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EARLY DETECTION OF COOLANT BOILING IN RESEARCH REACTORS WITH MTR-TYPE FUEL

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ABSTRACT

In this paper, a reactor core monitoring system having the function of early detection of boiling in the coolant channels of research reactors with MTR-type fuel is introduced. The system is based on the on-line analysis of signals of various ex-core and in-core neutron detectors. Early detection of coolant boiling cannot be accomplished by the evaluation of the DC components of these detectors in a number of practically important cases of boiling anomaly. It is shown that the noise component of the available neutron detector signals can be used for the detection of boiling in these cases. Experiments have been carried out at a boiling setup in the research reactor HOR of the Interfaculty Reactor Institute, Technical University Delft, The Netherlands.

INTRODUCTION

Thermohydraulic conditions in the core of research reactors can change significantly due to conversion from highly enriched to low enriched fuel. Also, safety margins towards onset of boiling vary. The presence of boiling is undesirable in research reactors, as boiling can easily yield high void fractions in the coolant channels and it can cause large reactivity changes [1]. Coolant boiling is, therefore, prevented by all means in order to guarantee safe and reliable operation. This paper describes a possible method for early detection of coolant boiling. A potentially dangerous event which may lead to coolant boiling is the sudden (partial) blockage of coolant channels. A number of voidage-detection methods is based on monitoring sudden decrease of the neutron flux caused by the negative void effect. Studies performed during the implementation of such a method in the research reactor (HOR) of the Interfaculty Reactor Institute (IRI), TU Delft, The Netherlands, show that an initial reactivity step of 50 pcm, or 5 % of neutron flux decrease was needed in most cases in order to generate trip conditions [2].

At the first phase of the development of coolant boiling anomaly, the changes in the neutron flux are not strong enough to initiate reactor trip. At certain disadvantageous positions in the core, moreover, coolant boiling may develop and remain undetected even at a very advanced stage. By monitoring the small fluctuations (noise) of the neutron flux around its average value can furnish us with the proper information to detect the anomaly at an early stage. Boiling detection based on neutron noise analysis is introduced in this paper.

Research aiming at studying boiling neutron noise has been conducted for years in IRI in the NIOBE project (Noise Investigations On Boiling Effects) [3]. In this research, physical phenomena related to boiling in research reactors with plate-type fuels have been analysed thoroughly. Presently, a project has started at ECN, Petten, which aims at the implementation of the results obtained at NIOBE for the High Flux Reactor (HFR) in Petten.

HFR uses MTR-type fuel assemblies [4] which are similar to those used at HOR. The fuel assemblies have horizontal cross section 8.1 cm × 7.7 cm and active length of 60 cm both at HFR and HOR. An HFR-assembly contains 23 vertically arranged curved fuel plates, while an assembly in the HOR has 19 flat fuel plates. The uranium is about 93 % enriched in ^{235}U in both reactors at the present. A typical core lattice of HFR is a 9 × 9 array with 33 fuel assemblies, while the HOR has a 7 × 6 array with 25 fuel assemblies. The power of HFR is 45 MW, which is much higher than the power of HOR (2 MW). This higher power at HFR needs more intensive cooling than at HOR. Accordingly, the coolant speed in the fuel assembly is 7 m/s and 0.5 m/s in HFR and HOR, respectively. HOR has narrow coolant channels of width 0.3 cm. The channels of HFR are even narrower (0.255 cm). Boiling in narrow coolant channels has a few special features analysed in detail during the NIOBE experiments. The peculiar character of boiling in narrow channels has important implications on boiling detection methods in reactors with plate-type fuels.

ECN has experience with on-line monitoring of operational parameters of nuclear reactors, including Borssele PWR, and HFR [5]. In the framework of the present investigations the on-line monitoring system of ECN has been connected to the boiling setup in HOR during the experiments from May to July, 1992. The results indicate that it is possible to detect coolant channel boiling/void in NIOBE.

EXPERIMENTS

Experiments have been carried out at the NOIBE boiling setup of IRI. Here, the main properties of this setup are given [6]. NIOBE consists of a simulated MTR-type fuel assembly within a closed coolant loop, a circulation pump, two flowmeters, and a number of thermocouples and in-core detectors. The simulated assembly has an almost square cross-section (dimension: 7.7 cm × 8.1 cm) and an active length of 62.5 cm; it is located next to the core of HOR. The pump and the control valves are found at positions above the pool water level.

The simulated fuel assembly has three electrically heated fuel plates. The heating power can be varied continuously or step-wise by making use of electrical power units at each plate separately. The heating power of a plate can reach a maximum of 7 kW. By varying the heating power of the plates, different levels of coolant boiling can be induced in NIOBE. There are two coolant channels in the simulated assembly between plates no. 1 and 2, and plates no. 2 and 3, respectively. The coolant is pumped through the channels with the circulation pump. The flow rate in each channel can be adjusted by remote controlled valves. Both coolant channels have a rectangular cross-section of dimensions 6.15 cm × 0.5 cm. The total length of a channel is 62.5 cm.

In the experiments, signals of both incore and excore neutron detectors were used. Excore detectors are ionisation chambers located around the reactor core. The incore neutron detectors are self-powered neutron detectors (SPNDs) with Cd-Mg emitters. SPNDs are arranged in strings.

The SPND strings are movable in axial direction. Each string consists of two SPNDs at a fixed distance. In the present experiments, strings no. 1 and no. 4 were used. The axial positions of the lower detectors, SPND 1/L and SPND 4/L, were at 30 cm measured from the bottom of the fuel plates. The distance between the detectors in both of these strings was 10 cm, thus the higher detectors (SPND 1/H and SPND 4/H) were located at elevation of 40 cm. The temperature of the fuel plates and the coolant is measured by chromel-alumel thermocouples. In the experiments, signals of a thermocouple at the outlet of channel 1 (TC_{out}) and of a thermocouple in the third plate ($TC_{3.3}$) have been monitored. In addition, flow signals in both coolant channels (FL/1 and FL/2) and the voltage of the heating applied at plate no. 2 have been available.

Different thermohydraulic states of the coolant can be generated in the coolant channels of the simulated assembly by varying the electrical heating power and the flow rate. In these experiments, void effects in the coolant channels of NIOBE have been simulated by two means: (a) increasing the electrical heating power locally; (b) injecting Nitrogen gas into a coolant channel.

Data Transmission and Signal Processing

Detector signals have been conditioned in order to have values in the range of - 5 V to 5 V. The conditioned signals entered the signal patch panel (SPP) located in the noise measurement room outside the reactor hall of the HOR. No additional signal conditioning (e.g. filtering) took place before the signals entered SPP. Both AC and DC components of the signals have been processed using the micro-processor based signal conditioning unit (SCU) and the data transmission unit. This system can handle up to 16 channels in DC and AC modes and it has been used in earlier experiments on fuel dynamics in HFR [7, 8]. Data have been transmitted to the ECN site located at a distance of 120 km from HOR via synchronous modems by using a common telephone line.

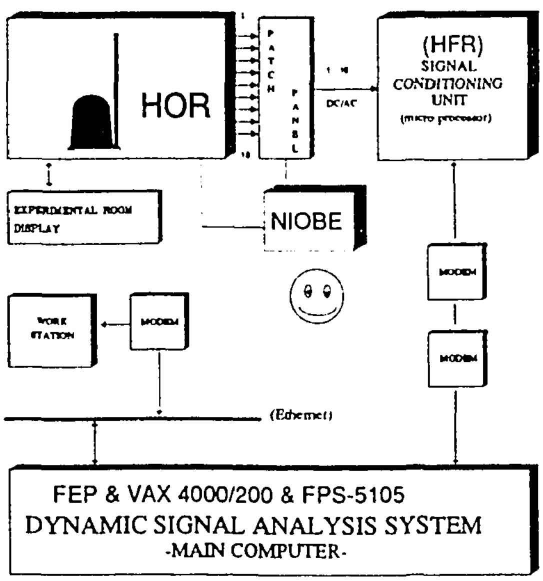

Figure 1: *Schema of Measurement System of the Boiling Experiment*

The signals pass front end processing (FEP) and enter a VAX 4200 computer equipped with an array processor. The array processor performs Fast Fourier-Transformation (FFT) of the time series and calculates auto- and cross-spectra. In a typical experiment, FFT analysis is done in every 4 s for a measurement with sampling rate of 32 samples per second. In real-time calculations, the spectra are calculated by exponential averaging. At the same time, the AC/DC signals are stored on disk for further off-line analysis. The AC/DC signals, together with the results of the on-line time- and frequency-domain analysis have been transferred back to the IRI by using another telephone line and two asynchronous modems. The schematic view of the data acquisition system used during the experiments is given in Fig.1. The results of both on-line and off-line analysis of the two types of boiling/void signals will be given in the paper.

DISCUSSION OF EXPERIMENTAL RESULTS

Boiling of the coolant in the channels of NIOBE has been initiated by increasing the electrical heating power at the fuel plates of the simulated assembly in experiment IRI10A. In Figure 2, the heating voltage (DC signal) is displayed vs. time (the duration of each block is 4 s). The experiment starts with stationary thermohydraulic conditions corresponding to coolant state without boiling in the channels; see Figure 2 from 1 to 500 blocks. This is followed by some transients till block no. 1200, after which stationary thermohydraulic state with intensive coolant boiling is maintained till the end of experiment IRI10A. The maximum void fraction in the coolant channels was about 50 % according to numerical calculations. Figures 3 and 4 display DC components of in-core SPND and ex-core neutron detector signals, respectively. The SPND DC signal shows gradually decreasing absolute value in Figure 3 (note: the SPND signals are measured in negative volts). This decrease is in the order of 1.7 %. On the other hand, ex-core detectors do not detect significant DC variations; see Fig. 4.

In experiment IRI12A, no electrical heating has been applied at the fuel plates of NIOBE. Instead, we have injected nitrogen gas into a coolant channel in order to produce void effects. The nitrogen gas passes through the channel in the form of bubbly/slug flow. In Fig. 5, the control signal of the nitrogen flow is shown. After some preliminary attempts, a relatively high void fraction has been established in the channel at block no. approximately 4200. Based on the measured value of the nitrogen flow rate and the measured terminal velocity of bubbles in between the plates, the maximum void fraction value of about 20 % has been found in experiment IRI12A. During the second half of this experiment, the nitrogen flow has been continuously reduced to zero. In the experiment with nitrogen injection, changes of the DC signals due to boiling were insignificant for in-core SPNDs (Fig. 6) and for ex-core neutron detectors as well (Fig. 7).

The analysis of the AC signals of the neutron detectors (i.e. neutron noise analysis) have been carried out by the code FAST, which is a real-time multi-channel time- and frequency-domain code [5]. The real-time power spectra are computed by using exponential averaging and the dynamic behaviour of the signal is identified continuously. In experiment IRI10A, the analysis has been started from the first block with averaging of 300 blocks of data (duration of 1200 s). In every following analysis, this data window has been shifted by 25 blocks (100 s), yielding 77 sets of auto-power spectra (APSDs) for each detector signal and their cross-power spectra (CPSD). In the analysis, signals of 3 SPNDs, 3 ex-core detectors, and 2 thermocouples have been evaluated.

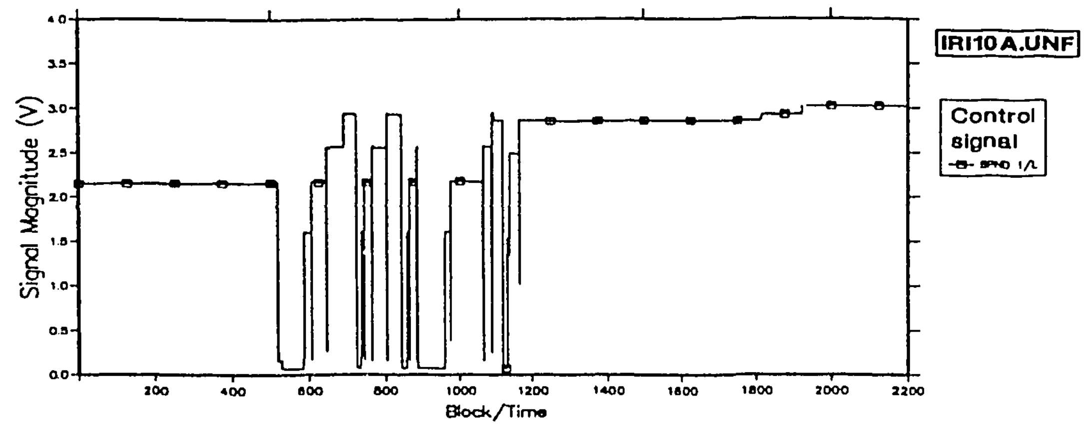

Figure 2: *Control Signal (heating power level) in Experiment IRI10A*

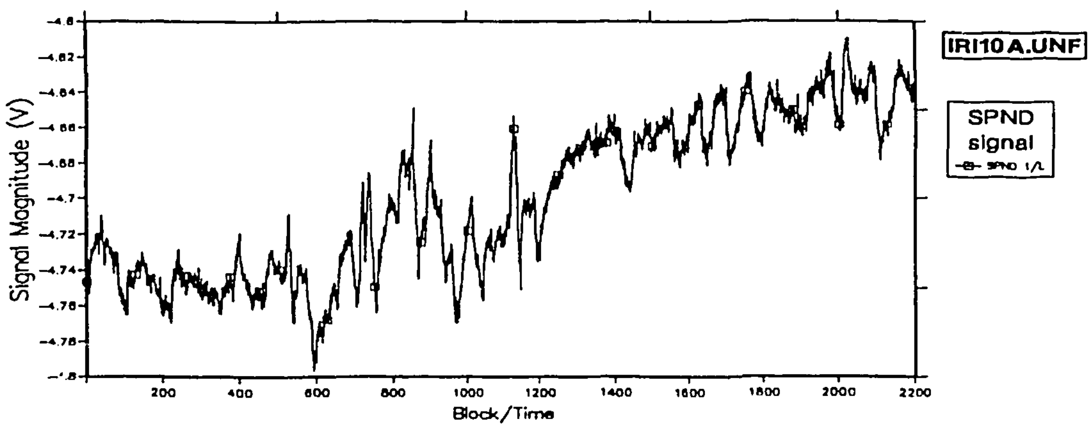

Figure 3: *DC Component of the Signal of SPND 1IL in Experiment IRI10A*

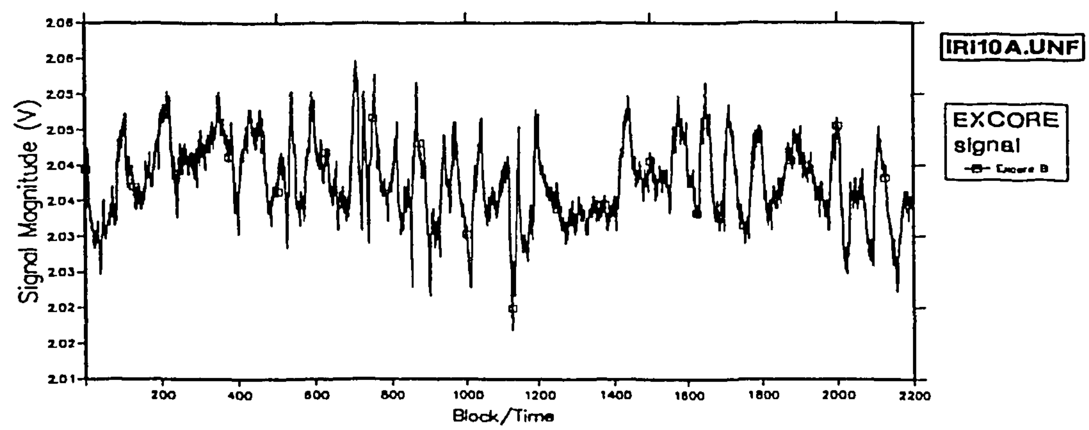

Figure 4: *DC Component of the Signal of Detector EXCORE B in Experiment IRI10A*

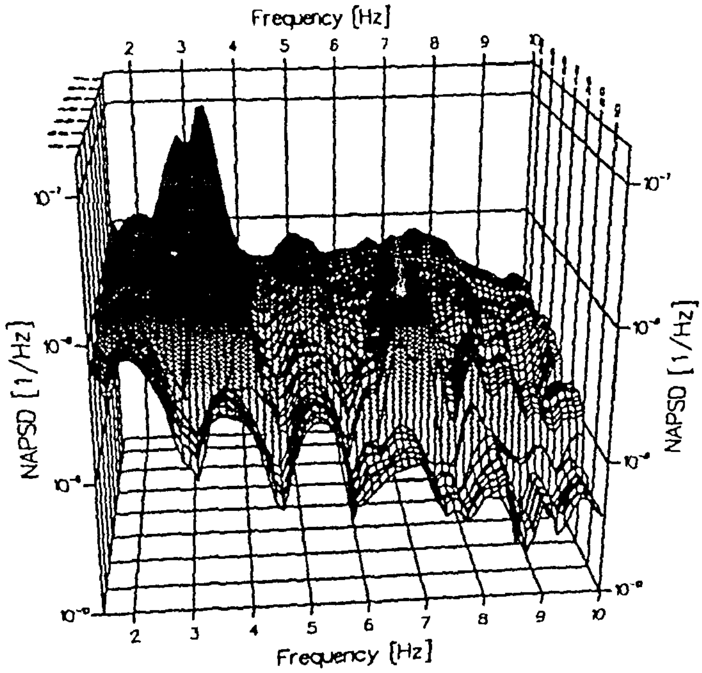

Fig. 8: *NAPSD functions versus time for SPND 1/L in Experiment IRI10A, Frequency from 1.5–10.0 Hz.*

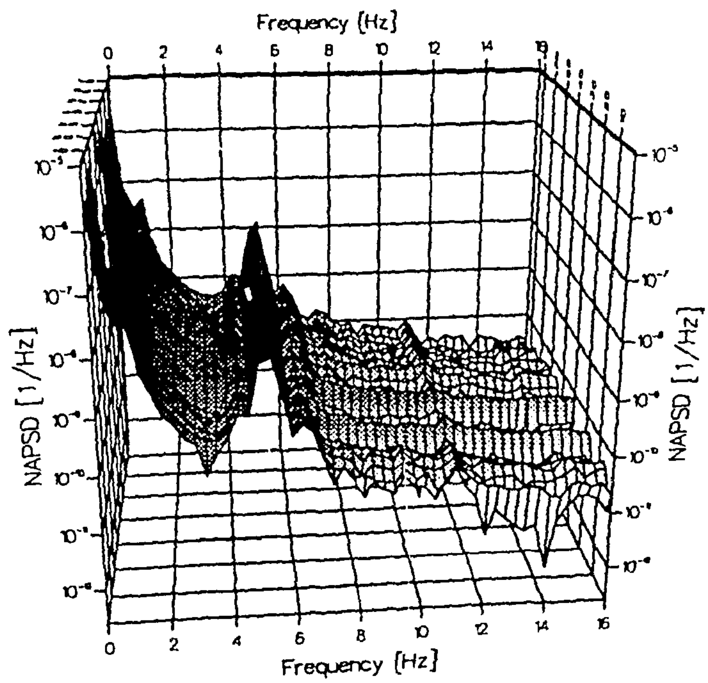

Fig. 9: *NAPSD function versus time for Ex-Core Neutron Detector B in Experiment IRI10A.*

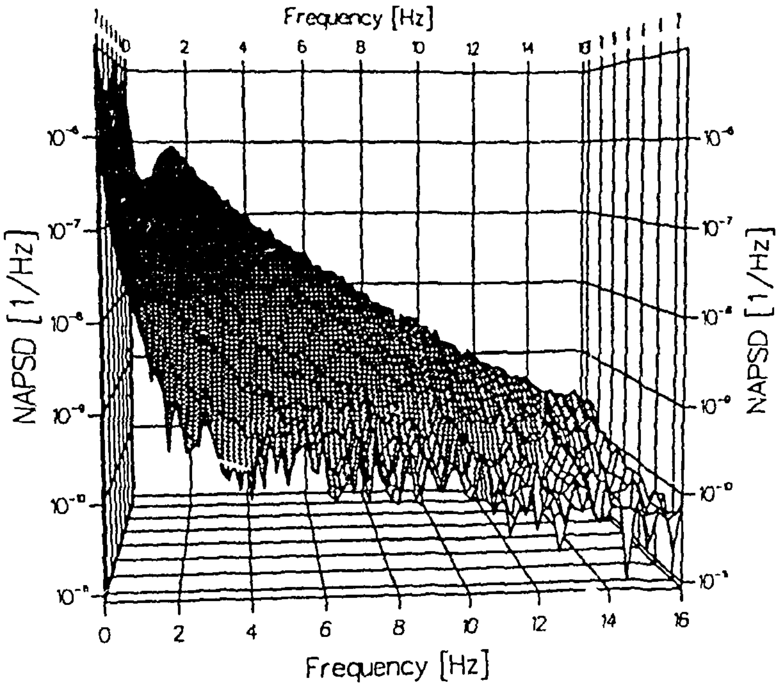

Fig. 10: *NAPSD function versus time for SPND 11L in Experiment IRI12A.*

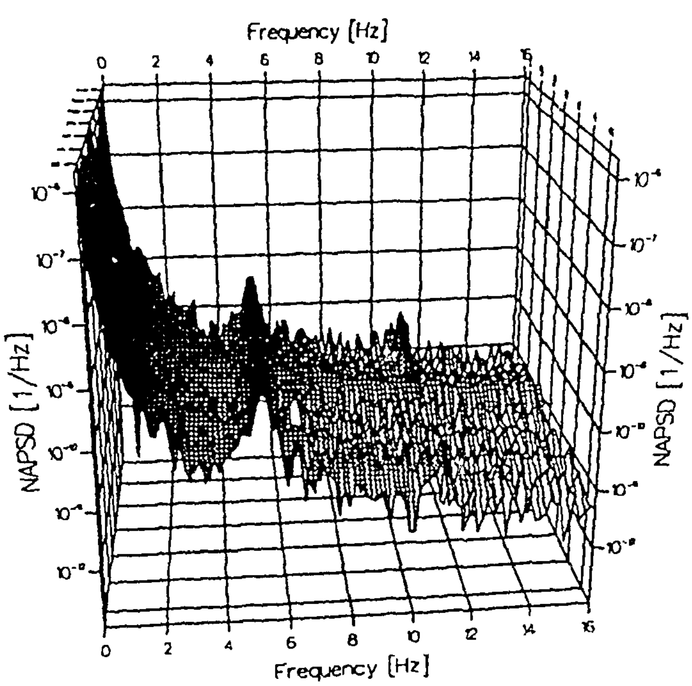

Fig. 11: *NAPSD function versus time for Ex-Core Neutron Detector B in Experiment IRI12A.*

in experiment IRI12A shows an increase of 1.60×10^{-3}, which corresponds to 1.12 pcm reactivity. The void fraction value in the coolant channel (maximum of 20 %) evaluated from this reactivity effect is in good agreement with the actual value determined from the known values of nitrogen flow.

CONCLUDING REMARKS

Results of experiments with coolant boiling in actual reactor environment are presented. Coolant boiling in the channels of a simulated fuel assembly has been detected based on the analysis of neutron noise. The experiments indicate that even a very small amount of void can be detected at the early stage of boiling in the coolant channels having a reactivity effect of less than 1 pcm. The coolant boiling in these circumstances can be detected at a very early stage by the methodology outlined in this paper.

Although boiling induced variations in the DC component of the neutron detector signals could not produce an unambiguous criterion for boiling detection in the case of low level of boiling (void fraction in two coolant channels below 50 %), but in combination with noise criteria DC analysis can facilitate early identification of coolant boiling in nuclear reactors. In the recent years, also several new methods and algorithms have been developed for the identification of changes in signal patterns either by using DC signals with powerful sequential statistical tests or by applying classical algorithms to identify spectral changes in real-time, or by using neural networks as spectral pattern classifiers.

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