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Current Status on the Development of Sodium Boiling Detection System in Japan

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Abstract

Some studies for confirmation of the usefulness of the measurements of boiling sound and fluctuations of sodium temperature, flowrate and neutron flux for detection of sodium boiling have been curried out in Japan.

For the development of acoustic detection system, acoustic transmission decay and velocity change by fuel pins, gas plenum and neutron shield were measured.

Acoustic transmission from the reactor core to the detectors which were installed in the upper core structure and the upper flange of reactor vessel were studied theoretically and experimentally using the reactor vessel mockup.

Sodium boiling acoustic spectra which were dependent of detector positions were obtained in the out-of-pile experimental facility. Acoustic background caused by flow and electric noise were measured in the Experimental Fast Reactor.

On the other hand, coolant temperature and flowrate fluctuations caused by the sodium boiling were measured by the Temp/Flow detector which were mounted on the outlet of fuel subassembly.

Simulation tests by computer on the correlation method between neutronic and acoustic signals were carried out.

Current status and future plans about these studies in Japan are summarized briefly in this paper.

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1. Introduction

Detection of sodium boiling and boiling position in early stage are necessary because of high power density and positive reactivity coefficient of sodium void in center core of LMFBR.

For this reason, development of sodium boiling detection technique has been conducted in Japan.

The phenomena which could be used for sodium boiling detection are boiling sound, void, fluctuation change of temperature, flow and neutron flux. As boiling could happen by fuel coolant channel blockage before fuel failure occures, boiling detection method have advantage to prevent fuel failure in comparison with fission product detection method.

Many studies on acoustic detection method to be considered as the most useful means of boiling detection have been conducted so far.

These are boiling experiments in water and sodium test loops, acoustic propagation study, development of high temperature microphone and background noise measurement, etc..

We do not have authorized program of sodium boiling experiment in real LMFBR plant yet. So it is necessary to design acoustic detection system of LMFBR plant based on many simulation test results which include out-of-pile experiments at various different test conditions.

Other useful method of boiling detection is neutron flux fluctuation measurement, which is based on the reactivity change of void coefficient. But volume of void which causes effective change of reactivity may be larger than that of early stage of sodium boiling. So simulation study for improvement of detection sensitivity using acoustic and neutronic cross-correlation method are being conducted.

Void due to boiling could not arrive to the position of subassembly outlet instruments, but change of temperature and flow fluctuation might propagate to these detectors position.

This method have an advantage to detect abnormal fuel position,so out-of-pile tests have been conducted for confirmation of usefulness of this method.

The R&D programs which have been conducted in Japan are reviewed in this paper; Sodium boiling experiments in chapter 2, acoustic propagation study in chapter 3, measurements of background noise in Experimental Fast Reactor in chapter 4, acoustic and neutronic cross-correlation study in chapter 5, boiling detection by temperature and flow fluctuation measurements in chapter 6 are described respectively.

2. Detection of acoustic signal with sodium boiling

Measurements of sodium boiling acoustic energy level and spectrum are necessary in order to evaluate the possibility of sodium boiling detection by acoustic method.

For this purpose, sodium boiling experiments have been conducted using out-of-pile sodium boiling test loop shown in Fig.1.

Wire wrapped type of 37 heater pins, of which length is 1850 mm and outer diameter is 6.5 mmØ, are included in a hexagonal test tube.

Acoustic detectors of accelerometer and AE sensor were mounted on the supporting frame of the test section and on the side wall of the expansion tank through the wave guide rods. The expansion tank was 9 m away from the test section.

Sodium boiling was generated by increasing step by step the DC electric heater power up to maximum 650 KW.

Fig.2 shows the heat flux dependence of S/N ratio of acoustic level which was obtained by the accelerometer AC-102 on the supporting frame. In this case, sodium flowrate was 0.04 m/sec and inlet flow temperature was 438.1°C.

Acoustic level increased with time and heat flux. And S/N ratio reached to the value of about 30. The same order of acoustic level of S/N ratio was obtained by the accelerometer AC-101 which was mounted on the expansion tank.

Fig.3 shows an example of the sodium boiling acoustic spectrum detected by the accelerometer AC-102. In this case, sodium flowrate and inlet flow temperature were same as in Fig.2, and heat flux was 4.5 W/cm^2.

The dotted line indicates the spectrum of non-boiling state, and solid and chain line are those of boiling state. The resonant frequency of detector sensitivity is 30 kHz, so absolute level above 10 kHz is not correct. But the acoustic level increased with the inception of boiling over the wide range, and peak frequency at the 13 kHz region were observed. But the same peak was observed under the non-boiling state, so it does not to be characteristic to sodium boiling.

The frequency spectrum by the accelerometer AC-101 on the expansion tank has a peak at the 11 kHz region. And 11 kHz and 13 kHz frequency peaks were obtained by hitting the test section mechanically. So these peaks seem to be the effect of resonnance vibration of the test section structure.

3. Acoustic propagation study

Even if the boiling energy level is high, boiling detection is impossible if acoustic propagation decay between the boiling and detector position is large. So propagation tests were conducted using a simulation mockup of reactor vessel in Fig.4 which has fuel assemblies, upper core structure and water flow loops.

First, propagation decay arises within the fuel subassembly. Propagation decay as well as acoustic velocity along the direction of subassembly axis were different at the each position of fuel pellet, gas plenum and neutron shielding block. Total decay ratio was about 50 dB and acoustic velocity was smaller in fuel pellet than in pure water, and in gas plenum it was the same order of the value of shear velocity.

On the other hand, propagation decay along the direction perpendicular to the subassembly axis was about 25 dB/SA, so propagation to the radial direction through whole core seems to be difficult. So main acoustic propagation path to the detector position is the direction of subassembly outlet.

Acoustic energy level distribution from the outlet of subassembly were spreaded by the neutron shielding block.

Two locations of acoustic detectors were considered. One position is within the upper core structure, and it has advantage of short distance to the boiling position, while it has problems of sensitivity and durability. Another position is on the upper flange of reactor vessel, it has opposite properties to the former.

The propagation decay rate was about 10 dB to the upper core structure through the heat shielding plate and about 20 dB to the region of sodium upper level.

There were not large difference between the detection sensitivities of the accelerometers which were mounted on several places of reactor vessel wall, and they were not affected by the existence of upper core structure.

Flow noises were smaller in the upper core structure than on the vessel wall, but the final S/N ratio of these two types of detectors were of the same order.

4. Acoustic background noise detection in the Experimental Fast Reactor

Background noise in the plant influences to the possibility of boiling detection.

Three high temperature acoustic detectors are installed in the upper core structure of the Experimental Fast Reactor "JOYO". Location of these sensors are between the driver and blanket fuel region, and at the height of 400 mm above the subassembly outlet.

The sensors are dipped in the liquid indium which is isolated from coolant sodium using SUS tube. The crystal of sensor is $LiNbO_3$ in which Li is enriched to Li^7 for endurance against neutron radiation and attached to be soldered to the SUS diaphragm. Detection sensitivity is -160 dB (0dB=1V/μbar) over the frequency range of 10 - 150 kHz.

The RMS and frequency spectrum of background noise were measured under the several operational conditions of JOYO, i.e. sodium temperature was 250 °C — 460 °C, flowrate was 0 — 5 m/sec and pressure was 0 — 0.7 kg/cm^2G.

Fig.5 shows the flow dependence of background noise spectrum at the reactor shut down. Background noise at 20 % and 100 % flow level were larger about one decade than at 16 % flow level (during pony motor operation) over the range of 0 — 50 kHz. There was not large difference between spectrum of 20 % flow and 100 % flow except below 5 kHz region.

Peak at 20 kHz — 30 kHz region is supposed to be the effect of electric noise mainly from pump control system of primary coolant loop, and peak of 40 kHz region to be the effect of aliasing of 60 kHz peak.

Flow dependence of RMS value was not recognized for the frequency range of 10 - 50 kHz and flow range of 20 — 100 %, but RMS increased about twice with the flow increase for the frequency range of 5 — 10 kHz.

The spectrum and RMS value were almost constant for the reactor power range of 0 — 75 MW at the constant flow of 100 %.

5. Acoustic and neutronic cross-correlation study

The void caused by sodium boiling is in principle detectable by the neutron fluctuation from the reactivity change if the void coefficient of reactivity is not practically zero. But neutron flux fluctuation is affected by the change of temperature and flow and the control rod vibration. So these background noises are important factors in the boiling detection problem.

Fig.6 shows the relation between the detectable void volume and background noise level using the reactivity estimator based on the optimal estimation technique. Reactivity change of 0.3 ¢ is detectable for the case of neutron noise level of 2 %, and this corresponds to the 300 cm^3 void volume at the position of 2 $m¢/cm^3$.

Such large void volume is unexpected at the early stage of boiling. So correlation study with other kind of signal such as the acoustic signal are being conducted for the improvement of detection sensitivity.

The preliminary study was started using computer simulation method. Void signals of 50 msec pulse width were generated at the mean rate of 150 msec, and acoustic signal and neutron flux were calculated by the reactor dynamics simulation computer. Four noise generators were used for the random modulation of acoustic noise level, neutron noise level, void generation period and void volume.

The coherence function between acoustic and neutronic signals were obtained changing the S/N ratio of acoustic boiling signal and neutronic boiling signal independently.

Coherence of 0.7 was obtained for the case of neutron signal S/N ratio of 1 and acoustic signal S/N ratio of 2. From this preliminary test, coherence method was found to be useful.

6. Boiling detection by temperature and flow fluctuation signals

Some studies have been conducted for the confirmation of whether detection of the boiling by temperature and flow sensors is possible, because generation and extinction of void due to boiling causes the fluctuation of temperature and flow at the outlet of subassemblies.

Test section was almost the same as that in Fig.1, and has 61 wire wrapped type mimic pins which length and diameter were 1568 mm and 6.5 mmφ, respectively. 37 pins were heated electrically and 54 flow channels were blockaged by the SUS plate.

T/C s' of 0.3 mmφ within the fuel pin bundle and Eddy Current Temp/Flow Sensor at the outlet of subassembly were used.

Test condition was that inlet coolant temperature was 500 °C, heat flux was 60 W/cm^2 and initial flow rate was 1 m/sec. Boiling was attained by decreasing the flowrate.

Boiling was generated at the back of the blockage plate, and the temperature fluctuation increased up to more than 10 times. At the end of pin bundle, any change of fluctuation level was not found, but spectrum of temperature fluctuation had frequency peak of 4 Hz which corresponded to the boiling generation period.

At the outlet of subassembly, RMS and frequency spectrum of temperature and flow fluctuation did not show distinguishable change. This may be because of large flow mixing at the outlet of pin bundle.

Fig.7 and Fig.8 are time chart of values of fluctuation, RMS, AR(Auto-regressive) of temperature and flow signals measured by the T/C and flow sensor at the outlet of subassembly. From the raw data of fluctuation and RMS, distinction between boiling and non-boiling may be impossible, but AR value, especially of flow signal, seems to be affected by the boiling. So signal processing by AR method of temperature and flow rate signals seems to have possibility to detect sodium boiling.

7. Conclusion

Boiling detection is important for the prevention of fuel failure and safety of reactor operation. So many kinds of developments have been conducted, and the following results were obtained so far;

(1) Sodium boiling acoustic signals are detected at the near and far (about 9 m) distance from the boiling position in the 37 pins test section, so acoustic method is effective means for boiling detection.

(2) Acoustic signals from the reactor core in the simulation model of reactor vessel are detected by the sensors in the upper core structure and on the reactor vessel wall at the same order of S/N ratio.

(3) Acoustic background noises in the Experimental Fast Reactor "JOYO" are independent of reactor power over the frequency range of 10 - 50 kHz.

(4) Computer simulation tests about the correlation of acoustic and neutronic signals confirmed it to be useful for improvement of boiling detection.

(5) AR (Auto-regressive) method for processing of temperature and flowrate fluctuation signals has possibility for boiling detection more than RMS method.

Boiling detection has hopeful prospect from the results of various kinds of studies. But for the establishment of final detection system, still several experiments must be carried out; measurements of absolute boiling energy, improvement of durability and S/N ratio of detector, improvements of detection sensitivity of boiling and boiling position by correlation method between acoustic, neutronic, coolant temperature and flowrate signals,etc..

For these purpose, R&D will be continued using out-of-pile sodium boiling 91 pins test section, water reactor, etc. in Japan.

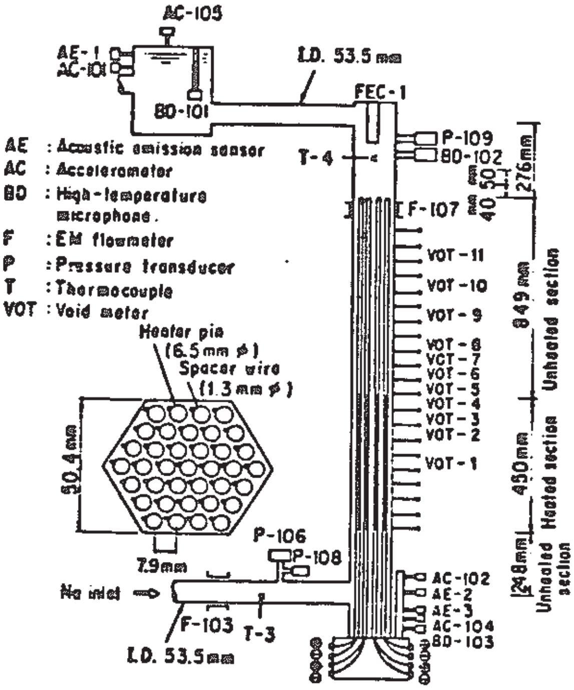

Fig.1 Sodium boiling test section

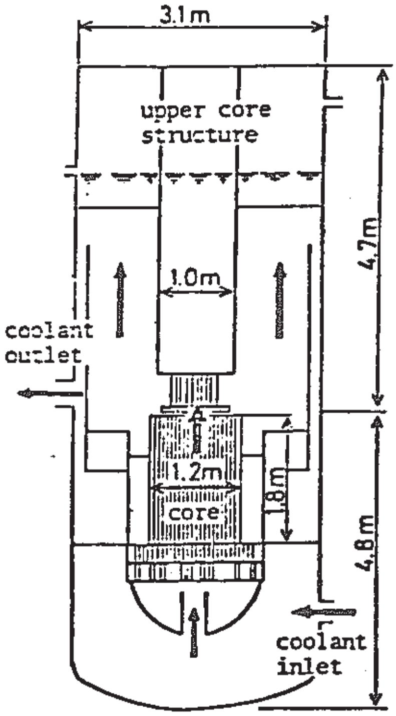

Fig.4 Simulation model of LMFBR

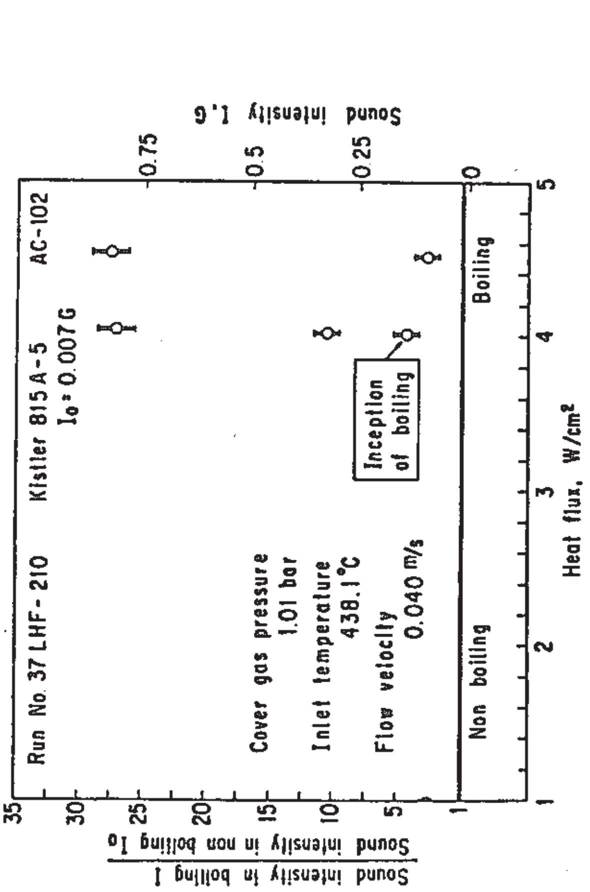

Fig.2 Effect of heat flux on the intensity of acoustic signals measured by accelerometer AC-102 during state boiling Run No.37LHF-210

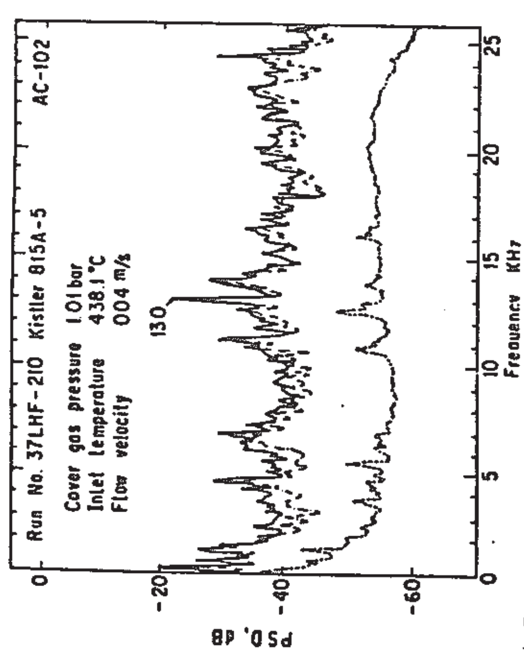

Fig.3 Frequency spectra of acoustic signals measured by accelerometer AC-102 during steady-state boiling Run No.37LHF-210

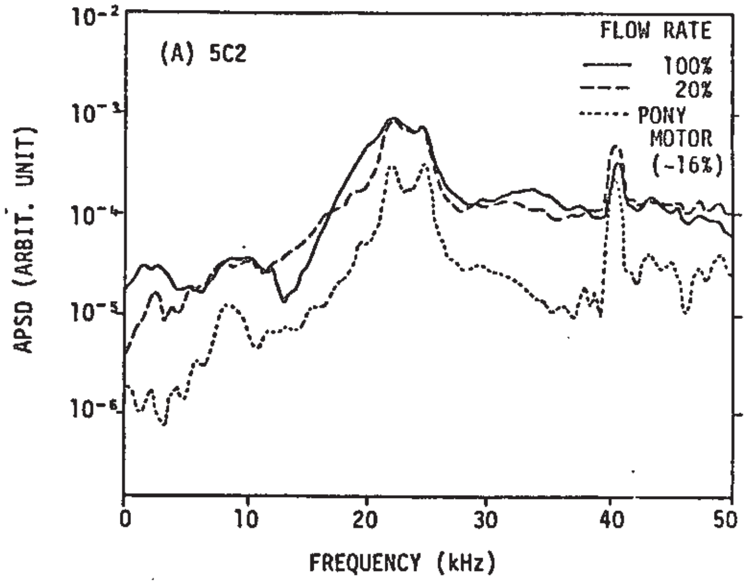

Fig.5 Auto power spectral densities of in-core acoustic signal (Reactor shut down)

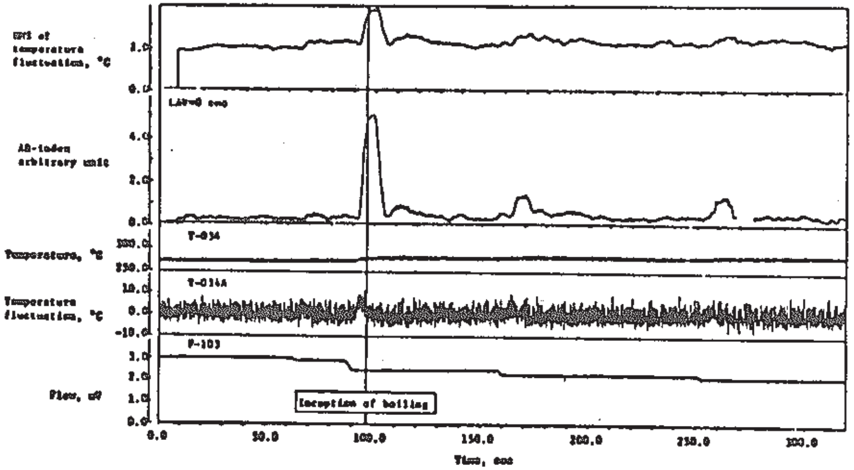

Fig.7 RMS value and AR-index of temperature fluctuation measured by the subassembly outlet thermocouple

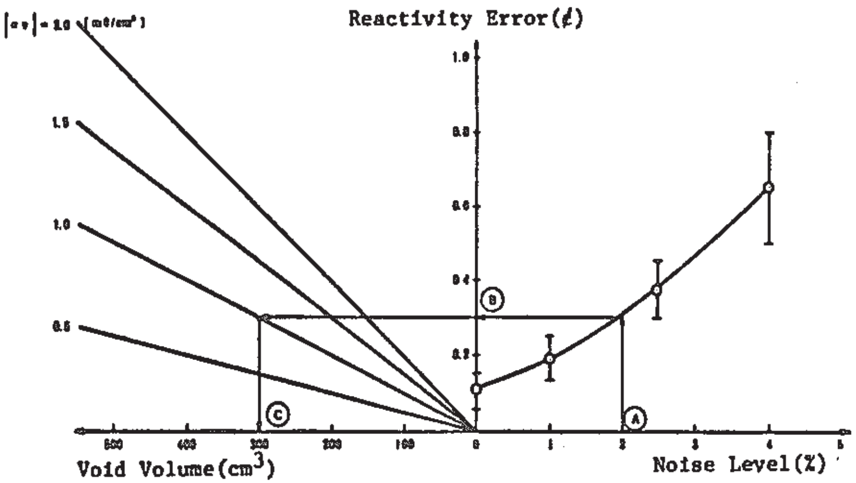

Fig.6 Relation between neutron noise level and detectable void volume

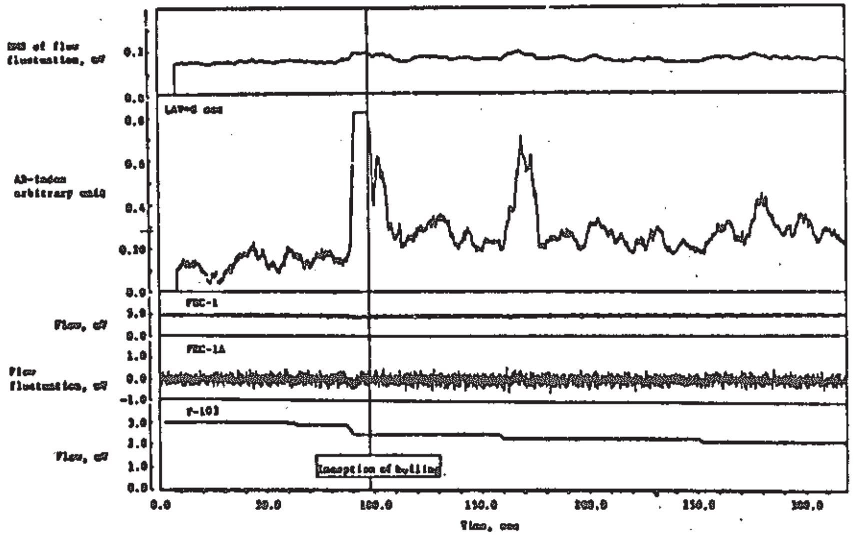

Fig.8 RMS value and AR-index of flow fluctuation measured by the subassembly outlet flowmeter