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EXPERIMENTAL EVALUTION OF THE CHANGING ENTROPY OF LIQUID IN ACOUSTIC COMPRESSION PULSE

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For the case of forming of the acoustic one-polar compression wave with due account of provisions of acoustics, thermodynamics, momentum and energy conservation laws is shown the possibility of changing entropy determination in real liquids. The experimental evaluations of changing entropy in water and glycerine at compressive pressure values of 0.5 to 50 MPa and the effect duration of 70…80 ms were made.

In general case the radiation and propagation of acoustic waves in real media is connected with the simultaneous manifestation of mechanical and thermodynamic processes. The uptodate physical description of these processes is given by hydrodynamics equations [1-3]:

$$r\,\frac{d\bar{u}}{dt} = -\nabla p + h\Delta\bar{u} + (z + \frac{h}{3})\,grad\,(div\,\bar{u}) + r\bar{f}\,; \qquad (1)$$

$$\frac{\partial r}{\partial t} + div\; r\,\bar{u} = m\,; \qquad (2)$$

$$rT[\frac{\partial S}{\partial t} + (\bar{u}\nabla)S] = div(c\nabla T) + z\,(div\bar{u})^2 + \frac{h}{2}(\frac{\partial u_n}{\partial x_k} + \frac{\partial u_k}{\partial x_n} - \frac{2}{3}d_{nk}\frac{\partial u_l}{\partial x_l})^2 + Q\,; \qquad (3)$$

$$p = p(r, S); \qquad (4)$$

$$de = TdS - pdV; \qquad (5)$$

where: *ñ* - medium density; *v* - mass velocity at space point of medium (mass velocity vector); *p* - pressure; η, ξ - shear and bulk viscosities; *f* - external force affecting the liquid mass unit; m - mass source (usually m=0); *V* - volume per mass unit; *T* - absolute temperature; *S* - specific entropy; χ - thermal conductivity coefficient; Q - velocity of heat increase from external sources; *p*(*ñ*,*S*) - medium state thermodynamic function; ε-specific internal energy of the medium. Time and space coordinates are given in Eiler form. The system of equations (1-5) is not closed – considering η, ξ, *f*, *m*, χ, Q, *p*(*ñ*,*S*) known, eight unknowns v (v_x, v_y, v_z), *ñ*, *p*, *T*, *S*, ε and seven equations (1-5) are available. To solve this problem the presumption $dS(t) \equiv 0$ ($S \equiv$ Const) is commonly used. This approach allows to provide the closure of system (1-5) by way of exclusion of unknown *S*.

In acoustics the entropy impact is taken into account only for the cases of description of shock waves and absorption of acoustic waves [1-3]. In [4] on the basis of analysis of (1-5) it is shown, that with due account of the change of entropy (p=p(*ñ*,*S*), $S(t)\neq$Const) in real continuous media together with acoustic fields, there should exist entropy fields of dynamic character varying from the classical processes of absorption of acoustic waves in their propagation. In [4] also for the one-dimensional dynamic compression of the liquid medium the following ratios had been obtained:

$$E_M(t) = E_A(t) + E_r(t) + E_S(t), \qquad (6)$$

$$K_M(t) = K_A(t) + K_r(t) + K_S(t), \qquad (7)$$

$$F_M(t) = F_A(t) + F_r(t) + F_S(t), \qquad (8)$$

where E_M - full mechanical energy spent by the source for the compression of the liquid; E_A - acoustic wave energy; $E_ñ$ - kinematic part of the energy of the motion of the liquid; E_S - thermodynamic part of energy connected with the changing entropy of the liquid dynamically compressed; K_M - momentum translated into liquid from the compression source; K_A - momentum in acoustic wave; $K_ñ$ - momentum connected with the kinematic part of the motion of the liquid; K_S - momentum translated by the source to the thermodynamic (entropy) field; F_M - force affecting the liquid from the source side; F_A - force spent to change pressure (p_A) in liquid; $F_ñ$ - force spent for kinematic acceleration of the liquid; F_S - force spent to change entropy of the liquid medium; τ - current time of the source impact on the medium. At known values of mechanical and acoustic parameters by (6-8) the information may be obtained on changing the thermodynamic field in liquid being dynamically compressed.

Presenting (6) with the accuracy to the second-order terms of minority and (7, 8) with the accuracy to the first order of minority for the cases of liquid compressed by the round flat piston with surface area σ in a cylindrical tube of the same area, system (6, 7, 8) may be presented in form of:

$$E_S(t) = s\int_0^t P_M(t)\,v_M(t)\,dt - s\int_0^t P_A(t)\,v_A(t)\,dt, \qquad (9)$$

$$K_S(t) = s\int_0^t P_M(t)\,dt - s\int_0^t P_A(t)\,dt, \qquad (10)$$

$$F_S(t)/s = P_M(t) - P_A(t), \qquad (11)$$

where $P_M(t)$ - pressure on the liquid medium from the side of the compressing piston [$P_M(t)=F_M(t)/σ$]; $P_A(t)$ - acoustic pressure in liquid [$P_A(t)=F_A(t)/σ$]; $n_M(t)$-compressive piston motion velocity; $n_A(t)$ - mass velocity in the acoustic wave of compression. Values $P_A(t)$, $n_A(t)$ are taken at the piston surface and at the fixation of pressure and mass velocity at distance h from the piston as the function of acoustic pressure and mass velocity in (9-11). They are presented in form of $P_A(t,h)=P_A(t-h/c)$ and $v_A(t, h)=v_A(t-h/c)$, c-the speed of sound in liquid.

In the plane propagating acoustic wave:

$$P_A(t)= ñ_0\, c_0\, v_A(t)\,, \qquad (12)$$

$$v_ì(t)= v_A(t)\,, \qquad (13)$$

where (12) is given in linear approximation [3] (values $ñ_o$, c_o are taken for nondisturbed medium), and (13) follows from the principle of continuity (2). With due account of (12, 13) expression (9) is converted into:

$$E_S(t) = s\int_0^t \frac{P_A(t)\left[P_M(t) - P_A(t)\right]}{r_0\,c_0}\,dt\,. \qquad (14)$$

The specific increment of the thermodynamic part of energy $DE_S(t)$ and specific increment $DS(t)$ at temperature T (deg. K) (relatively to the nondisturbed state of the liquid) at moment t in volume $s\cdot c_o\cdot dt$ with mass of liquid $ñ_o\cdot s\cdot c_o\cdot dt$ with account of (14) are found by:

$$ÄE_S(t)=P_A(t)\cdot(P_M(t)–P_A(t))/(ñ_0c_0)^2 \qquad (15)$$

$$ÄS(t)= ÄE_S(t)/T_0\,. \qquad (16)$$

To make estimations by (10,11,14-16) used as the emitter should be a source of mechanical force (pressure) with controllable parameters $F_M(t)/σ$ or $P_M(t)$. It is noted in [5] that such source is the pulse electrodynamic emitter (PEDE). Standard PEDE [5,6] consists of a flat electrically conductive metal piston located (axial symmetrically) over the flat spiral coil coated with a thin layer of electric insulation. The exterior surface of the piston is loaded onto the medium. When current flows through the spiral coil of PEDE the opposite eddy current is induced in metal piston, so that the piston is repulsed from the coil and compresses the medium under investigation. It is noted in [5] that PEDE belongs to acoustic systems irreversible by energy and that the force developed at the PEDE piston in minor displacements of the piston is determined in compliance with [7]: $F_M(t)=I^2(t)dL/dZ$, where $I(t)$- instantaneous value of electric current flowing through PEDE, dL/dZ- inductivity gradient by the piston displacement axis (Z). The pressure distribution on the PEDE piston surface is sufficiently uniform [6]. Consequently, at piston area σ:

$$Đ_M(t)= (I^2(t)\cdot dL/dZ)/ó\,. \qquad (17)$$

Value dL/dZ is measured by known electromechanical methods (measuring the PEDE inductivity values at fixed change of the piston position by axis Z). When the conditions are observed, i.e. the height of the clearance between the piston and the coil, the piston thickness and the value of the piston displacement at the time of radiation (emittance) are much less than value of the PEDE piston radius, so that in the linear approximation dL/dZ=Const is observed. Value $I(t)$ in PEDE is fixed by current metering devices directly at the time the medium is affected by the pulse compression.

Thus parameters and functions included in formulae (10,11,14-16) are accessible for measurement, which allows to find E_S, K_S, $DE_S(t)$, $DS(t)$ in real liquids.

The principle of the experimental unit for the evaluation of the changes in entropy of a liquid in the course of its acoustic compression is given in Fig.1. The unit comprised pulse electrodynamic emitter 1 fixed on massive base 2, upright metal tube 3 (tubes of steel, copper, bronze were used), liquid under investigation (distilled boiled water or glycerine) 4 poured into tube 3 at the bottom of which piston PEDE 1 was located, electric current source 5, current discharge $I(t)$ control system 6, current form $I(t)$ and amplitude I_o measurement system 7, calibrated piezoelectric hydrophone (acoustic pressure sensor) 8, acoustic pressure form $P_A(t)$ and amplitude P_{A0} measurement and registration system 9.

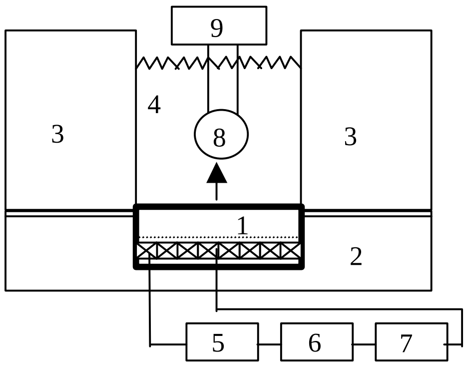

Fig.1

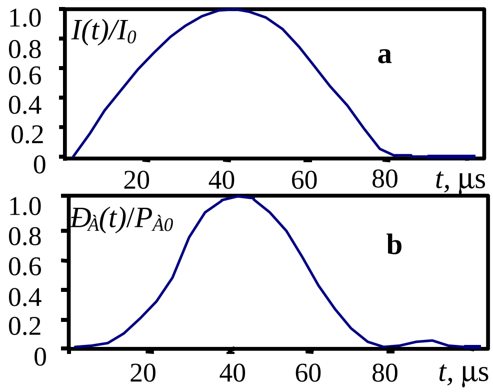

Fig.2

Electric current source 5 through current discharge control system 6 provided the current discharge on PEDE 1, the current form and amplitude being fixed by measurement system 9. In compliance with (17) the pressure compressing the liquid was developed on the piston, the piston moved upwards and plane compressive wave had arisen in the liquid, the acoustic pressure wherein was received by hydrophone 8 and fixed by measuring and registration system 2. Presented in Fig. 2 are standard measured oscillograms of current shapes (Fig. 2a) and acoustic pressure (Fig. 2b), the shown dependencies are rated by peak value of the current (I_o) and acoustic pressure (P_{A0}) respectively. A number of conditions was provided in the course of the experiment: the compressive pulse duration was within the limits τ_o = 70…80 µs (for the operation of calibrated hydrophones in the field of uniform sensitivity), the density and the speed of sound of tube walls ($ñ_T$, c_T) was $ñ_T>ñ_o$; $c_T>c_o$; $(ñ_T c_T) >> (ñ_o c_o)$; the tube wall thickness was greater than the inner radius of the tube, the liquid column height was within the limits of 0.3…0.6 m (the excessive hydrostatic pressure of not more than 0.01 MPa, the atmospheric pressure of not more than 0.1 MPa), the thickness of compressing piston (b) satisfied the conditions of $b<<0.1\tau_o c_o$, $bñ_M<0.1\tau_o c_o ñ_o$ ($ñ_M$-is piston metal density), dL/dZ of PEDE was measured when PEDE 1 was located within the concrete experimental unit (Fig.1), the hydrophone section area was much less than the tube channel section area, values $I(t)$ and $P_A(t)$ at τ_o=70…80 µs were measured in a wide band (not narrower than 0.5-40 kHz), measurements of $P_A(t)$ and P_{A0} were taken at several points in variations of distance h from PEDE piston within the limits of 10-200 mm, by the view of dependence $P_A(t-h/c)$ at various h the absence of shock waves, dispersion and absorption at the section measured was controlled. To raise the accuracy of measurement the investigation has been conducted with various specimens of PEDE and hydrophones in tubes with channel diameters of 20 to 100 mm. Parameters $ñ_o$, c_o, T_o are in water: $ñ_o$ = 1000 kg/m^3, c_o = 1460 m/s, T_o = 291^{0}K; in glycerine: $ñ_o$=1260 kg/m^3, c_o=1900 m/s, T_o=291^{0}K.

The measurement results for peak amplitude values of P_{M0}, P_{A0}, DS_0 are given in Fig.3 and Fig.4. Fig.3 shows the experimental dependence of the amplitude of acoustic pressure P_{A0} on the amplitude of liquid compressing pressure P_{M0}. Fig.3a shows the dependences for water – 1 and for glycerine – 2 at $0 \le P_{M0} \le 12$ Mpa; Fig.3b shows the dependence for water – 3 at mechanical compressing forces up to $5 \le P_{M0} \le 50$ MPa. The error of measurement of absolute values of P_{A0} is 20%; P_{M0} is 6% at P_{M0} of 2 to 35 MPa. Fig.4 shows the experimental dependence of the amplitude of increment of specific entropy DS_0 on the amplitude of liquid compressing pressure P_{M0} for water (Fig.4a,b) and for glycerine (Fig.4c) calculated by data of Fig.3. The error in the evaluation of absolute values of DS_0 is 30% at P_{M0} of 2 to 30 MPa. By the presented data (Figs.3;4) it is possible to set dependence $DS_0=\Delta S_0(P_{A0})$ for water $DS_0 \approx (14\pm6)\,10^{-9}\ P_{A0}$ and for glycerine $DS_0 \approx (5\pm2)\,10^{-9}\ P_{A0}$, where the dimensionality of DS_0 is [J/(kg·deg)] and P_{A0} is [Pa]. Also by the results of measurements of P_{M0}, $P_{A0}(P_{M0})$ in Fig.3 and temporary dependencies $I(t)$, $P_{A0}(t)$ in Fig.2 it is possible by (10,14,17) to evaluate $K_S(\tau_o)$, $E_S(\tau_o)$. Thereby for P_{M0}<(16-20) MPa it follows from the experimental evaluation that $E_S(\tau_o)>E_A(\tau_o)$, $K_S(\tau_o)>K_A(\tau_o)$.

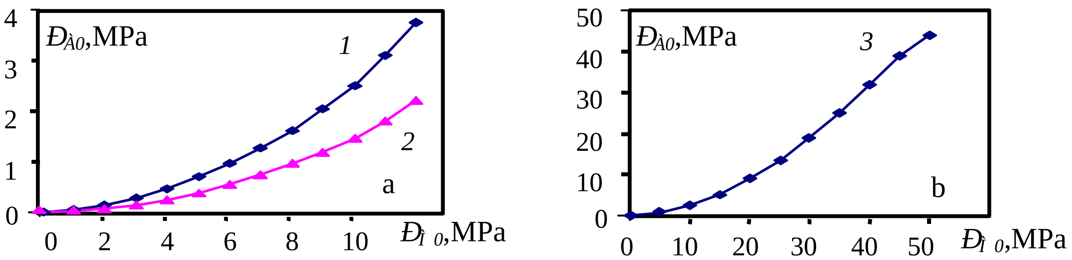

Fig.3

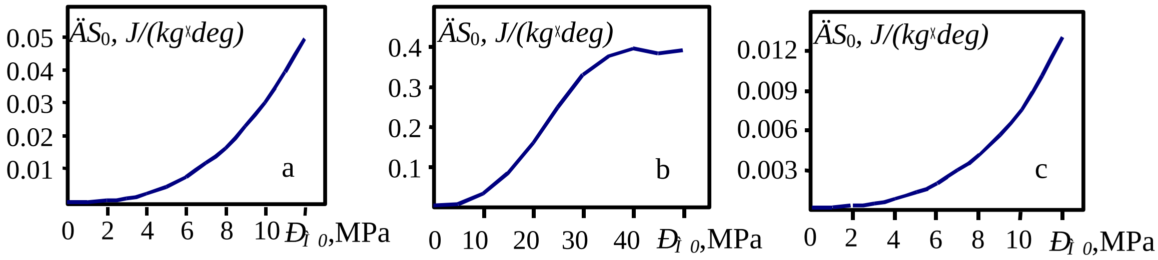

Fig.4

The preliminary information on the character of the effect of the change of entropy obtained by above mentioned method of compressive wave formation may be used for the expansion of the ideas of acoustic processes in real liquids.

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