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THERMODYNAMIC EFFECTS AT INTERACTION BETWEEN LASER BEAM AND HEAVY - VISCOUS LIQUIDS

Hikmet Gafaroglu Hassanov

Azerbaijan State Oil Research and Project Institute (AzNSETLI),
Aga - Neymatullah str. 39, 370033, Baku, Azerbaijan
hhassanov@yahoo.com

Abstract - Influence of laser radiation on thermodynamic properties of heavy - viscous liquids is investigated. Mathematical model taking into account liquids viscosity and their thermal specifications is firstly developed. Inverse problem for acoustic pressure is solved. Formula for determining thermodynamic parameters of liquid is obtained. Effect of main laser beam characteristics (radiation duration and intensity) on generation of non - stationary states in liquid is estimated.

Keywords - Heavy – viscous liquid, laser radiation, light intensity, acoustic pressure

1. INTRODUCTION

For handling some technological processes which take place in chemical and oil industry, effect of external physical fields on these processes promise the sufficient benefit. First of all this aspect is due to the essential change of physical parameters of liquids considered under the fields. So, it is of great interest to elucidate, how these parameters are altered due to the fields action.

Effect of permanent electric and magnetic fields on physical properties of various liquids have been widely investigated both theoretically, and experimentally. But influence of high - frequency electromagnetic fields, namely laser beam, on liquids behaviour is not considered enough to present time. In interacting strong laser radiation with liquid there are various opto - thermodynamic effects in dependence on beam intensity. Because of the laser beam absorption by liquid acoustic waves arise and propagate (these waves are usually called as opto - acoustic effect). The effect in liquids may appear as a result of two physical mechanisms - electrostriction and medium heating [1,2].

In all existing investigations devoted to the interaction between laser beam and liquids, the last media are taken as non - viscous (in other words, ideal). With connection to this circumstance the influence of liquids' viscosity and thermal conductivity on propagation and / or absorption of acoustic waves generated by the laser action are neglected. Moreover, interaction of the laser beam on heavy - viscous liquids, for example, oils and oil - products, drilling muds and cement slurries used for drilling wells are not studied in general.

From 1991 we have been theoretically and experimentally studying the effect of the laser beam on oil and oil - products [3, 4]. Experiments carried out with drilling muds, mazouts, various oils allow us to determine opto - acoustic signals form. On the base of these signals new opto-acoustic method for investigation of heavy - viscous liquids thermodynamic properties is developed [5]. Account of heavy viscosity and thermal conductivity of the liquids leads to new effects arising under the laser radiation action which are not still involved.

2. SOLVING THE PROBLEM

Taking into account above mentioned, in this article the interaction of strong laser beams with heavy - viscous liquids is investigated. Let laser beam with intensity J falls from transparent medium (air) onto absorbing liquid surface. In the liquid the light intensity is determined by formula [1]

$$J(x,y,z,t) = J_0 f(t) H(x,y)\exp(-\alpha z); \tag{1}$$

hereafter, it is considered the wave propagation along the axis z , J_0 - light intensity on the absorbing liquid boundary, H (x , y) - light intensity distribution by cross - section, f (t) - dimensionless function that describes its dependence on time and usually have Gaussian form, i.e. [1]

$$f(t) = \frac{1}{\sqrt{\pi}} \exp\left[-\left(\frac{t}{\tau}\right)^2 \right], \tag{2}$$

where τ - the laser radiation duration. We will involve parts of linear perturbations in motion equation, so for determining an acoustic pressure one has the following equation used in [1]

$$\frac{\partial^2 P}{\partial t^2} - c_0^2 \frac{\partial^2 P}{\partial z^2} - \left[\frac{1}{\rho_0}\left(\xi + \frac{4}{3}\eta\right) + \kappa\left(\frac{C_p}{C_V} - 1\right)\right] \frac{\partial^3 P}{\partial z^2 \partial t} = -\frac{\alpha c_0^2 \beta J_0}{2C_p} f(t)\exp(-\alpha z) \tag{3}$$

where all the quantities are well - known. One takes that all the liquid physical parameters insufficiently change under the laser radiation action, so they may be proposed as permanent. The differential equation (3) should be resolved at zero initial conditions

$$P(z,t=0) = 0 \quad , \quad \frac{\partial P(z,t=0)}{\partial z} = 0, \tag{4}$$

and boundary those, which given accordingly to nature of the phenomenon considered. Then, from additionally selected boundary condition the effect of the laser beam on the parameters of liquid studied is found.

For resolving the differential equation (3) at the initial conditions (4) Laplace - transformation is used. In images the equation (3) acquires the next form

$$b^2 \frac{d^2 P^*(z,s)}{d z^2} = s^2 P^*(z,s) + A f^*(s) \cdot e^{-\alpha z}, \tag{5}$$

where the following abbreviations are introduced

$$b^2 = c_0^2 + s\left[\frac{1}{\rho_0}\left(\xi + \frac{4}{3}\eta\right) + \kappa\left(\frac{C_p}{C_V} - 1\right)\right] \quad , \quad A = \frac{\alpha c_0^2 \beta J_0}{2C_p},$$

$$P^*(z,s) = \int_0^\infty P(z,t)e^{-st}dt \quad , \quad f^*(s) = \int_0^\infty f(t)e^{-st}dt$$

Solution of the equation (5) is well - known and may be expressed by the formula

$$P^*(z,s) = \frac{Af^*(s)e^{-\alpha z}}{\alpha^2 b^2 - s^2} + C_1 e^{-\frac{s}{b}z} + C_2 e^{\frac{s}{b}z} \tag{6}$$

where C_1 and C_2 are constants of integration which should be defined from the boundary conditions. From the solution (6) it is shown, the right side consists of three summands. The first summand in (6) describes perturbations localized near surface in area of the laser radiation absorption. The last two summands correspond to acoustic waves expanding within medium (C_1) and from medium to boundary (C_2). Because of limited dimensions of the absorbing medium, wave motion to the boundary should be absent due to causality principle, i.e. $C_2 = 0$. So, the solution of the equation (3) exposes that opto - acoustic signal is summed from the localized perturbation stimulated by the liquid heating and the acoustic wave running within the liquid.

On the liquid free boundary (transparent medium - gas, absorbing medium - liquid) increment of acoustic pressure is equal to zero, i.e. $P = 0$ at $z = 0$. From this condition C_1 is defined. For finding required parameter additional boundary condition is given, namely change of acoustic pressure by time at section $z = l$, for example

$$P(l,t) = \varphi(t) \tag{7}$$

The boundary conditions in images have the following form :

$$P^*(z=0,s) = 0 \quad , \quad P^*(l,s) = \varphi^*(s) = \int_0^\infty \varphi(t)e^{-st}dt; \tag{8}$$

Having used the conditions (8), one obtains the next equation for finding required quantity

$$(\alpha^2 b^2 - s^2)\varphi^*(s) = Af^*(s)\left(e^{-\alpha l} - e^{-\frac{s}{b}l}\right) \tag{9}$$

Let's estimate influence of the laser radiation intensity and duration on the liquid physical properties in terms of determined moments method [3]. For this purpose one expands functions f * (s) and φ * (s) in series by degrees of s

$$\begin{aligned} f^*(s) &= f_0 + sf_1 + s^2 f_2 + \cdots, \\ \varphi^*(s) &= \varphi_0 + s\varphi_1 + s^2\varphi_2 + \cdots \end{aligned} \tag{10}$$

where the values f_n and φ_n are calculated from expressions

$$f_n = \int_0^\infty [f(\tau) - f_\infty] \frac{\tau^n}{n!} d\tau, \qquad \varphi_n = \int_0^\infty [\varphi(\tau) - \varphi_\infty] \frac{\tau^n}{n!} d\tau \tag{11}$$

Inserting the values of $f^*(s)$ and $\varphi^*(s)$ from the series (10) into the equation (9) and comparing coefficients at the same degrees of s, we have the following system of equations for determining required quantities

$$\begin{cases} \alpha = \dfrac{2}{l}\left(1 + \dfrac{2C_p}{\beta J_0 l}\dfrac{\varphi_0}{f_0}\right), \\ \xi + \dfrac{4}{3}\eta + \rho\kappa\left(\dfrac{C_p}{C_V} - 1\right) = -\rho c_0^2 \dfrac{\varphi_1}{\varphi_0} + \dfrac{c_0^2 \beta J_0 \rho l(\alpha l - 2)}{4C_p}\dfrac{f_1}{\varphi_0} + \dfrac{c_0 \beta J_0 \rho l}{2\alpha C_p}\dfrac{f_0}{\varphi_0} \end{cases} \tag{12}$$

The system of formulae (12) allows us to qualitatively estimate the influence of the laser radiation on the liquid physical parameters. On the base of obtained experimental data informative part of function $\varphi(t)$ could be represented like

$$\varphi(t) = \varphi_\infty (1 - e^{-k_1 t}) \tag{13}$$

hereafter κ_1 and φ_∞ are empirical magnitudes and should be determined from the experiment. Via the formulae (11) and (12) one yields

$$\varphi_0 = \frac{\varphi_\infty}{k_1}, \quad \varphi_0 = \frac{\varphi_\infty}{k_1^2}, \quad \frac{\varphi_1}{\varphi_0} = \frac{1}{k_1} \tag{14}$$

By the same way the values of f_0 and f_1 are found. Taking into consideration, that accordingly to [6] the next relationships are valid

$$\int_0^\infty \exp\left[-\left(\frac{t}{\tau}\right)^2\right] dt = \frac{\sqrt{\pi\tau}}{2}, \quad \int_0^\infty t \cdot \exp\left[-\left(\frac{t}{\tau}\right)^2\right] dt = \frac{\tau^2}{2}, \tag{15}$$

after simple calculations one will acquire

$$f_0 = \frac{\sqrt{\pi\tau}}{2\sqrt{2}}, \quad f_1 = \frac{\tau^2}{2\sqrt{2}}, \quad \frac{f_1}{f_0} = \frac{\tau}{\sqrt{\pi}} \tag{16}$$

Account of the expressions (14) and (16) in the formula (12) gives us the following result

$$\begin{cases} \alpha = \dfrac{2}{l}\left(1 + \dfrac{4\sqrt{2}\,C_p}{\sqrt{\pi}\beta J_0 l}\dfrac{\varphi_\infty}{k_1\tau}\right), \\ \xi + \dfrac{4}{3}\eta + \rho\kappa\left(\dfrac{C_p}{C_V} - 1\right) = \rho c_0^2 \tau\left[\dfrac{1}{2\sqrt{\pi}} - \dfrac{1}{k_1\tau} + \dfrac{\sqrt{\pi}\beta J_0 l k_1}{4\alpha C_p c_0 \varphi_\infty}\right] \end{cases} \tag{17}$$

From the first formula in the system (17) it should be concluded, the absorption coefficient α depends on both liquid thermodynamic parameters, and the laser radiation characteristics. The second equation in (17) results in

$$\xi = \rho c_0^2 \tau\left[\frac{1}{2\sqrt{\pi}} - \frac{1}{k_1\tau} + \frac{\sqrt{\pi}\beta J_0 l k_1}{4\alpha C_p c_0 \varphi_\infty}\right] - \frac{4}{3}\eta - \rho\kappa\left(\frac{C_p}{C_V} - 1\right) \tag{18}$$

Certainly, the volume viscosity ξ is exposed during expansion and compression of liquid only, i.e. when non - stationary processes take place in the liquid. So, in the case studied (J_0 = const) the laser radiation duration τ necessary for generating sufficiently non - stationary processes should be

$$\tau \succ \left[\frac{\rho c_0^2}{k_1} + \frac{4}{3}\eta + \rho\kappa\left(\frac{C_p}{C_V} - 1\right)\right] \cdot \left(\frac{\rho c_0^2}{2\sqrt{\pi}} + \frac{\rho c_0 \sqrt{\pi}\, J_0 \beta l k_1}{4\alpha C_p \varphi_\infty}\right)^{-1} \tag{19}$$

Naturally, if the laser radiation duration is less than that found from the formula (19), the volume viscosity ξ may be neglected in the processes description. The same deduction could be made relative to radiation intensity J_0 as well. From the expression (18) it is concluded, if the laser radiation intensity satisfies the condition

$$J_0 \leq \left[\frac{\rho c_0^2}{k_1} - \frac{\rho c_0^2}{2\sqrt{\pi}}\tau + \frac{4}{3}\eta + \rho\kappa\left(\frac{C_p}{C_V} - 1\right)\right] \frac{4\alpha C_p \varphi_\infty}{\rho c_0 \sqrt{\pi}\,\tau\beta l k_1}, \tag{20}$$

then arising non - stationary processes in liquid are not enough for volume viscosity manifestation.

As it was marked above, the radiation absorption obeys Bouger's law, i.e. the acoustic pressure amplitude generated by the laser radiation as the function of the distance from boundary $z = 0$ is defined by

$$P(z) = P_0 \exp\left[-\frac{2z}{l}\left(1 + \frac{4\sqrt{2}\,C_p}{\sqrt{\pi}\beta J_0 l}\frac{\varphi_\infty}{k_1\tau}\right)\right] \quad (21$$

From the last formula one is able to find such an important magnitude as the liquid volume expansion coefficient β

$$\beta = \frac{4\sqrt{2}\, C_p \varphi_\infty}{\sqrt{\pi}\, k_1 \tau J_0 l \left(\frac{1}{2} \ln \frac{P_0}{P_1} - 1 \right)}, \tag{22}$$

where the magnitude P_1 is the acoustic pressure amplitude on distance $z = l$ from the liquid free boundary.

At last it should be noted, the formula (22) is valid under the condition $\alpha l > 2$ only. The last inequality is always satisfied for above case due to the first expression in the system (17). The formula (22) allows to qualitatively estimating the influence of the laser radiation parameters on the volume expansion coefficient.

3. CONCLUSION

High – frequency electro – magnetic waves essentially change the thermodynamic properties of viscous liquids. The most obviously this aspect is manifested for the coefficient of optical absorption α that has been proved in present paper. Observing the law $\alpha (J)$, one can evaluate how the laser radiation effects on acoustic waves propagation within the liquid. Found dependences of the parameter α on various characteristics of the laser radiation and liquid studied allow us to optimally handle the liquid properties during various technological processes. Such an opportunity is very important for practical purposes in oil and gas transportation, medicine etc.

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