DEVELOPMENT OF HIGH-FREQUENCY PRESSURE OSCILLATIONS DURING HEAT TRANSFER WITH FORCED LIQUID MOTION

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This article presents the results of an experimental investigation of high-frequency pressure pulsations developing during heat transfer to n-heptane with different flow speeds and pressures.

Many articles devoted to bubble boiling have reported development of vibrations, whistling, and loud noise accompanying this process. The causes of pressure-pulsation development have not been studied and opinions on how to approach this problem vary [1-4].

The present investigation was conducted to study the relationship between high-frequency oscillations and the character of heat transfer during forced liquid motion. The results of an experimental investigation of the high-frequency oscillations developing during heat transfer to n-heptane with different flow speeds and pressures are presented below.

Our investigation was conducted with an apparatus typical of that used for study of heat transfer with forced liquid motion and fitted with equipment to measure the high-frequency pressure pulsations. Liquid motion was produced by forced nitrogen supply from the working tank. The working portion consisted of a tube fabricated from 1Kh18N10T steel, which had a diameter of 2.02/2.52 mm and a total length of 135 mm. The tube was heated with ac current over a 15 mm stretch. This short heated-segment length was used in order to prevent resonance phenomena. The length of the hydrodynamic-stabilization section before the inlet to the heated section was 60 mm. The heat flux was determined from the measured current and the voltage drop over the heated section, while the liquid flow rate was found from the pressure drop at the delivery sleeve. The temperature of the outer tube surface was measured midway along the tube length with two Chromel–Alumel thermocouples and PP-1 potentiometers (class 0.2). The temperature of the inner wall surface was calculated from the temperature drop in the tube wall. The liquid temperature at the inlet and outlet of the working section was measured with Chromel–Copel thermocouples and ÉPP-09 potentiometers (class 0.5), while the static liquid pressure was measured with standard manometers. A piezoelectric pressure-pulsation sensor was installed at the outlet of the working section. The sensor pulses were amplified by a piezoamplifier and fed to secondary instruments (an audio-frequency spectrometer and an electronic oscillograph). The type SZ4 audio-frequency spectrometer provided band-by-band analysis of the electrical oscillations over the frequency range from 44.9 to 23,000 Hz. This range was divided into 27 bands. The band width was 1/3 octave. The spectrometer-screen scale was calibrated in decibels, with a dynamic range of 30 dB. The spectrometer provided a sensitivity reduction of 50 dB in 10 dB stages. The spectrometer was used to determine the discrete frequency spectrum and the amplitude of each frequency in decibels, while the oscillograph was used to observe the overall pulsation pattern.

We conducted several series of experiments with different heat-transfer regimes. The parameters characterizing heat transfer and pulsation were measured simultaneously.

The first series of experiments was conducted at a subcritical pressure ($0.37 \leq \pi \leq 0.74$; $P_{cr} = 26.4 \cdot 10^5$ N/m^2). Three types of heat transfer were observed, depending on the load: convective, bubble, and film. No high-frequency pressure pulsations were observed in the convective heat-transfer region or in the initial bubble-boiling region. There were only slight pulsations with average frequencies of from 200 to

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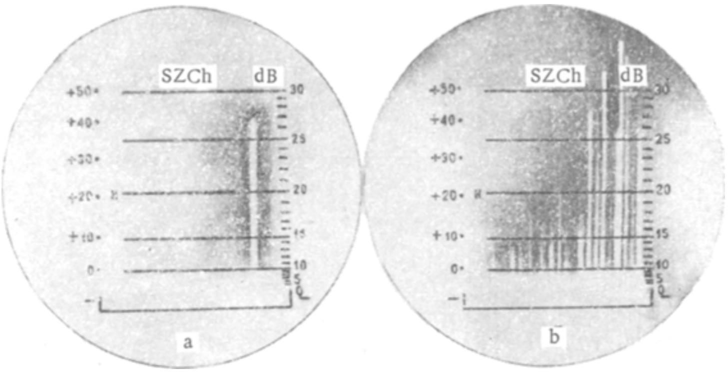

Fig. 1. Spectrograms of pulsations ($P = 9.81 \cdot 10^5$ N/m^2, W = 10 m/sec, $t_l = 25$°C) developing under full bubble-boiling regime (average frequency of 6400 Hz and amplitude of 37 dB correspond to $0.18 \cdot 10^5$ N/m^2) (a) and with film boiling regime (average frequency range of 3000-20,000 Hz and amplitudes of 35-45 dB correspond to $0.147 \cdot 10^5$-$0.46 \cdot 10^5$ N/m^2) (b).

2000 Hz, which are characteristic of turbulent flow and are not associated with heat transfer. A narrow spectrum with average frequencies of from 6000 to 8000 Hz developed in the region of full bubble boiling, their amplitudes varying periodically under constant electrical loading. Figure 1a is a photograph of the spectrogram typical of these oscillations. The minimum heat fluxes at which such oscillations developed in various experiments indicated the experimental relationship $t_{st} = f(q)$ (see Fig. 2A). It must be noted that, in individual experiments, no pulsations developed until the heat flux reached a level close to critical. The stability of the oscillations and their amplitudes increased with the heat flux, while the width of the spectrum remained unchanged. After the transition from bubble boiling to film boiling, pressure pulsations with a broad frequency spectrum (from 3000 to 20,000 Hz) developed in all cases (see Fig. 1b). The abrupt increase in wall temperature observed in this case without any change in electrical load was accompanied by severe noise and an increase in the amplitude of the entire spectrum of frequencies.

The second series of experiments was conducted at pressures close to the critical level ($0.74 \le \pi \le 1.3$). A characteristic feature for these conditions was the absence of any distinct boiling "plateau" (see Fig. 2B). At $t_{st} > t_{sat}$, the system exhibited high-frequency oscillations with average frequencies of from 6000 to 8000 Hz; their amplitudes remained unchanged with time under constant loading. A smooth increase in the load led to gradual broadening of the spectrum and to an increase in oscillation amplitude. A frequency spectrum similar to that which arose after the transition from bubble to film boiling was subsequently established.

As a result of our experiments, we can consider it proved that film boiling is accompanied by development of pressure pulsations with a broad frequency spectrum, from 3000 to 20,000 Hz; the presence of high-frequency pressure oscillations is not characteristic of bubble boiling. The development of pressure pulsations with a narrow frequency spectrum in the region of full bubble boiling is obviously due to nucleation of film "elements" near the heat-exchanging surface. The fact that the observed frequency spectrum did not become broader as the heat flux was increased to the critical level, while the character of the dependence of the heat-transfer constant on the heat flux $\alpha = f(q)$ also remained unchanged obviously indicates that film development is impeded under an intense bubble-boiling regime. On the other hand, the conditions for development of film boiling are more favorable at higher pressures, as is indicated by the stability of the pulsations that arose at $t_{st} > t_{sat}$ and the continuous expansion of the frequency spectrum with increasing thermal loading. It should be noted that noticeable differences in the character of heat transfer and in the pressure pulsations accompanying heat transfer were not detected either at subcritical ($P = 24.5 \cdot 10^5$ N/m^2) or supercritical ($P = 30.4 \cdot 10^5$ and $33.9 \cdot 10^5$ N/m^2) pressures.

In order to study the influence of the liquid temperature on the development of high-frequency pressure pulsations, we conducted experiments in which the liquid temperature was varied smoothly from 25 to 100°C, the working pressure was $24.5 \cdot 10^5$ N/m^2, and the flow speed was 10 m/sec. With $t_l = 25$°C, we first reproduced the heat-transfer regime under which a narrow frequency spectrum appeared (see Fig.

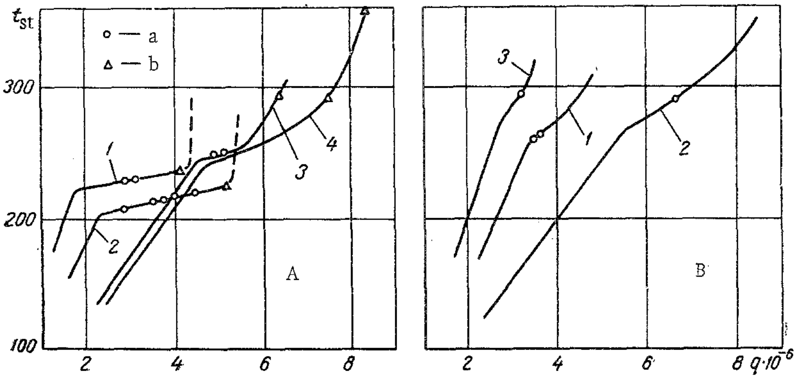

Fig. 2. Comparison of start of development of high-frequency pulsations in different experiments with observed character of heat exchange at $t_l = 25$°C. a) Start of narrow-spectrum pulsations; b) start of broad-spectrum pulsations. A: 1) $P = 12.25 \cdot 10^5$ N/m^2, $W = 5$ m/sec; 2) $9.81 \cdot 10^5$ and 10; 3) $19.62 \cdot 10^5$ and 15; 4) $19.62 \cdot 10^5$ and 20; B: 1) $P = 24.5 \cdot 10^5$ N/m^2 and $W = 10$ m/sec; 2) $30.4 \cdot 10^5$ and 15; 3) $33.9 \cdot 10^5$ and 5, t_{st}, °C; q, W/m^2.

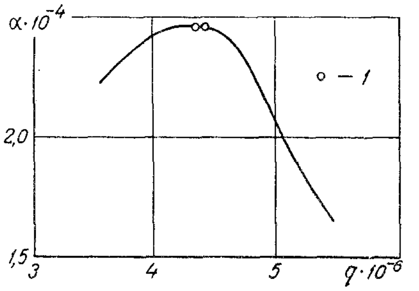

Fig. 3. Heat-transfer constant as a function of heat flux (the points labelled 1 represent the onset of narrow-spectrum pulsations) at $t_l = 100$°C, $W = 10$ m/sec, and $P = 24.5 \cdot 10^5$ N/m^2; α is in W/m^2·deg and q is in W/m^2.

2B, curve 1). With a constant electrical load, we then began to heat the liquid at the inlet to the working section and simultaneously observed the high-pressure pulsations. The oscillation amplitude began to drop at a liquid temperature of 50°C and the oscillations became unstable (appearing and disappearing); they disappeared altogether at a liquid temperature of 80-100°C. The pattern characteristic of bubble boiling was observed. In order to make the transition from bubble to film boiling, we began to increase the electrical load with a constant liquid temperature of 100°C. No pressure pulsations appeared until a definite heat flux was reached; an increase in the heat-transfer constant with rising thermal load was observed in this region (see Fig. 3). A further rise in the heat flux led initially to appearance of pressure pulsations with a narrow frequency spectrum; the spectrum then gradually became broader, the frequency amplitudes rose, and the pattern characteristic of the film regime was gradually established. In the graph of the function $\alpha = f(q)$, this corresponds to the region of decreasing heat-transfer constant with increasing heat flux (Fig. 3).

Thus, while an increase in heat flux after development of the narrow frequency spectrum at a liquid temperature of 25°C, a pressure of $P = 24.5 \cdot 10^5$ N/m^2, and a flow speed of $W = 10$ m/sec led to rapid expansion of the observed spectrum and establishment of a film boiling regime, the high-frequency pressure oscillations disappeared when the liquid temperature was increased, which corresponded to development of bubble boiling. A further increase in the heat flux with a constant liquid temperature (100°C) led to development of a film boiling regime, which was accompanied by appearance of pulsations with a frequency spectrum that was first narrow and then broad. These experiments conform to the hypothesis that the narrow frequency spectrum produced in the region of full bubble boiling is due to nucleation of individual "film elements" on the heat-exchanging surface.

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