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ABSTRACT

Out-of-pile experiments were carried out with the sodium test loop SIENA in O-arai Engineering Center of PNC, and the feasibility studies had been made on the local boiling detection by use of temperature and flow fluctuations. The studies showed that the temperature fluctuation transferred the information on local boiling toward the end of the bundle, but hardly to the outlet. In addition, it was proved that the anomaly detection method, which used the algorithm of whiteness test method to the residual time series data of autoregressive model, is an effective one for detecting anomaly such as local boiling.

INTRODUCTION

For the safety operation of liquid metal fast breeder reactor, it is very important to detect a local boiling within a subassembly at its initial stage. Since flow blockage is one of the most typical causes of local boiling, many efforts have been concentrated on the study of detecting the flow blockage by use of temperature fluctuation at the outlet of subassembly[1],[2]. In-pile and out-of-pile experiments have been made on the local boiling detection by use of the same fluctuations[3],[4],[5]. The results showed that the utilization of temperature fluctuation was promising for the boiling detection of fast breeder reactor. However, further studies may be required for the application of the techniques to the actual anomaly detection system.

Out-of-pile experients were carried out with the sodium test loop SIENA in O-arai Engineering Center of PNC. One of the main purposes of the experiments is to examine the feasibility of detecting local boiling accident by use of temperature and flow fluctuations. In order to make clear whether or not the detection is feasible, the following subjects are investigated in this paper through the interpretation of boiling experimental data:

(1) Statistical properties of temperature and flow fluctuations in the downstream of the blockage under local boiling conditions;
(2) Sensitivity of newly developed anomaly detection method which uses fluctuation signals.

EXPERIMENTAL EQUIPMENT

Figure 1 shows the schematic representation of the electrically heated 61-pin bundle test section used in the present study. The diameter of each pin is 6.5 mm and the pin pitch is 7.9 mm. The clearance of neighboring pins is kept constant by wire spacers. The outer 24 pins of the test section are dummy pins. The 36 % central-type tight blockage is attached at the middle position of heated section.

Chromel-Alumel thermocouples represented by T-XXXX in Fig. 1 are located at various positions of the test section. The thermocouple T-004 is an ungrounded type sheathed thermocouple whose diameter is 4.8 mm, and the others are grounded type sheathed thermocouples whose diameters are 0.3 mm. The eddy current type flow-meter is installed at the outlet of the bundle.

The data acquisition system of fluctuation signals is shown in Fig. 2. The temperature and flow signals are transmitted to the control room using double shielded cables. The fluctuation signals are obtained from specially designed fluctuation measuring cicuits. The circuits consist of a low noise AC amplifier and a band pass filter. The specification of these components is as follows:

AC amplifier	gain	:	60 dB (max.)
	low cut off frequency	:	0.01 Hz
Band pass filter	low cut off frequency	:	0.01 Hz
	slope	:	40 dB/dec
	high cut off freqeuncy	:	15 Hz
	slope	:	200 dB/dec

OPERATING PROCEDURE AND LOCAL BOILING EXPERIMENT

The flow velocity was initially maintained at the constant value of 1.5 m/sec, and the heat flux of each pin was adjusted to be 61 W/cm^2. When the steady state condition was attained, the flow velocity was decreased stepwise.

Figure 3 shows typical signals obtained in the local boiling experiment (Run No. 61WLB-101). FEC-1A is the flow fluctuation signal measured by the eddy current type flow-meter. T-024 and T-024A are the temperature and its fluctuation signals measured at the outlet, respectively. T-021G and T-021GA are the readings of the thermocouple whose location is 34 mm downstream of the blockage. P-111 is the pressure at the outlet. Inception of local boiling was monitored by this pressure signal. F-103 is the flow signal at the inlet of the test section.

The inlet sodium flow was decreased stepwise at 62, 86, 157 and 251 sec. The local boiling was initiated at about 95 sec, after the second reduction of flow rate. Three steady state local boiling tests were conducted under different conditions: "Local boiling I", "Local boiling II" and "Local boiling III". At the second and third reductions of flow rate, conspicious increases were found in both the temperature and its fluctuation signals measured at the position immediately behind the blockage (T-021G and T-021GA). During the local boiling II and III tests, T-021G had reached the sodium saturation temperature. On the other hand, the temperature at the outlet, T-024, increased gradually by only 3 to 5 °C at each step of flow reduction. Conspicious changes were hardly found in the outlet temperature fluctuation, T-024A, during the flow decreases except the second one. The flow fluctuation, FEC-1A, did not show any visible changes not only during the flow reductions but also at the onset of local boiling.

ANOMALY DETECTION METHOD

An anomaly detection method, which uses fluctuation signal, is generally based on the comparison of a typical statistical index of fluctuation signals at normal state with that at anomalous state. Power spectral density (PSD), RMS value, Skewness factor etc. are usually used for this purpose. It is desirable that the anomaly detection method take into account enough information from fluctuation signals to judge the operational status of a reactor, because the anomaly phenomena have not been thoroughly understood and the relation between anomaly status and temperature (or flow) fluctuation has not been fully clarified.

We have developed an anomaly detection method which uses the auto-regressive model (AR model). We called it Whiteness Test Method (WTM) in the present paper. Signal processing procedure of WTM is summarized as follows:

<u>STEP 1</u>

$$\varepsilon_n = \underline{x}_n - \sum_{i=1}^{M} \hat{a}_i \, x_{n-i} \qquad \cdots\cdots\cdots (1)$$

ε_n : residual time series data of the AR model fitting
$\underline{x}_n$: fluctuation signal to be diagnosed
$\hat{a}_i$: preparatively determined AR model coefficients of fluctuation signal at normal state

<u>STEP 2</u>

$$\Psi_{\varepsilon\varepsilon}(n,\tau) = \frac{1}{L} \sum_{j=1}^{N_o} \varepsilon_{n-j} * \varepsilon_{n+j-\tau} \quad , \ \tau = 1,2,\ldots,\tau_{max} \qquad \cdots\cdots (2)$$

L : number of data used for computing $\Phi_{\varepsilon\varepsilon}(n+N_o,\tau)$
N_o : number of sampled data in the monitored interval
τ_{max} : maximum lag number of autocovariance function $\Phi_{\varepsilon\varepsilon}(n,\tau)$

<u>STEP 3</u>

$$\Phi_{\varepsilon\varepsilon}(n+N_o,\tau) = \Phi_{\varepsilon\varepsilon}(n,\tau) + \Psi_{\varepsilon\varepsilon}(n,\tau) - \Psi_{\varepsilon\varepsilon}(n-L,\tau) \qquad \cdots\cdots\cdots (3)$$

The values of L and N_o are so selected that L/N_o shall be integer.

<u>STEP 4</u>

$$I(n+N_o,M,L,\tau_{max}) = \sum_{\tau=1}^{\tau_{max}} | \Phi_{\varepsilon\varepsilon}(n+N_o,\tau) |^2 \qquad \cdots\cdots\cdots (4)$$

$I(n+N_o,M,L,\tau_{max})$; AR index

STEP 5 $I_{mt}{}^{l} \leq I(n+N_o, M, L, \tau_{max}) \leq I_{mt}{}^{u}$: Normal

Otherwise : Anomary

where $I_{mt}{}^{l}$, $I_{mt}{}^{u}$ are lower and upper alarm levels.

The WTM algorithm has been developed for a mini-computer system. The computing time and the memory size of the WTM for each fluctuation signal are about 10 msec and about 150 words, respectively.

TEMPERATURE AND FLOW FLUCTUATIONS UNDER LOCAL BOILING CONDITIONS

RMS Value of Temperature Fluctuation

Figure 4 shows the RMS values of temperature fluctuations observed at several axial positions behind the blockage. The following items were made clear from these analyses:

(1) At the position immediately behind the blockage, the RMS values of temperature fluctuations under local boiling conditions were about 15 times larger than that under non-boiling condition.
(2) In the downstream beyond 144 mm from the blockage, noticeable changes were not found in the RMS values of temperature fluctuations between the two conditions.
(3) The RMS values of temperature fluctuations observed at the outlet were about 5 times larger than those at the end of the bundle.

PSD of Temperature Fluctuation

Figures 5 and 6 show the PSDs of the same temperature fluctuations under non-boiling and local boiling III conditions. The temperature fluctuations in the bundle had spectral peaks around 4 Hz. The peaks were due to the repetitive cycle of bubble formation and collapse. On the other hand, the temperature fluctuation at the outlet had no spectral peak.

PSD of Flow Fluctuation

As shown in Fig. 7, no conspicuous feature of local boiling was found in the PSDs of flow fluctuations measured at the outlet of the bundle.

Transfer and Coherence Functions of Temperature Fluctuations

Figures 8 and 9 show the transfer and coherence functions between several couples of temperature fluctuations under the local boiling III condition: one is always fixed to that measured at immediately behind the blockage (T-021GA) and another is selected from those measured at various downstream locations.

Concerning the transfer functions, peaks appeared around 4 Hz only for the cases with the temperature fluctuations measured within the region less than 66 mm (T-021J) downstream of the blockage. Otherwise, the peak was attenuated remarkably. In the case of coherence functions, conspicuous peaks were found within the whole bundle section. However, it was hardly found at the outlet.

These analyses made clear the following items:

(1) The inconsistency between transfer and coherence functions, both calculated with the temperature fluctuation at the end of the bundle, was mainly due to the strong attenuation of fluctuation level during the axial motion of fluid (see Fig. 4). This fact proves that the information on local boiling is transferred almost linearly to the end

of the bundle even though it is fairly small. Figure 4 shows the amount of information on local boiling transferred to the end of the bundle.

(2) At the outlet of the bundle, both transfer and coherence functions are small in whole frequency range. From this fact, it is deduced that the temperature fluctuation at the outlet is hardly correlated to that at the boiling position. The temperature fluctuation at the outlet may be generated mainly by the turbulent mixing of the coolant flowing through the passage from the end of the bundle to the measured position, since the RMS value of temperature fluctuation at the outlet is about 5 times larger than that at the end of the bundle.

FEASIBILITY OF LOCAL BOILING DETECTION

Figures 10 and 11 show the result of the anomaly detection by the RMS method and the WTM applied to the temperature and flow fluctuations, where the sampling interval and averaging time were selected to be 0.016 and 8.0 seconds, respectively. Concerning the RMS values of temperature and flow fluctuations, noticeable changes were not found during the run. In the AR index of temperature fluctuation, remarkable increases were found immediately after the reductions of flow rate. However, conspicuous increases were not always found in the AR index of flow fluctuation.

The RMS values of temperature and flow fluctuations under local boiling conditions were larger than those under non-boiling condition. The amount of the difference ($\leq$ 20 %) was, however, insufficient to detect local boiling.

Figure 12 shows the ratio of the average AR index under steady state local boiling conditions to that under non-boiling condition (averaging time is 32 sec). The ratio of the temperature fluctuations was from 1.5 to 1.8, and that of the flow fluctuations was from 2.0 to 2.5. This figure also shows that the ratio increases with boiling intensity.

As mentioned in the previous section, there was little correlation between temperature fluctuation at the boiling position and that (or the flow fluctuation) at the outlet of the bundle. Consequently, it is easy to infer that the local boiling may be detected only when the local boiling region is large enough to affect the temperature distribution at the outlet of the bundle or generate global flow oscillation due to void formation and collapse.

CONCLUSIONS

Analyses of temperature and flow fluctuations under local boiling conditions yielded the following conclusions:

(1) The strong correlation was found for the temperature fluctuations observed at the boiling position and the end of the bundle, while the correlation has not been clarified with regard to the fluctuations at the subchannel outlet.

(2) It will be promising to detect local boiling accident when the boiling intensity becomes fairly large.

(3) The whiteness test method (WTM) of fluctuation signal was a sensitive and reliable method for detecting a local accident within a subassembly.

ACKNOWLEDGMENT

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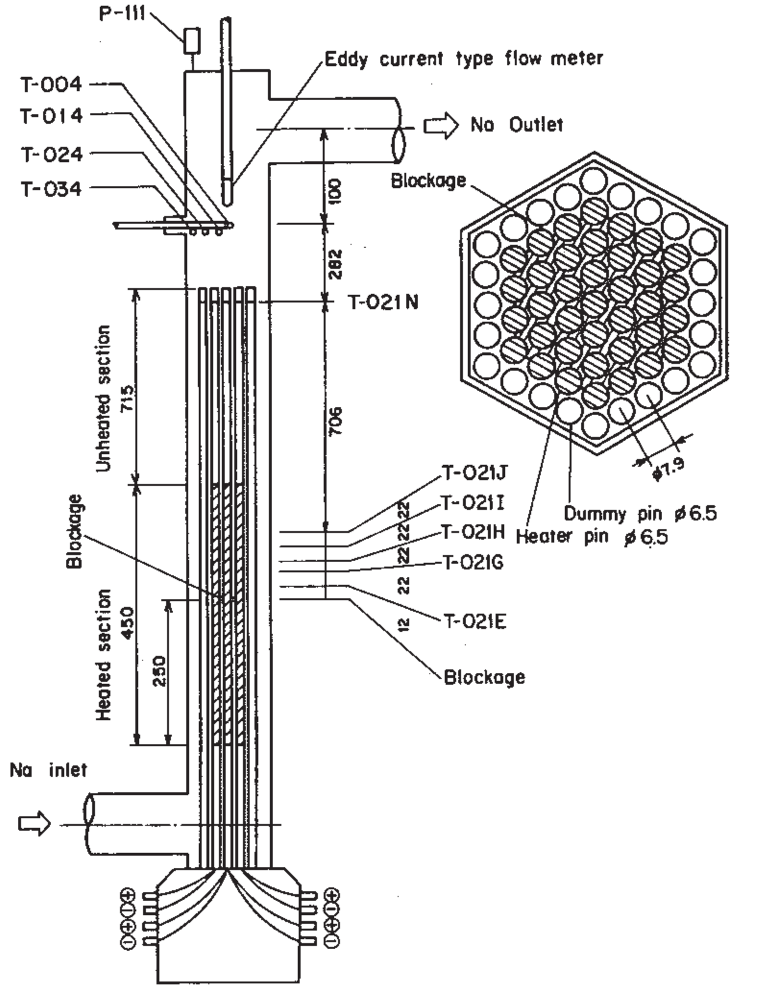

Fig. 1 Locally blocked 61-pin bundle test section

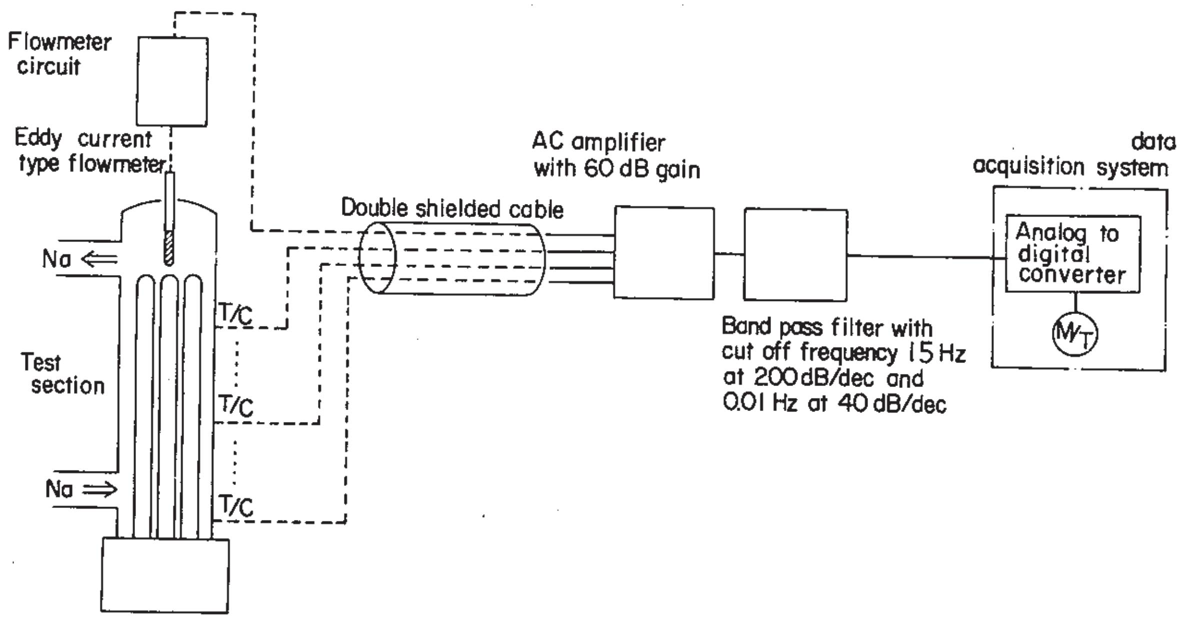

Fig. 2 Schematic diagram of the data acquisition system of fluctuation signals

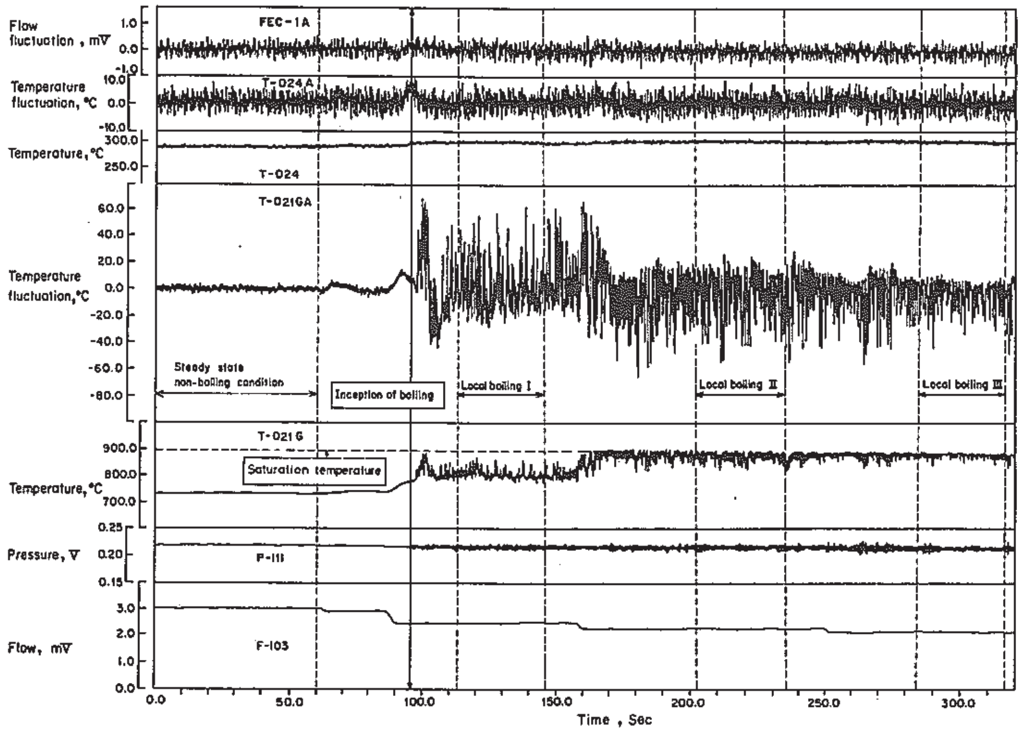

Fig. 3　Signals under local boiling condition (Run No. 61WLB-101)

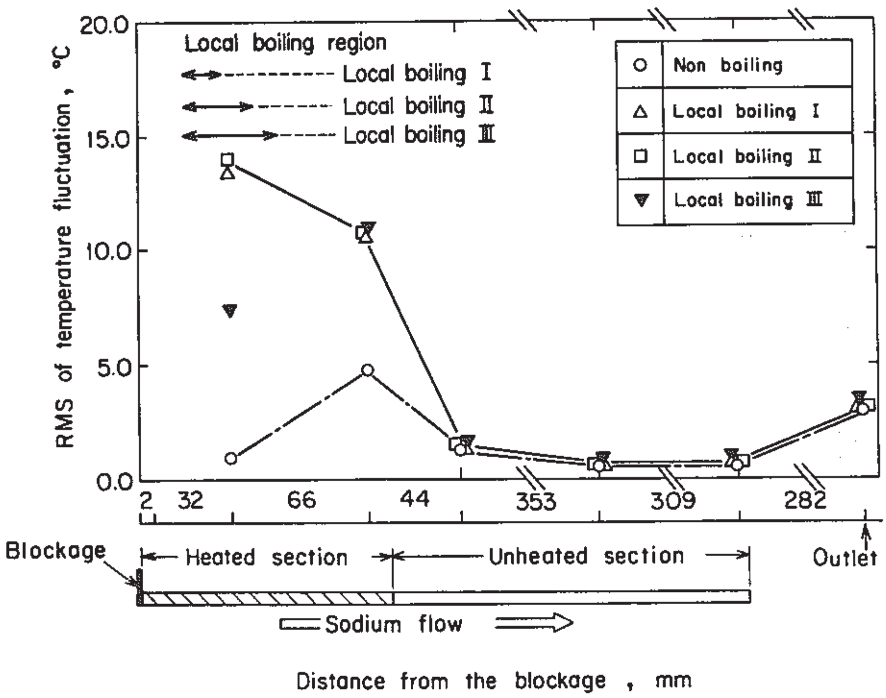

Fig. 4　RMS values of temperature fluctuations observed at several axial positions behind the blockage (Run No. 61WLB-101)

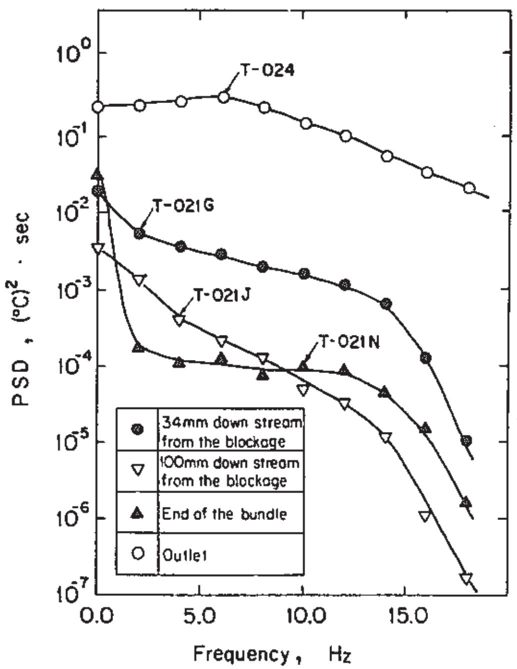

Fig. 5 Power spectral densities of temperature fluctuations observed at several axial positions,
-- Non-boiling condition
(Run No. 61WLB-101)

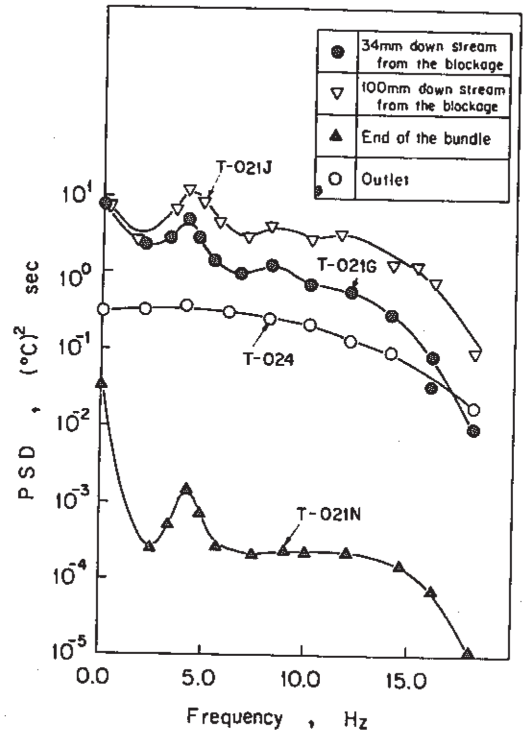

Fig. 6 Power spectral densities of temperature fluctuations observed at several axial positions,
-- Local boiling III condition
(Run No. 61WLB-101)

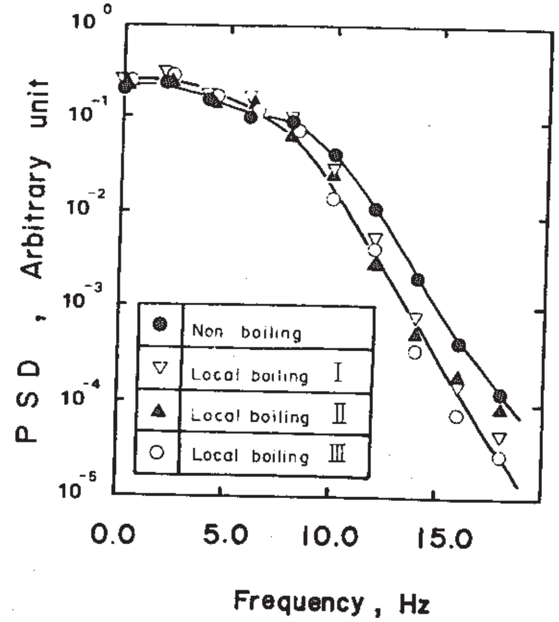

Fig. 7 Power spectral densities of flow fluctuation observed at the outlet of the bundle
(Run No. 61WLB-101)

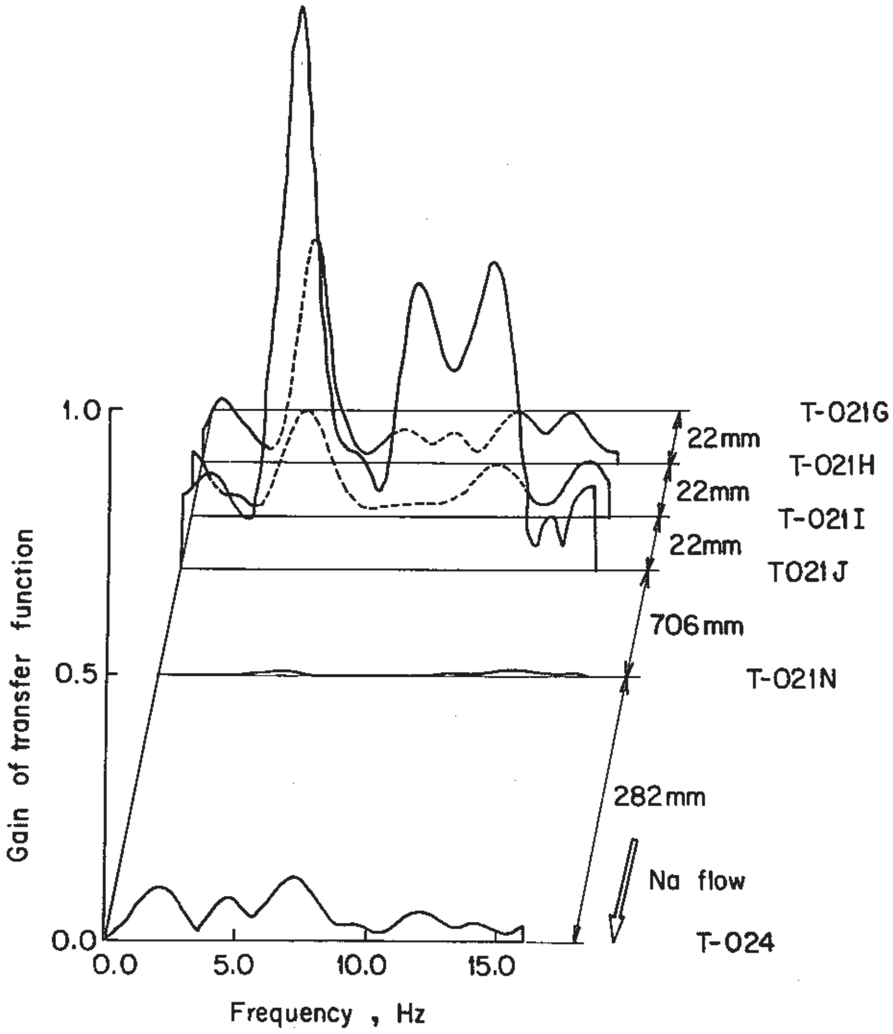

Fig. 8 Transfer functions between several couples of temperature fluctuations, one is T-021G and the opposite is one of the others (T-021H,..., T-024), -- Local boiling III condition (Run No. 61WLB-101)

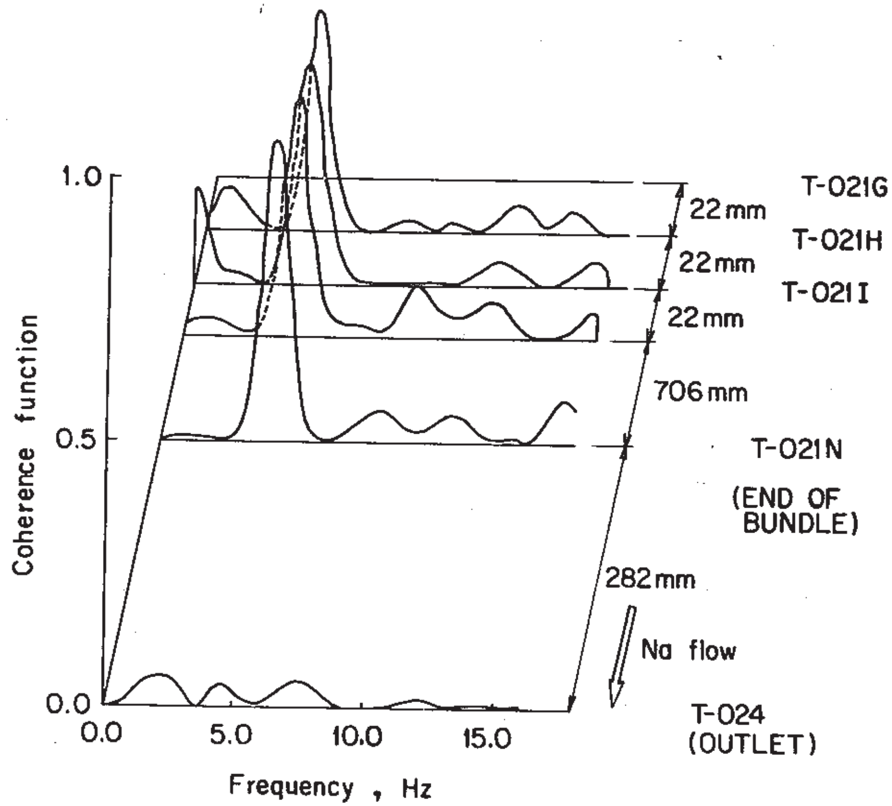

Fig. 9 Coherence functions between several couples of temperature fluctuations, one is T-021G and the opposite is one of the others (T-021H,..., T-024), -- Local boiling III condition (Run No. 61WLB-101)

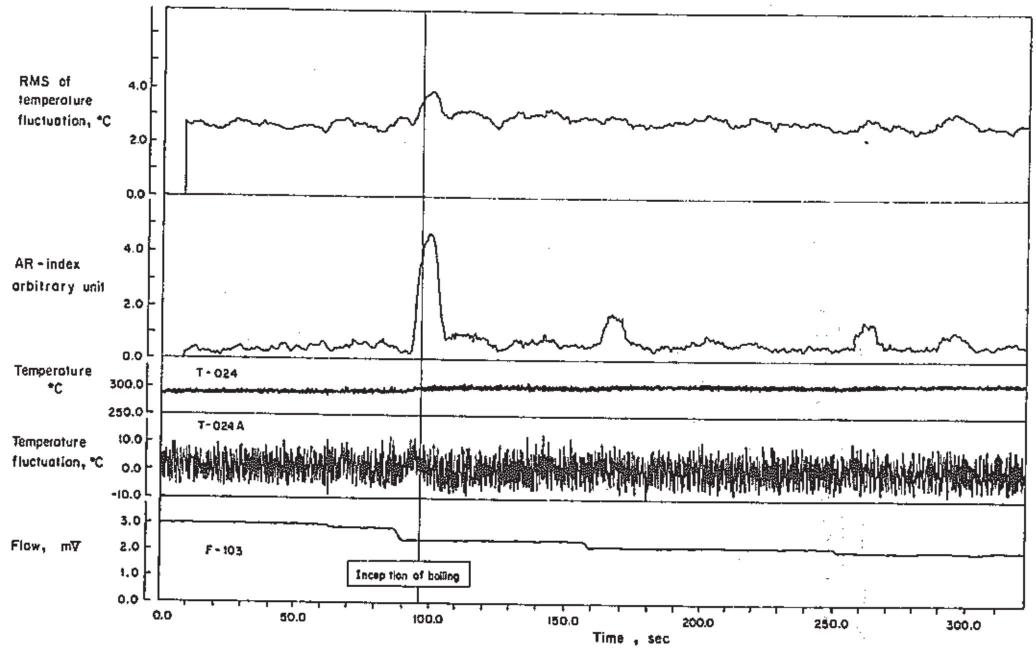

Fig. 10 RMS value and AR index of temperature fluctuation measured at the outlet of the bundle (T-024) (Run No. 61WLB-101)

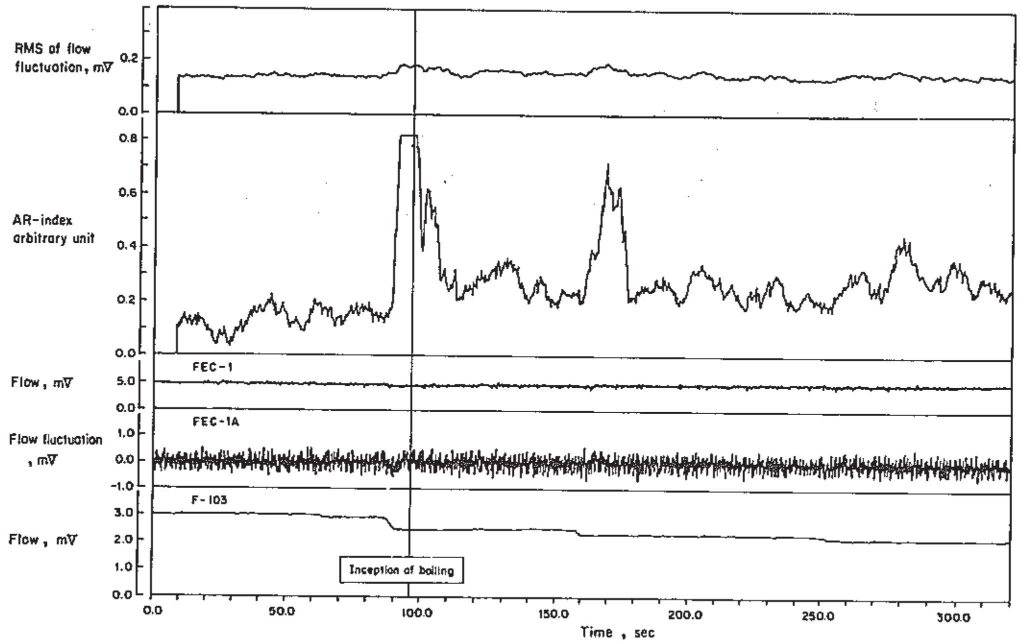

Fig. 11 RMS value and AR index of flow fluctuation measured at the outlet of the bundle (FEC-1) (Run No. 61WLB-101)

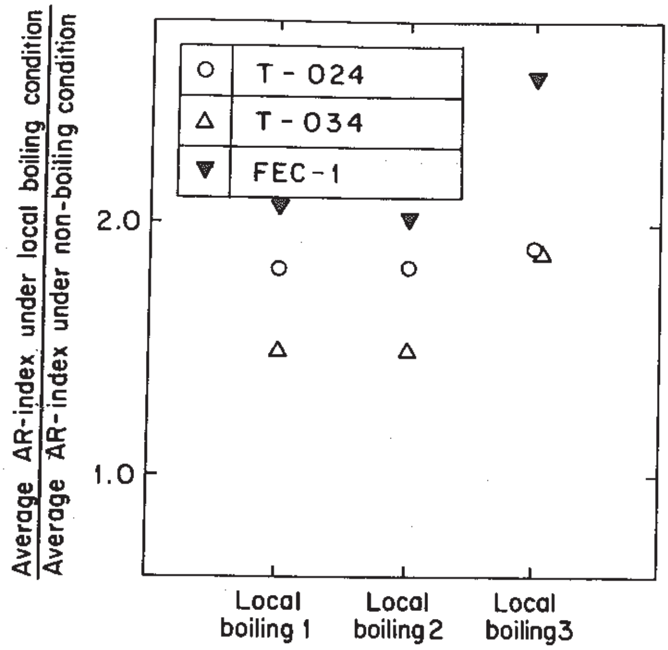

Fig. 12 Ratio of the average AR index under boiling condition to that under non-boiling condition (Run No. 61WLB-101)