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Thermoacoustic phenomena at boiling subcooled liquid in channels

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Abstract—The problem of thermoacoustic phenomenon (ThAPh) of subcooled liquids boiling in channels is studied. The importance of the problem is well-known as high frequency pressure oscillations are responsible for destroying and ruining not only tube sections, but apparatus and equipment units as a whole. The problem has not been explored well enough up until now. The authors thoroughly explored previous investigations and continued with detailed studying of the problem theoretically and experimentally. As a result, they proposed an original theoretical model of the phenomenon which has been completely confirmed by the experiments. The results obtained by the authors can have very important practical applications.

1. INTRODUCTION

It is known that the boiling of subcooled liquid in channels in many cases is accompanied by high-frequency pressure oscillations (HFO) of considerable amplitude. The physical nature of HFO as well as the character of acoustic phenomena at boiling under conditions of great volumes is connected with the effect of vaporization centers. The frequencies of these oscillations coincide with the acoustic frequency and thus the oscillations themselves and the mechanisms producing them may be qualified as thermoacoustic phenomena (ThAPh).

Experience [1, 2] proves that ThAPh can be the cause of many break-down situations in facilities and apparatus containing the heat-loaded channels with high densities of local and middle heat fluxes, of the order 10^6–10^7 W m^{-2}; such facilities often involve various SHF units and lasers. The very high technical value and high cost of these units makes the problem of ThAPh analysis extremely pressing to-day for the whole range of these units' operation.

The target of experimental and theoretical-calculation studies was greatly determined by the circumstances mentioned above and by the state of the problem that is analysed below; the studies being carried by the authors for over ten years. The main scientific results of this research are presented in this paper.

2. STATE OF THE PROBLEM

The investigations of ThAPh at forced flow of boiling liquid in the ranges of subcritical state parameters were carried out by many research groups. The known experimental data given in refs. [1–14] are notable for: the diversity of the range of frequencies in HFO, for non-univalued dependencies of the amplitude-frequency HFO characteristics on different factors; for contradictory results.

The physical notion of the origin and development of HFO according to the researches carried out before 1976 is rather well presented and discussed in ref. [11]. The existing knowledge about natural development of HFO phenomenon was considerably enlarged by monographs [4, 5] as well as others.

However, in the long run, the authors of these and some other researches directly or indirectly proceed from the physical assumption, based on the notions of HFO origin, as being the self-excitation of oscillations' phenomenon. But here the results of the theoretical analysis are not compared with the experimental data or are compared indirectly.

At the same time there is a generally accepted point of view [11] that the oscillations can be excitated as a result of growth and collapse of bubbles at subcooled liquid boiling. These statements in various forms are present in most previously published papers. There is central inconsistency in the physical notions of many authors and in the theoretical set-up of their calculated models.

Thus, the state of the problem being analysed can be estimated in the following way:

(1) There is no unique physical notion of the causes of either arising or conditions of existing HFO pressure in cooled channels, meaning that it is possible for experimental regularities to be explained without contradiction.

(2) The existing HFO models, under conditions of forced liquid flow, ignore the structural changes in the two-phase flow pattern and do not consider the laws of the internal boiling process characteristics (the den-

NOMENCLATURE

P	pressure, oscillational amplitude	q	heat flux density
w	liquid flow rate	d_{max}	maximal bubble diameter
$\bar{C}$	sound velocity	Z	number of vaporization centers.
V	vapour bubble void		
K	wave number	Greek symbols	
L	channel length	Δt_{subc}	subcooled liquid
S	cross-sectional channel area	ρ'	liquid density
d_{eqv}	equivalent channel diameter	ν'	kinematic viscosity of liquid
f_c	natural oscillational frequency	$f\omega$	frequency of bubble formation
t	fluid temperature	Π	heated section perimeter.

sity of vaporization centers, the frequency of their acting etc.). This agrees poorly with the point of view of most authors on the effect of vaporization centers in causing the pressure oscillations.

(3) The known experimental data are fragmentary, these data are not systematized and practically do not represent the domain conditions, geometrical and physical parameters, that are characteristic of thermal regulation systems (ThRS), SHF-instrumentation and laser engineering. These last circumstances determined the essence and the volume of the experimental studies [15–18].

3. MEANS, VOLUME AND METHODS OF EXPERIMENTAL STUDIES. TYPICAL EXPERIMENTAL RESULTS

The typical configurations of HFS cooling and laser channels as well as those of fullsize pilot channel models, used in the experimental studies are given in Table 1. Figure 1 illustrates the design version of working sections; the reserving facilities for pressure pick-up is included. The hydraulic circuit of the experimental rig is typical for the liquid ThRS and includes the pumps, filter, changeable working sections, a flowmeter, a heat-exchanger, volume re-filling tanks and a heater. To measure the liquid temperature some chrome-copper thermocouples were used. Measuring the static pressure at the in-put and out-put from the working sections was realized with calibrated manometers.

To measure pressure oscillations in the working section some special tensometric and piezoelectric pressure picks-up were applied. The measuring, registering and results treatment systems, for taking up pressure oscillations with the tensometric-type sensors, contained: a tensometric amplifier, having an output connected with the oscillograph with bifilar suspension, a cathode-ray oscillograph, a spectrum analyser and a magnetograph. When using the piesoelectric pressure pick-up the signal from the sensor came directly to the magnetograph, the spectrum analyser and the cathoderay oscillograph. The methods of the experimental data treatment were standard and were completed by constructing some particular empirical dependencies of the amplitude–frequency characteristics (AFCh) of high-frequency pressure oscillations according to the main variable factors. The experimental results obtained can be divided into three groups:

(1) experimental data on HFO when boiling in short capillaries;

(2) experimental data on HFO when boiling in long cylindrical channels;

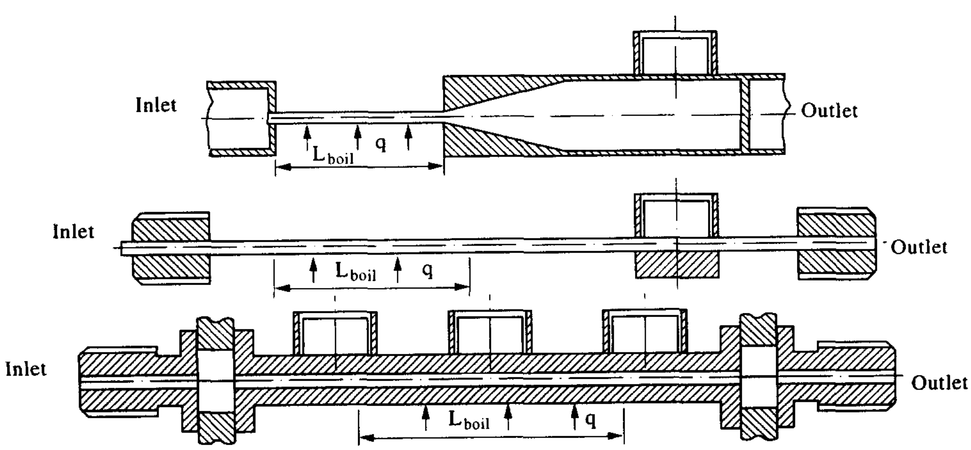
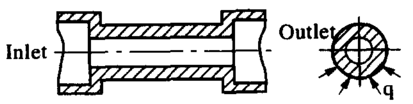
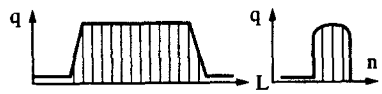
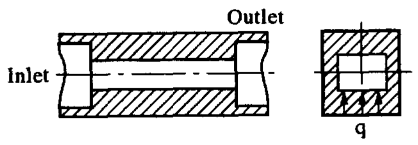
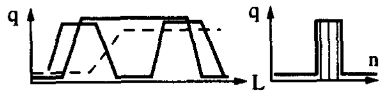
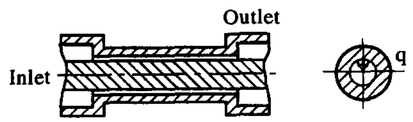
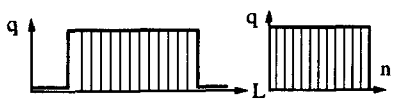
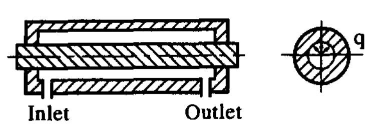
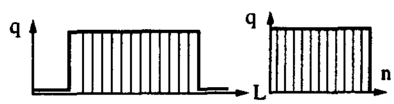


Fig. 1. Working sections.

Table 1. Typical configurations of cooling channels and heat flux distribution in length and perimeter of the channel

Channel configuration	Heat-flux distribution	Reproducibility of results [%]
		30
		50
		10
		5
The others		5

(3) the experimental data when boiling in a long channel of rectangular cross-section and the load variable in the length and perimeter.

Let us consider each group of experimental data in order. The experiments that are referred to in the first group have been carried out on stainless-steel pipes of diameters: $d = 0.5$, 1.0, 1.5, 2.0, 3.0 and 3.5 mm and length 60, 100 and 120 mm. The dependencies obtained (Fig. 2) confirm the known facts that on boiling the subcooled liquid in capillaries (0.5 mm) the changes of frequency and of amplitude for pressure oscillations can have monotone or shock character. This fact has been established in other experiments carried out by some other researchers with different channel geometries. The experiments have also proved the possibility of realizing necessary changes in the character and level of pressure oscillations at the expense of a rational choice of cooling conditions.

In the experiments in the long channel of round

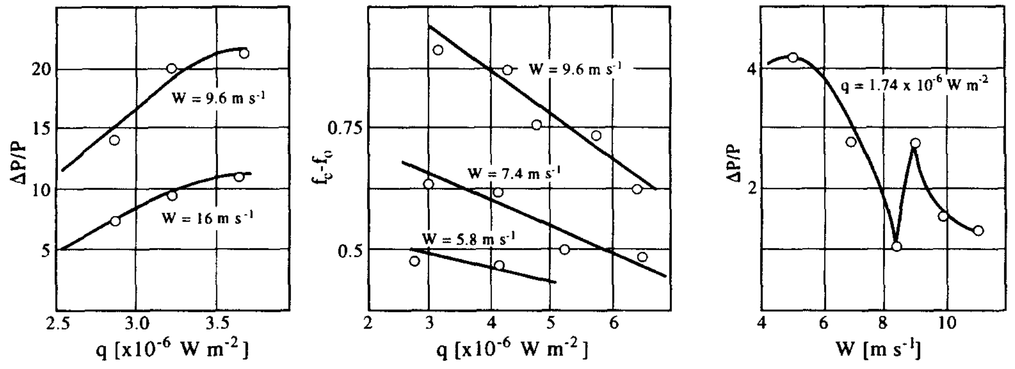


Fig. 2. Changing the oscillational frequency at water boiling in capillaries.

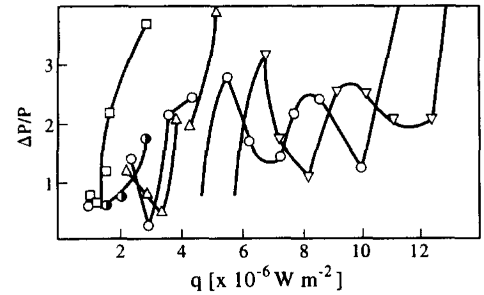


Fig. 3. Changing the amplitude of pressure oscillations in long channels.

cross-section the pipe used had inner diameter of 4 mm and a working length 725 mm.

The results of treatment over 150 spectrograms on HFO pressure are given in coordinates f and q for the principal maximum energy spectrum. But the analysis of spectrograms does not provide the possibility to determine one-valued quantitative relations, evaluating the degree of influence for the service conditions' parameters upon AFCh HFO (Figs. 3 and 4).

Some general trends can be tracked on further experimental data treatment. In the experiments with a long channel of rectangular cross-section the working section imitated the cooling channels of real facilities and had dimensions of 3 × 5 × 410 mm. The length of the heated section and the situation of the section to be heated in each series of experiments was left unchanged. As it was shown in ref. [23] the absolute level of pressure oscillations in a channel can reach 70–100% of the operation pressure; this was also observed in our experiments.

In the experiments with the channel of rectangular cross-section the thin-walled heaters have been applied: $\delta \leqslant 50$ μm. It is known that at such a wall-thickness of electrical heaters fed from an alternating current power source, the electrical current frequency strictly corresponds to the oscillations of heat emission. This last reason determines the agreement of periodicity in the actions of boiling centers with alternating electrical current frequency. In these situations the agreement with the current frequency characteristics of HFO should be expected. It was completely

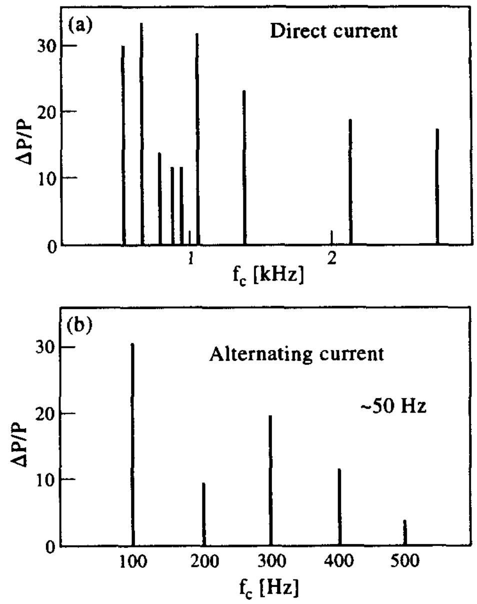


Fig. 5. High-frequency oscillation spectrum on heating by: (a) direct current; (b) alternating current.

confirmed by experimental data (Fig. 5). The above mentioned result can have very important in practical application.

In order to exclude the possibilities of misinterpretation of experimental data some experiments carried out with alternating current have been repeated with direct current. The typical results presented in Fig. 5 confirm the above stated consideration.

The empirical generalization of obtained and known experimental data, determining the border of existing, considerable in amplitude, HFO pressure has the form:

$$w\Delta t_{\text{subc}} > 190 \frac{q^{1.2} d_{\text{eqv}}^{0.2}}{(\rho')^{1.2} C_p \tau^{0.2} (\nu')^{0.2}}. \quad (1)$$

The obtained experimental results were indicative of the necessity in most urgent developments of an efficient theoretical model.

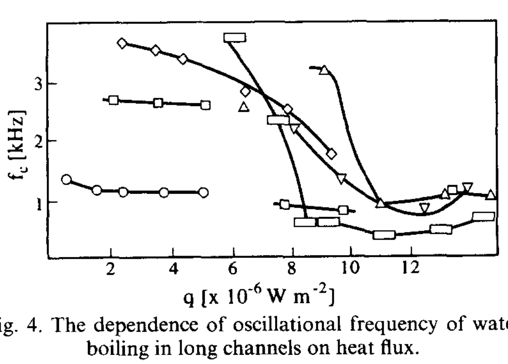


Fig. 4. The dependence of oscillational frequency of water boiling in long channels on heat flux.

4. PHYSICAL CONCEPT ON HFO MECHANISM. APPROXIMATE HFO MODEL IN VAPOURGENERATING CHANNELS

The general conception of thermo-acoustic phenomena, when the subcooled liquid is flowing in the heated channels, can be considered as following:

(a) The sources of forced HFO pressure on boiling the subcooled liquid in channels are the acting vaporization centers.

(b) The elastic medium undergoing the effect of forced oscillation sources is presented by the vapour–liquid fluid, restricted by the channel-walls and by 'rigid' or 'soft' boundaries at the inlet and outlet (depending on the channel construction).

(c) The elastic oscillations in the vapour–liquid medium depend on volume concentration of the vapour phase as well as on its distribution in the channel, i.e. on the flow pattern. The analysis shows that for the conditions of experiments to be carried out by the authors and for treatment of known experimental data there are a number of typical vapour–liquid patterns that are shown in Fig. 6.

(d) The vaporization centers on well-developed boiling form the distribution system and, in many cases, some coherently acting sources of forced oscillations. The acting frequencies of these sources are actually the internal characteristics of the boiling process and mainly depend on q, P_s, Δt_{subc} and to a smaller degree on ρw.

These dependencies cannot be obtained analytically and thus, for the model of first approximation, they can be found from half-empirical treatment of a few experimental data on internal boiling characteristics during flowing of the subcooled liquid in channels. This was realised in ref. [17].

(e) The coincidence of frequencies in vaporization centers action with natural oscillational frequencies of the vapour–liquid medium in channels creates favourable preconditions for developing resonance thermoacoustic oscillations, the formation of standing pressure waves of large amplitude, included. The particular form of these resonance phenomena, the sizes of their amplitudes, the situation of maxima and minima, depend on the flow-pattern, the conditions mentioned above and dissipative effects. A special case is presented by subharmonic oscillations.

If we have in view the real cooling channels, the distribution of heat load in them and characteristic oscillational frequencies, then such channels should be regarded as an oscillating system with the lengthwise dispersed sources of forced oscillations and corresponding pressure field. The methods of constructing the calculated relations for such cases and calculated relations themselves are given in ref. [18]. The main principles of the model in HFV calculations under the conditions mentioned above are as follows:

(1) The 'narrow' channels with absolutely rigid walls are considered under conditions of one-dimensional fluid flow. All characteristics of pressure waves satisfy linear equations and depend on co-ordinates; the time dependence is harmonic.

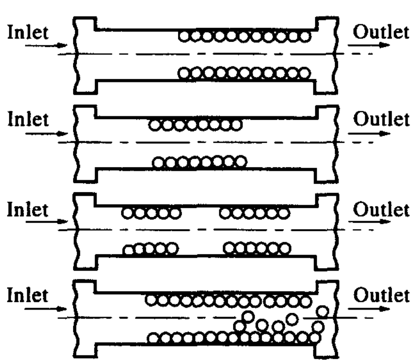


Fig. 6. Some typical patterns of vapour-liquid flows on boiling the subcooled liquid at different heat flux distribution in length.

(2) Phase transition is determined by heat rejection from the channel walls. The pressure waves have no considerable effect on bubbles, evolution and on general regularities of the phase transition.

(3) The compressibility of the vapour–liquid medium β is determined at known values, this one of adiabatic of phases β' and β'' according to the scheme:

$$\beta = \varphi\beta'' + (1-\varphi)\beta'. \tag{2}$$

(4) The dispersion of pressure waves is absent. The dissipation of oscillational energy is taken into account as the losses for radiation of mechanical energy at the inlet and outlet.

(5) The volume of vapour bubbles varied according to harmonic law:

$$V(\tau) = V_{max} \exp(-i\omega\tau). \tag{3}$$

(6) The velocity of propagation for pressure waves is accepted as an average value along the channel length in case of presence of sections with one- or two-phase-state of heat-transfer medium according to the pattern:

$$\bar{C} = L \Big/ \left[\frac{L - L_{Boil}}{C'} + \frac{L_{Boil}}{C''}\right]. \tag{4}$$

On determining the value of L_{Boil} and the co-ordinates for the boiling section boundaries the calculating procedures are required to find the borders of initial vapour generation on the wall, the vapour phase appearing in the flow ($\varphi > 0$) etc.

For this purpose, in the model, the known correlations are recommended to be applied. The obtained dependence of the pressure oscillation amplitude on the main factors, using the calculation results, have the form:

$$P(x) = \frac{\rho \bar{C} V_{max} \omega Z \Pi}{KS} \cdot F(KX, KL \ldots) \tag{5}$$

where $F(KX, KL\ldots)$ is a known combination of periodic functions. The above described model was applied for theoretical analysis of experimental study results.

5. CALCULATING THEORETICAL HFO ANALYSIS BASED ON THE PROPOSED MODEL

Calculating theoretical analysis proves:

(A) In all cases, to be excluded the case of uniform distribution of vaporization centers along all the channel length (the situation that theoretically can be realized on boiling the saturated fluid) the resonance in a channel occurs at coinciding action frequency of the variable liquid–volume sources (acting vaporization

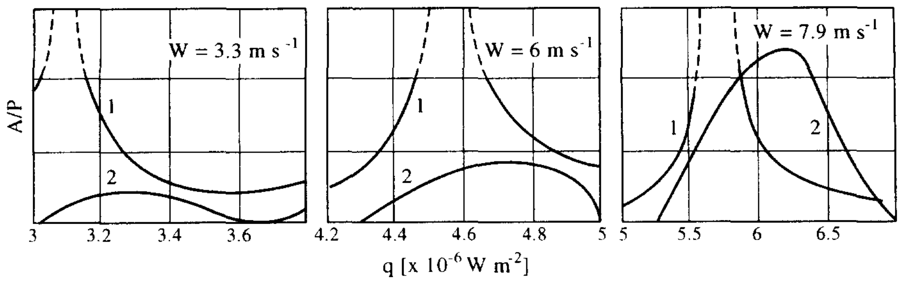


Fig. 7. Comparison of experimental and calculation data: 1—calculation; 2—data of experiments according to ref. [6].

centers) with the natural frequency of oscillating system: vapour–liquid flow channel.

$$nf = mf\bar{C}; \quad KL = n\Pi. \tag{6}$$

(B) The location of the sections of boiling relative to the channel inlet and outlet and, consequently, relative to the co-ordinates of loops and nods in the standing waves plays a very significant role in forming the energy oscillation spectrum in the channel. From the calculated relations it follows that the largest amplitude of pressure oscillation corresponds to the location of the boiling section relative to the loop of a standing pressure wave, defined by the natural frequency of an oscillation system under fixed boiling condition parameters. Depending on the number of the frequency mode, to the loop of which the section of boiling gets, in the channel the various modes of frequency can be excited in turn or at the same time. This effect is confirmed by experimental data [5].

(C) When measuring one of the conditions' parameters, let us say, q, the dependence $p(x) = F(q)$ can have one or a few local maxima or it can vary monotonically. At this, the frequency spectrum of oscillations can vary smoothly or by shock. This situation was observed, practically, in all experiments, carried out on different rigs in a wide range of experimental condition variations.

Let us consider concrete typical cases by comparing experimental data with calculating theoretical results, obtained on applying the proposed model. Figure 7 presents experimental data [6] for three maxima of pressure oscillation amplitude on varying the heat load. In the given example the deviation of the computed heat-load value when the resonance occurs does not exceed 20% from the value determined in experiments.

The comparison of calculated dependencies with experimental data [5] that are given in Fig. 8 has qualitative character and confirms, first of all, the assumption about the resonance form of local maxima of increasing pressure oscillation amplitude on changing q (the calculation was carried out to determine the resonance q-values when the frequencies of natural and forced oscillations coincide).

Figure 9 illustrates the possibilities of calculation on applying the proposed model to explain the phenomena observed in the experiments: changing the modes of frequencies, changing the amplitude and oscillational frequency by shock or by smooth oscillation. In the example given here, the changing of frequency modes, from first to third, takes place at monotonic load varying. In these apparatus experiments such load variation (from 15%) can twice result in a sharp change in the oscillational intensity and it could be interpreted as a shock-type changing of oscillation amplitude. By way of computation we can prove that shifting the border of beginning the fluid boiling in a channel on changing the conditions' parameters (which is considered by the model proposed) can result in multimodal excitation of oscillations, in shock-type or monotonic changing of the main maximum frequency in the oscillation spectrum, in monotonic, shock-type decreasing or increasing oscillation amplitude etc. i.e. it can result in the phenomena observed during experiments.

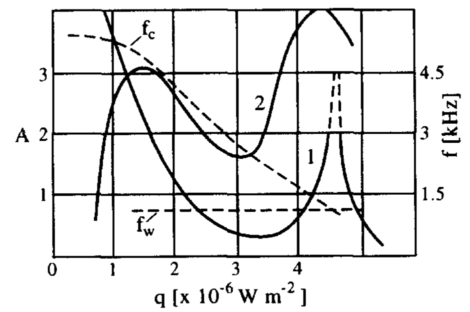


Fig. 8. Comparison of experimental and calculation data: 1—calculation; 2—data of experiments according to ref. [5].

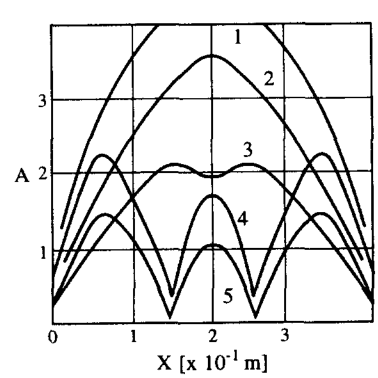


Fig. 9. The dependence of mode of frequency on the heat flux considering the calculation results.

Thus, the suggested approach to the analysis of the observed phenomena as well as to the results of 'ordinary' resonance in an oscillating system: 'channel–vapour–liquid flow' in the presence of forced oscillation sources (the effect of vapour bubbles) allows us to explain all the versatility of the facts observed in experiments without any contradictions. It can also serve as the basis when selecting the operational conditions for various thermotechnical facilities securing reliable work without breaking-down, in the cooling of HFS systems and lasers, in particular.

6. CONCLUSIONS

The experimental studies carried out and already known and their analysis based on the proposed physical model of the phenomena, allows us to come to the following conclusions. Thermo-acoustic phenomena when boiling subcooled liquid in channels should be considered as resonance phenomena in vapour–liquid media at existence of forced oscillation sources. The corresponding effect is exerted by arising centers of vaporization. The resonance occurs when the frequency of vaporization centers coincide with the natural oscillational frequencies of vapour–liquid flows the vapour-pressure of which depends on the flow pattern, channel geometry and vapour and gas particle volumes of the flow.

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