New branch of laser physics—Optothermodynamics

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Attention is called to the fact that the possibility of generating optical radiation with a programmed pulse waveform makes it possible to pose the question of changing macrosystems that interact with radiation from a given initial state to a given final state along a prescribed transition path.

The capabilities of modern laser physics, which are connected with the generation of pulsed optical radiation with pulse waveforms that are programmed in time and in space, uncovers extensive prospects for new applications of lasers in physics, chemistry, and technology. In the present article we wish to call attention to the fact that even now it is possible to point to definite applications of this type and to formulate the ensuing concrete problems and concrete prospects. This application can be called optothermodynamics.

We have in mind the use of laser radiation with a programmed pulse waveform to convert a given macroscopic system from an initial state to a given final state along a definite transition path, by releasing in the system heat that comes from dissipation of the laser radiation.

A typical example of an optothermodynamic problem was recently formulated in [1], that of strong compression and heating, by means of a laser pulse, of a plasma core of a spherically irradiated target for the purpose of obtaining a thermonuclear reaction.

There are, however, also other optothermodynamic problems, which require much less laser energy and are therefore fully realistic even at the present state of the art. First among them is the question of an optically-controlled transition of matter to a transcritical state, and in particular to the vicinity of the critical point itself. The solution of this problem would make it possible formulate on a different basis the study of the properties of matter in the transcritical state, and primarily its optical properties. In particular, it becomes possible to study a new effect— "stimulated critical opalescence."

Let us consider the problem of the transition to a specified transcritical state in somewhat greater detail, using a concrete example that has the greatest bearing on a realistic organization of an experiment. Let the radiation be focused in a liquid with a known absorption coefficient $\alpha = \alpha(V, T)$ and equation of state $V = V(p, T)$ (V is the specific volume). The investigated macrosystem is the volume of liquid surrounded by a cylindrical part of the focal region, with a radius equal to a (the length of the region is $L \gg a$). The question is: what must be the laser waveform in order to transfer the system from a given initial state (p_0, V_0) to a given final state (p_1, V_1). Figure 1 shows the (p, V) plane of the liquid (the solid lines are isotherms). The transition from the initial state O, for example, in the vicinity of the critical point K (circled) is possible along many paths, four of which are shown (OAK, OBK, OCK, $OC'K$). It is clear from *a priori* considerations that transitions with maxima (OBK and $OC'K$) require more laser energy than transitions without maxima (OAK and OCK), since in the former case a greater fraction of the absorbed laser-pulse energy is converted into the energy of the hydrodynamic flow of the liquid (in final analysis—into sound). The transition curve itself is determined by the equations $p = p(t)$ and $V = V(t)$ ($0 \leq t \leq \tau$, where τ is the pulse duration), i.e., by the temporal dependences of the pressure and of the specific volume during the course of the irradiation pulse, which are determined in turn by the waveform of the pulse [the intensity $I = I(t)$] and by the hydronamic equations supplemented by the relations for $\alpha = \alpha(V, T)$, $V = V(p, T)$, and the specific internal energy $\epsilon = \epsilon(V, T)$ of the liquid. This

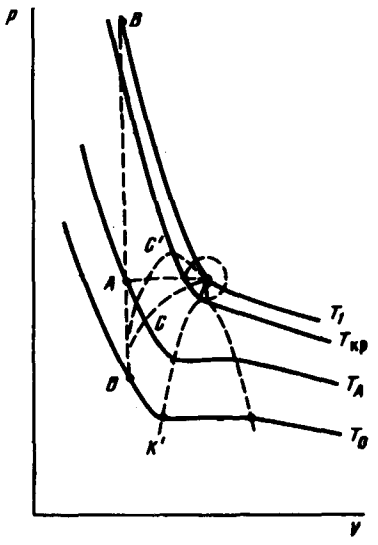

FIG. 1.

quantitative problem can be solved in rigorous form, of course, only with the aid of a computer, and this procedure makes it possible to find the optimal laser pulse waveforms. We note that inasmuch as the laser energy required for these problems is relatively low, in the real experiment the criterion for the optimal transition (pulse waveform) can be not the condition that the pulse energy be minimal, but the realistic possibility of programming its given waveform. It is also necessary to stipulate that the transition curve not lie too close to the phase stratification curve KK' (to avoid the possible occurrence of metastable state during the course of the transition).

Let us estimate the required laser pulse energy and its approximate waveform for the transition OAK, which consist of an isochoric section OA ($V = V_0$), and an isobaric section AK ($p = p_1$). The isochoric section of the transition is realized under the condition that the time of energy input on it $t_{0A} \ll a/c(p_1, V_1)_1$ [$c = c(p, V)$ is the speed of sound], and the energy in the laser pulse is

$$W_{OA} = \pi a^2 \int_0^{t_{OA}} I\,dt = \pi a^2 \int_{T_0}^{T_A} \frac{c_V\,dT}{V_0 \alpha(V_0, T)} \approx$$

$$\approx \pi a^2 \frac{c_V (T_A - T_0)}{V_0 \alpha_0} = \pi a^2 \frac{p_1 - p_0}{\alpha_0 \Gamma(V_0)}, \quad (1)$$

where c_V is the specific heat of the liquid at constant volume, T_A is the temperature at the point A, $\alpha_0 = \alpha(V_0, T_0)$, and $\Gamma(V)$ is the Gruneisen coefficient. As will be shown, the temperature increment $(T_A - T_0)$ amounts to only several degrees, and therefore the temperature dependence of c_V and of α can be neglected in this interval. The liquid is heated from the temperature T_A to the temperature T_1 mainly on the isobaric section AK and expands. The laser energy W_{AK} needed

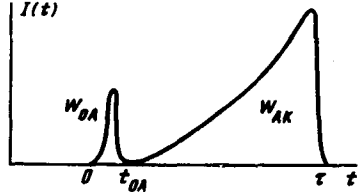

FIG. 2.

for this purpose is given by

$$W_{AK} = \pi a^2 \int_{t_{OA}}^{\tau} I\,dt = \pi a^2 \int_{T_A}^{T_1} \frac{c_p[V(p, T), T]\,dT}{V(p_1, T)\alpha[V(p_1, T), T]} = \pi a^2 \frac{c_p(\tilde{V}, \tilde{T})}{V\alpha(\tilde{V}, \tilde{T})}(T_1 - T_A), \quad (2)$$

where $T_A \leq \tilde{T} \leq T_1$; $\tilde{V} = V(p_1, \tilde{T})$. Since $(T_1 - T_A)/(T_A - T_0) \gg 1$ and $c_p(\tilde{V}, \tilde{T})/c_p(V_0, T_0) > 1$ (see [2]), we have $(W_{AK}/W_{OA}) \gg 1$, i.e., the bulk of the laser-pulse energy corresponds to the isobaric section of the transition. Owing to the monotonic increase of the specific heat $c_p[V(p, T), T]$ as $T \to T_1$, the pulse intensity at $t > t_{0A}$ should also increase. The approximate form of the entire laser pulse is shown in Fig. 2.

We present numerical estimates for ethyl alcohol ($T_{cr} = 516.3\,^\circ$K, $p_{cr} = 63$ atm, $V_{cr} = 3.6$ cm^3/g), assuming a transition from the normal state [$V_0 = 1.26$ cm^3/g, $p_0 = 1$ atm, $T_0 = 293\,^\circ$K, $\Gamma(V_0) \approx 1$] into the transcritical state with $T_1 = 520\,^\circ$K, $p_1 = 66$ atm, and $V_1 = V_{cr}$. At $\alpha = 0.5$ cm^{-1} we obtain $W_{OA} \approx 0.1$ J and $t_{OA} = 4 \times 10^{-8}$ sec ($a/c \approx 4 \times 10^{-7}$ sec). The temperature rise on the isochoric section $(T_A - T_0) \approx 3.4\,^\circ$K, and the ratio is $(T_1 - T_A)/(T_A - T_0) \approx 0.66$. If $c_p(V_1, T_1)/c_p(V_0, T_0) = 3$, then $W_{AK} \approx 20$ J. The total pulse duration is $\tau \approx 4 \times 10^{-7}$ sec.

Other examples of optothermodynamic problems are those connected with production in a medium of high pressures that vary in a specified manner in time. The solution of such problems may be of interest, for example, in the technology of manufacturing synthetic minerals, optimal generation of sound signals in liquids, and also for high-pressure chemistry. The optothermodynamic approach can be used also to study the physical nature of the influence of laser radiation on the superconducting transition temperature in alloys, and effect discovered in [3], and in general for the study of programmed phase transitions.

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[1] J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman, Nature 239, 139 (1972).
[2] L. D. Landau and E. M. Lifshitz, Statisticheskaya fizika (Statistical Physics), Nauka, 1964 (Pergamon, 1971).
[3] V. N. Gridnev, I. Ya. Dekhtyar, L. I. Ivanov, N. V. Karlov, G. P. Kuz'min, M. M. Nishchenko, A. M. Prokhorov, N. N. Rykalin, and V. A. Yakushnevich, ZhETF Pis. Red. 18, 258 (1973) [JETP Lett. 18, 154 (1973)].