MEASUREMENT OF THERMAL PRESSURE IN A SUBSTANCE HEATED BY LASER EMISSION

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Measurement of the thermal pressure in a substance heated instantaneously by laser emission can be used to find the equation of state of the substance in the region $\rho = \rho_0$. The devised piezoelectric method has been used to determine the values of the Grüneisen coefficient for heated paraffin. These values are in good agreement with the results obtained by another method in [2].

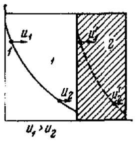

Fig. 1

Instantaneous and uniform heating of a flat layer of substance produces a thermal pressure in it

$$p_T = e_T \rho \Gamma = \frac{E}{m} \rho \Gamma = \frac{E}{x} \Gamma . \qquad (0.1)$$

Here e_T is the energy per unit mass of substance, ρ is the density, x and m are the thickness and mass of the layer, respectively, E is the energy contained in the layer, and Γ is the Grüneisen coefficient. If the heated layer is bounded by a vacuum, a rarefaction wave will propagate from this boundary. If the other boundary of the heated layer is "hard" (for instance, a denser substance with lower compressibility $\rho_0 c_0^2$), then the pressure after the arrival of the rarefaction wave at this boundary will decrease and become negative, which may lead to fracture of the substance. At a pressure $p_T \leqslant \rho_0 c_0^2$ the rarefaction wave front will be narrow and the time before breakaway of the heated layer will be small. The time t before the arrival of the wave is x/c, where c is the speed of sound when the density of the substance is normal. The equation of state of the substance can always be written in the form

$$p = p_x(\rho) + \Gamma \rho \left[e - e_x(\rho) \right] . \qquad (0.2)$$

The coefficient Γ depends on two parameters — the entropy S and the density ρ.

Assuming that Γ does not depend strongly on ρ and taking into account that when $\rho = \rho_0$ the elastic energy $e_x(\rho)$ and the pressure $p_x(\rho)$ are absent we obtain an expression for the speed of sound

$$c^2 = (dp / d\rho)_s = c_0^2 + \Gamma (\Gamma + 1) e_T . \qquad (0.3)$$

The impulse during the time of action of the pressure is

$$I = \frac{p_T x}{c} = \frac{E \Gamma}{\sqrt{c_0^2 + \Gamma(\Gamma + 1) E / m}} . \qquad (0.4)$$

The effect of breakaway of the instantaneously heated layer and the above relationships were discussed more fully in [1, 2].

It follows from 0.1 and 0.4 that I and p_T depend significantly on Γ and this can be used to find $\Gamma(e_T, \rho)$, i. e., the equation of state of the substance in the poorly investigated region $\rho = \rho_0$. The substance can be heated instantaneously by absorption of laser radiation.

Experiments with paraffin [2] and the resulting relationship $I = I(e_T)$ in this case enabled us to find the value $\Gamma = \Gamma(e_T)$ for this substance. This relationship was used to calculate the curve $I = I'(e_T)$ for the case of nonuniform (exponential) heating of the layer and the result was in good agreement with the experimental curve [2]. This confirmed the breakaway theory, expounded in [1], and the possibility of determining the thermodynamic state of an instantaneously heated substance with constant density $\rho = \rho_0$ from the mechanical impulse.

However, besides the determination of the impulse I it is of interest to measure directly the amplitude of the pressure p_T in the compression wave propagating into the cold "hard" substance. A knowledge of p_T for different absorbed energy concentrations can also be used to determine the state of the substance, i. e., to find the relationship $\Gamma = \Gamma(e_T)$. Hence, the value of Γ obtained by different methods can be compared. In addition, the determination of Γ from p_T is fundamentally better, since formula (0.1) is exact, whereas formula (0.4) is approximate, which may lead to some errors in the region of strong heating, where the impulse created on the boundary layer during the time between the arrival of the rarefaction wave and separation of the layer, or until the moment when p = 0, cannot be neglected.

It should be noted that the relationship $\Gamma = \Gamma(e_T)$ can be determined from p_T for substances which have a fairly high breaking strength and, hence, do not fracture at these energy concentrations. Finally, pressure measurements are of interest since they provide direct evidence of the validity of the initial assumptions of the theory [1].

§1. The variation of the pressure with depth in a flat layer of substance is actually of an exponential nature (when the absorption coefficient is constant). An experimental investigation of the equation of state under such conditions encounters particular difficulties. In fact, if a piezoelectric transducer 2 (Fig. 1) for recording the pressure curve is placed behind the uniformly heated substance 1, the perturbations due to heating at various distances from the transducer will arrive there at various speeds (since the speed of sound in the substance depends on the degree of heating) and the recorded picture of the pressure will not correspond exactly with the pressure variation in the layer.

The experiments can be simplified by creating a uniform or "almost uniform" distribution of pressure with depth. By selecting a layer x_0 thick, which is a fraction of the range of the radiation [2], we can regard the pressure distribution in such a layer as constant, i. e., we can speak of some mean pressure $p_T = \langle p_T \rangle = \text{const}$. If the same surface of the transducer has a coating which strongly reflects radiation, then passage of radiation through the layer in the reverse direction will further even out the energy and pressure distribution.

For instance, if the thickness of the layer of investigated substance is ≈0.7 of the range of laser radiation in this substance and the layer is mounted on a silver backing (the reflectivity of silver for the wavelength of a ruby laser is 95%), the calculated nonuniformity of the distribution of absorbed energy over the depth of the layer will not exceed 25%, as against 50% without the reflecting surface. With reduction in the thickness of the layer the nonuniformity of the energy distribution will become less, but the condition of instantaneousness of the heating imposes limitations on the minimum thickness of the layer.

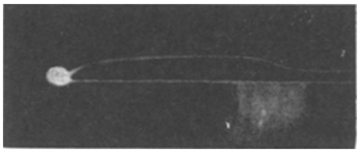

Fig. 2

When the pressure amplitude in the transducer is not too high in comparison with its bulk modulus we can use an acoustic approximation and the pressure p_* in the compression wave detected by the transducer will be associated with p_T by the relationship

$$p_T = p_* \left(1 + \frac{\rho c}{\rho_* c_*} \right) . \qquad (1.1)$$

Here ρ, c and ρ_*, c_* are, respectively, the density and speed of sound in the investigated substance and in the substance of the transducer.

§2. Measurement of thermal pressure is of interest also from the viewpoint of investigating the propagation of short waves, generated by the heating of the surface layer, through various materials. The condition of instantaneousness of heating can be written in the form $\tau < t$, where τ is the time of "pumping" energy into the layer. In the present state of laser technique the "pumping" time, i. e., the duration of the "giant pulse," can be reduced to 4–5 nsec, which gives waves up to 0.1 mm long. In view of this the determination of the pressure in the given case reduces to measurement of the amplitude of very short waves, which means that the detecting device must satisfy particular requirements.

For direct recording of the pressure the thickness d of the transducer must be less than, or at least not more than, the thickness of the heated layer, i.e., $d \leq 0.1$ mm. However, the pressure can also be determined by a thick ($d > x$) transducer, which will record the penetration of the short wave into the transducer and its propagation through it [3].

With the method of measurement which we used we were able to solve this problem but for accurate determination of the equation of state it is more convenient to have a longer lifetime of the pressure (greater than x/c). For this purpose the free surface of the heated layer must be removed by the application of a transparent, but harder, material on the vacuum side.

The colored paraffin which was selected for investigation in [2] and also in the present work enabled us to increase the lifetime of the pressure by using this method.

Taking $\rho c = 2.03$ g/cm^2 • sec for paraffin and $\rho c = 38.7$ g/cm^2 • sec for the piezoelectric ceramic lead titanate zirconate (LTZ), and if the free surface of the paraffin is covered with lead glass ($\rho c \approx 40$ g//cm^2 • sec), we can regard the pressure in the paraffin layer as "quasi-static," i. e., as existing for much longer than the time of propagation of the acoustic wave through the transducer.

§3. To record and measure the amplitudes of the short waves and to measure the thermal pressure we designed a transducer based on LTZ piezoelectric ceramic. The transducer was calibrated in a miniature shock tube, where a shock wave of rectangular profile was generated. An oscillogram of the pressure recorded by the transducer is shown in Fig. 2. The calibration signal in the ideal case should be table-shaped; the slight rise of the horizontal part is due to distortion of the compressed region in its motion through the transducer, whose thickness d is comparable to the diameter D (in our experiments D/d = = 2) [3]. The piezoelectric modulus obtained from the oscillograms was $1.5 \cdot 10^{-9}$ C/kg when the range of pressure in the wave was 40–130 atm. Another method of calibration, in which an accelerated piston is used, was described in [3].

§4. Using the specially constructed transducer calibrated by the above method we measured the thermal pressure in instantaneously heated paraffin and determined the Grüneisen coefficient. The setup of the experiment is shown in Fig. 3.

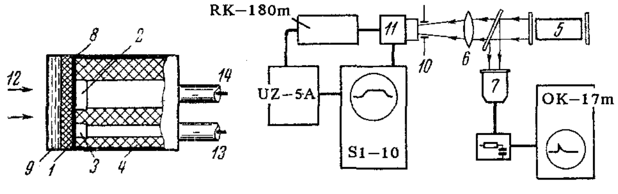

Fig. 3

A layer of colored paraffin 1, 0.2 mm thick (the range of the radiation in it is 0.3 mm) was deposited on the surface of the transducer, whose working (2) and trigger (3) parts, as well as insulator 4, were coated with a polished film of vacuum-evaporated silver. The reflectivity of the coating was 0.95. The other surface of the paraffin was in contact with transparent glass plate 9 ($\rho c = 30$ g/cm^2 • sec) to ensure that the pressure in the layer was "quasi-static."

Beam 12 of Q-switched ruby laser 5 (the duration of the signal at half-power was $\tau = 20$ nsec) was directed by lens 6 (without further focusing in the case of small concentrations) onto the surface of transducer 11. The signal produced in the transducer was amplified and then recorded by an S1-10 oscillograph. The energy of the laser pulse was measured by an FEK-09 coaxial photocell 7. The photocell was calibrated with a calorimeter on which the laser beam fell after passing through diaphragm 10, which was mounted in the plane of the transducer and had an aperture of the same area as the working area of the transducer (0.3 cm^2). Figure 4 shows a typical oscillogram of the pressure signals recorded in the experiments.

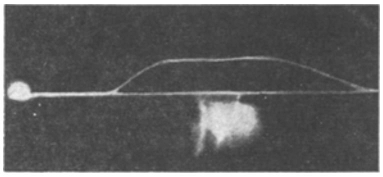

Fig. 4

The shape of the signals was similar to that obtained in calibration with a stepped wave (Fig. 2). However, the rise of the amplitude observed in calibration was compensated in this case, presumably by the gradual removal of the pressure in the layer.

It should be noted that the resolution of the whole measuring channel (transducer, amplifier, and oscillograph) was high enough to transmit the increase in pressure in the layer of substance without frequency distortions. A comparison of the front of the pressure signal (Fig. 4) with that of the laser light signal recorded by the FEK-09 photocell showed good agreement.

Below we give the values of the Grüneisen coefficient Γ calculated from formula (0.1) for several values of absorbed energy E (in joules), ratios E/m_0 (cal/g) and measured pressure p_T(atm) :

$E =$	0.035	0.040	0.042	0.045	0.047	0.047
$E/m_0 =$	1.50	1.70	1.80	1.93	2.02	2.02
$p_T =$	121	127	154	153	162	168
$\Gamma =$	2.70	2.50	2.87	2.66	2.70	2.80
$E =$	0.056	0.067	0.098	0.103	0.107	0.107
$E/m_0 =$	2.40	2.91	4.20	4.40	4.60	4.60
$p_T =$	160	226	306	271	325	338
$\Gamma =$	2.27	2.64	2.46	2.06	2.38	2.48
$E =$	0.071	0.077	0.090	0.087	0.082	0.086
$E/m_0 =$	4.36	4.70	5.50	7.15	6.77	8.40
$p_T =$	286	290	324	400	407	500
$\Gamma =$	2.77 *	2.52 *	2.40 *	2.29 *	2.43 *	2.44 *

The values of Γ marked with an asterisk were obtained by measurements with a quartz piezoelectric transducer. For comparison we give some values of Γ obtained in [2] from the breakaway impulse

$E/m_0 =$	20	30	50	60	70	90	120	130	160
$\Gamma =$	2.69	2.70	2.79	2.68	2.40	1.96	1.55	1.43	1.20

Since the power of the laser and the dimensions of the transducer imposed some restriction on the experiments, the energy concentrations were below those attained in [2].

Assuming that the Grüneisen coefficient at low absorbed energy concentrations is constant we see that the presented data do not contradict this and, moreover, agree very accurately with one another. The experiments showed the applicability of the selected method of measuring thermal pressure in a plane layer of instantaneously heated substance. The agreement between the Grüneisen coefficients obtained by the two methods confirms the correctness of the breakaway pressure theory expounded in [1].

The employed piezoelectric method can be used to measure pressures acting for up to 10^{-8} sec and produced by laser emission in the surface layers or on the actual surface of certain solids. It should be noted that deposition of a thicker and denser layer on the surface of the layer of substance heated by laser radiation increases the duration of action of the pressure and also increases the accuracy of its measurement. This could be one method of increasing the pressure impulse I, for the same amount of supplied energy E due to recoil of the additional mass of the transparent layer, which is important for some laser applications.

The extension of experiments into the region of greater energy concentrations and greater pressures is limited with the transducer of the present design, since the intense light flux causes the deterioration of the reflective coating and the appearance of a "parasitic" pressure impulse. These obstacles could possibly be removed by absorbing the excess energy with a glass light filter placed between the transducer and the heated layer. If the range of the radiation in the filter is much greater than the range of radiation in the investigated substance, the "parasitic" pressure would be suppressed.

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