EXCITATION OF HIGH-FREQUENCY PRESSURE OSCILLATIONS DURING HEAT EXCHANGE WITH DIISOPROPYLCYCLOHEXANE

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Experimental data are presented on heat transfer with diisopropylcyclohexane accompanied by high-frequency pressure oscillations. A hypothesis is advanced relating to the mechanism causing these oscillations.

There have recently been several papers which have examined or touched upon the question of pressure oscillations arising in the presence of heat transfer to or from a liquid flowing a tube. This is a matter of great practical interest, since in many cases these pressure oscillations may present a hazard as regards the strength and stability of heat exchangers. This question is also of theoretical interest, since it concerns the physical nature of heat transfer during a change in the state of aggregation of a material.

The most interesting data are given in [1, 2], in which there is a description of pressure oscillations during heat transfer with a liquid in the supercritical region. Meanwhile, it is known that heat transfer in the subcritical region with surface boiling of a liquid moving in a tube is accompanied by intense mechanical vibrations, "buzzing," and noise. These oscillations have not received special study, however.

The present article gives the results of an experimental investigation of high-frequency pressure oscillations excited during heat transfer with diisopropylcyclohexane (DICH) under conditions of forced motion inside a tube, at both subcritical and supercritical pressures. DICH is an organic liquid similar in physical properties to kerosene. Its elementary composition is $C_{12}H_{24}$, its specific weight 8030 N/m^3, its critical pressure 1.96 MN/m^2, and its critical temperature 650° K.

The tests were carried out in a heat-exchange system with an electrically heated heat-release element, the liquid being supplied with the aid of an MSh-3A gear pump. A special feature of the equipment was the presence of a special piezoelectric dual-beam type IAN-100 pressure indicator, made by "Elektronika" (Hungary), allowing measurement of the characteristics (frequency and amplitude) of the pressure oscillations excited during heat transfer. The heat-release element (HE) was a seamless type 1Kh18N10T stainless steel tube of diameter 1.6 mm, wall thickness 0.15 mm, and working length 30 mm. The pressure probe was mounted in a tube of diameter 2.5 mm at a distance of 65 mm from the point of exit of the liquid from the HE. Measurement of all the regime parameters (pressure, heat flux, rate of flow and temperature of liquid), and of the characteristics of the pressure oscillations (frequency and amplitude) was accomplished with an accuracy not less than 2–5%.

In the process of heat transfer from the DICH to the cooled surface of the HE hard carbonaceous deposits were formed, causing a spontaneous increase of the wall temperatures. It is necessary to allow for this in evaluating the values of t_W given in the present paper. In order to avoid large wall temperature increases due to this cause, each series of tests was conducted in a new HE.

Figure 1 shows the results of the most typical series of tests on heat transfer from DICH at the subcritical pressure of 1.45 MN/m^2.

The liquid temperature at the inlet to the HE was kept constant in all the tests, at a level of 293°–300° K. The liquid temperature at the HE outlet was different in all tests, dependent on the values of flow velocity and heat flux, but did not exceed 315°–320° K. The top part of Fig. 1 shows curves of the relation $t_W = \varphi(q)$ with characteristic areas $t_W = \text{const}$ for the region of heat transfer with surface boiling of the liquid. Comparison of the heat transfer data with the measured pressure oscillations shows that the latter arise whenever surface boiling of the liquid begins. In the test results shown in Fig. 1 the pressure oscillations are characterized by frequencies of from 3000 to 15 000 cps, and amplitudes ranging from 0.2 to 2.0 MN/m^2.

The frequencies shown in Fig. 1 relate to the most pronounced, dominant pressure oscillations. Besides these frequencies, one could see on the oscilloscope screen a whole spectrum of higher frequencies. As may be seen from the data presented, the pressure oscillations were characterized by different frequency, but we did not observe any kind of dependence of change of frequency on heat flux and liquid flow velocity. From a comparison of the various frequencies, it may be noted that they differ by multiples of 1700 cps. If we assume that the frequency $f_0 = 1700$ cps is the fundamental frequency of the oscillations, then the other frequencies are very close to the following values: $f_1 = 2f_0 = 3400$ cps, $f_2 = 3f_0 = 5100$ cps, $f_3 = 4f_0 = 6800$ cps, and so on.

Some deviation from these values may be due to errors of measurement, and also to the fact that the fundamental frequency may change with change of the compressibility of the stream of liquid as a function of temperature and vapor content. The amplitude of the pressure oscillations in all the series of tests increased with increase of heat flux. No influence of liquid flow velocity on this dependence could be observed. As the heat flux increased, the rate of increase of the amplitude was slowed down. Figure 2 shows the results of tests of heat transfer with DICH at a subcritical pressure of $p_0 = 1.45$ MN/m^2 and supercritical pressures of

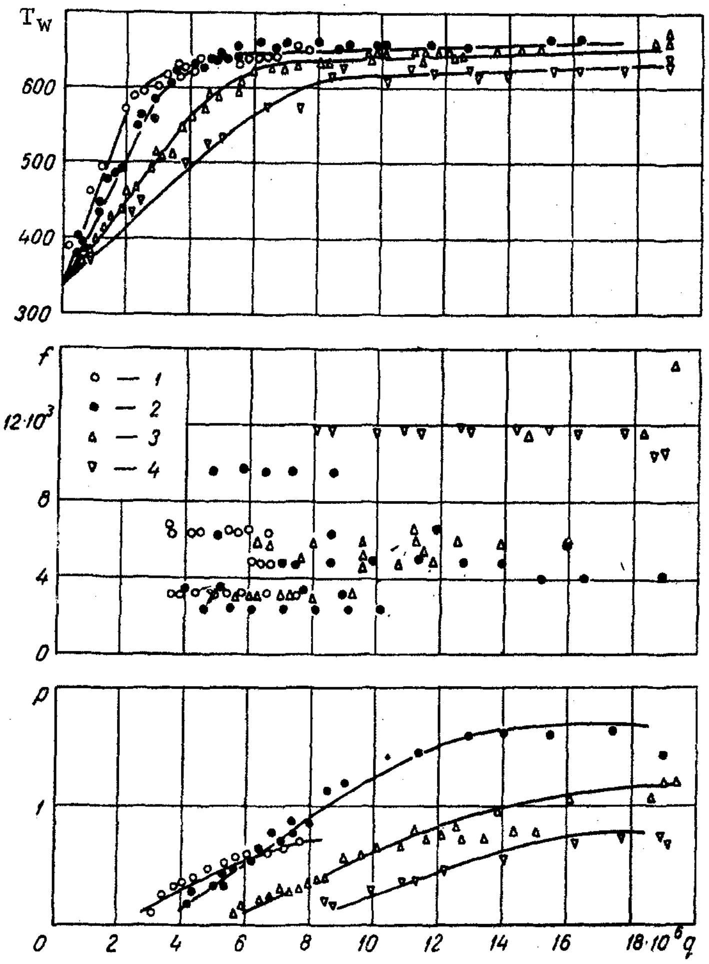

Fig. 1. Dependence of wall temperature T_W (°K), frequency f (cps), and pressure oscillation amplitude p (MN/m^2) on heat flux q (W/m^2) at 1.5 MN/m^2 and various flow velocities of DICH: 1) 8 m/sec; 2) 12.5; 3) 15; 4) 22.5.

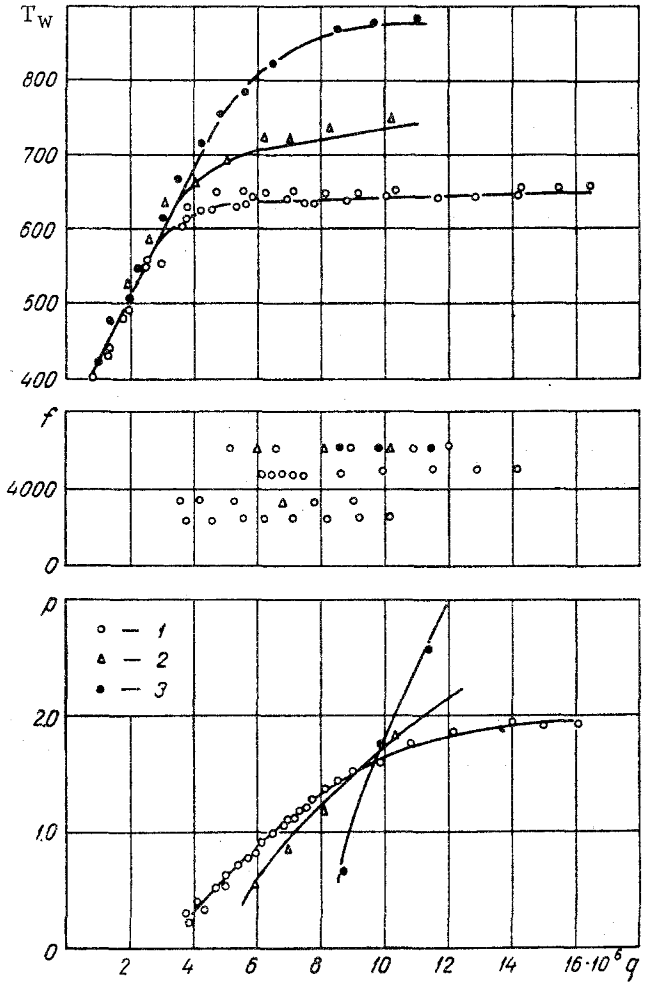

Fig. 2. Dependence of wall temperature T_W (°K), frequency f (cps) and amplitude of pressure oscillations p (MN/m^2) on heat flux q (W/m^2) for a DICH flow velocity of 12.5 m/sec at various pressures: 1) 1.45 MN/m^2; 2) 3.9; 3) 5.9.

$p_0 = 3.9$ and 5.9 MN/m^2. Comparison of the results of these tests shows that there are regions of enhanced heat transfer at both subcritical and supercritical pressures. It is most interesting that the characteristics of the pressure oscillations arising in the region of enhanced heat transfer have roughly the same values of both frequency and amplitude. The rate of increase of amplitude with increase of heat flux is the greater, the higher the pressure, a matter which cannot be explained by transition from subcritical to supercritical pressure; the tests carried out earlier on heat transfer with water established the same relationship in the subcritical pressure range.

The experimental data obtained permit us to express the opinion that the heat transfer regime with surface boiling (or pseudo-boiling) of the liquid is not always to be recommended for heat exchangers, since the excitation of high-frequency pressure oscillations may then be dangerous as regards to strength and stability.

As regards the causes of excitation of high-frequency pressure oscillations during heat transfer with liquids flowing inside tubes under conditions of forced convection and large heat flux, the following suggestions may be put forward. According to contemporary ideas [3, 4, and others], the critical point defines the boundaries of two regions differing only in the nature of the transition of the material from one state to the other, by separation of the new state of aggregation in the form of a macroscopic phase (boiling with $p_0 < p_{cr}$) or in finely dispersed form ($p_0 > p_{cr}$). The above discussion of the nature of the transition of the material from one state to the other allows us to suggest that the heat transfer mechanism with surface boiling of a liquid in the subcritical state region, and the mechanism of surface pseudo-boiling in the supercritical region, are identical.

Heat transfer with surface boiling of the liquid with $p_0 < p_{cr}$ is observed whenever $t_l < t_s < t_w$ (t_s is the saturation temperature); heat transfer with surface pseudo-boiling at $p_0 > p_{cr}$ is observed whenever $t_l < t_m < t_w$ (t_m is the temperature corresponding to maximum heat capacity). At subcritical pressure and the temperature conditions specified, vapor bubbles are formed from the liquid boundary layer, which is superheated relative to t_s; these bubbles condense when they fall into the liquid stream core, which is cool with respect to t_s. At supercritical pressure, separate volumes of liquid with decreased density (gas) are formed from the liquid boundary layer which is superheated with respect to t_s; these volumes, falling into the liquid stream core, which is cool with respect to t_s, condense. In both cases the additional turbulence of the liquid stream caused by these processes promotes a sharp increase of heat transfer. It is known that the formation and condensation of vapor bubbles under conditions of surface boiling, and probably similar processes in surface pseudo-boiling, proceed very energetically and with very great frequency. It may be expected that the rapid formation of vapor bubbles or isolated gas volumes causes sudden local deceleration of the liquid, and hence a micro-hydraulic shock, with the formation of a wave of increased pressure. However, it is more probable that the formation of shock waves occurs not with the growth of vapor bubbles or of gas cavities, but when they condense. It is known that when cavitation bubbles collapse, a shock wave arises in which the maximum pressure reaches tens and hundreds of atmospheres. Since the practical essence of the cavitation process of surface boiling (or pseudo-boiling) is the same, it is very probable that the source of the self-oscillations of pressure arising during heat transfer is the shock waves formed during condensation. The pressure wave created is propagated along the liquid stream at the velocity of sound. The presence of vapor or gas bubbles in the stream increases its compressibility sharply and correspondingly decreases the velocity of sound. Thus, for example, according to the data of [5], the presence in a stream of water at 1.45 MN/m^2 of 10% vapor (by volume) lowers the velocity of sound by a factor of 10. Since, in the conditions in which the tests were conducted, two-phase flow may exist only in the working length of the HE, according to the laws of acoustics the reflection of sound waves from the surface of the HE will be the greater, the larger the reflection coefficient **R**,

$$R = \left(\frac{C_2\rho_2 - C_1\rho_1}{C_2\rho_2 + C_1\rho_1} \right)^2,$$

where C_1 and C_2 are the velocities of sound in the single-phase and two-phase media; ρ_1 and ρ_2 are the densities of these media.

Reflection causes the formation along the HE of standing pressure waves whose frequency will be multiples of some fundamental determined by the length of the HE and the velocity of sound in the two-phase stream of fluid. The presence of periodic pressure oscillations brings order to the process of surface boiling (or pseudo-boiling), and compels the bubbles to develop and break down in time with the pressure oscillations.

With increase of pressure, when t_s (or t_m) increases, and the degree of superheat of the liquid in the wall region decreases, while the subcooling in the stream core increases, the processes of formation of bubbles of vapor (or gas) are suppressed, while condensation processes are stimulated; when the pressure is decreased the picture is reversed.

SUMMARY

1) During heat transfer with DICH under forced motion inside a tube transition to the regime of surface boiling (or pseudo-boiling) is accompanied by the occurrence of high-frequency pressure oscillations. Under our test conditions these pressure oscillations were characterized by frequencies ranging from 3000 to 15 000 cps and amplitudes from 0.2 to 2 MN/m^2.

2) The characteristics of the high-frequency pressure oscillations for subcritical and supercritical pressures are roughly identical.

3) With increase of heat flux the amplitude of the oscillations increases the more strongly, the higher

the pressure; the rate of increase of amplitude slows down in proportion to the degree of increase of heat flux.

4) It may be supposed that the cause of the pressure oscillations during surface boiling (or pseudo-boiling) is shock waves due to the collapse of vapor or gas bubbles.

5) It is evident that heat transfer with surface boiling (or pseudo-boiling) cannot always be recommended for heat exchangers, since the occurence of high-frequency pressure oscillations may present a hazard with respect to the strength and stability of the whole system.

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