Experimental Study of Steady-State Boiling of Sodium Flowing in a Single-Pin Annular Channel

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An experimental study was carried out on steady-state boiling of sodium flowing in the annular channel formed around an electrically heated simulation of a fuel pin. In the present experiment, the inlet temperature and flow rate were held constant, and the heat flux was gradually increased up to the inception of boiling. Thereafter, the heat flux was further increased step by step until the surface temperature of the heater pin marked a sharp rise, indicating the occurrence of dry-out. Records were obtained of the changes brought by the increasing heat flux to boiling phenomena, with particular reference to the behavior of the two-phase flow pattern and to the characteristics of boiling noise, as well as of the frequency of bubble formation.

It was made clear that there exists a region in which steady-state boiling will be established, and under these conditions the two-phase flow pattern changes sequentially from bubbly flow to slug flow and then to annular flow. This behavior of sodium boiling in a narrow channel is quite similar to the case of water.

With rising heat flux, the level of noise intensity associated with boiling first increased sharply to attain a maximum point, then decreased somewhat and remained constant thereafter until dry-out.

The frequency of bubble formation depended on the size of the bubble. The product of bubble frequency and equivalent diameter was found to be constant.

KEYWORDS: ***sodium boiling, single pin, two-phase flow, acoustic noise, bubble growth, steady state, forced convection, annular channel***

I. INTRODUCTION

Much effort is now being directed to developing the sodium-cooled fast-breeder reactor. In such reactor systems, sodium boiling which could occur in certain types of accident is an important problem for reactor safety considerations, since it may possibly lead to fuel melting through instabilities occasioned in the sodium flow or through the lowering of heat transfer from fuel to sodium.

Experimental studies have been carried out in this connection, using the Sodium Boiling Test Loop installed in the Oarai Engineering Center of the Power Reactor and Nuclear Fuel Development Corporation. Steady-state boiling was produced in sodium flowing in the annular channel formed around an electrically heated simulation of a fuel pin. Records were obtained on the changes brought by increasing heat flux to boiling phenomena, with particular reference to the behavior of the two-phase flow pattern, acoustic boiling noise and the frequency of bubble formation. This paper is a sequal to the preceding report(1) which mainly covered incipient boiling of sodium.

In most studies of forced-convection liquid-metal boiling reported to date(2)~(4), the inlet temperature and flow rate were

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held constant and a single one-step increase in power was imposed on the test heater. The behavior of sodium boiling in such experiments usually follows the pattern of the violent slug expulsion model, and steady-state boiling is rarely observed. Takahashi *et al.*[6] have conducted an experiment on sodium boiling using direct joule heating. In their case, continuous steady-state boiling was observed, because, with direct joule heating, the input power is sharply depressed upon formation of the vapor phase. On account of this close relationship between boiling intensity and power input that is established in the case of direct joule heating, however, the boiling phenomena observed in their experiment would differ in nature from the steady-state boiling established under constant heat flux.

In the previous paper, on the other hand, the authors have shown that incipient boiling could be initiated in a state of quiet steady-state boiling even with the inlet temperature and flow rate held constant, when the heat flux was gradually increased.

In the present study, the experiment was continued with the heat flux further raised gradually after boiling inception. A discussion will be presented on the changes with rising heat flux observed in boiling phenomena, with particular reference to the behavior of the two-phase flow pattern. Some information gained on the acoustic boiling noise and the frequency of bubble formation will also be given.

II. EXPERIMENTAL EQUIPMENT AND OPERATING PROCEDURES

This paper is a sequel to the preceding report[1] in which the experiment equipment and general operating procedures are described in detail. Only a brief recapitulation will be given here. The main circulation loop comprises an electromagnetic pump, two electromagnetic flowmeters, a preheater, a test section, an expansion tank and a cooler.

The test section, as seen in **Fig. 1**, is constituted of a vertical annular channel formed between an electrically heated pin (*i.e.* heater pin) 6.6 mm in diameter and 780 mm long and a type-316 stainless-steel tube of 9.8 mm inside diameter. The heater pin has an effective heated length of 600 mm and three thermocouples inserted underneath a 0.6 mm thick cladding. The inlet and outlet temperatures also were measured with thermocouples. Potential-tap-type void-meters were used for observing the behavior of bubbles. The sodium velocities at the inlet and outlet were measured with electromagnetic flowmeters. Additionally, a microphone was set near the test section for detecting boiling noise.

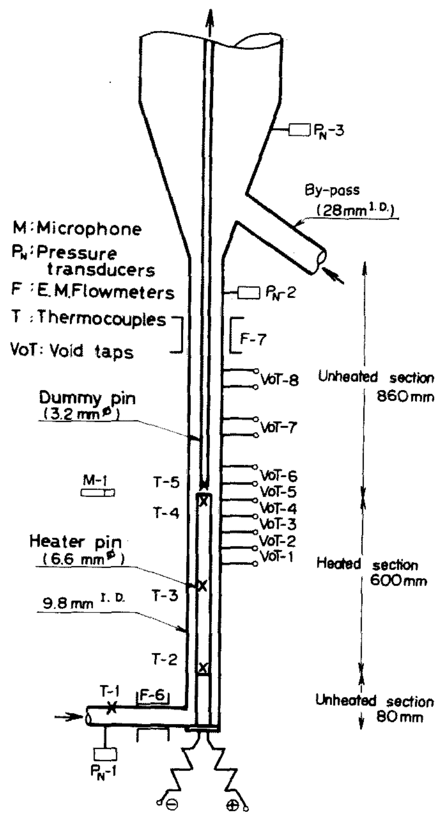


Fig. 1 Test section

In the present experiment, the inlet temperature and flow rate 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 the surface temperature of the heater pin began to rise sharply, confirming that the test section had not failed even under dry-out conditions. In one run in which steady-state boiling was realized, the test section was exposed to sodium at temperatures ranging between 600° and 900°C during about 3 hr and half from the start of the power increase to extinguishment of boiling.

III. RESULTS AND DISCUSSIONS

1. Two-phase Flow Patterns in Steady-state Boiling

(1) Incipient Boiling

Figure 2(a) represents typical patterns of inlet and outlet flow velocities, inlet and outlet temperatures, pin-surface temperatures, and void fraction during the stage of incipient boiling. The experimental conditions are: 0.01 kg/cm^2·G system pressure, 2.38 l/min inlet flow rate (equivalent to a velocity of 0.96 m/sec), and 561°C inlet temperature.

As it can been seen in the figure, the outlet flowmeter F-7 registers an abrupt change upon boiling inception, which is followed by oscillations. These oscillations indicate a repetition of bubble formation, escape and disappearance at a fixed frequency. But the inlet flow rate is maintained constant, as confirmed by the record of F-6. On the other hand, the pin-surface temperature T-4, which is close to the boiling region, is seen to fluctuate after boiling inception. The other pin-surface temperatures T-2 and T-3 indicate no fluctuations, being located upstream of the region influenced by boiling. It is clear from the outlet temperature T-5 that the liquid around the vapor bubbles is highly subcooled. When the tip of the bubble enters the subcooled liquid, its growth is markedly inhibited. Thus, the void-meter VoT-4 cannot detect incipient boiling since it sends no output signals before a considerable amount of bubbles has accumulated.

(2) Bubbly Flow

Figure 2(b) shows the changes of heat flux, flow velocities, temperatures and void fraction after the establishment of bubbly flow. In this stage, all temperatures except the inlet temperature T-1 rise with increasing heat flux. At this stage, however, the outlet temperature T-5 is still below saturation, and the boiling continues in a subcooled environment. The void fraction increases up to about 0.3, keeping almost a constant value. It is to be noted that, while the inlet flow rate (F-6) is maintained at a nearly constant value, the outlet flowmeter F-7 registers violent oscillations.

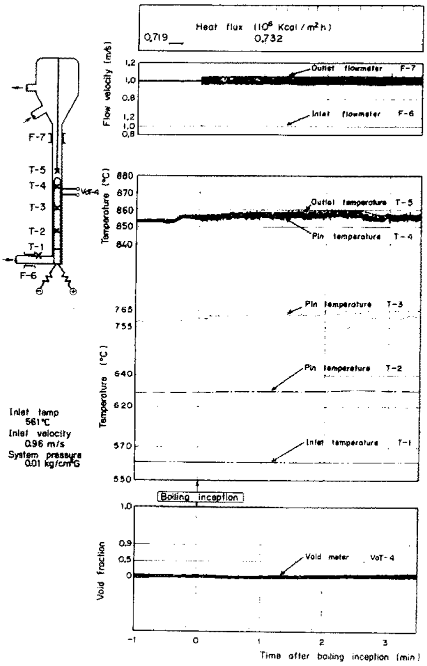
(3) Slug and Annular Flows

Figure 2(c) shows the changes of heat flux, flow velocities, temperatures and void fraction under conditions of slug flow and annular flow. Violent oscillations are recorded for the outlet flow velocity during the first half of the period covered, and the void fraction gradually rises during this period, to reach a value of about 0.7. This first stage may be considered to represent a region of slug flow. During this period, the pin-surface temperatures T-2, T-3 and T-4 reveal no apparent signs of any particular change in flow pattern.

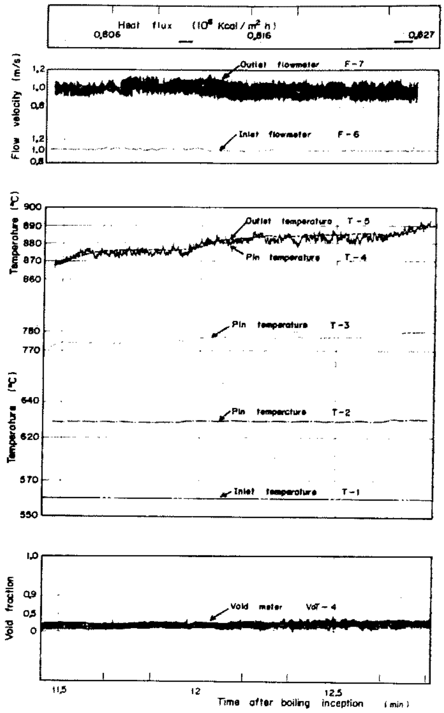
Further increase of the heat flux to 0.857 $\times 10^6$ kcal/m^2·hr produces an alteration in mode of the outlet flow signals from F-7. This change is brought about by the bubbles reaching the position of this flowmeter. The bubbles cause violent oscillations in the void-meter signals, on which is superposed a ripple pattern of fairly long period. These oscillations in the void fraction signals have an upper limit around 0.9, as seen in the right-hand half of Fig. 2(c). The outlet flow rate, on the other hand, settles down from the violent oscillations set up during slug flow to a steady ripple that appears to mark a pattern similar to that of the void fraction. The outlet temperature T-5 attains the saturation temperature of sodium, which commences saturated boiling.

The foregoing behavior is considered to indicate the onset of annular flow (or annular-mist flow), in which saturated sodium vapor or vapor mixed with liquid sodium globules flows between films of liquid sodium flowing along the wall surface. The liquid films are estimated to be approximately 0.13 mm thick, to correspond to a void fraction of 0.8.

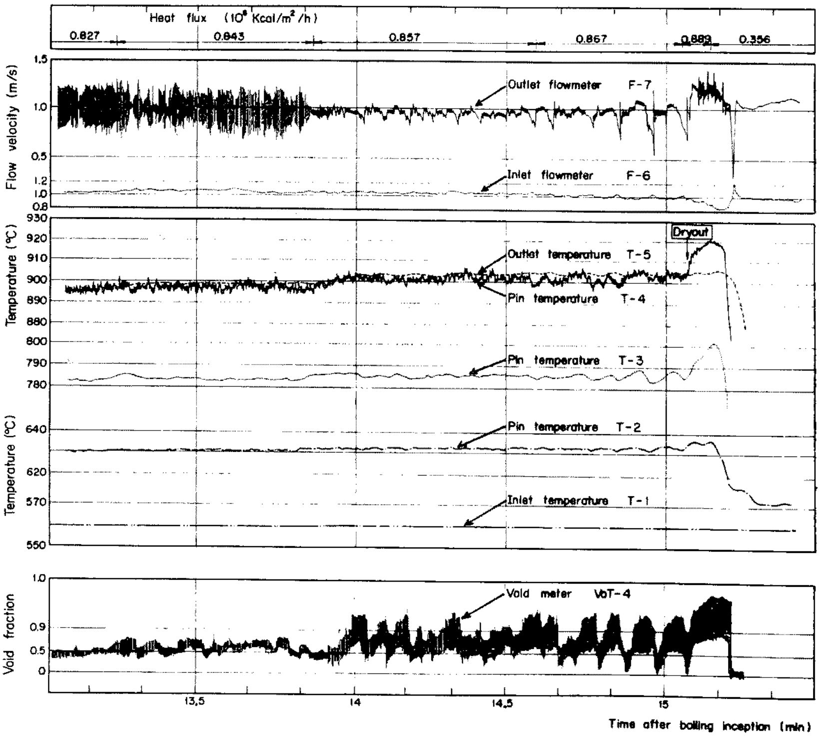
Upon further increase of the heat flux up



(a) Incipient boiling



(b) Bubbly flow



(c) Slug flow and annular flow

Fig. 2 Records of signals from flowmeters, thermocouples and void-meter is steady-state boiling run B-102 to 0.889×10^6 kcal/m^2·hr, the pin-surface temperature T-4 is seen to register a sharp rise, marking the occurrence of dry-out of the residual liquid film. This causes a large amount of vapor bubbles to be generated, which transiently depresses the inlet flow rate, as reveals by the sharp valley appearing in the record of F-6. The outlet flow rate, on the other hand, is increased by the ejection of liquid. The heater pin then became exposed to the danger of burn-out, and the input power to the heater pin was therefore quickly slackened down to a heat flux of 0.356×10^6 kcal/m^2·hr. The heat capacity possessed by the heater pin, however, prevented the pin-surface temperatures from lowering immediately.

2. Acoustic Noise Associated with Boiling

It has been affirmed in a number of published studies that the characteristic acoustic noise accompanying boiling phenomena could usefully serve as indicator for observing the intensity of boiling, and that the detected noise signals could be used for controlling the operation of heat exchangers. In particular, anomalous coolant boiling was considered to be detectable in its incipient stage in liquid-cooled reactors, which are free from boiling in normal operation. Particular interest has been drawn to this approach in connection with LMFBRs, in which coolant boiling could lead 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 appeared to be the most promising[(6)].

In order to utilize acoustic signals for this purpose, however, it is necessary before all to know the manner in which the characteristics of the observable data (frequency spectrum, intensity) depend on the principal variables governing the boiling process, which are heat flux, pressure and subcooling. The effect of changes in the heat flux on the noise intensity has been the subject of published studies[(7)~(9)] and it can be considered established that the intensity tends first to rise sharply, and then to remain virtually constant irrespective of further increase in heat flux. The frequency spectrum changes little with heat flux. The effect of pressure and subcooling on the acoustic noise has been treated by Kichigin & Povsten[(10)]. These studies however were carried out on pool boiling of ordinary nonmetallic liquids, particularly water. To the present authors' knowledge, there exists extremely little data on liquid-metal boiling.

In order to gain further knowledge on this aspect, a study was undertaken on the effect of heat flux on the intensity and the frequency spectrum of acoustic noise associated with boiling of sodium under forced convection.

(1) Instrumentation System

Figure 3 depicts the instrumentation and data processing system for the acoustic noise signals. The system was devised for detecting, conditioning, recording, and analyzing the acoustic signals that accompany boiling.

A microphone was set near the test section of the experimental installation. The microphone—a Sony Model ECM-21—had a flat response up to 40 kHz. This sensor was connected to a tape recorder—a Sony Model 9540—which served to record, store and reproduce the boiling acoustic noise signals. Noises up to 20 kHz could be recorded with a tape speed of 9.5 cm/sec. For monitoring, a Pioneer Model SE-100 headphone was used.

A Rion Model SA-21 ⅓ octave real-time spectrum analyzer was used for the spectral measurements. This unit has a frequency range from 44.5 Hz to 22.4 kHz. The spectral display appears on the screen of a cathode ray tube with the frequency of the applied signal scaled on the horizontal axis, and the intensity of the signal displayed on the vertical axis. The frequency scale is logarithmic.

An NF Circuit Model M-172TA AC voltmeter was used for measuring the acoustic intensity, conditioned by a Multimetrics Model AF-120 active filter. The AC voltmeter has a frequency range from 5 Hz to 2 MHz.

(2) Spectrum of Acoustic Noise

Figure 4 shows the frequency spectra of

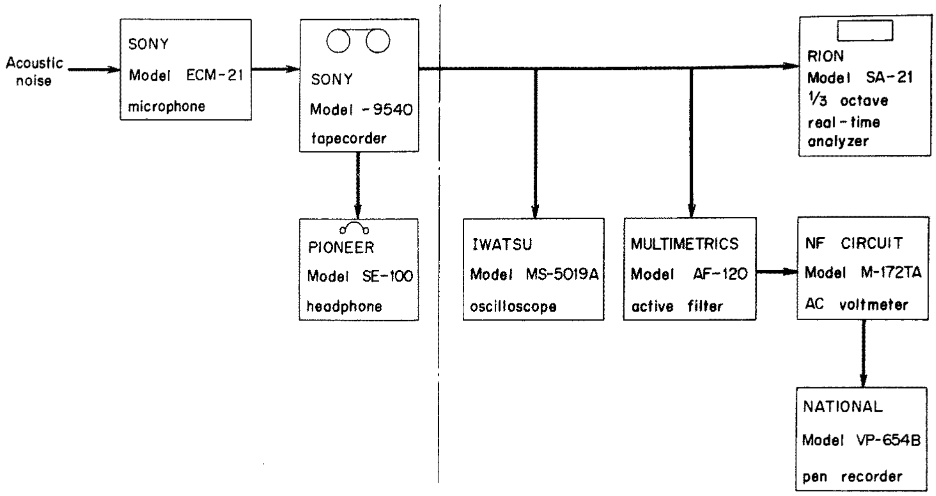


Fig. 3 Instrumentation and data processing system for boiling acoustic noise signals

acoustic noise recorded during boiling as well as before its onset, in a run during which steady-state boiling was generated (run B-102). It can be seen that the configuration of the frequency spectrum does not change markedly upon boiling inception, but that the boiling causes a considerable increase in intensity at all frequencies. Distinct peaks are also observed in the kilohertz range for all the measurements, more particularly when boiling has set in. These peaks may well be related to the characteristics of the resonances of the test section system and/or the microphone[11].

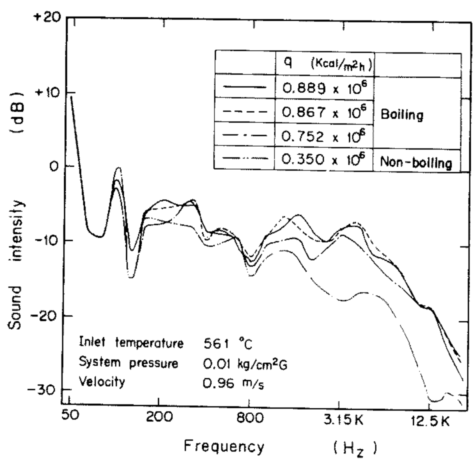


Fig. 4 Frequency spectra of acoustic noise with boiling—steady-state boiling run B-102

From the foregoing observations, it will be seen that spectral analysis reveals little information about boiling, since boiling causes only a general rise in intensity and does not bring about any radical change in the spectrum characteristics. It follows, therefore, that to perform a spectral analysis would not be very useful, as it would only increase the measurement time without producing much positive information. It would appear to be much more reasonable to rely on wide-band intensity measurements, by which an increase in band-width could be utilized to reduce measurement time without sacrificing sensitivity.

(3) Intensity of Acoustic Noise

Figure 5 shows the effect of changes in heat flux q on the intensity ratio I/I_0 for the steady-state boiling run B-102, where I is the noise intensity at given flux q, and I_0 the noise intensity when devoid of boiling. Each curve represents the acoustic intensity, as registered after passage through the particular high-pass filter that is indicated in the figure. It is seen that with any high-pass filter, the acoustic intensity first tends to increase sharply upon boiling inception, as the heat flux is gradually raised, and after attaining a maximum, decreases somewhat to remain more or less constant thereafter. This particularity is accentuated as the cut-

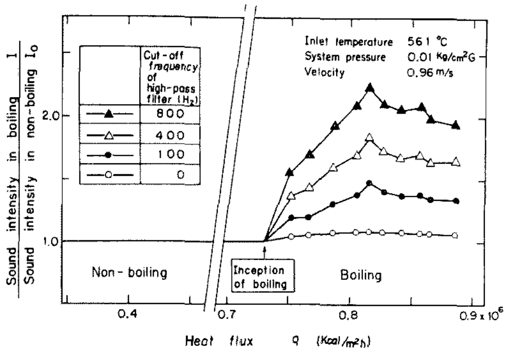


Fig. 5 Effect of heat flux on intensity of acoustic noise with boiling—steady-state boiling run B-102

off frequency of the filter is made higher.

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). Fully developed boiling, established after the point of maximum intensity, should correspond to slug flow and annular flow.

The foregoing observations would indicate that wide-band intensity measurements should be most useful for application to reactor operation (to set off an alarm, to reduce reactor power automatically *etc.*). The irrelevant pump noise and other hydrodynamic noises can be eliminated with a high-pass filter to improve the signal-to-intensity ratio.

3. Bubble Size and Frequency

The size and shape of vapor bubbles departing from a heated surface are strongly influenced by the manner in which they are formed. For non-metallic liquids that wet the heated surface, the size of bubbles at departure from the heated surface has been studied by a number of people[12]. Fritz[13] considered a balance between buoyancy and surface tension forces to derive the expression for departure diameter:

$$d_0=0.0208\,\theta\left[\frac{\sigma}{g(\rho_l-\rho_v)}\right]^{1/2}, \qquad (1)$$

where θ, σ, g, ρ_l and ρ_v are contact angle, surface tension, acceleration due to gravity, liquid density and vapor density respectively.

A formula for predicting bubble frequency on a heated surface has not yet been well established. Jakob[14] has observed that the frequency f of bubble formation depends on the size of the bubbles upon their departure from the heated surface, and suggested for hydrogen and water bubbles the relation

$$fd_0=280\ \text{(m/hr)}. \qquad (2)$$

Nishikawa *et al.*[15] proposed the equation $fd_0=400$ m/hr. Later Zuber[16] derived the form

$$fd_0=0.59\left[\frac{\sigma g(\rho_l-\rho_v)}{\rho_l^2}\right]^{1/4}. \qquad (3)$$

Under conditions where the bubble departure process is governed by dynamic forces, the relationship becomes fd_0^2=const.[17] For water at atmospheric pressure, bubble departure diameters are in the range of 1∼2.5 mm and bubble frequencies in the range of 20∼40 sec^{-1}.

Most past studies have been conducted on pool boiling with ordinary nonmetallic liquid as medium. There are no data on sodium boiling under forced convection. This led the present authors to carry out a study on sodium to examine the bubble size and frequency in subcooled boiling under forced convection. In **Fig. 6** the frequency f is plotted against the diameter d_0 of an equivalent sphere having the same volume as the bubble when it attained its maximum size.

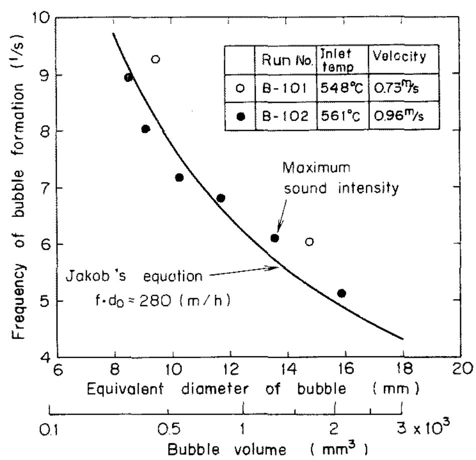


Fig. 6 Relation between equivalent diameter of bubble and frequency of bubble formation in steady-state boiling

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 justifies 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.

The volume of the bubble was evaluated by integrating the increment of outlet flow rate between the instant of bubble formation and that of its attaining maximum volume. From Fig. 6, it is seen that the frequency lowers with increasing bubble diameter, and that this diameter decreases with increasing flow velocity. A hyperbolic curve can be drawn, which roughly represents the relation between diameter and frequency. This relationship is expressed by

$$fd_0=280 \text{ (m/hr)}.$$

This formula is similar in form to that proposed by Jakob for pool boiling with ordinary liquids, which is somewhat unexpected, since the present experiments were conducted under forced convection and hence under conditions that can be considered dynamically controlled.

The maximum acoustic intensity indicated in Fig. 5 corresponds to a bubble diameter of approximately 13.5 mm.

IV. CONCLUSIONS

An experimental study was carried out on the steady-state boiling of sodium flowing in the annular channel formed around an electrically heated mock-up pin. In the present experiment, the inlet temperature and flow rate were held constant, and the heat flux was gradually increased up to the inception of boiling. Thereafter, the heat flux was further increased step by step until dry-out occurred. Records were obtained of the changes brought by the increasing heat flux to boiling phenomena, with particular reference to the behavior of two-phase flow patterns and the characteristics of boiling noise, as well as of bubble size and frequency.

Analyses of the results obtained permit the following conclusions to be drawn.

(1) For sodium boiling in a narrow channel, there exists a region in which steady-state boiling will be established, and under the conditions the two-phase flow pattern changes sequentially from bubbly flow to slug flow and then to annular flow. This behavior is quite similar to the case of water. This is an important point to be borne in mind in reactor safety considerations, since it means that local boiling will not necessarily always bring about instability of flow.

(2) The spectra of acoustic noise emitted with boiling do not differ distinctly from that registered when boiling is not apparent. If the noise is filtered to eliminate its low-frequency components, the level of noise intensity associated with boiling first increases sharply with rise in the heat flux to attain a maximum value, then decreases somewhat and remain constant thereafter until dry-out. The above observations point toward the usefulness of wide-band intensity measurements for reactor operation.

(3) The frequency of bubble formation depends on the size of the bubble at its point of maximum development. The product of bubble frequency and equivalent diameter is a constant which is in good agreement with the value of 280 m/hr suggested by Jakob for pool boiling with water.

[NOMENCLATURE]

d_0 : Departure diameter of bubble
f : Frequency of bubble formation
g : Acceleration due to gravity
I : Acoustic noise intensity
I_0 : Acoustic noise intensity in the absence of boiling

q : Heat flux
ρ_l : Liquid density, ρ_v : Vapor density
σ : Surface tension, θ : Contact angle

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—REFERENCES—

(1) KIKUCHI, Y., *et al.*: *J. Nucl. Sci. Technol.* **11**[5], 172~186 (1974).
(2) PINCHERA, G.C., *et al.*: *Trans. Amer. Nucl. Soc.*, **11**, 691~692 (1968).
(3) PEPPLER, W., SCHULTHEISS, G.F.: *KFK*-874, (1968).
(4) SCHLEISIEK, K.: *Nucl. Eng. Design*, **14**, 60~68 (1970).
(5) TAKAHASHI, K., *et al.*: *J. Nucl. Sci. Technol.*, **9**[11], 670~679 (1972).
(6) ANDERSON, T.T., *et al.*: *ANL*-7469, (1970).
(7) OSBORNE, M.F.M., HOLLAND, F.H.: *J. Acoust. Soc. Amer.*, **19**, 13~20 (1947).
(8) SCHWARTZ, F.L., SILER, L.G.: *Trans. ASME, J. Heat Transfer*, Ser. C, **87**, 436~438 (1965).
(9) JAMES, L.C.: *Nucl. Eng.*, **10**, 18~22 (1965).
(10) KICHIGIN, A.M., POVSTEN, S.G.: *Fluid Mech. Sov. Res.*, **2**[3], 154~157 (1973).
(11) NISHIHARA, H.: *J. Nucl. Sci. Technol.*, **11**[1], 1~7 (1974).
(12) See, for instance, "*Boiling Heat Transfer*", (1964), Japan Soc. Mech. Engineers, Tokyo.
(13) FRITZ, W.: *Phys. Z.*, **36**, 379 (1935).
(14) JAKOB, M.: "*Heat Transfer*," Vol. 1, (1958), John Wiley & Sons Inc., New York.
(15) NISHIKAWA, K., *et al.*: *Trans. JSME*, **18**[67], 47, 53; **18**[76] 19, 23, 29 (1952).
(16) ZUBER, N.: *Int. J. Heat Mass Transfer*, **6**, 53 (1963).
(17) IVEY, H.J.: *ibid.*, **10**, 1023 (1967).