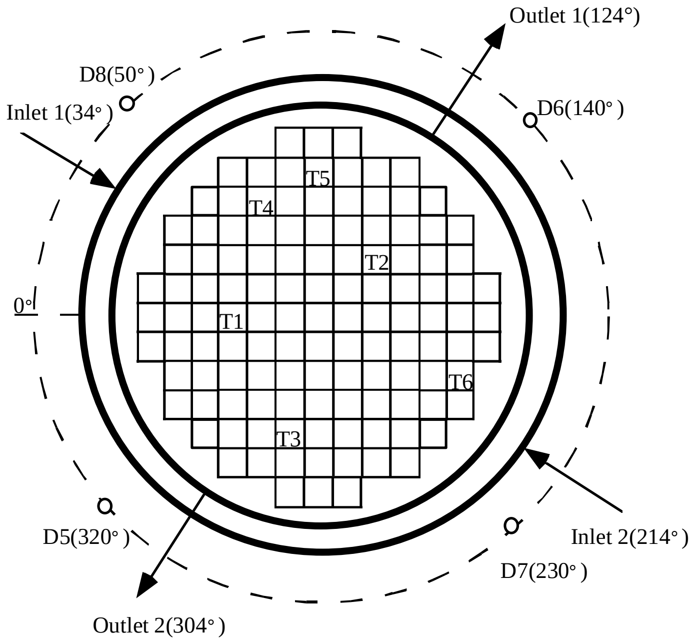
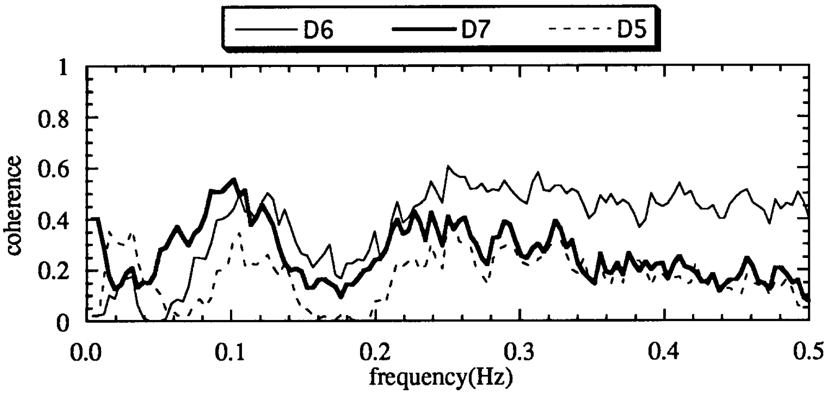


Figure 2. Coherences and phase relation between D8 and other ex-core neutron detector signals

(a) coherence



(b) phase relation

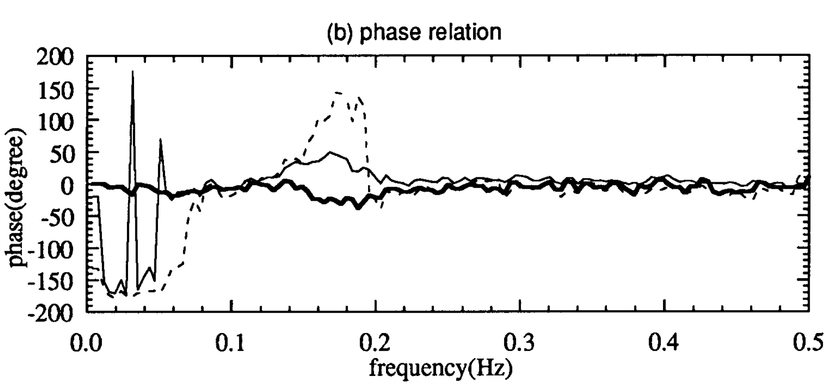


Figure 3. Azimuthal change of the normalised PSD of ex-core neutron-flux signals

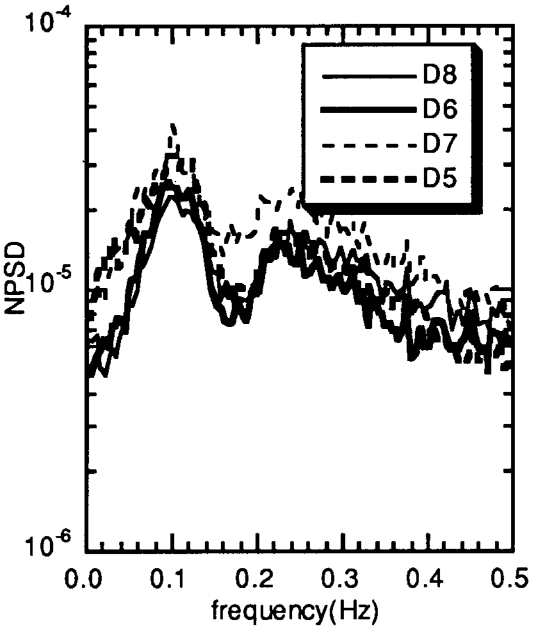
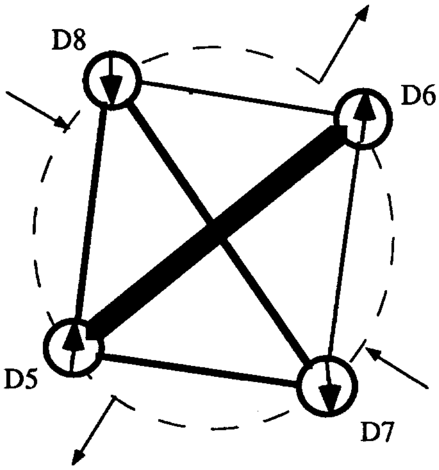


Figure 4. Coherence and phase relation of the ex-core neutron-flux signals at ~0.3 Hz

Coherence value is indicated by the width of the lines connecting detector symbols. Arrows in the circles indicate phase angle.



thermohydraulic fluctuation. Accordingly, the core-wide motion of the neutron-flux seems to increase the power of its fluctuation. The object of this paper is to clarify space-dependent dynamics, therefore there is no further investigation of these core-wide motions. Refer to [7] for a more detailed examination.

In the frequency range of 0–0.05 Hz (see Figure 2 again), D8's phase relation to D7 is ~0° (in-phase), while its relations to D5 and D6 are ~-180° (out-of-phase); the diagonal pair has an in-phase relation and neighbouring pairs have an out-of-phase relation (see azimuthal position of the detectors in Figure 1). This relation is depicted in Figure 4, where the second azimuthal mode is observed. Another specific feature in this frequency range is that the coherence between D5 and D6 at this frequency range is significantly strong (see Figure 4). This space-dependent dynamics is examined more carefully in the next section.

The other frequency range, in which the phase relations are not 0°, is ~0.18 Hz (see Figure 2). At this range the neighbouring pairs, D8-D6 and D8-D5 do not have the same phase relation. Besides, all coherences are so small that the phase mode which satisfies all phase relations, i.e. the arrows in Figure 4, is not uniquely determined. Consequently the fluctuation in this frequency range does not form co-operative motion, being localised and decaying faster.

The longitudinal correlation as well as the azimuthal correlation was also investigated. All the coherences are close to unity and all the phase differences are almost nil, indicating that the ex-core neutron-flux does not vary with the vertical position, that is, longitudinal dependent dynamics are hardly present.

Correlation between core-exit thermocouple signals and ex-core neutron detectors signals

In this section space-dependent dynamics are examined in more detail by adding the core-exit thermocouple signals to the analysis.

As mentioned in the section entitled *The reactor signals used for analyses*, there are six thermocouple signals available above the core. The sensor signals are expected to indicate approximately the core-exit coolant temperature right under the sensor positions (see Figure 1), although the coolant flow is somewhat mixed between each sensor and the core top.

In Figure 5 phase differences between the core-exit thermocouple signals (T1) and the ex-core neutron detectors (D8, D6, D7 and D5) are shown. The most remarkable feature observed in the graph is that phase relations at ~0 Hz from T1 to D8 and D7 are in-phase, while those for D6 and D5 are out-of-phase. This is indirect evidence of azimuthal dependent dynamics described in *Space dependence of neutron-flux fluctuation*. Nuclear reactors are designed such that reactivity decreases when the moderator temperature increases, for the sake of safety. So the phase relations from T1 to D8 and D7 do not seem proper, but this relation is possible even for properly operated reactors, if it possesses space-dependent dynamics, because one neutron-flux signal can no longer represent the neutron-flux averaged over the whole reactor. Table 1 summarises the phase differences at ~0 Hz for all combinations. T2 and T5 have the same phase pattern as T1; T6 has the same phase pattern as T3. The phase pattern for T4 is unique and does not belong to the two groups above.

Next, the coherences between each core-exit thermocouple signal and each ex-core neutron detector signal are examined (see Table 2). Most of the high coherences seem to be associated with the negative phase relation, therefore it seems the neutronic-thermohydraulic correlation is negative as long as it is strong.

Figure 5. Phase relations between core-exit thermocouple signal (T1) and the ex-core neutron-flux signals, D5-D8

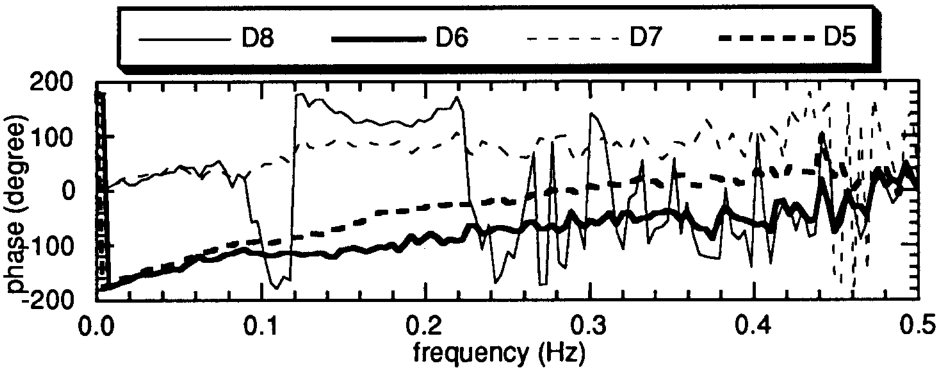


Table 1. Phase difference between the ex-core neutron detector signal and the core-exit thermocouple signal estimated values at 0 Hz.

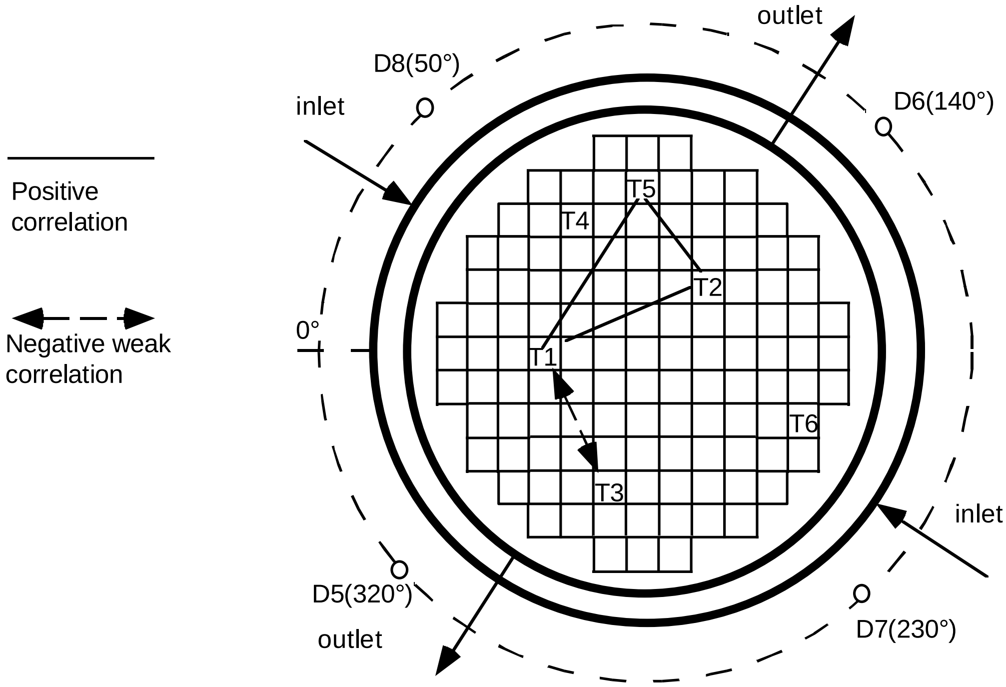
	D8	D7	D6	D5
T1	0°	0°	-180°	-180°
T2	0°	0°	-180°	-180°
T5	0°	0°	-180°	-180°
T3	-180°	-180°	0°	0°
T6	-180°	-180°	0°	0°
T4	0°	-180°	-180°	-180°

Table 2. Coherence between the ex-core neutron detector signal and the core-exit thermocouple signal

Coherences are averaged over 0–0.3 Hz and values more than 0.1 are high-lighted.

	D8	D7	D6	D5
T1	0.08	***0.18***	***0.27***	***0.53***
T2	0.06	0.05	***0.28***	***0.31***
T5	0.06	0.03	***0.26***	***0.23***
T3	0.05	***0.24***	0.03	0.06
T6	0.05	***0.15***	0.07	0.05
T4	0.04	0.05	0.06	0.05

Figure 6. Correlation relations between core-exit thermocouple signals



We already saw the out-of-phase mode from ex-core detector signals in *Space dependence of neutron-flux calculation*, with the result indicating that the out-of-phase mode is relevant to the space dependency of the coolant temperature dynamics, and is not caused by some mechanical oscillation such as shell-mode oscillation of the core barrel. A strong coherence between D6 and D5 was observed as mentioned in *The reactor and signals used for analyses* (see Figure 4). These two detectors are azimuthally located near the two outlets, which also suggests that coolant flow dynamics play a key role in the space-dependent neutron-flux dynamics.

In addition to the above results, correlations between each pair of thermocouple signals were investigated, and the results summarised in Figure 6. The figure shows that the coolant temperatures at T1, T2 and T5 are positively correlated, and all remaining pairs do not have a strong correlation. Accordingly it is surmised that the coolant flows coherently under these three thermocouple sensors. Table 2 already indicated that these three signals are negatively correlated to a diagonal pair of the ex-core neutron detector, D6 and D5, hence the strong correlation between D6 and D5 at the low frequency (see Figure 4) could be ascribed to the coherent coolant flow. The border of the coherent flow is between T4 and T5, because T4 has no correlation to this although it is close to T5. Such a sudden change of dynamics in space is also a non-linear effect.

The negative weak correlation between T1 and T3 is visible in Figure 6. The coherent coolant flow mentioned above seems associated with some weaker coherent flow which has a phase reverse of the original one. Because T3 is negatively correlated to D7 (see Table 2), the associated reverse fluctuation seems to cause a second-azimuthal mode of space-dependent neutron-flux fluctuation displayed in Figure 4. At the moment, however, we do not have a means to prove this hypothesis.

Concluding remarks

At the frequency of ~0.03 Hz, the second azimuthal mode of neutron-flux fluctuation was observed by analysis of the ex-core neutron detector signals located at different azimuthal positions. This mode is detected also from the core-exit thermocouple signals. Therefore it is surmised that this mode is not caused by mechanical oscillations such as shell-mode oscillation of the reactor core-barrel, but a solid power fluctuation caused by the thermohydraulic effect.

The detailed examination suggested that the coherent coolant flow in the core seems to cause a weak coherent flow with reverse phase, and this combination is probably the origin of the azimuthal dependent neutron-flux fluctuation. The future studies should encompass the same kinds of analyses in different PWR plants, and comprehensive numerical experiments.

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