THE CONNECTION BETWEEN THE HEAT EXCHANGE CRISIS AND THE HIGH-FREQUENCY NATURAL PRESSURE OSCILLATIONS (DISCUSSION)

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The characteristics of natural pressure oscillations which occur in surface boiling of a liquid moving along tubes are described, and their influence on the process of heat exchange is examined.

The absence up to now of a reliable method of calculating the heat exchange crisis in liquid which moves along tubes is due to the inadequate state of research on the process of surface boiling. Hence, for example, the influence of high frequency natural pressure oscillations which always accompany this process is not taken into account. It can be shown that many phenomena associated with the occurrence of the heat exchange crisis can only be understood when the presence of these high frequency oscillations is taken into account.

Many research workers have observed that heat exchange with surface boiling is accompanied by a characteristic sound ("whistle," "hum," or "Cavitation noise" [2, 18, 19, 22, 25, and others]. Up to now the explanation has been that these sound effects are caused by high-frequency natural pressure oscillations arising in surface boiling of a liquid. The basic characteristics of these high-frequency oscillations were determined by heat exchange experiments with water, ethyl alcohol, diisopropylcyclohexane, and other liquids [4-6].

The shock pressure waves which occur in condensation (ringing) of vapour bubbles as this takes place by cavitation are the probable cause of the appearance of high-frequency oscillations. Cavitation and surface boiling, according to their physical nature, represent one and the same process of formation and destruction of vapour bubbles at certain relationships between the temperature and the pressure of the liquid; The pressure waves which occur are propagated from the centres of the ringing bubbles (where the pressure can reach hundreds, and thousands of atmospheres) along the flow of liquid at sonic speed in the two-phase medium. Owing to the reflection of these pressure waves from any boundaries which can be, for example, the boundaries of the two-phase flow (length of the heat liberating element), stationary waves with frequencies divisible by the frequency of the basic harmonic f_0 will occur:

$$f_0 = \frac{C}{2L}. \tag{1}$$

In heat exchange experiments with water the frequencies of the high frequency oscillations were in the harmonic series: 1250, 2500, 3750 Hz etc., [6]; in the case of heat exchange with ethyl alcohol [5], and diisopropylcyclohexane [4] the pressure fluctuations were characterized by frequencies 1020, 2040, and 3060 Hz, and 1700, 3400, and 5100 Hz, respectively.

It is evident that the pressure fluctuations generated by the surface boiling process will influence in turn this process: with decrease of pressure, when T_s is reduced and the excess heat of liquid around the wall of the tube is increased ($T_{wall} - T_s$), vapour bubbles will be formed, but in the case of pressure increase, when T_s increases and the underheating of the liquid in the center of the flow increases ($T_a - T_{li}$), condensation will take place. The frequency of the pressure fluctuation will be determined by the ratio (1), but of all the harmonics only those which satisfy the possibility of forming and destroying vapour bubbles will be generated.

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If the pressure variations inside the heat liberating element are characterized by a stationary wave, then the amplitude of the high frequency oscillations along the length of the heat liberating element will vary according to the law

$$A = A_{\max}(1 - R)\sin\left(2\pi f\tau + \frac{2\pi y}{\lambda}\right). \tag{2}$$

In accordance with this equation pressure peaks will be located at the ends of the heat-liberating elements and at a distance of $\lambda/2$ from them, where the amplitude is maximum, but pressure nodes will be found at a distance of $\lambda/4$ from the ends and further at a distance of $\lambda/2$, where the amplitude of the vibrations is equal to zero.

As the heat flux increases, the amplitude of the oscillations increases the more intensively the higher the pressure. The corresponding graphs plotted from experimental data are given in [4-6], and it can be seen from these that the measured amplitudes of the high frequency oscillations reach 15-40 atm. The frequency of the high frequency oscillations does not depend on the pressure; it grows with increase in the thermal flux: it jumps from the lowest to the highest harmonics. With increase in the frequency of the high frequency oscillations, the temperature of the cooled surface decreases which indicates improved heat exchange.

Analysis of the influence of high frequency oscillations with the characteristics described above on the heat exchange in the case of surface liquid boiling enables us to make a new approach to evaluation of the physical nature of many phenomena with which it is accompanied. We will examine some of these.

1. Up to now the cause of the influence of the geometrical dimensions of the tube on q_{cr} has not been established conclusively; some authors consider that L and d do not have a noticeable influence on q_{cr} [1, 13, 14, 20]; according to other data it is necessary to take into account the dimensions of the tube without fail when calculating q_{cr} [3, 10, 11, 12, 17, 27, and others].

In accordance with the majority of experimental data, q_{cr} increases with decrease in the length of the tube. It can be assumed that this is caused by the increase of the frequency of the high frequency oscillations with decrease in the length of the tube (1); the increase in the frequency moreover always promotes improvement in the heat exchange. In this direction the variation of the diameter should influence q_{cr}: the smaller the diameter of the tube the more stable the high frequency oscillations and the lower the temperature of the wall at which they occur, and consequently, the higher the thermal flux which upsets the stability of the surface boiling process. The influence of d on the stability of the high frequency oscillations is probably caused by the fact that, the lower the d, the more intense will be the pressure variations when other conditions are equal, since less energy is required to form them.

2. In accordance with existing concepts, at a critical pressure when phase conversions of the first order cannot exist, the heat flux which is dependent on the process of surface boiling (the magnitude of the area t_{wall} = const on the curve $t_{wall} = \varphi(q)$) is equal to zero [7-9, 13, and others]. This however is not confirmed by many experimental data. Hence for example heat exchange research with diisopropylcyclohexane showed us that the area t_{wall} = const on the curve $t_{wall} = \varphi(q)$ did not vary noticeably when the pressure increased right up to the critical pressure; the characteristics of the high frequency vibrations did not vary either [4]. Photography of the heat exchange process in carbon dioxide at a supercritical pressure made it possible to establish that the same bubbles are formed near the heat emitting surface as in the case of surface boiling under subcritical pressure conditions [24]. These facts, which would appear to contradict the principles of thermodynamics can be understood when the action of the pressure variations in the surface boiling process is taken into account.

When there are high frequency natural pressure oscillations present then the surface boiling process will depend not only on the static pressure but also on the amplitude of these high frequency oscillations:

$$P = P_s - A. \tag{3}$$

In such a case and at pressure exceeding its critical value phase conversions can be expected. This can occur in the condition

$$P - A_{\max} < P_{cr} \quad (\text{for } P > P_{cr}). \tag{4}$$

The contradictory results obtained by different authors when investigating the influence of pressure on q_{cr} can be explained by the presence of high frequency oscillations. In accordance with generalized equations describing the heat exchange crisis, the relation $q_{cr} = \varphi(P)$ has a maximum when $P \sim P_{cr}/3$. If it is assumed that the determining factor on the process of surface boiling has a minimum pressure ($P = P_{wall} - A_{max}$) then on the section of the relationship $q_{cr} = \varphi(P)$, where q_{cr} increases, the presence of high frequency oscillations will reduce q_{cr}, but on the section, where q_{cr} decreases with increase in pressure, the high frequency oscillations will increase q_{cr}.

3. Together with many other research workers* we have noted that in the case of heat exchange with surface liquid boiling the temperature of the wall along the length of the tube varies greatly although the heat flux remains constant. The nature of the variation of T_{wall} along the length of the tube does not follow any determined rule: the sections with higher temperature are distributed at different locations of the tube; with increase in the thermal flux these sections are suddenly displaced. An especially sharp nonuniformity of distribution of T_{wall} along the length of the tube was observed in the case of thermal flux close to the critical flux. Unfortunately these experimental data were not published probably because the nonuniformity of distribution of T_{wall} along the length of the tube was related to measuring errors, the presence of tube wall irregularities and other similar causes.

It can be assumed that the nonuniform distribution T_{wall} along the length of the tube corresponded to the distribution of intensity of surface boiling, which depended on the magnitude of the amplitude of the high frequency oscillations. In the stationary wave the maximum amplitude of pressure variations is found in loops, but the minimum is found in nodes; correspondingly, the intensity of the heat exchange varies, and consequently, so does the temperature of the cooled surface. When the frequency of the high frequency oscillations varies with increase in the thermal flux, then this will involve variation in the arrangement of the nodes and loops, in accordance with which the distribution T_{wall} varies along the length of the tube. The process of surface boiling intensifies and the amplitude of the high frequency oscillations increases with increase in the thermal flux. This involves a sharper difference in the intensity of heat exchange in the nodes and loops, and consequently, a sharper difference in the temperature distribution of the wall.

4. According to the existing concepts the heat exchange crisis in the case of movement of liquid along the tubes must always arise at the outlet and of the tube. However, it is known that in many cases the "burning" of the walls of the tubes takes place at midlength or even at the outlet end. Without finding an explanation from these facts, the experiments in which the "burning" did not take place at the outlet end are related to random phenomena and these experimental data are not taken into account in generalization.

According to our ideas the heat exchange crisis must occur at the nodes of the high frequency oscillations, and consequently it can take place at any point along the length of the tube in relation to the frequency of the pressure variations.

5. Some authors reported that when the heat flux increased there was a jump-like increase in the frequency of the formation of vapour bubbles [21, 23, 26]. The data about the jump-like increase in the frequency of high-frequency oscillations with increase in the heat flux [4-6] makes it possible to assume that this involves a corresponding increase in the frequency of formation of vapour bubbles.

The author explains this by the fact that the ideas put forward in this article are debatable and can come up against objections. He hopes, however, that discussion of these ideas could be useful for developing a method of calculating heat exchange in surface boiling of a liquid, which is so necessary for engineers, working in many fields of technology.

NOTATION

A	is the amplitude of pressure of high frequency oscillations;
A_{max}	is the maximum amplitude of pressure of high-frequency oscillations;
c	is the speed of sound;
d	is the diameter of the tube;
f	is the frequency of the high-frequency oscillations;
L	is the length of the heat-liberating element;

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P	is the pressure;
P_{cr}	is the critical pressure;
P_s	is the pressure of saturated vapours;
q	is the heat flow;
q_{cr}	is the critical heat flux;
R	is the reflection coefficient;
T_l	is the temperature of the liquid;
T_s	is the saturation temperature;
T_{wall}	is the temperature of the wall;
y	is the flow coordinate of the heat-liberating element;
λ	is the length of wave;
τ	is the time.

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