SOLAR OPTO-HYDRAULIC LASER AS A NEW TECHNOLOGY IN VIBRATION ENGINEERING

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The opto-hydraulic laser (actuator) to direct transform the energy of solar radiation into mechanical vibrations is described. The device consists of a chamber with active liquid and optical fiber to deliver energy of light inside. As power supplier was used solar concentrator of diameter 300 mm. The vibration generation occurs owing to oscillation a single bubble emerged on the end of fiber in liquid. The model of self-organization of heat cycle by non-linear motion of the bubble is presented to describe main strokes of transformation of radiant energy into energy of mechanical vibrations.

1 Introduction

The generation of vibrations in liquid by a process of self-organization of heat cycle (SOHC) had been found by interaction of continuous wave (CW)-laser light with binary solution [1]. The main feature of such process which was called as *thermocaviation* is accumulation of heat induced by light in period between adjoined hydraulic pulses, that allows to apply the laser beams with rather low average power (threshold of thermocavitaion is about $0.1W$) for movement of bodies , cutting transparent materials , pump liquids [2].

This paper is to describe opto-hydraulic actuator (OHA) of vibrations in liquids is due to thermocavitation induced by light delivered inside by optical fiber. It so turns out, that the general mechanisms of energy transfer, responsible for the creation of vibrations from heat on macroscopic " mechanical level ", are rather similar to mechanisms of stimulated coherent radiation in usual optical laser if we take into account only the general energy balance without consideration the quantum nature of laser light. While optical laser is able to be described by theory of phase transition of second order [3], the thermodynamic model for processes of phase transitions of first order stimulated by mechanical vibration can be considered as model of opto-hydraulic laser (OHL).

There is a rather important aspect of studies around generation of vibration by CW-light differs it from experiments on forming cavities by high-power pulses of laser, which usually called as opto-hydraulic effect [4]. This is principal possibility to reach a threshold of generation OHL by solar excitement that is announced in this paper. The direct creation of vibrations by solar light seems as a good opportunity to use the sun in several new engineering technologies instead of laser radiation. The feature of OHL to accumulate energy of light in form of heat between sequence mechanical pulses gives unique possibility to reach thermodynamic forces which much exceed forces of equilibrium radiation pressure.

This paper is to present OHA and its simple laser-like thermodynamics model of its generation.

2 The principle of generation

Let us consider a cell of volume V with local source of heat induced by light in volume v in its center when $v \ll V$. Pumping solar radiation (1) (Fig.1) was focussed by concentrator (2) into optical fiber with radius r (3) delivers intensive focussed light into center of a cell (4) with an absorbing liquids (5) with coefficient of absorption $\alpha \sim 1/r$. For experiments in lab conditions, the lens (2‘) was used instead of concentrator to focus radiation of multimode argon laser (1‘) with three lines of generation near maximum in spectra of solar light. The continuous wave light: solar or CW-laser beam have power P enough to form a single bubble (6) at the end of the fiber. This is common scheme of OHA which is able to generate periodic vibrations.

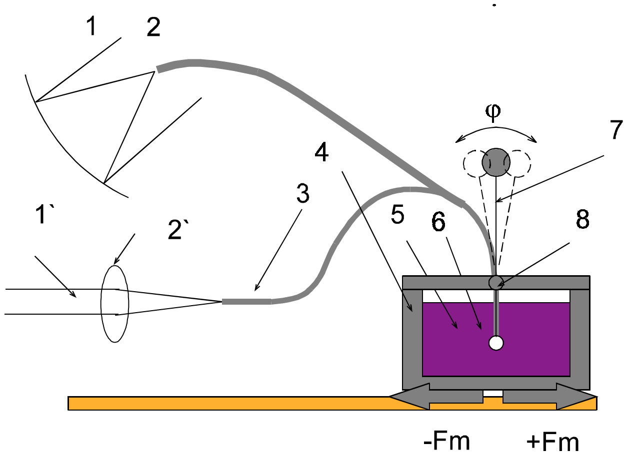

Fig.1 Schema of OHA

2.1 Excitement of OHL and cluster nucleation.

Mechanical effects, which can be obtained from usual boiling [5], for example in usual kettle, are very low because there is no initial mechanical non-equilibrium. Boiling has temperature, which is coincident with temperature of saturated steam $p_s(T)$ by given external pressure p_o [7] $p_s(T) = p_o$. Growing and possible collapsing of bubbles by boiling is very near point of equilibrium. Generally, the function of OHL is based on current mechanical non-equilibrium between internal $p_s(T)$ and external p_o pressures during all process of production of mechanical energy which begin from initial mechanical non-equilibrium between external pressure and pressure of saturated steam inside a critical nucleolus of radius $R_c(T)$ calculated form simplest formula.

$$p_s(T) = p_o + 2\frac{\sigma(T)}{R_c(T)} \tag{1}$$

where $\sigma(T)$ is surface tensity. The problem of efficiency by OHL generation is problem to have as high as possible difference between $p_s(T)$ and p_o by movement into metastable state of liquid with as small as possible $R_c(T)$.

There are two main mechanisms of nucleation in theory of phase transitions: homogeneous and heterogeneous [5]. By generation of mechanical energy by OHL in several difference liquids, it appears, that the best results to have effective generation of vibration is by using the binary solution, particularly solution of water with alcohol. To explain such fact the new cluster mechanism of nucleation [8], which is responsible for strong periodical motor-like regime of generation is proposed. The mechanism of cluster nucleation is based on a known fact that alcohol and their aqueous solutions are referring to so-called associated liquids, inclined to cluster formation. Briefly mechanism of cluster nucleation can be explained as boiling up of the clusters of volatile component of alcohol in mother - phase of water. Since pressure of saturated steam $p_s^w(T)$ for water is higher than the same pressure for alcohol $p_s^a(T)$, a cluster of define mass can serve as the nucleolus , which allows to reach more high temperatures of metastable states, than it is available in one-component alcohol. The mechanisms of cluster nucleation is described in [8].

In order to have thermodynamic model of one-cycle operation of OHL, which consists of relatively long accumulation of thermal energy in heating volume (excitement) and next fast mechanical " discharge " (work cycle), let us assume that in active volume v exists only one nucleolus (cluster) with critical radius R_c.

2.2 Self-organization of heat cycles

Thermodynamic model of system, which can directly transform CW-radiation into sequence of hydraulic shocks can be described by simplest equations which consist of equations of both mechanical and thermal motion . Mechanical system was approximated by known equation of Raleigh [9] for spherical cavity of radius R, with variable velocity of its wall. The bubble is involved into thermal cycle in which it simultaneously is as " piston " and " cylinder ". Notice, the motion of a bubble in thermal field induced by light is able to form a natural thermal cycle to produce vibrations without any construction [11]

For the sake of simplicity, let us consider for a while only two kineric equations for mechanical and thermal degrees of freedoms to describe the basis of OHL function. We can write down this equations by assumption that heat capacity c and density ρ of liquid are constants in following way:

$$\frac{du}{dt} = \frac{(p(T) - p_o)}{\rho R} - \frac{3u^2}{2R} - \frac{2\sigma(T)}{\rho R^2} \tag{2}$$

$$\frac{dT}{dt} = \frac{1}{\rho v c}\left\{-(T - T0)\frac{1}{\tau_1} - \left[(T - T0)\frac{1}{\tau_2} - 4\pi\lambda(T)u\rho_s(T)\right]R^2 + P\right\}$$

here, T is temperature of steam in the bubble which assumed to equal to temperature of volume v, $p(T), \rho_s(T)$ is pressure and density of steam, $\lambda(T)$ - latent heat, $\sigma(T)$ is the surface tension coefficient; p_o and T_o are the external pressure and temperature τ_1 is time of life of exited state which undergoes spontaneous thermal relaxation.

The first term of thermal equation is responsible for spontaneous dissipation of energy, which always take place according law of Newton. Stimulated processes of heat transfer is described by the second term in this equation which is responsible for both : the stimulation of dissipation of thermal energy by the bubble *outside* with character time τ_2 and the provocation of phase transition *inside*. Two equations (2) is a system to describe both current thermal $(T - T0)$ and $(p(T) - p_o)$ mechanical non-equilibrium.

For excitement when $R < R_{cr}$ the solution of system actually comes down to the analysis of only for second equation of (2) with $R = 0$, whose solution is the equation of energy accumulation of a cycle

$$T(t) = T_o + \frac{P}{c}\tau_1(1 - e^{-\frac{t}{\tau_1}}) \tag{3}$$

From (3) with known P, c and from the maximum period of oscillation of OHL we can estimate the constant τ_1 of time of leave of exited state, which is associated with both diffusion and convective losing of energy during process of excitement OHL.

For $R > R_{cr}$ the system (2) was solved by the Runge-Kutta method for following thermodynamic variables. The pressure inside was approximated by integrated form of Clapeyron equation $p(T) = 255\exp(5100(0.027 - \frac{1}{T})10^3 Pa$ with constants which was picked for best suit to experimentally measured pressure of saturated steam of C_2H_5OH the latent heat from temperature accepted by Watson approximation [10]

$$\lambda(T) = \lambda(T_o)\left[\frac{1 - \frac{T}{T_c}}{1 - \frac{R_o}{T_c}}\right]^{0.4}$$

$Rc = 1.1910^{-8}m$, $\rho_s(T) = \frac{p(T)\mu}{RT}$,were μ is molar weight, Rc is gas constant.

Main principle of OHL operation is self-organization of heat cycle (SOHC) owing to the mechanical non-equilibrium defined by difference between current pressure $p(T(t))$ of saturated steam and external pressure $p_o(T_b)$. Fig.2. presents the results of calculation of the mechanical properties of OHL: **left)** is dependence of ratio $P(t) = \frac{p(t)}{p_o}$ of internal $p(t)$ and external p_o pressures from relative volume $v(t) = \frac{V(t)}{v}$,where $V(t)$ is volume of bubble, v is initially excited volume ; **right)** is the indicator diagram of mechanical energy dynamics as dependence of kinetic energy $K(t) = \frac{2\rho u^2 R^3}{W}100\%$ from potential energy $\Pi(t) = \frac{\frac{4}{3}\pi R^3(p-p_o)}{W}100\%$ expressed as percents of energy W of excitement. In brief, SOHC consists of following phases. First is the growing of bubble from point A to the point of mechanical equilibrium B. In point B kinetic energy has a first maximum on stroke of expansion. From inertia the bubble pass equilibrium B and has reached point C of maximum of potential energy due to the fact that pressure inside becomes less than outside pressure. As it follows from indicator diagram kinetic energy in this point is equal to zero. From C-point begins collapsing stroke which ends at point D by hydraulic shock when kinetic energy has second main maximum.

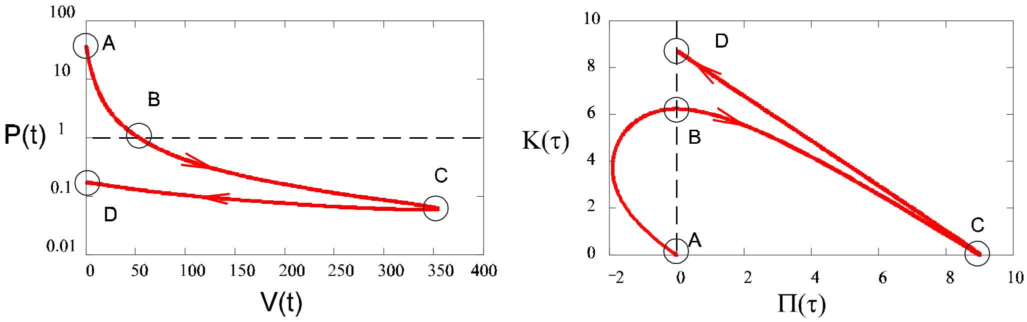

Fig.2. Indicator diagrams for a shock generation.

The indicator diagram (Fig 1) shows actual efficiency equal to about 8% for a hydraulic shock. If we compare this result with maximum available from Carnot theorem in nonequilibrium interpretation given in [6] we will have obtained for accepted $T - T_o = 466K - 273K$ thermal Carnot limit equal to 24.4% . Notice that equilibrium Carnot limit should be 41.4%.

3 Experiments

3.1 The generation

In detail, the experimental studies of OHL generation by laser excitement is described in several work[11] [2]. To show difference of generation of OHL from usual boiling Fig.3 presents two fragments of refractometric measurements of temperature [2]. By typical temperature of boiling $Tb = 80C$ maximum temperature of overheating (inverse) state by generation was about $Th = 210C$ by room temperature $To = 20C$. Fig.4 presents the typical form acoustic signal detected by hydrophone during work stroke of OHL. on which we can find also two maximums (B) and (D) that is in correlation with indicator diagram on Fig.2.

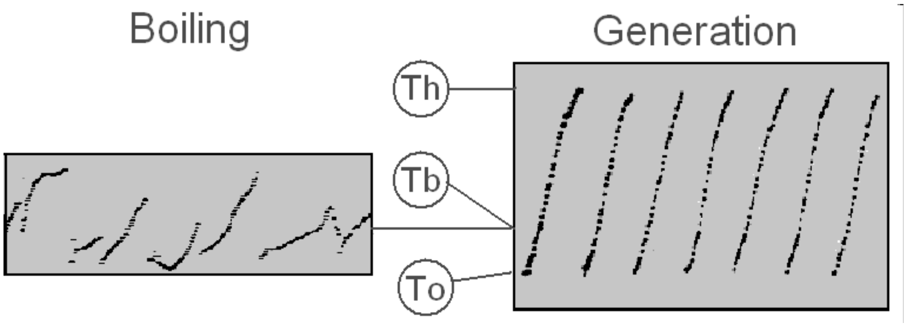

Fig.3. Difference between boiling and opto-hydraulic generation

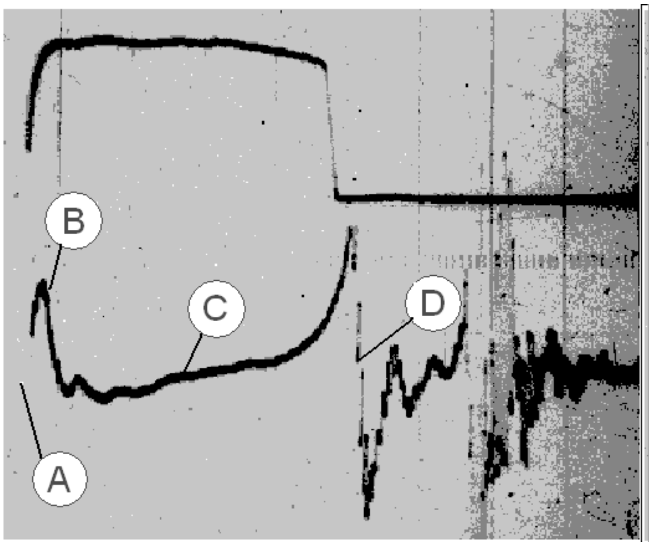

Fig.4. Intensity of light reflected from a bubble (upper) and form of acoustic signal (under)

3.2 Vibration sliding of bodies

The vibrations induced by OHA are able to give motion of chamber in the given direction. In experiment on motion driven by continuous wave laser radiation, the beam was focused into optical fiber with diameter about 0.5 mm. Another end of fiber was put into vessel with active liquid. The vessel has on top a simple construction, which is able to change position of local excitement with regard to center mass of vessel as it is shown on Fig.1.

OHA with Ar-laser about 1W gives the motion of bodies (weight 50g) on plane desk with velocity about 1-2mm/s from vibration mechanism of sliding [2]. To investigate the body motion dynamics, a piezosensor was fixed on the desk for recording the pressure pulses arising in the process of motion. At the same time an optical blade was mounted horizontally on the cell, its ends illuminated with probe two He-Ne laser beams. The passed light intensity was recorded by two photodiodes, their signals directed by a double-beam oscilloscope. The analysis of oscillograms obtained in this way allows to present the dynamics of sliding as follows. OHA is the source of hydraulic shock and elastic deformations arising in both the desk and in cell's bottom. The each shock is non-central, i.e. the pulse acting on the cell has both a normal and a tangential component and as a result the body acquires both translation and rotational motion. After the short flight, the body meets the table at a point and due to the normal component acquires a moment larger than its moment of inertia. After the next flight the body is hit by the front part of the table at point and stops, having thus displaced through a certain distance. With frequency of repetition $100Hz$, continuous motion was observed, its measured velocity having values of up to $2mm$ per a second in direction which is able to be chosen by the handle on the top (Fig.1) even up on a slanted plane with inclination of up to 5 degrees.

3.3 The jet production and pumping of liquids

The intensive sound of OHA was used in the experiments on attraction a bubble from closed volumes and to change of level of liquids in thin capillary tubes. The acousto-capillary effect is known to consist in an anomalously deep fluid penetration into capillaries and narrow pores under the influence of ultrasound. In this effect, rise of a fluid in the capillary tube is due to acoustic cavitation bubbles arising at the end of capillary. Sound was generated by OHL arising with the illumination by continuous argon laser of a cell where a capillary tube was vertically placed. Solutions of various organic fluids in water with ethanol in concentrations sufficient for obtaining laser radiation absorption of the order of $20 - 500 cm^{-1}$ were used as absorbing fluids. The size of caustic at cell wall was of the order of $10 - 500 \mu m$. Under these conditions, acoustic pulses were periodically excited in the fluid with a frequency of $20 - 1000 Hz$ caused by the formation and collapse of a single cavitating bubble. The opto-capillary effect was observed in a glass capillary tube placed vertically so that its lower end was immediately above the cavitating bubble. The effect was observed as the influence of radiation on level of liquid capillary tube. The fluid rose significantly higher than its equilibrium level determined by the balance of the fluid column and the capillary pressure. The dependence of the efficiency of laser-induced opto-capillary effect, measured by the excess height of fluid level over its equilibrium value, on the power of pumping radiation was also studied. With fixed pumping radiation power, the dependence of the efficiency of the opto-capillary effect on caustic size at the sell wall, which influenced the frequency of appearance of the cavitating bubble, was investigated. It was found that in the frequency range of $25 - 1000 Hz$ fluid level was practically independent on frequency.

Next application is vibration pumping of liquids. The optical way of inducing vibrations has the opportunity to place the cavitating bubble not just under the capillary end but also inside the tube by illuminating it with high focused radiation through the optical fiber. This made it possible to implement the mode of continuous fluid pumping through the capillary tube. A simplest device for vibration opto-capillary pumping ([2]) consisted of a glass tube with internal diameter of 1 mm inserted vertically into the vessel with the fluid. The upper, free tube end was bent downwards. The capillary was illuminated by radiation about 0.5 W at the height of $5mm$ from fluid level in the vessel, the fluid flowing continuously out of the free end at a rate of the order of $2cm^3/min$.

Second method of pumping was realized in so-called steady opto-hydraulic effect, when no visible pulses of hydraulic shocks observed. The flow of liquid occurs from special profile of tube by define additional velocity of liquid in the tube. Mechanisms of acceleration of liquids in this case and thrust force occurred is right the same that is in jet propulsion engines. The some details of experiment and solving of problem to balance of heat and mass by this phenomena can be found in [14] .

The regime of filling blind pores and attracting gas bubbles was realized by using blind thin capillary with $10 \mu m$ diameter [2] filled by gas bubbles connected with a tube with diameter 5 mm. The tube was filled with fluid and illuminated with a laser beam to induce vibrations. The filling of the blind capillary with gas by the fluid was observed at a velocity of $0.2 - 1mm/1s$.

Thus, the effectiveness of continuous radiation (threshold power 100 mW) for capillary filling and fluid pumping and acceleration of rigid bodies has been demonstrated experimentally. The obtained results allow to hope for applying vibration generation by OHL in the processes of impregnating porous bodies, cleaning surfaces, etc., where ultrasound is now being used. The separate possible interest is use of solar radiation to induce vibrations by OHL.

3.4 Solar vibrations

To check possibility of use of solar light as an environmentally clean and cheap source of energy in several vibration technologies of mass-transfer previously described, the preliminary experiments with solar radiation have been conducted.

Solar OHL has collector of solar light diameter of $300mm$ and optical fiber of diameter $3mm$ of length $400mm$ which allows to deliver concentrated light outside of collector dish into chamber of about 0.25 liter of volume. The first and major result of solar experiments is the fact that threshold of OHL-generation *can be reached* by given delivered energy and intensity of solar light. The frequency of vibrations is observed to be around $1Hz$ accompanying by large mechanical effects. Besides, it was made a model of free-piston heat engine which consist of piston in form of cylinder of diameter $10mm$ which was filled on half by active medium. The piston was put into cylinder mounted in focus of collector. The amplitude of vibrations was about $5mm$ with frequency 0.5 Hz.

The major aim of this paper is to attract an attention of people working in mechanical engineering for new sphere of research: *solar vibrations*. The rationalism of such approach is based on huge amount of evidence laser experiments which can be considered as an imitation of solar vibrations in lab conditions.

4 Conclusion

The main results of this letter can be formulated as following.

It is shown that the vibrations of a spherical cavity in non-equilibrium heat field induced by the continuous light can be considered as laser-like system, when there are the internal and the external entropy production stimulated by mechanical motion. Such kind of phase transition can be called as stimulated phase transition of first order, when liquid according to existence own macroscopic mass has involved the effects of inertia in the velocity of phase transition.

The indicator diagram have been obtained as the example to describe the renewable process [6] in homogeneous medium which is able to rise the vibration energy from initial chaotic thermal energy. This result can be considered as the new actuator to input mechanical energy into liquid by the CW-light thorough the non-linear dynamic between potential and kinetic energy of a bubble. The proposed one-stroke model does not solve the problem of generation in general but it can serve as an introduction to the problem.

At last, as it has been shown, OHL with solar pumping can be used to direct generation of large vibration forces. Such fact can be used in several new environmentally sound solar technologies for acceleration of solids, liquids and gases. There is a reasonable change that the unique possibility of OHL to accumulate solar light in form of thermal energy which after is realized in form of mechanical shocks can find an own sphere of application in vibration mechanics.

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