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ACOUSTIC NOISE WITH SODIUM BOILING IN A SEVEN-PIN BUNDLE

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ABSTRACT

This paper deals with the acoustic noises associated with sodium boiling in a seven-pin bundle, six central channels of which were blocked.

The acoustic intensity first increased with rise in the heat flux, and after attaining a maximum, decreased somewhat to remain more or less constant thereafter. At the final upstream voiding which resulted in the dryout, however, the acoustic intensity increased sharply.

The frequency spectrum did not change markedly during boiling. Distinct peaks observed in the high frequency range for all the measurements could well be related to the characteristics of the resonances of the experimental system which is not the waveguide, but the test section and/or the expansion tank. On the other hand, the peak observed at the low frequency was due to the repetition of bubble formation and collapse.

INTRODUCTION

Anomalas sodium boiling due to local flow blockages should be detected in its incipient stage in LMFBRs, since sodium boiling could propagate the fuel failure, finally leading to total core failure. Among the various methods proposed for the detection of boiling, the measurement of acoustic noise signals associated with the boiling phenomenon appears to be the most promising.

In the previous paper(1), which dealt with the single-pin forced-convection sodium boiling experiments, the authors showed that the spectra of acoustic noise emitted with boiling did not differ distinctly from that registered when boiling was not apparent. If the noise was filtered to eliminate its low-frequency components, the level of noise intensity associated with boiling first increased sharply with rise in the heat flux to attain a maximum value, then decreased somewhat and remained constant thereafter.

In the present paper, some informations will be given of the acoustic noise associated with sodium boiling in a seven-pin bundle, which may be related to the frequency of bubble formation and the bubble size.

EXPERIMENTAL EQUIPMENT AND OPERATING PROCEDURES

A series of seven-pin forced-convection sodium boiling experiments were carried out in the SIENA loop at PNC's Oarai Engineering Center. Figure 1 shows the schematic diagram of the SIENA loop and the positions of the acoustic transducers.

In order to simulate a LMFBR fuel assembly, an electrically heated seven-pin bundle was centered in a hexagonal tube of 24 mm in inside flat-to-flat distance. Each pin was 6.5 mm in diameter and had a 450 mm heated length. The pitch-to-diameter ratio (P/D) was 1.22. The central six channels of the bundle, which corresponded to 42% of the total bundle cross-sectional flow area, were blocked by a 0.5 mm thick stainless steel plate at 350 mm downstream from the start of the heated zone. The detail of the test section is described in another paper by the authors$^{(2)}$.

Three types of acoustic transducers were used in order to measure the boiling acoustic noise. The first were accelerometers — Kistler Model 815A5 — mounted onto waveguides which were placed to the expansion tank. Secondly strain-gauge-type pressure transducers — Shinkoh Models PR-5S and PR-10S — were provided at the inlet and the outlet of the test section to measure the changes of pressure in boiling sodium. The third was a Sony Model ECM-21 microphone which was set outside the test section.

Figure 2 shows the instrumentation and data processing system for the acoustic noise signals. The signals from the acoustic transducers were then amplified and recorded on an Ampex Model FR-1800L tape recorder. The tape recordings of the acoustic signals were analysed using an EMR Model 1510 real-time analyser. An NF Circuit Model M-172TA AC voltmeter was used for measuring the acoustic noise intensity, conditioned by a Multimetrics Model AF-120 filter.

In the present experiment, the inlet temperature and flowrate were held constant and the heat flux was gradually increased to boiling inception. After boiling had thus set in, the heat flux was further increased step by step until dryout occurred.

INTENSITY OF ACOUSTIC NOISE

Figure 3(a) shows the effect of changes in heat flux q on the intensity ratio I/Io measured by the accelerometer Ac-102 during the steady-state boiling run 7(6)LB-214, where I is the noise intensity at given flux q, and Io the noise intensity when devoid of boiling. In this figure the experimental results are also shown of the bubble size and frequency. It is seen that the acoustic intensity first tends to increase with rise in the heat flux, and after attaining a maximum, decreases somewhat to remain more or less constant thereafter. This tendency is similar to the previous single-pin experiments$^{(1)}$. At the final rapid upstream voiding which resulted in the dryout, however, the acoustic intensity increases sharply.

During the first stage of boiling, preceding the attainment of maximum noise intensity, the boiling is considered to be in a state of developing nucleate boiling (mainly bubbly flow). In this state the acoustic noise caused by the collapsing bubble increases with rising the heat flux since the liquid around the bubble is yet subcooled so highly that the bubble collapses completely although the bubble becomes larger with higher heat flux.

Fully developed boiling may be established after the point of maximum noise intensity. The decreasing noise intensity can be attributed to the two factors, as described by I.D. Macleod et al.$^{(3)}$. The first is the decrease of subcooling, which slows down the bubble collapse and so reduces the noise source. Secondly, the increased amount of vapor in the channel increases absorption.

The final noise increase at the rapid upstream voiding is due to the sodium-hammer phenomenon, which is occurred at the time when the disturbance waves of liquid film on the channel wall, which travel fast in the annular-mist flow, collide with the downstream liquid column.

Figure 3(b) shows the effect of heat flux on the acoustic noise intensity measured by the pressure transducer P_N-105 during the same boiling run 7(6)LB-214. The tendency indicated in this figure is similar to that in the former Fig. 3(a).

SPECTRUM OF ACOUSTIC NOISE

Figure 4(a) shows the frequency spectra of acoustic noise measured by the accelerometer A_c-102 during the boiling run 7(6)LB-214. It can be seen that the boiling causes a considerable increase in intensity at all frequencies, but the frequency spectrum does not change markedly during boiling, from boiling inception until dryout. Distinct peaks are observed for all the measurements. The analyses of frequency spectra are described in detail in the reference 4. Only a brief recapitulation will be given here. First the peaks in the kilohertz range are not peculiar to the boiling acoustic noise, but related to the characteristics of the resonances of the experimental system, because the frequency spectrum of boiling acoustic noise is similar to that of acoustic noise with striking the test section by a hammer. Secondly the resonance peaks are not due to the waveguide, but due to the test section and/or the expansion, since the frequency spectrum is not influenced by the length of waveguide.

Figure 4(b) shows the frequency spectra of acoustic noise measured by the pressure transducer P_N-105 during the same boiling run 7(6)LB-214. The frequency range in this figure is lower than that in the former Fig. 4(a). The peak which is observed at the frequency of 19.6 Hz for the heat flux of 10.319×10^5 kcal/m^{2}h, is due to the repetition of bubble formation and collapse. The peak at 4.4 Hz for 12.613×10^5 kcal/m^{2}h is also due to the bubble repetition.

BUBBLE SIZE AND FREQUENCY

The effect of heat flux on the bubble size and the frequency of bubble formation has already been shown in Fig. 3(a). The experimental results were evaluated according to the following assumptions.

The sodium bubble is considerably larger than the water bubble, because of the high liquid-to-vapor density ratio of sodium. It is considered that the generation of a second bubble is inhibited by the pressure rise due to the development of the first bubble in the narrow space of the channel. This justisfies the assumption that only one bubble exists at one time, which permits evaluation of the frequency of bubble formation from the observed oscillations of the outlet flowmeter records, during the period preceding the arrival of the bubbles to the flowmeter position. On the other hand, the volume of the bubble may be evaluated by integrating the increment of outlet flowrate between the instant of bubble formation and that of its attaining maximum volume.

In Fig. 5 the frequency f is plotted against the diameter d_o of an equivalent sphere having the same volume as the bubble when it attained its maximum size. In this figure the experimental results(1) are also shown of a single-pin geometry. It is seen that the frequency lowers with increasing bubble diameter. At the fixed frequency the bubble generated in the seven-pin geometry is larger than that in the single-pin geometry. This fact can be attributed to the two-dimensional bubble growth which is created in the seven-pin geometry. The bubble can expand not only in the axial direction, but also in the radial direction.

A hyperbolic curve represents Jakob's relation for pool boiling with ordinary liquid(5), which is expressed by $f \cdot d_o = 280$ (m/hr). It is seen that the single-pin experiment is in good agreement with Jakob's equation.

CONCLUSIONS

An experimental study was carried out of acoustic noises associated with forced convection sodium boiling in a locally blocked seven-pin bundle. Analyses of the experimental results yielded the following conclusions.

(1) The boiling caused a considerable increase in acoustic noise intensity. The noise intensity with boiling first increased with rise in the heat flux, and after attaining a maximum, decreased somewhat to remain constant thereafter. At the final upstream voiding which resulted in the dryout condition, however, the noise intensity increased sharply. This final increase of noise intensity was attributed to the sodium-hammer phenomenon which occurred when the disturbulence waves on the channel travelled fast in annular-mist flow to collide with the downstream liquid column.

(2) The frequency spectrum did not change markedly during boiling, from boiling inception until dryout. Distinct peaks observed in the high frequency range for all the measurements could well be related to the characteristics of the resonances of the experimental system which is not the waveguide, but the test section and/or the expansion tank. On the other hand, the peak observed at the low frequency was due to the repetition of bubble formation and collapse.

(3) The frequency of bubble formation lowered with increasing the bubble size at its point of maximum development. The product of bubble frequency and equivalent diameter obtained in the present seven-pin experiment was larger than that in the previous single-pin experiment.

ACKNOWLEDGMENT

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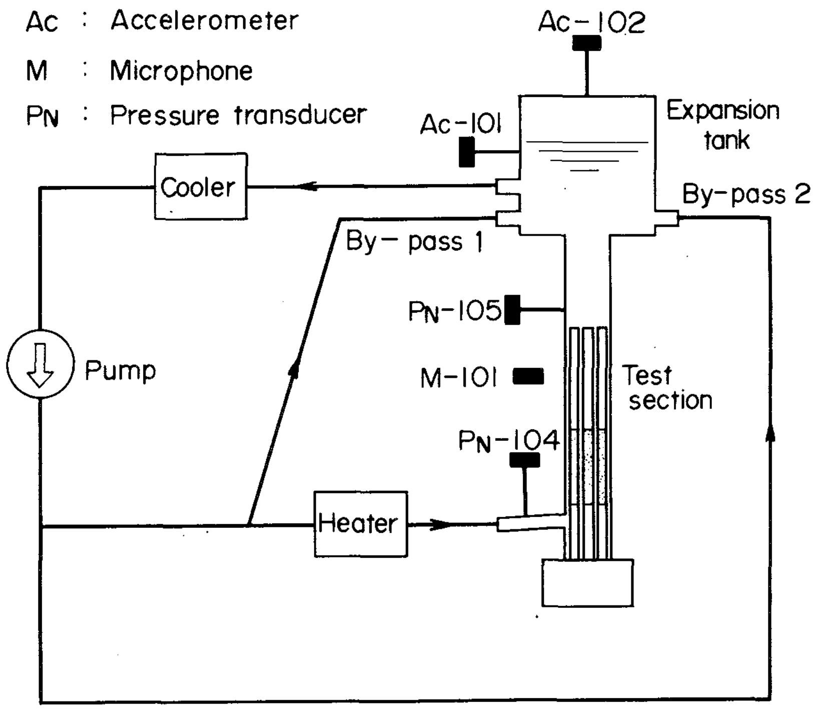

Fig. 1 Schematic diagram of the SIENA loop and the positions of acoustic transducers (PNC-FS-268)

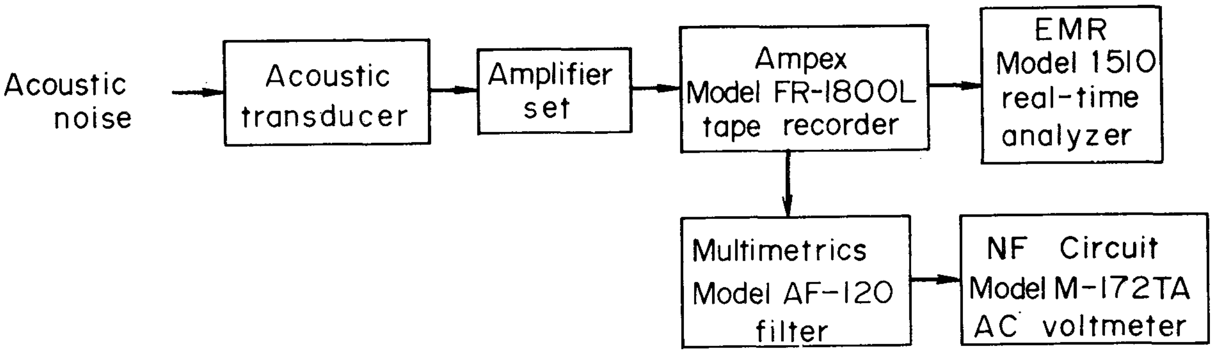

Fig. 2 Instrumentation and data processing system for boiling acoustic noise signals (PNC-FS-269)

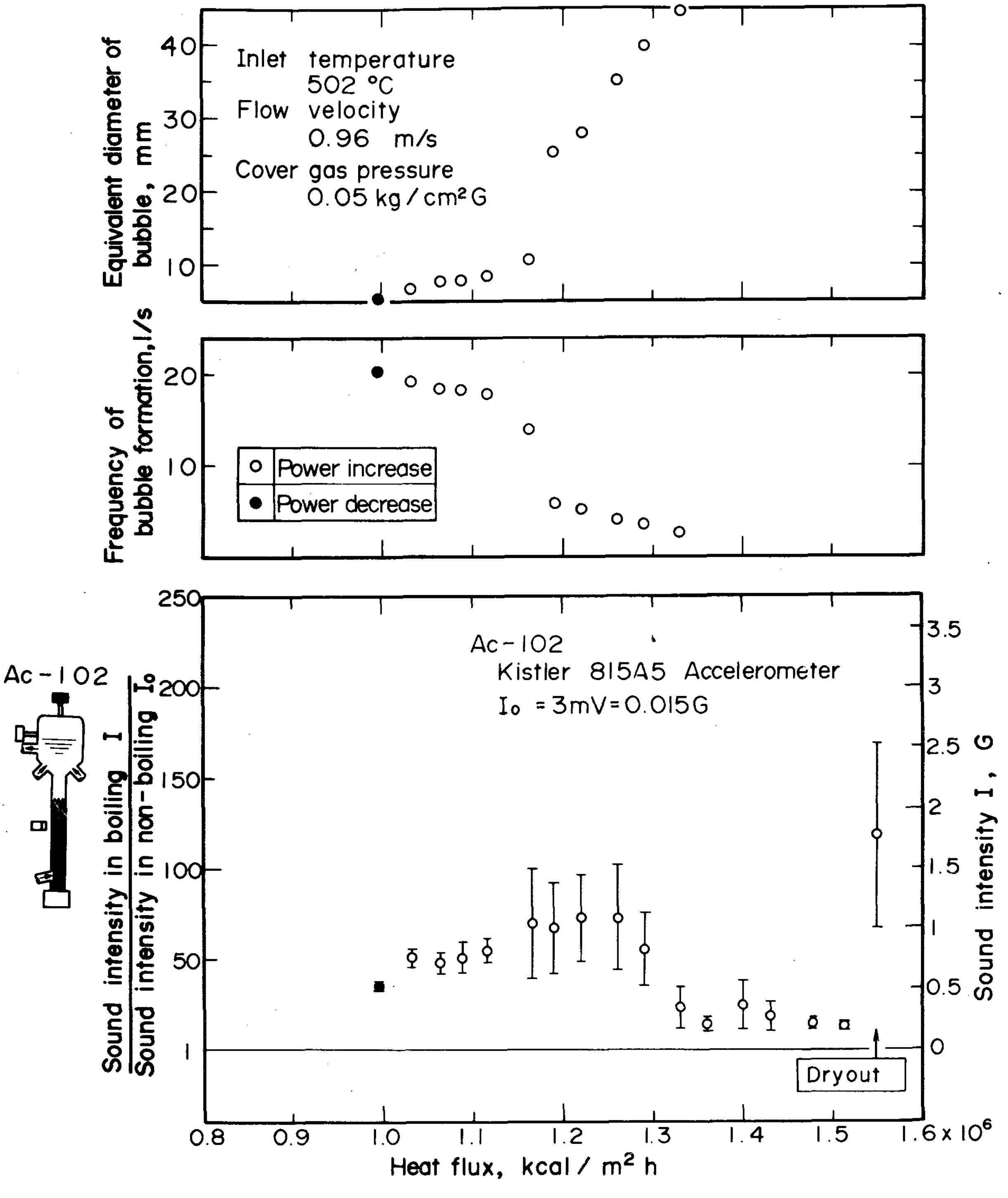

Fig. 3(a) Effect of heat flux on intensity of boiling acoustic noise, frequency of bubble formation and equivalent diameter of bubble — steady-state boiling run 7(6)LB-214 (PNC-FS-270)

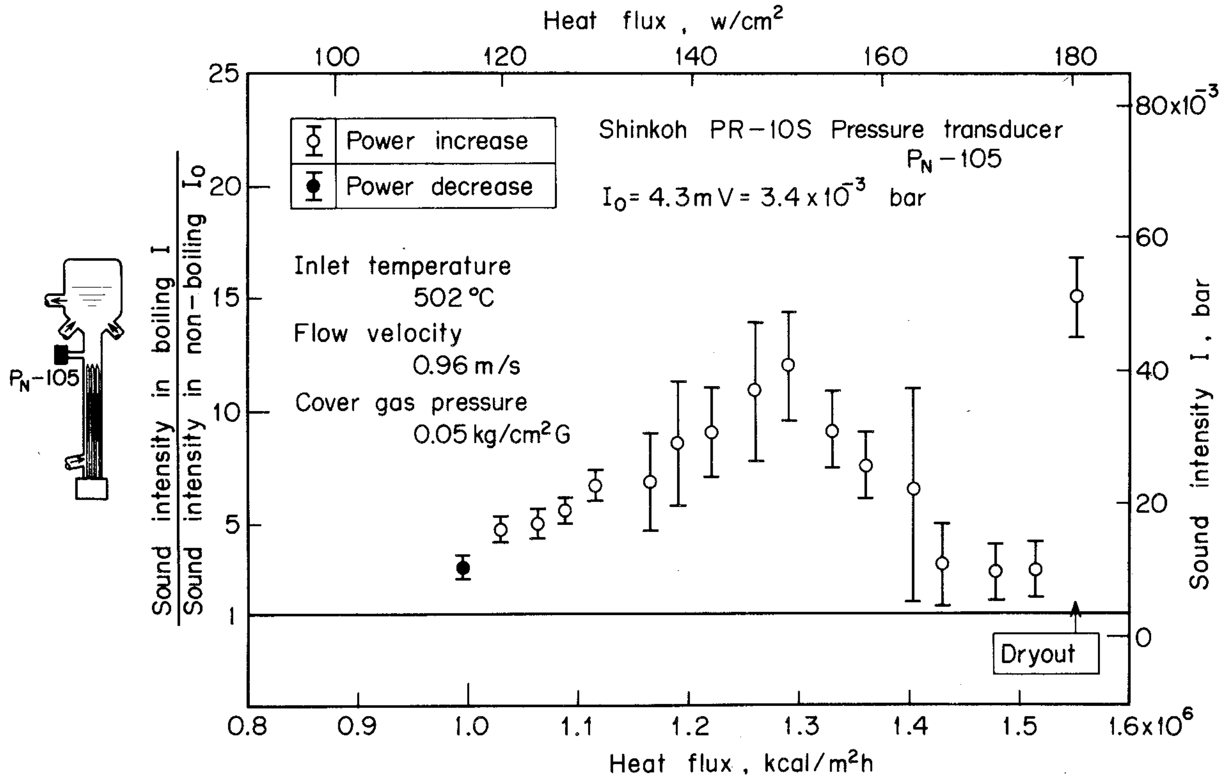

Fig. 3(b) Effect of heat flux on intensity of acoustic noise with boiling in a locally blocked seven-pin bundle —steady-state boiling run 7(6)LB-214 (PNC-FS-264)

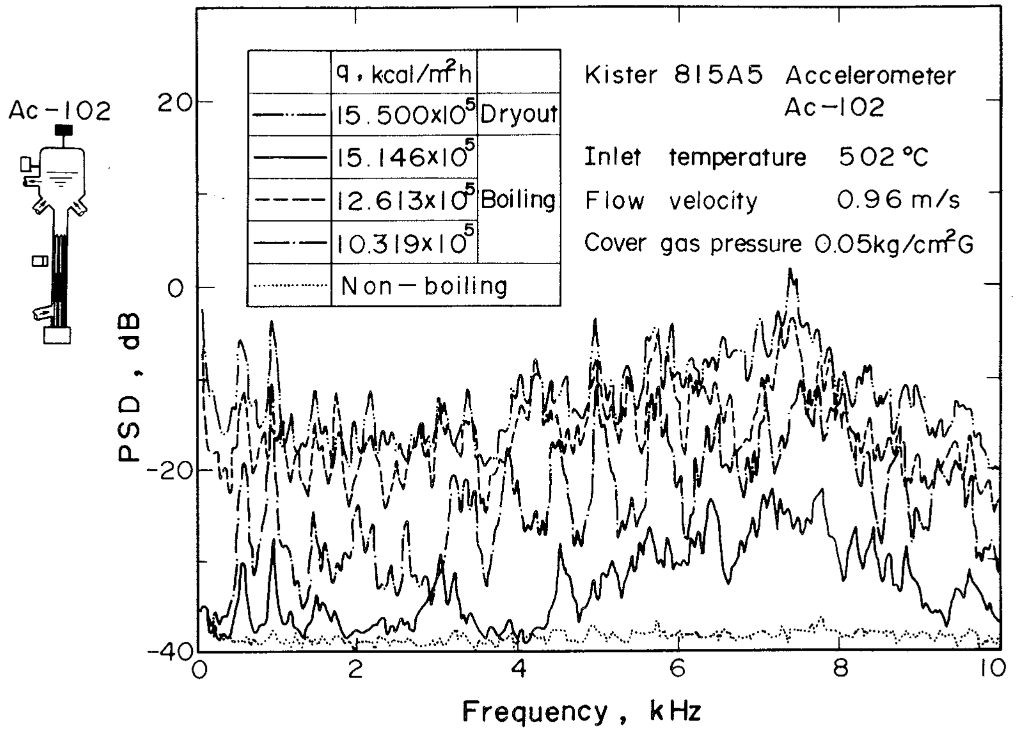

Fig.4(a) Frequency spectra of acoustic noise with boiling in a locally blocked seven-pin bundle — steady-state boiling run 7(6)LB-214 (PNC-FS-271)

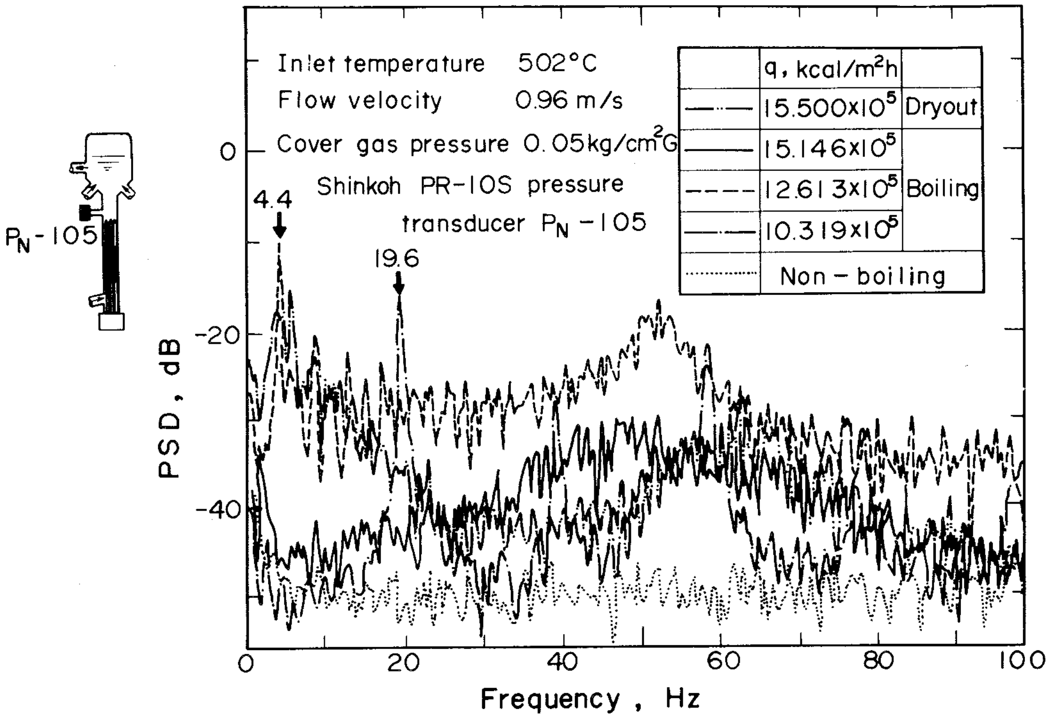

Fig.4(b) Effect of heat flux on frequency spectra of acoustic noise with boiling in a locally blocked seven-pin bundle.—steady-state boiling run 7(6)LB-214 (PNC-FS-272)

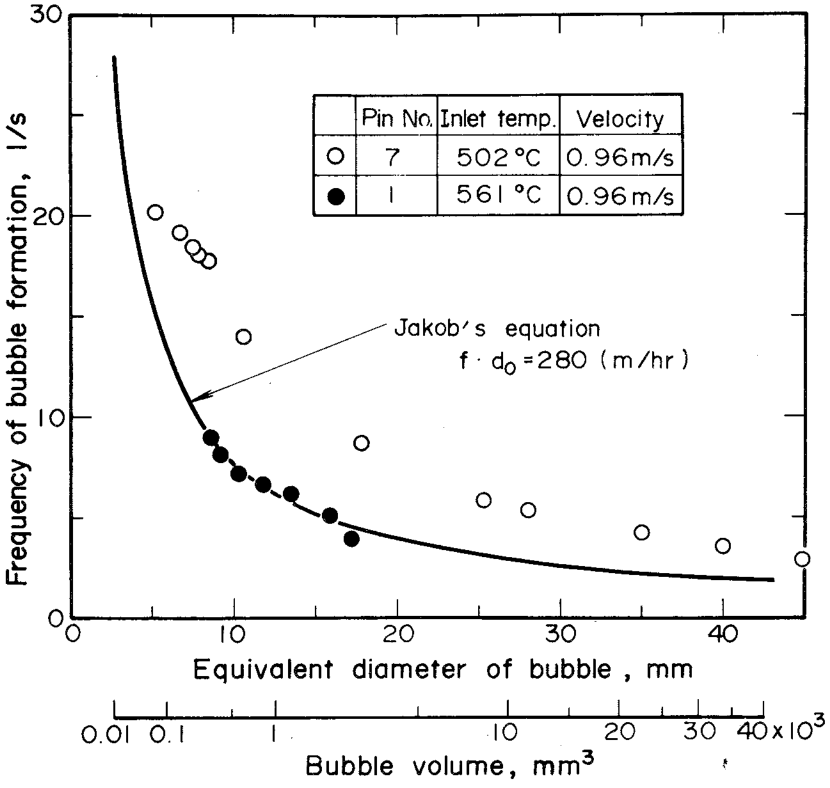

Fig. 5 Relation between equivalent diameter of bubble and frequency of bubble formation (PNC-FS-275)