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HEAT TRANSFER TO A LAMINAR FLOW OF TOLUENE OF SUPERCRITICAL PRESSURE IN THE REGION OF DEVELOPMENT OF HIGH-FREQUENCY THERMOACOUSTIC INSTABILITY

Ch. M. Verdiev

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Results and the procedure of an experimental investigation of heat transfer in combination with high-frequency thermoacoustic self-oscillations of the pressure of toluene, $t_{liq} < t_m$, $t_w/t_m = 1.15-1.90$ *are presented. A criterial heat transfer equation in a vast region of excitation of thermoacoustic pressure self-oscillations is proposed, and the boundary for the onset of the development of the oscillatory process is found.*

In the past decade, the number of reports on investigating heat transfer at supercritical pressures (SCPs) accompanied by high-frequency (HF) thermoacoustic self-oscillations (TASOs) of the pressure of the heat-transfer agent has decreased. In spite of the topicality of the problem of the reliability of heat-exchange apparatuses and the search for new efficient methods of intensification of heat transfer, the laminar regime at SCPs is the least studied. The investigations are limited to several works [1-4] in which the heat transfer is accompanied by TASOs of the pressure for small Reynolds numbers.

The possibility of energy transferring efficiently with small losses and the use of nonstandard methods of intensification and optimum control of heat-transfer processes seem very promising. A significant increase in the heat-transfer coefficient and, consequently, an increase in the heat-transfer rate with a fixed density of the heat flux due to realization of efficient regimes and organization of pulsating oscillations or initiation of powerful effects of thermoacoustic self-oscillations open up new ways of solving the problem of heat transfer at SCPs.

The known investigations of SCP heat transfer cover mainly the near-critical region of variation in the liquid temperature. This is due to the fact that a heat-transfer agent that arrives at a boiler is heated to a nearly critical temperature. As the heat-release rate of power-generating units increases further at SCPs, heat-exchange apparatuses with organization of heat-transfer processes between a wall and a liquid with insignificant underheating of it to a pseudocritical temperature can be designed. Studying the regularities of the heat transfer is of great interest since here we observe an improved regime of heat transfer [4-6]. These regimes can be accompanied by TASOs of the liquid pressure, which imposes additional conditions on the course of the process and makes it difficult to calculate the heat-transfer coefficient.

The use of organic heat-transfer agents of high technical-and-economic and performance-technical indices that are easily integrated with low- and high-potential energy sources in creating highly forced steam-turbine converters is a promising trend in autonomous heat power engineering [7, 8]. In spite of the evident topicality of the problem of investigating a hydrocarbon heat-transfer agent in a fluctuating flow, there has been no suitable mathematical model as yet for calculating amplitude-frequency characteristics (AFCs) and finding the regions of the existence of oscillatory regimes from the viewpoint of the use of this regime as the working regime [9-13]. This is explained by the absence of clear physical ideas of the process investigated. And the results of the known works are conflicting, defy systematization, and are difficult to analyze. Furthermore, they are obtained basically on units not designed for investigating HF thermoacoustic instability (there are no clear-cut boundary conditions at the ends of the heat-exchange channel) [1-4].

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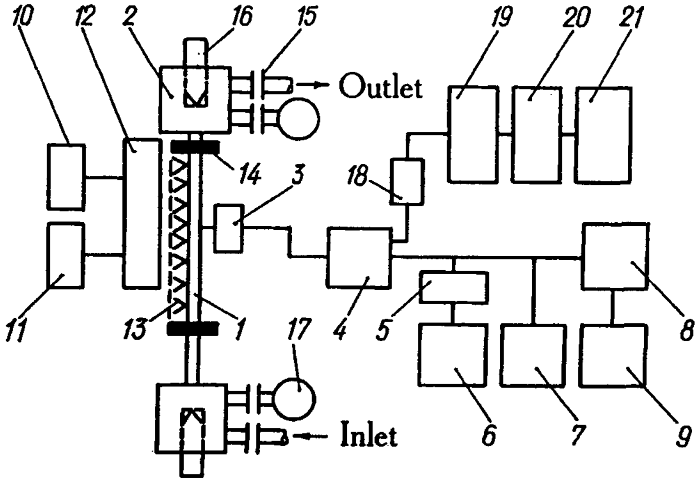

Fig. 1. Block diagram for measuring the temperatures of a wall and a liquid in combination with the parameters of thermoacoustic self-oscillations of the pressure of the heat-transfer agent: 1) experimental tube (an acoustically open channel), 2) acoustic decouplers (capacitors of constant pressure), 3) DDI-21 high-frequency inductance pressure transducer, 4) IVP-2 inductance two-channel converter, 5) PNSh-4 voltage converter, 6) N-117/1 loop oscillograph, 7) S1-68 electron oscillograph, 8) SK4-56 panoramic spectrum analyzer, 9) N-307 fast-acting plotting device, 10) KSP-4I electron automatic potentiometer, 11) V7-23 multipurpose digital voltmeter, 12) electromechanical switch, 13) block of Chromel–Copel thermocouples, 14) current leads of tough-pitch copper, 15) fluoroplastic electric decouplers, 16) sleeves for Chromel–Copel thermocouples, 17) standard pressure gauges, 18) matching amplifier, 19) K1113 PV1 analog-to-digital converter, 20) KR580 VV55 parallel interface, 21) IBM-486 DX5 personal computer.

The aim of this work is to investigate heat transfer at SCPs in a laminar regime of toluene flow in combination with the oscillatory process occurring in a tube and to propose criterial equations of the heat transfer in the region of excitation of pressure TASOs and for determining the boundaries of existence of high-frequency thermoacoustic instability.

Measuring Procedure and the Equipment Used. To study the pulsation regime, we designed an experimental setup with an open cycle of the motion of a heat-transfer agent whose circulation was effected using a four-plunger pump. For investigating the stability of a heat-exchange tube and AFCs of pressure TASOs of the heat-transfer agent, use was made of specially manufactured acoustically open channels with a coefficient of reflection of pressure waves that is close to unity [5]. The measuring scheme developed for AFCs of pressure TASOs also records the moment at which the oscillations occur (Fig. 1).

The acoustic signal was analyzed and processed using an IBM-486DX5 personal computer (with the method of fast Fourier transform) connected via a KR580 VV55 parallel interface to the output of a K1113 PV1 analog-to-digital converter (ADC). Prior to feeding to the personal computer for processing, the analog signal of the acoustic pressure is converted to an eight-digit code using the ADC.

A DDI-21 inductance pressure transducer that receives TASOs is installed in the middle portion of the tube. It is directly connected to an IVP-2 inductance HF converter whose range of working frequencies is 0–10 kHz. The amplitude of low-frequency pressure pulsations controlled by the transducer and produced by the four-plunger pump had the order of ±1% of the static pressure maintained in the tube. The measurements were performed by an S1-68 oscillograph. To evaluate the effect of pulsations of the pump on the heat transfer, we conducted comparative experiments by supply of a liquid to the experimental tube both by displacement with compressed air from balloons (without pressure oscillations) and using the pump. The results of these experiments were in complete agreement. Thus, pressure oscillations of the indicated intensity do not have an effect on the process of heat transfer.

The measurement error was ±10% for the amplitudes of pressure TASOs and ±5% for their frequencies. The measurements of the oscillation amplitudes and frequencies were duplicated in a real time scale by measuring their magnitudes directly on the screen of the S1-68 oscillograph and an SK4-56 panoramic spectrum analyzer connected with an N-307/1 fast-acting plotting device that was used for recording and analysis of spectrograms and their subsequent documentation.

To investigate the heat transfer in ascending motion of toluene, we used vertically arranged tubes of IKh18N10T steel of the following geometry: $d_{\text{outs}}/d_{\text{ins}} = 4.0/3.5$ (mm); $L/L_{\text{heat}} = 420/220$, $180/140$ (mm).

In the experiments, the regime parameters were varied within the limits: $t_{\text{liq}}/t_m = 0.08-1.0$; $t_w/t_m = 0.15-1.60$; $q = (0.3-4.9)\cdot 10^5$ W/m^2; $\rho u = 90-300$ kg/(m$^2\cdot$sec); $\text{Gr} = 2\cdot 10^3-4\cdot 10^6$; $\text{Re} = 400-2300$.

To establish the reliability of the procedure used in determining the local heat-transfer coefficient, we conducted a series of calibration experiments on the heat transfer in a laminar regime in the convective region. The results of the experiments showed good convergence of the experimental data with data calculated by the equation [4]

$$\text{Nu} = 0.33\,\text{Re}^{0.50}\,\text{Pr}^{0.43}\,(d/x)^{0.40}\,. \tag{1}$$

The error did not exceed ±15%, which is allowable, taking into account the difficulty of conducting the experiments in the regime of excitation of TASOs of the pressure of the heat-transfer agent. The heat-exchange tube had an unheated segment in the forepart for ensuring thermal and hydrodynamic stabilization of the flow. The wall temperature was measured by Chromel–Copel thermocouples arranged uniformly in eight cross sections of the tube. The diameter of the thermocouple wires was 0.3 mm. To prevent heat losses in the radial direction, the tube was isolated from the external medium by densely wound asbestos cord. The procedure for determining the heat-transfer coefficient is no different from the universally adopted procedure. The measuring procedure and errors for the individual quantities are described in detail in [5].

Temperature Regime of the Tube Wall. Figure 2a presents a typical distribution of the tube-wall temperature away from the inlet as a function of the heat-flux density. A similar distribution of the wall temperature was observed in [2-4]. However the authors failed to allow for the effect of TASOs of pressure on the heat transfer. In these works, there are no generalizing dependences of the heat transfer in a pulsation flow regime. The description of the heat transfer is one-sided in character, does not correspond in full measure to the regularities of the actually occurring process of heat transfer, and fails to allow for the oscillatory component of the heat transfer.

On the initial segment AB, there is normal convective heat transfer. When the wall temperature approaches the pseudocritical temperature t_m, the specific inflection BC forms, which is explained by the fact that the thermophysical properties of the heat-transfer agent change sharply and in a distinctive way in the wall region. In particular, the specific heat at constant pressure passes through a maximum, and the intensification of the heat transfer increases sharply as compared to normal convective transfer. As the heat flux increases, the intensity of the heat transfer decreases somewhat on segment CD. Starting with the heat flux $q = 2.0\cdot 10^5$ W/m^2, corresponding to point D of the plot $t_w = f(q)$, TASOs of the pressure of the heat-transfer agent that have a profound effect on the heat transfer are excited in the acoustically open channel. On segment CD the wall temperature decreased by 100°C. A further increase in the heat flux leads to a slight increase in the wall temperature on the terminal segment EF. It is noteworthy that with significant heat loads the TASOs of the pressure were not attenuated, as was the case in [14], but, on the contrary, were characterized by stable amplitudes and frequencies (Fig. 2b and c). In the experiment, we recorded the first harmonic of the pressure oscillations at a frequency of 400 Hz. The amplitude of the acoustic pressure increased smoothly with the heat load and attained 2.0 MPa, ensuring a regime of "mild" excitation. No upper bound of the TASOs of the pressure was found.

The plot $t_w = f(q)$ illustrates well the existence of individual regimes of flow: a viscous regime on segment AB, a viscous-gravitational regime on segment BCD, and a specific pulsation regime on segment DEF. In this region

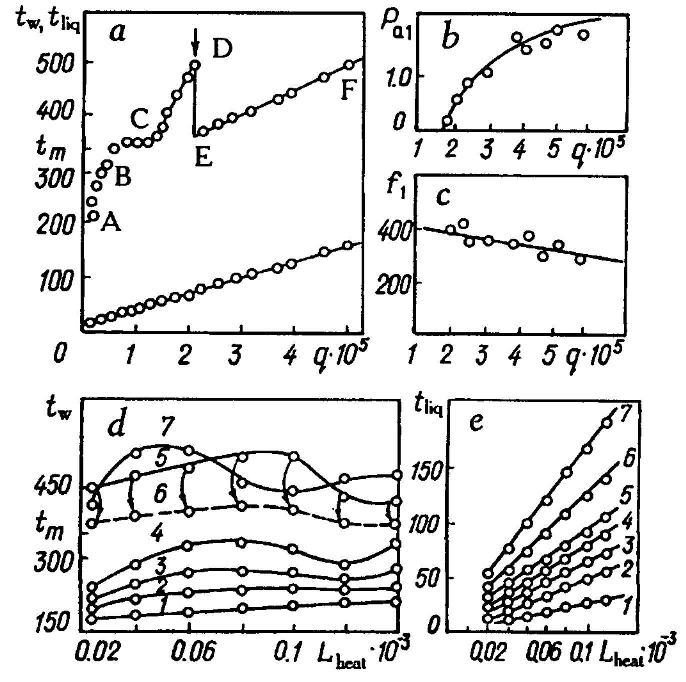

Fig. 2. Measurement the wall temperature and the amplitude-frequency characteristics of thermoacoustic self-oscillations of the pressure of toluene for $P_{cr} = 4.8$ MPa; $\rho u = 180$ kg/(m^2·sec); $Re_{inl} = 800$; $t_{liq}^{inl} = 25$°C; $L/L_{heat} = 180/140$ (mm); $d_{outs}/d_{ins} = 4.0/3.5$ (mm); a) $t_w = f(q)$; b) $P_{acl} = f(q)$; c) $f_1 = f(q)$; d) $t_w = f(L_{heat})$; e) $t_{liq} = f(L_{heat})$ [$q \cdot 10^5$: 1) 0.55, 2) 0.59, 3) 0.64, 4) 0.76, 5) 1.13, 6) 1.73, 7) 3.80]. The arrows indicate the direction of variation of the temperature in the oscillatory regime. t_w, t_{liq}, °C; q, W/m^2; P, MPa; f, Hz.

of heat fluxes, the TASOs of the pressure of the heat-transfer agent are superimposed on viscous-gravitational flow (the external field of a standing wave that exists between the inlet and the outlet of the tube).

For small temperature differences, the distribution of the wall temperature along the tube length is monotonic in character, which corresponds to the normal law of convective heat transfer (Fig. 2d, curves 1 and 2).

When the temperature of the tube wall approaches the pseudocritical temperature t_m, the monotonic character of the variation of the wall temperature is disturbed, which is due to the difference of the local heat-transfer coefficients along the tube length. As a consequence the wall temperature acquires a distinctive wavy character (curves 3 and 4). There are no pronounced maxima of the wall temperature along the tube length characteristic of an impaired regime of heat transfer. The similar variation of the wall temperature is primarily due, as has been indicated above, to the sharp change in the thermophysical properties of the substance in the wall layer of the tube at the pseudocritical temperature. A further increase in the heat flux leads to a decrease in the wall temperature in the terminal part of the tube (curve 5). This is explained by the effect of free convection on the heat transfer, whose action begins to actively propagate from the end of the tube to its start. The ratio Gr/Re increases and attains the order of several thousand, which indicates the occurrence of significant thermogravitational forces. For the heat flux corresponding to the threshold value, whose magnitude depends on the regime parameters, TASOs of the pressure of the heat-transfer agent are generated in the experimental tube.

Thus, the viscous-gravitational regime of flow gives way to the pulsation regime with a characteristic decrease in the wall temperature over the entire segment of heating (curve 6). As the heat flux increases under the action of the TASOs of the pressure of the heat-transfer agent the heat transfer is additionally intensified and as a consequence the rate of temperature increase decreases, which is well illustrated by curve 7. Deformation of the wall temperature under the action of TASOs of pressure was noted by many authors· [2-4, 15-17]. This leads to an additional error in calculating the local heat-transfer coefficient and therefore we need to allow for the acoustic mechanism of heat transfer [10]. Use of existing data on SCP heat transfer obtained without using means of

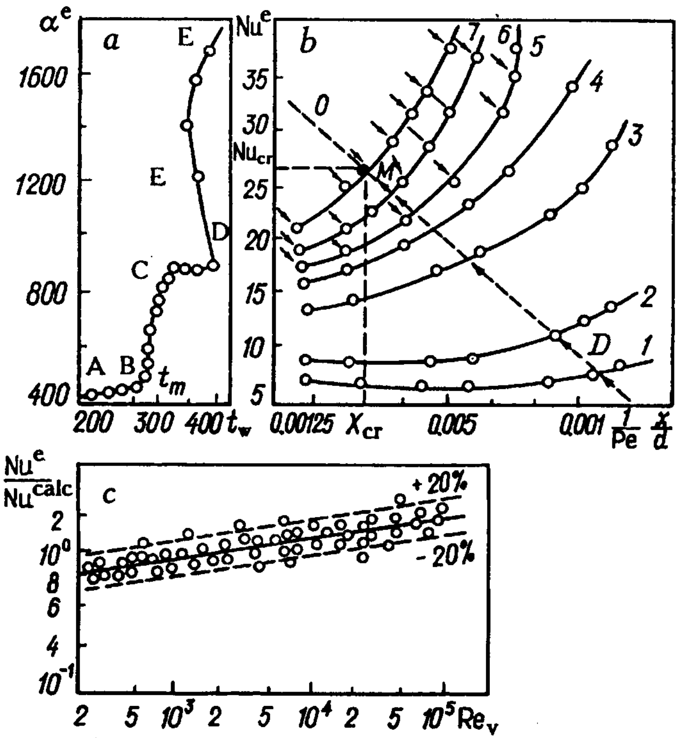

Fig. 3. Change in the heat-transfer coefficient as a function of the wall temperature, the reduced length of the tube, and the modified amplitudinal vibrational Reynolds number: a) $\alpha^e = f(t_w)$; $P_{cr} = 4.6$ MPa; $\rho u = 280$ kg/(m^2·sec); $t_{liq}^{inl} = 25°$C; $\mathrm{Re}_{inl} = 1000$; $x/d = 25$; $L/L_{heat} = 420/225$ mm; $d_{outs}/d_{ins} = 4.0/3.5$ (mm); b) $\mathrm{Nu}^e = f((1/\mathrm{Pe})(x/d))$; $P_{cr} = 8.0$ MPa; $\rho u = 100$ kg/(m^2·sec); $t_{liq}^{inl} = 25°$C; $\mathrm{Re}_{inl} = 500$ [$q \cdot 10^5$, W/m^2: 1) 0.14, 2) 0.47, 3) 0.84, 4) 1.37, 5) 1.54, 6) 2.10, 7) 2.70]; c) $\mathrm{Nu}^e/\mathrm{Nu}^{calc} = f(\mathrm{Re}_v)$. Curves constructed in the oscillatory regime are denoted by arrows.

acoustic diagnostics of the heat-transfer channel for stability must be approached with a certain degree of caution since inaccurate results that fail to allow for the effect of the oscillatory regime on the heat-transfer agent can be obtained.

Change in the Heat-Transfer Coefficient as a Function of the Heat-Flux Density. On the plot $\alpha^e = f(t_w)$ (Fig. 3a), we can clearly trace the regimes of convective heat transfer found on the dependence $t_w = f(q)$ (Fig. 2a) (the boundaries of the regimes are denoted by the same letters). We note that the normal regime of convective heat transfer is completed on segment AB and subsequently changes to an improved regime – on segment BCDE. The improved regime of heat transfer is formed in the first stage as a result of a sharp change in the thermophysical properties of the substance (segment BC) and the effect of free convection (segment BD). In the second stage, the additional improvement (segment DEF) occurs as a result of generation of TASOs of pressure.

Change in the Heat-Transfer Coefficient along the Tube Length. Figure 3b presents the dependence $\mathrm{Nu}^e = f((1/\mathrm{Pe})(x/d))$ obtained before the oscillations and in the pulsation regime of flow. Analysis of the experimental data for small Reynolds numbers shows that in flows in the presence of heat transfer and large temperature differences at SCPs a sharp change in the physical properties of the substance contributes to the occurrence of free motion. Therefore the stability of the laminar motion is disturbed and the viscous regime changes to a viscous-gravitational regime. One regime becomes the other along the tube length. Thus, on the heated length, two regimes of heat transfer can exist simultaneously, and this leads to a characteristic nonuniform distribution of the heat-transfer coefficient along the experimental segment.

From the plot of the distribution of the heat-transfer coefficient on the initial thermal segment it follows that, for $t_{liq} < t_w < t_m$, the change in the heat-transfer coefficient along the tube length does not differ from normal regularities of convective heat transfer (curve 1). As the heat flux increases further (P = const, ρu = const, $t_{\text{liq}}^{\text{inl}}$ = const), the temperatures of the wall and the liquid increase and, in the initial thermal segment, the regular character of the change in the heat-transfer coefficient is disturbed under the action of free motion. As has been indicated above, the effect of the free motion on the heat-transfer intensity begins to propagate from the outlet of the tube to its inlet. On the curve $\text{Nu}^{\text{e}} = f((1/\text{Pe})(x/d))$, a distinctive inflection forms whose coordinates Nu_{cr} and X_{cr}, the line OD, and the point M move to the initial part of the tube as the heat flux increases (curves 2-7). With the heat flux $q = 1.7 \cdot 10^5$ W/m^2, TASOs of the pressure of the heat-transfer agent are generated in the heat-transfer channel. This indicates the viscous-gravitational regime becoming the pulsation regime (curve 5), after which additional intensification of the heat transfer due to the special features of the acoustic mechanism of heat transfer (destruction of the wall layer of liquid of low density and disturbance of the flow hydrodynamics) occurs in the channel. A further increase in the heat load leads to an increase in the coefficient of heat transfer over the entire segment of heating. Analysis of the curves obtained confirms that the regime of regular convective heat transfer always changes to the improved regime, which is maintained in the tube with increase in the heat flux at first owing to the free convection and then due to the additional effect of the pressure TASOs. In the terminal part of the tube, the heat transfer is several times higher than in the initial part. The initial thermal segment of stabilization disappears (curve 7). Calculation of the heat transfer by existing criterial equations is quite inefficient here.

Generalization of Experimental Data on Heat Transfer before Development of the Oscillatory Process in the Tube. An analysis of the experimental data shows that we can use the following criterial equations for calculating the boundary of the change of the viscous regime to the viscous-gravitational regime in a stable region of the flow of the heat-transfer agent before excitation TASOs [4]:

$$X_{\text{cr}} = 2.9\,(\text{Re}/\text{Gr})^{1.10}\,; \tag{2}$$

$$\text{Re}_{\text{cr}} = 0.32\,\text{Re}_{\text{inl}}^{1.25}\,(\text{Gr Pr})^{0.15}\,, \quad \text{Gr Pr} < 10^6\,; \tag{3}$$

$$\text{Re}_{\text{cr}} = 0.85\,\text{Re}_{\text{inl}}^{1.05}\,(\text{Gr Pr}\cdot 10^{-6})^{0.5}\,, \quad \text{Gr Pr} < 10^6\,. \tag{4}$$

In the viscous regime of flow, for small temperature differences, Eq. (1), which yields good convergence of the results, $t_{\text{liq}} < t_m$, $t_{\text{w}} < t_m$, is used for calculating the heat transfer.

It is established that, in the viscous-gravitational regime before development of the oscillatory process in the tube, the equation

$$\text{Nu} = 0.033\,\text{Re}^{0.50}\,\text{Pr}^{0.43}\,\text{Gr}^{0.415}\,. \tag{5}$$

is used ($t_{\text{liq}} < t_m$, $t_{\text{w}} > t_m$).

Since on the tube length, in the general case, when the heat fluxes are high, the viscous and viscous-gravitational regimes can exist simultaneously (before pulsations of the heat-transfer agent occur), Eqs. (1) and (5) are used for calculating the local Nu with allowance for dependences (2)-(4), which make it possible to find the real boundary along the tube length that divides these regimes. As the experiment shows, with development of the oscillatory process in the tube the inflection on the dependence $\text{Nu}^{\text{e}} = f((1/\text{Pe})(x/d))$ moves to the initial part of the tube, and then the thermal segment of stabilization disappears (curve 7). In this case, it is inefficient to use Eqs. (1)-(5) for calculating the heat transfer.

Generalization of the Experimental Data on Heat Transfer in the Pulsation Regime of the Flow of the Heat-Transfer Agent. The experimental data on heat transfer obtained for ascending motion of toluene in a vertical tube in the region of the pulsation regime are described by one equation ($\text{Gr} = 0.5 \cdot 10^5 - 4 \cdot 10^6$; $\Delta t = (100-350)$ °C, Fig. 3c):

$$\text{Nu}^{\text{p.r}} = 0.315\,\text{Re}^{0.50}\,\text{Pr}^{0.43}\,\text{Gr}^{0.415}\,\text{Re}_{\text{v}}^{0.15}\,, \tag{6}$$

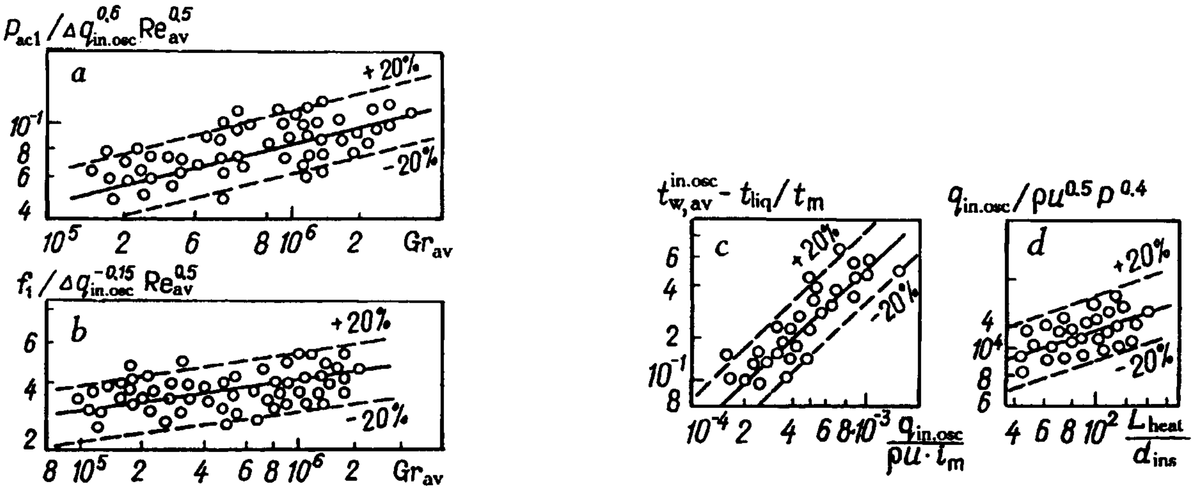

Fig. 4. Amplitude (a) and frequency (b) of the acoustic pressure of the first harmonic of TASOs and average temperature of the wall (c) and heat load (d) that correspond to the lower bound of oscillations vs. regime parameters and criteria.

where $Re_v = 2\pi f_1 P_{ac1} d_{ins}/\mu_{liq}$ is the modified amplitudinal vibrational Reynolds number [5]. For the amplitudes and frequencies of the first harmonic of the TASOs, we used the empirical dependences [5] (Fig. 4a and b)

$$P_{ac1} = 0.524\cdot 10^6\, \Delta q_{in.osc}\, Re_{av}^{0.25}\, Gr_{av}^{0.20}\,, \tag{7}$$

$$f_1 = 6.1\, \Delta q_{in.osc}^{-0.15}\, Re_{av}^{0.50}\, Gr_{av}^{0.14}\,. \tag{8}$$

It is established that TASOs of the pressure are excited, as a rule, at the fundamental frequency of the process while the higher harmonics starting with the second have small amplitudes, are rapidly damped, and have no effect on the heat transfer.

To calculate the threshold boundary of pressure TASOs in the laminar regime, we can use emprical dependences obtained in the transition region of the flow of an organic heat-transfer agent [5] (Fig. 4c and d):

$$q^{in.osc} = 3950 P^{0.40}\, \rho u^{0.50}\, (L_{heat}/d_{ins})^{0.25}\,, \tag{9}$$

$$t_{w,av} = [120\, (q_{in.osc}/\rho u\cdot i_m) + 1]\, t_m\,. \tag{10}$$

The given complex of Eqs. (1)-(10) enables us to calculate the heat transfer in the viscous, viscous-gravitational, and pulsation regimes.

Conclusions. When the temperature of the liquid at the inlet to the tube is constant, i.e., in the regime of large subcoolings from t_{liq} to t_m, no upper bound of the TASOs of the pressure is found while the lower bound depends on the regime parameters and the geometry of the tube.

Analysis of the experimental data in convective heat transfer under conditions of SCPs shows that, for a more accurate calculation, we need to take into account the acoustic mechanism, introducing the corresponding correction in the criterial heat-transfer equation.

In a wide range of variation of the regime parameters, we obtained a high level of intensification of the heat transfer in the laminar regime, $t_{liq} < t_m < t_w$, due to excitation of TASOs of the pressure of the heat-transfer agent, which can be allowed for in developing new methods of intensification of heat transfer with initiation of pulsating flows when highly forced, economic heat-exchange apparatuses of SCPs that use organic heat-transfer agents are designed.

NOTATION

t_w, tube-wall temperature; t_m, pseudocritical temperature of the liquid that corresponds to the specific heat at constant pressure; t_{liq}, mass-mean temperature of the liquid; P, static pressure; P_{cr}, critical pressure; L, tube length; d, tube diameter; x, distance from the inlet to the heated segment; i_m, enthalpy of the liquid that corresponds to the specific heat at constant pressure at the pseudophase-change temperature; f_1, frequency of the first harmonic (mode) of the TASOs of the pressure of the heat-transfer agent; P_{ac1}, amplitude of the first harmonic (mode) of the acoustic pressure in the standing wave; μ, kinematic viscosity; Nu, Nusselt number; Re, Reynolds number; Pr, Prandtl number; Gr, Grashof number; Pe, Péclet number; $\mathrm{Re}_v = 2\pi f_1 P_{ac1} d_{ins}/\mu_{liq}$, modified amplitudinal vibrational Reynolds number; X_{cr}, critical reduced length of the tube divided by the point of inflection of the plot $\mathrm{Nu}^e = f((1/\mathrm{Pe})(x/d))$ into two parts with different regularities of the course of heat transfer; q, specifc heat flux; $\Delta q_{in.osc} = q_c - q_{in.osc}$, change in the current specific heat flux in the pulsation regime relative to the initial boundary of oscillations; ρu, mass velocity. Subscripts and superscripts: e, experimental; liq, liquid; p.r, pulsation regime; calc, calculated; inl, inlet; av, average value of the quantity or the criterion; ac, acoustic; c, current value of the specific heat flux; in.osc, initiation of oscillations that corresponds to the lower bound of development of TASOs in the tube; outs, outside; ins, inside; heat, heated length of the tube.

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