# RELATIONSHIP BETWEEN THE NATURE OF ACOUSTIC OSCILLATIONS AND THE MODE OF SURFACE BOILING OF WATER IN ANNULAR CHANNELS

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The frequency and intensity of the acoustic oscillations produced by surface boiling of water in an annular channel in relation to the heat flux were investigated. The experimental data indicate that at the instant of transition from nucleate boiling to film boiling there is a distinct change in the nature of the acoustic oscillations. The plot of the frequency of the acoustic oscillations against the heat flux is similar to Nukiyama's boiling curve.

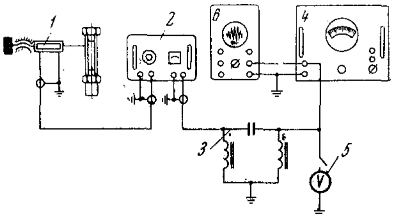

Fig. 1. Experimental setup. 1) Piezoelectric transducer; 2) amplifier; 3) filter; 4) frequency meter; 5) voltmeter; 6) oscillograph.

Several investigations of pool boiling have shown that the boiling of a liquid is accompanied by acoustic oscillations. There is a definite relationship between the mode of boiling and the intensity and frequency of these oscillations. Nesis [1] has made the most thorough analysis of acoustic oscillations in the case of pool boiling.

Hitherto experiments of this kind in the case of surface boiling and forced motion of a liquid have not been reported. Our investigation of the heat-transfer crises in the surface boiling of water flowing in annular channels 0.6–3.0 mm wide at velocities of 4–20 m/sec under a pressure of 0.4–0.8 MN/m$^2$ showed that acoustic oscillations with frequency $f$ = 8–10 kHz were produced in the region of the experimental elements at a certain value of the heat flux. These oscillations were detected with a piezoelectric transducer (a Rochelle salt crystal) and an EO-7 oscillograph. At low velocities (4–7 m/sec) a vapor film was visible on the heating surface at the moment of appearance of the acoustic oscillations and there was no reddening or overheating of the experimental element. A balanced bridge, used to detect the heat-transfer crisis, was unbalanced at the onset of the acoustic oscillations in all the regimes investigated in this work.

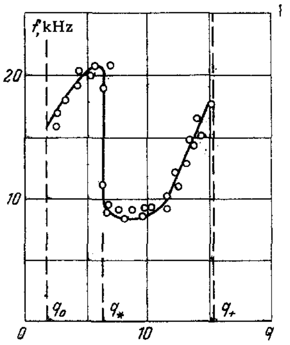

Fig. 2. Frequency $f$ (kHz) of acoustic oscillations against heat flux q (MW/m$^2$) for a velocity of 4 m/sec and subcooling of 70 deg.

The heat flux at which acoustic oscillations of frequency 8–10 kHz appeared increased with increase in the velocity, under heating, and width of the annular gap δ from 0.6 to 1.2 mm, and was independent of the diameter of the experimental element in the investigated range (6 and 14 mm).

An analysis of the described effects and a comparison of the experimental data with the results for heat-transfer crises in annular channels [2–4] suggested that acoustic oscillations with frequency 8–10 kHz appear at the instant of transition from nucleate boiling to film boiling, i.e., at the onset of the heat-transfer crisis.

The "noise limit" was evaluated as in [5], where the heat-transfer crises in a flow of water-vapor mixture in heated tubes were investigated

To verify the above hypothesis and to investigate the way in which the frequency and intensity of the acoustic oscillations accompanying the surface boiling vary with the heat flux we used the experimental setup illustrated in Fig. 1.

The piezoelectric transducer was mounted so that its needle received the oscillations of the annular channel outer tube, which was turned out of heat-resistant clear plastic. The signal from the piezoelectric transducer was transmitted to the input of a 28-IM low-frequency amplifier, and then to a filter, which cut off oscillations below 400 Hz, which are produced by rotating mechanisms and ac inductive interference. The frequency of the amplified oscillations was measured with an ICh-5a frequency meter, and the intensity was measured with a Goerz millivoltmeter. An EO-7 oscillograph was connected in parallel with the frequency meter for visual display of the change in the acoustic oscillations.

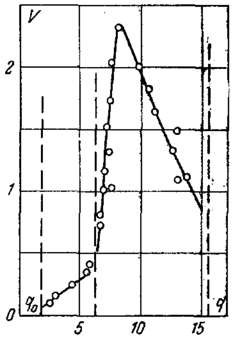

Fig. 3. Intensity of acoustic oscillations against heat flux for a velocity of 4 m/sec and subcooling of 70 deg.

The measurement of the oscillations intensity was relative, since we neglected the signal absorption by the flow of the outer tube of the annular channel. The millivoltmeter was connected only when the intensity was measured. Thus, with a constant amplification factor we obtained a relationship between the voltage generated by the transducer and the heat flux. The setup was checked with a ZG-12 audio generator.

We proceeded as follows. Keeping the velocity, pressure, and subcooling constant we altered the heat load on the experimental element, heated by dc current, by steps. After each step of 0.2–0.4 mW/m$^2$ we recorded the heating current, the voltage drop across the experimental element, the water temperature at the entrance and exit of the experimental section, and the intensity and frequency of the acoustic oscillations. The investigations were carried out in an annular channel 3.0 mm wide with veclocities of 4 and 10 m/sec, and subcooling of 70, 85, and 100 degrees. The heating surfaces were smooth stainless steel (1Cr18Ni9Ti) cylinders 6 mm in diameter.

No frequency measurements were done above 10 m/sec since the noise of the flow and the low intensity of the oscillations made it difficult to record the region of nucleate boiling. We merely determined the instant of transition from nucleat boiling to film boiling, which is characterized by a sudden change in the frequency and intensity of the sound.

The experiments showed that in the region of convective heat transfer ($q < q_0$) there were no acoustic oscillations in the investigated range of velocities and subcooling.* At heat fluxes slightly in excess of $q_0$ the frequency meter and the oscillograph began to detect weak acoustic oscillations of about 15 kHz. With increase in the heat flux the intensity and frequency of the oscillations increased. This was presumably due to the increase in the number of active vapor-forming centers and a consequent increase in the number of sound-emitting vapor bubbles. Nesis [1], Tokmakov [6], and Schwartz and Siler [7] came to a similar conclusion regarding the increase in intensity of the "acoustic noise" in the case of pool boiling.

At a certain value of the heat flux the surface becomes completely covered with vapor-forming centers and the frequency of the oscillations varies very slightly ($f$ = 19–21 kHz); the oscillation intensity continues to increase. A further increase in the heat flux leads to a sharp reduction of the oscillation frequency to $f$ = 8–10 kHz. This sharp change in the nature of the acoustic oscillations in surface boiling indicates a radical alteration of the hydrodynamics of the two-phase layer at the wall, i.e., a change from nucleate to film boiling. The heat flux at which acoustic oscillations of frequency 8–10 kHz begins is the critical flux.

The vapor film formed on the heating surface pulses and changes in shape and size. The oscillation frequency continues to decrease for some time as the heat flux increases, but the intensity increases sharply and the minimum frequency coincides with the maximum intensity. After reaching its minimum value ($f$ = 8–9 kHz) the frequency increases and goes beyond the threshold of audibility, while the intensity decreases sharply. A probable explanation is that as overheating is approached the vapor-liquid interphase becomes more stable; it is possible that other vapor films, which fuse with the one already existing, come into operation.

The observed relationship $f = \varphi(q)$ agrees qualitatively with Chang's wave theory of the heat-transfer crisis [8] for pool boiling of a liquid. As an example of the described relationships Figs. 2 and 3 show $f = \varphi(q)$ and $u = \varphi(q)$ obtained for a velocity of 4 m/sec and subcooling of 70 deg. At other values of the parameters of the process ($\omega$, $\Delta t^{-}$) the curves $f = \varphi(q)$ and $u = \varphi(q)$ were similar to those shown in Figs. 2 and 3.

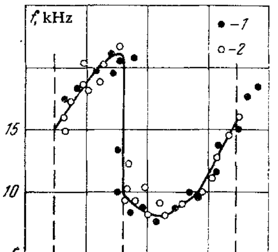

Fig. 4. Frequency of acoustic oscillations against heat flux for a velocity of 4 m/sec and subcooling of 100 deg: 1) Brass element; 2) stainless steel element.

The investigation showed that, irrespective of the velocity and subcooling, the change in boiling regimes occurred in the same frequency range, but at different heat fluxes. Reddening and overheating of the experimental elements usually took place at heat fluxes $q^+$, well in excess of the value of $q_*$. In some cases these values were commensurable. The value of $q^+$ is presumably affected by such factors as the thermal conductivity of the wall, its curvature, and the flow parameters.

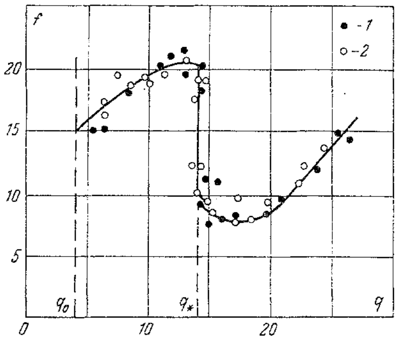

Fig. 5. Frequency of acoustic oscillations against heat flux for a velocity of 10 m/sec and subcooling of 85 deg. 1) Heat applied; 2) heat removed.

To test the effect of the material of the heating surface on the value of $q_*$ we conducted a series of experiments at a velocity of 4 m/sec on brass elements. The results of these experiments are compared in Fig. 4 with those obtained for elements made of 1Cr18Ni9Ti stainless steel. As Fig. 4 shows, the crisis on a brass surface occurred at the same heat fluxes and oscillation frequencies as on a stainless steel element. The limited power of the generator did not enable us to produce overheating of the brass heating surface. However, the experimental results confirmed that the material of the heating surface had no effect on the critical heat flux density, but affected the values of the heat flux at which overheating of the experimental element occurred ($q^+$). The oscillation frequencies were measured as the heat flux was increased and decreased. These experiments showed that the change from nucleate boiling to film boiling and vice versa occurred at the same heat fluxes (Fig. 5). Thus, we can infer that $q_{*1}$ and $q_{*2}$ are the same. These values will not be equal if $q^+$ is taken as the first critical heat flux density. A comparison of the curves of $f = \varphi(q)$ at different velocities and subcooling (Fig. 2, 4, 5) with Nukiyama's curve for pool boiling [9] shows that they are qualitatively similar. Hence, from a plot of oscillation frequency against heat flux we can determine the mode and nature of boiling of the liquid. The results obtained showed that by measuring the intensity and frequency of the sound we can foresee the approach of the heat-transfer crisis, regulate the release of heat, and prevent overheating of the heating surface.

From the presented results we can draw the following conclusions:

1. The change from nucleate boiling to film boiling is accompanied by a change in the nature of the acoustic oscillations.
2. The critical heat flux density in the case of surface boiling and forced movement of water is the same on experimental elements of stainless steel and brass.
3. The values of $q_{*1}$ and $q_{*2}$ are the same. There will be a difference if the heat flux at which reddening or overheating of the heating surface occurs is taken as the first critical heat flux density.
4. A plot of the oscillation frequency against the heat flux in the case of surface boiling in a forced flow indicates the mode and nature of boiling and is similar to Nukiyama's curve for pool boiling.

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*The value of $q_0$ corresponds to the heat flux at which the wall temperature in the given conditions is equal to the water saturation temperature. This value is calculated from the formulas for convective heat transfer in annular channels.

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