ON-LINE ESTIMATION OF LOCAL AND TOTAL CORE FLOW RATES BY NEUTRON NOISE ANALYSIS IN BWR

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Abstract

The extensive work on total and local core flow estimation for measurement by analysing in-core neutron noise signals was carried out using measured data of commercial BWR plants. A large database of LPRM signals and process data measured in this project enabled us to investigate the physical interpretation of the transit time measured by the LPRM neutron noise signals. The improved core flow estimation algorithm has been developed based on the new findings of logical inconsistency in the axial transit time of the void propagation measured directly LPRM B through D against LPRM B through C adding to C through D. The newly-developed algorithm showed a good agreement and predictability in the measurement tests during the RIP (reactor internal pump)-trip testing and the start-up testing of the first 1350 MWe-ABWR. The measurement results exhibited the verification and validation of the present flow estimation method within about five per cent estimation error for high flow rates and about ten per cent estimation errors over a wide-range operating area. The error shall be reduced especially in the low flow rate by considering the average of longer sampling period. Further findings of the LPRM fluctuation signals on the NRMS (normalised root mean square) against the void fraction divided by square root of the void velocity showed the possibilities of the two-phase flow monitoring by the in-core neutron noise analyses.

Introduction

For a safe and efficient operation of BWR plants, monitoring of two-phase flow conditions is of the most importance. In commercial BWR plants, the two-phase flow behaviour is monitored through analytical thermal-hydraulic model prediction using the total core flow rate measured by differential pressure. The in-core neutron detector (LPRM) signals have promising possibilities, which provide low-cost and useful tools for two-phase flow monitoring not only for total core flow but also for local core flow or two-phase flow regimes. In the past two decades, these possibilities have been widely studied [1-8]. Through these studies, qualitative behaviour of neutron and two-phase flow fluctuations was well understood. Nonetheless, there remains ambiguity of the quantitative behaviour, which arises from the questions, ”What kind of velocity of two-phase flow de we really measure?” and “Can we measure two-phase flow regimes?”. In order to apply the neutron noise analysis technique to two-phase flow monitoring, it is necessary to make this ambiguity clear.

In the present work, we evaluated the accuracy of the measurement of local and total core flow rates using in-core neutron noise signals, which were measured in operating BWR plants. In the first step, the discussion was introduced for the physical interpretation of the two-phase flow transit time, based on the measurements by LPRM neutron noise signals. The new evidence was found with deep understanding by the review of the transit-time behaviour. Also, we evaluated the two-phase flow velocity detection process by sub-channel void distribution analyses and field-of-view analyses of a neutron detector. Based on these results, the core flow estimation algorithm was improved and optimised, and an on-line core flow measurement system using personal computers has been developed. The tests for verification of the algorithm and the system were carried out in BWR-5 and ABWR type plants.

Interpretation of in-core neutron noise behaviour

Model description of two-phase flow

The present flow estimation algorithm is based on the drift-flux model [4], which leads to the radially-averaged steam void fraction, α, expressed as:

$$\alpha = \frac{J_g}{(C_0 \times J + V_{gj})} \tag{1}$$

and the vapour velocity, v_g, can be expressed as:

$$v_g = C_0 \times J + V_{gj} \tag{2}$$

where,

C_0: concentration factor,
V_{gj}: drift velocity,
$J = J_g + J_f = \alpha \bullet v_g + (1-\alpha) v_f$: volumetric flux of mixture,
J_g, J_f: volumetric flux of vapour and liquid,
v_g, v_f: velocity of vapour and liquid.

Also, the kinematic wave velocity, C_k, is defined as:

$$C_k = v_g + \alpha \cdot (J \cdot \frac{\partial C_0}{\partial \alpha} + \frac{\partial V_{gj}}{\partial \alpha} \qquad (3)$$

which implies the propagation velocity of the void fraction, α. The void correlation parameters, C_0 and V_{gj} were suggested by several formulations [4]. The kinematic wave velocity C_k gives the different value in velocities from the vapour velocity since the void correlation parameters depend on the void fraction, α.

Once the power distribution and inlet mass flow rate of the fuel channels are given, the steam quality, void fraction and various kinds of two-phase flow velocities can be calculated by using Eq. (1). On the other hand, if one of the two-phase flow velocities is measured, the inlet mass flow rate of the channel can inversely be estimated. However, various kinds of the parameters related to two-phase flow are included in the above-mentioned model such as C_k, v_g, v_f and J. Several different interpretations emerge from past studies regarding measured transit time. Kosary insisted that C_k could explain the measured transit time [2,4]. Chaudhary, however, insisted that the volumetric velocity J could explain the measured transit time [5]. Additionally, it was reported that two kinds of transit time, which corresponded to vapour and liquid velocities, were observed [6].

In these studies, the conclusions seem to be extracted from the data in limited conditions. The present work investigated the characteristics of two-phase flow velocity by extracting the conclusions, based on the amount of LPRM noise data acquired in various plant operating conditions.

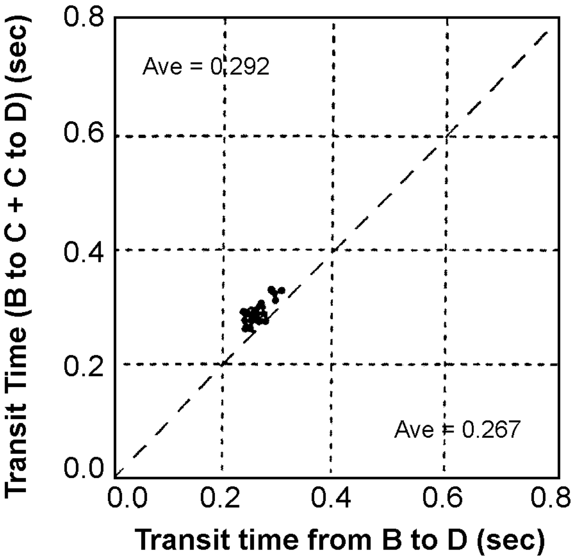
Interpretation of transit time

As new evidence of the interpretation of transit time, Figure 1 demonstrates an appeal to the logical inconsistency between the transit time measured for the different combination of LPRM detectors along the same string. Here, the comparison was made with the transit time measured directly from LPRM B to D, T_{BD}, against the summation by adding the transit time of LPRM B through C, T_{BC}, to C through D, T_{CD}. If LPRM signals measure the unique transit time, these two values should be consistent. Nonetheless, Figure 1 shows the relation,

$$T_{BD} = T_{BC} + T_{CD} - 25 msec \qquad (4)$$

The relation in Eq. (4) should make it understood that the slower propagating component was additionally included in the neutron fluctuating signals at the upper portion of the LPRM string. The slower propagating component is considered to be generated by the liquid phase, which suggests that the sensitivity of neutron signals depends on the void fraction near LPRM detectors. On the one hand, the detector response is physically sensitive to the vapour velocity in the lower void fraction region; on the other hand, it is sensitive to the liquid velocity in the higher void fraction region. The interpretation regarding these experimental results allowed us to propose the new calculation method of the transit time (Eq. 5).

Figure 1. Comparison of the transit time from LPRM B to D against LPRM B to C adding to C to D in the rated power and flow conditions for all 43 LPRM strings



$$
\begin{aligned}
T_{BC} &= w(\alpha_B)\cdot T_{g,BC} + (1-w(\alpha_B))\cdot T_{f,BC} \\
&= w(\alpha_B)\cdot \sum \frac{dz}{v_g(z)} + (1-w(\alpha_B))\cdot \int \frac{dz}{v_f(z)}
\end{aligned}
\tag{5}
$$

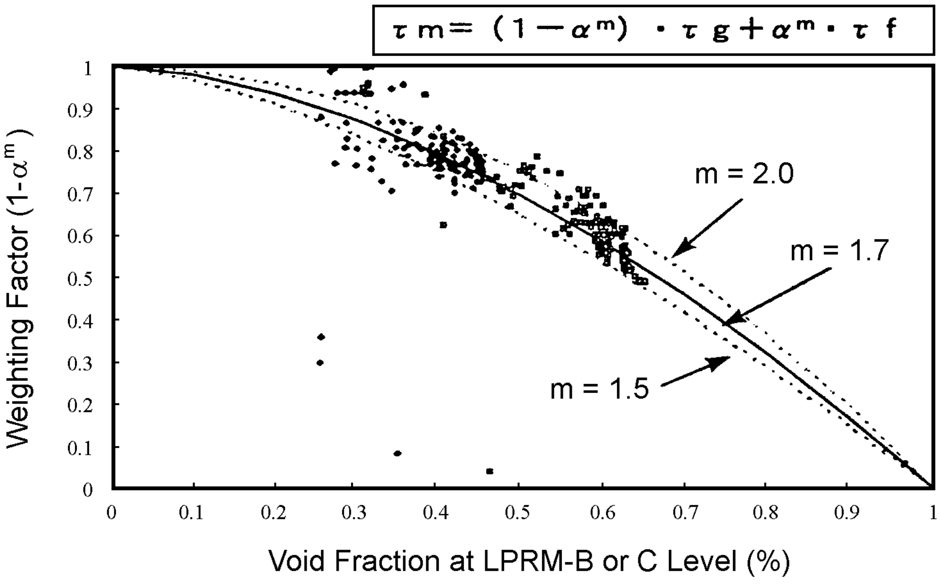
Here, the transit time from LPRM B to C levels, T_{BC}, is shown as an example. The transit time was calculated by the weighting of vapour and liquid velocities. The weighting factor in Eq. (5), $w(\alpha)$,should be determined as a function of the void fraction of the lower detector position, $w(\alpha_B)$ at LPRM B, since the cross-correlation function can just account for the statistical randomness of the upper stream detector. This weighting parameter should be determined empirically from LPRM noise data acquired in wide range operating conditions. Figure 2 shows the estimating results of the weighting, $w(\alpha)$, as a function of the void fraction, α,. Here, the weighting parameters are estimated so that measured transit time from LPRM-B to C and C to D should be equivalent to ones calculated based on the two-phase flow model. The data are based on the pump trip transient test which covers the operating range of core flow rates from 50% to 100%. From the figure, the weighting parameter can be read as:

$$
w(\alpha) = 1 - \alpha\cdot m\,, \qquad m = 1.7 \tag{6}
$$

The shape in the figure can well explain the above-mentioned physics for LPRM detector sensitivities. Eq. (5) can also explain the inconsistency of the axial propagation time as follows:

$$
\begin{aligned}
T_{BD} &= w(\alpha_B)\cdot T_{g,BD} + (1-w(\alpha_B))\cdot T_{f,BD} \\
&= w(\alpha_B)\cdot (T_{g,BC} + T_{g,CD}) + (1-w(\alpha_B))\cdot (T_{f,BC} + T_{f,CD}) \\
&\neq T_{BC} + T_{CD}
\end{aligned}
\tag{7}
$$

Figure 2. Void fraction dependency of the weighting parameter for the mixed transit time



In addition to this interpretation, the consideration is inevitable for the different characteristics of four fuel channels surrounding the LPRM detector, and the existence of inserted control rods, which leads to the different power distributions of the fuel channels, results in different two-phase flow velocities. These discussions introduced the following weighting method over the transit time four fuel channels:

$$T_{BC} = \sum \phi_i(B)\phi_i(C)\alpha_i(B)T_{BC}(i) \tag{8}$$

Here, ϕ_i is the neutron importance function of the detector position. The important assumption is the weight factor, $\alpha_i(B)$, which depends on the void fraction of the lower part. This assumption coincides with the former assumption of Eq. (5).

Another new proposal on the data pre-processing was made by removal of the global fluctuating component. The fluctuation of LPRM signals is caused by both the global reactivity fluctuation near the detector. In order to clearly grasp the two-phase flow behaviour through LPRM signals, it is effective to remove the global fluctuating component from LPRM signals [8]. Figure 3 shows measured LPRM signals, the right-side ones of which are original and the others are processed by removal of the global component. The figure clearly shows the void propagation feature from the lower part to upper part after the removal. This pre-processing is also very effective for determining the transit time based on the cross correlation function. As exhibited in Figure 4, the dependency of high-pass filtering cut-off frequency on estimating the transit time diminished by removal of the global component. This contributes greatly to the accurate core flow estimation in using LPRM noise signals. The radial flow interference was revealed with this pre-processed data. Figure 5 shows the correlation coefficients of LPRM-A signals, in which the lower-left LPRM string is chosen as the base signal for correlation. The positive values show in-phase fluctuating strings and the negative values show out-of-phase. We, by removing the global component, observed these flow interference features clearly.

Figure 3. LPRM raw data and removal of the global noise component at the locations A, B, C and D

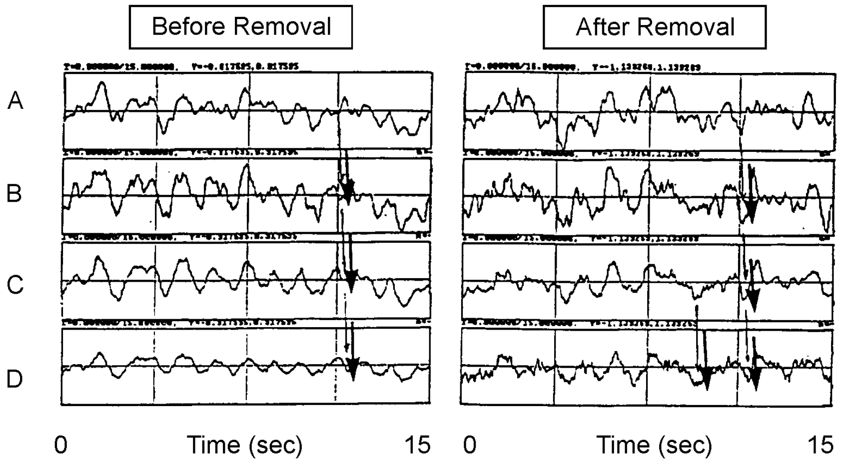


Figure 4. Cross-correlation functions of LPRM raw data and removal of the global noise for LPRM B and C by high-pass filtering

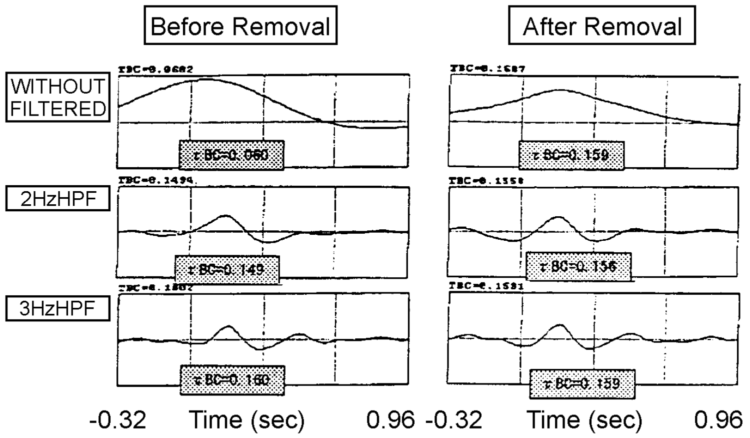
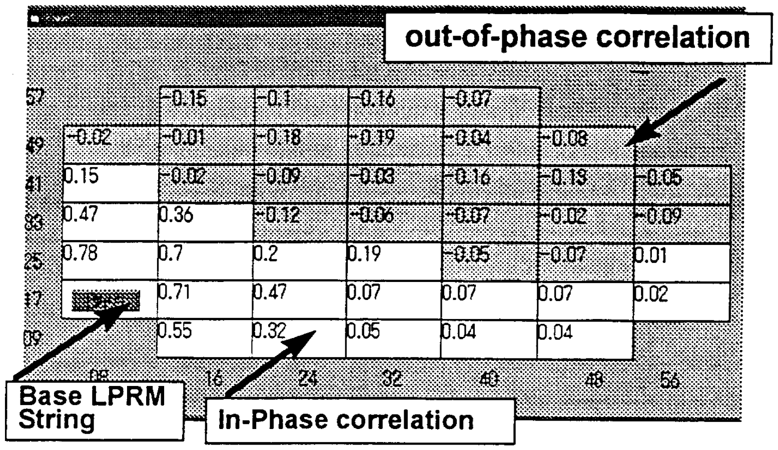


Figure 5. Out-of-phase correlation coefficients between the radial combinations of all LPRM A



	08	16	24	32	40	48	56
57		-0.15	-0.1	-0.16	-0.07		
49	-0.02	-0.01	-0.18	-0.19	-0.04	-0.08	
41	0.15	-0.02	-0.09	-0.03	-0.16	-0.13	-0.05
33	0.47	0.36	-0.12	-0.06	-0.07	-0.02	-0.09
25	0.78	0.7	0.2	0.19	-0.05	-0.07	0.01
17	▨	0.71	0.47	0.07	0.07	0.07	0.02
09		0.55	0.32	0.05	0.04	0.04	

Estimation procedure

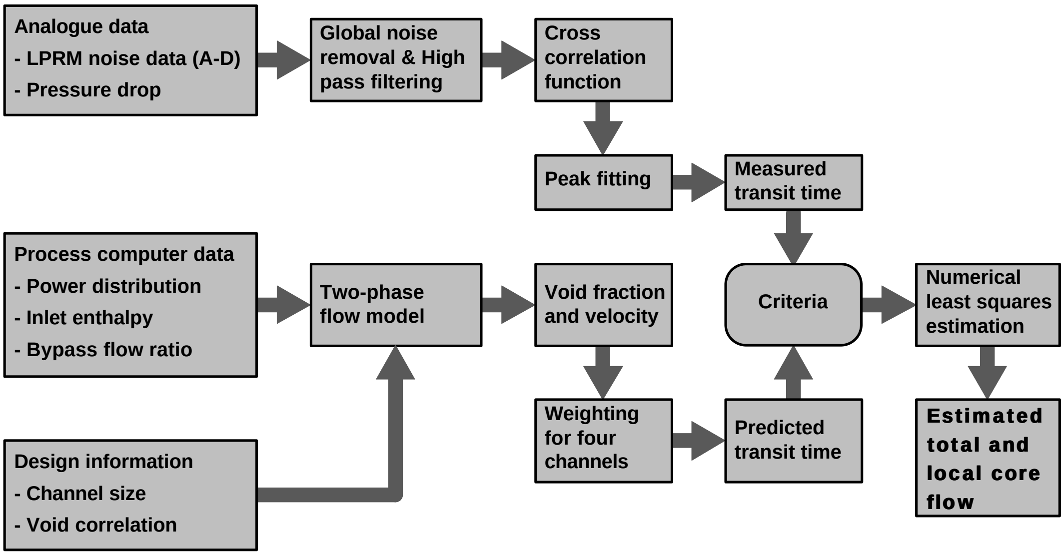
Estimation algorithm

On the basis of the above consideration, we have developed an on-line measurement system of the local and total core flow rates. Figure 6 shows the flow chart of the algorithm. The criteria for estimating the core flow adopted the method of the least squares sum of the calculated and measured time delays of void propagation over multiple LPRM strings as follows:

$$\mathrm{I} = \sum \{ w_1 \cdot (\mathrm{T}_{BC} - \mathrm{T}^{p}{}_{BC})^2 + w_2 \cdot (\mathrm{T}_{CD} - \mathrm{T}^{p}{}_{CD})^2 + w_3 \cdot (dP - dP^{p})^2 \} \tag{9}$$

In Eq. (9), T_{AB} of the lower part of LPRMs is omitted since LPRM-A level is considered the upstream of the boiling boundary in low core flow conditions. Also, the criteria may include the pressure drop; however, in the later described verification test, weighting, w_3, is set at zero. The total and local core flow rates can be estimated with reduced errors by minimising criteria numerically in Eq. (9).

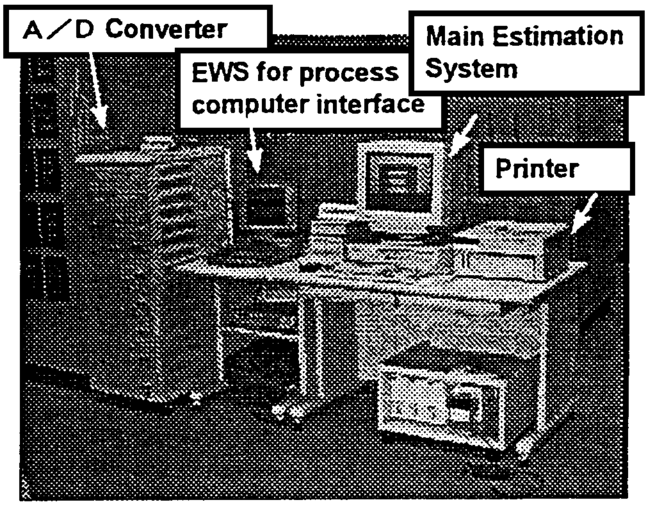
Figure 6. Estimation algorithm for core flow measurement



On-line system development

The process data information from the plant process computer system is necessary for the on-line flow estimating system of the core flow. The computer network system that combines the EWS and personal computers is built up to take in the process data. The estimation procedure is executed every five minutes in the current system by using the power distribution calculated in the process computer and LPRM analogue signals recorded for 60 sec lengths with 10 msec sampling frequency. Figure 7 shows the overview of the system hardware and the CRT display example. The system includes LPRM A to D detectors for 7 strings. Considering the CPU ability of the personal computer, real time core flow estimation will be possible within the time constant of a few-second order.

Figure 7. System hardware and CRT display for on-site and on-line testing demonstration of core flow measurement



Verification results

Verification with the re-start-up data of BWR-5

The verification tests of the present algorithm and system were carried out with the data of BWR-5 and ABWR. In the BWR-5 of 1100 MWe, the test data were measured by analogue data recorder for all 172 LPRM detectors at five different power-flow operating points, which cover from 30% to 100% core flow rates during start-up period after the annual outage. The power distribution data were also recorded from the process computer. After the analogue LPRM data were digitised by 10 msec sampling frequency and 60-second record-lengths, the total core flow rates were estimated by the present algorithm. As shown in Figure 8, the estimated core flow rates by LPRM neutron noise analyses well agreed with the measured core flow by the pressure difference over a wide range of core flow rates. The estimating error is regarded as 5% of the rated value in high core flow area, and as 10% in lower core flow area. In Figure 9, the data of the measured transit time of each LPRM string are compared with analytically calculated values. In this figure, a good correlation can be observed between individual LPRM strings, especially in higher core flow conditions.

Scattering is observed in lower flow rates. In order to reduce the estimation error in low flow conditions, longer statistical averaging of cross-correlation functions or averaging of numbers of LPRM strings are effective.

Verification with the start-up testings data of ABWR

The on-line flow estimating system was installed in the ABWR of 1356 MWe during the start-up testings, and various kinds of data were acquired and evaluated not only under normal power increase operating conditions but also transient testings such as a pump

Figure 8. Comparison of the core flow rates measured by LPRM noise signals and pressure drop

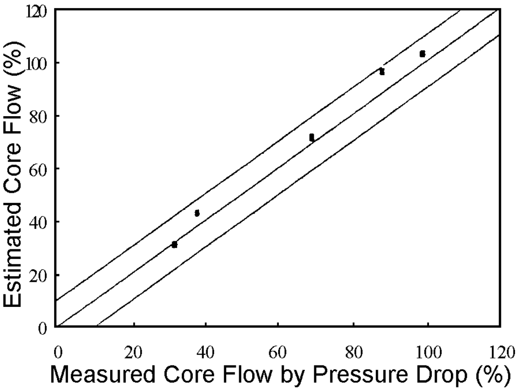
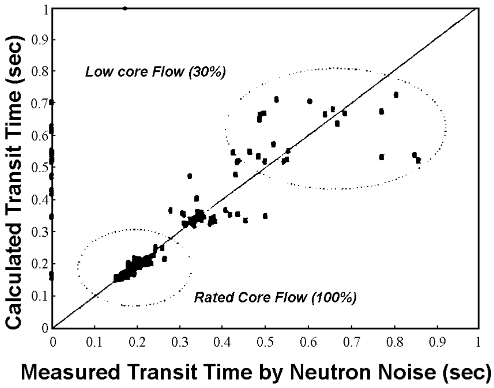


Figure 9. Comparison of the transit time measured by LPRM noise signals and calculated analytically



trip test. In the system, the LPRM noise data measured by seven strings and the power distribution derived from the process computer are stored as database by an interval of five minutes. In the present algorithm, there are several unknown parameters, which should be empirically optimised via accumulation of the noise database. A large amount of the database acquired in the current work should be very useful for verifying the validity of the algorithm and improving estimating accuracy. Figure 10 compares the total core flow estimation results with measured ones during three reactor internal pumps (RIP) trip tests. A good agreement suggests the usefulness of the present algorithm. Here, the estimation results based on the void propagation velocity C_k are also shown. As an additional interesting finding of the noise features of LPRM signals, Figure 11 shows the relation between LPRM normalised root-mean-square (NRMS) values and corresponding void conditions. NRMS values are calculated after 3 Hz-high-pass filtering for all LPRM detectors of A to D and averaged over seven strings. NRMS values are plotted as a function of the void fraction divided by square root of void velocity of the corresponding detector position. In [7], NRMS values are obtained by the square root of the void fraction divided by void velocity. The unique relationship in the figure suggests that this information can be used for the void fraction estimation as well as the transit time. Kozma *et al*. led the study to determine the flow patterns [9] by means of neutron noise analyses. Also, Figure 11 exhibits the possibility of flow regime monitoring by LPRM neutron noise analyses.

Figure 10. Comparison of the core flow rates estimated by LPRM noise signals with weighting to pressure drop base in the three-pump trip testing

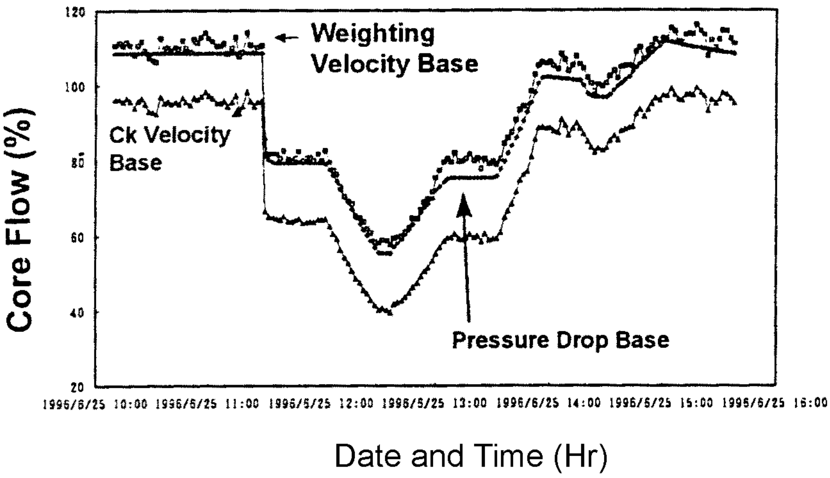
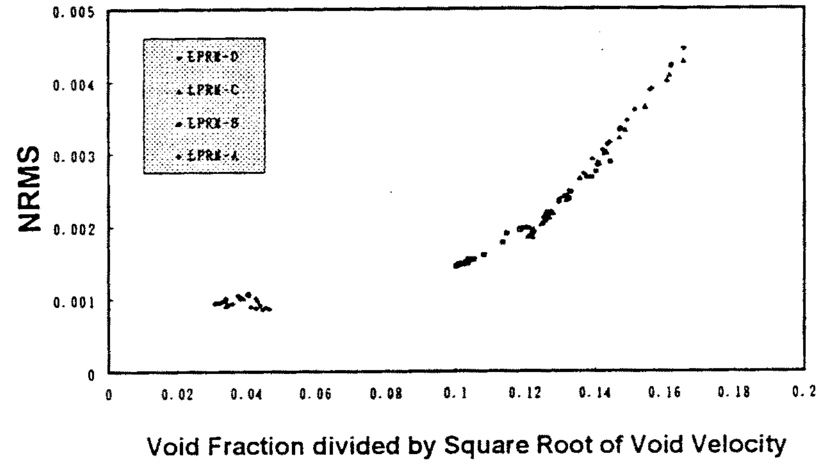


Figure 11. NRMS correlated with the void fraction divided by square root of void velocity



Remarkable summary

The extensive works to measure the reactor core flow were carried out by the advanced estimation algorithm using in-core neutron noise analyses of BWRs. Through LPRM noise data acquisition in various kinds of operating conditions, the validity of the present algorithm and the on-line measurement system for core flow estimation were confirmed. In particular, we proposed the concept of the LPRM transit time interpretation based on evaluating the neutron noise data in the operating plants. Besides the confirmation of flow estimating accuracy, further interesting findings were obtained in the present work. The physical interpretation on the new findings, which requires further studies, will be promising future possibilities of more sophisticated two-phase flow monitoring through the application of neutron noise analyses.

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