Effect of turbulent mixing on the compression of laser targets

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A study is made of the effect of turbulent mixing on the compression of laser targets. It is concluded on the basis of comparative calculations that turbulent mixing must be considered as one of the basic factors affecting target compression.

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The search for the optimal target design for use in pulsed thermonuclear fusion (laser and electron-beam fusion, etc.) has reached considerable proportions. The basic requirement imposed on a target design is generation of the maximum neutron output per unit laser energy, and, subsequently, thermonuclear ignition of a target and the maximum possible energy yield.

The basis tools used in the search for such target designs are the numerical calculations of target compressions which are based on the gas dynamics.

However, in the course of such exploratory calculations one must remember that, in the overwhelming majority of cases, gasdynamic flows that occur in the process of target compression are unstable in some regions. The attendant development of small perturbations that are always present in real designs, and the subsequent agitation of flow may substantially alter the overall flow pattern and radically affect the final result. Basic sources of perturbations are: 1) asymmetry of incident laser energy, 2) deviation of the shell shape from ideally spherical, 3) heterogeneity of material density, and 4) roughness of shell surface. Perturbations due to the first two sources may, in principle, be dangerous. However, there exists a real technical capability to reduce their initial amplitude in a manner such that during target compression the amplitude of perturbations remains within limits, without adversely affecting target performance. Peturbations due to the third source are clearly more difficult, although not impossible, to suppress.

Perturbations induced by the roughness of shell surface cannot, in principle, be fully eliminated. Moreover, the wavelength of such perturbations will always be much smaller than the characteristic dimensions of a target. Thus, as soon as the boundary between the D-T fuel and the shell becomes unstable,[1] small perturbations of the shell surface appear during a time that is negligibly small compared to the total time required to compress a target, proceed from the linear growth stage and become agitated, thus leading to turbulent mixing of the target material with the D-T gas.

To illustrate the extent and nature of the effect of turbulent mixing we conducted a series of numerical calculations of target compression involving a glass ball target filled with D-T gas. Target design and dimensions were similar to those used by Brueckner *et al.* in the investigation of D-T compression and neutron yield.[1] Shell thickness and the D-T mixture density varied during calculations.

Since the purpose of the calculations was to illustrate the effect of compression-induced turbulence on the target parameters, simplified assumptions were adopted with respect to the equation of state of materials, coefficients of electronic thermal conductivity, magnitude of bremsstrahlung losses, and method of deposition of the laser energy. The total calculated laser energy absorbed in a target was ~120 J and was generated, depending on the time, in the shape of a triangular pulse with 0.1-nsec duration. Each calculation was conducted under two options: in an ideal set-up without agitation flow. Calculation of the turbulence was made within the framework of a semi-empirical model[2] which consists of solving for each point of the flow the energy equation of turbulent pulsations ϵ_t and turbulent viscosity ν_t, concurrently with the gas-dynamic equation;these equations are shown below (for large Reynolds numbers):

$$\frac{d\epsilon_t}{dt} = \frac{1}{\rho}\,\mathrm{div}\,a\rho\nu_t\,\nabla\epsilon_t + a\left(\frac{\nabla P}{\gamma P} - \frac{\nabla\rho}{\rho}\right)\frac{\nabla P}{\rho} - k\,\frac{\epsilon_t^2}{\nu_t}\;;$$

$$\frac{d\nu_t}{dt} = \frac{1}{\rho}\,\mathrm{div}\,a\rho\nu_t\,\nabla\nu_t + \beta\,\frac{\nu_t^2}{\epsilon_t}\left(\frac{\nabla P}{\gamma P} - \frac{\nabla\rho}{\rho}\right)\frac{\Delta P}{\rho}\;;$$

$$a = 2; \qquad k = 0.4, \qquad \beta = 1,67\;.$$

The value of the constant β was determined by comparing the results of calculations with model experiments in turbulent mixing at the boundary of materials of different densities.[2] Processes of turbulent transfer of matter and energy are considered in the diffusion approximation. Namely, the following equations are solved for the total internal energy and mass concentration of each material in the mixture c_i:

$$\frac{dE}{dt} = \frac{P}{\rho^2}\,\frac{d\rho}{dt} - \frac{1}{\rho}\,\mathrm{div}\,(\mathbf{q} + \mathbf{q}_t), \qquad \frac{dc_i}{dt} = -\frac{1}{\rho}\,\mathrm{div}\,\mathbf{j}_{tc_i},$$

where $\mathbf{q}$ is energy flux specified by the normal thermal conductivity (in our case—electronic); and $\mathbf{q}_t$,$\mathbf{j}_{tci}$ are turbulent energy fluxes and masses of the corresponding mixture component, expressed as follows:

$$\mathbf{q}_t = -a\rho\nu_t\nabla\left(E + \frac{P}{\rho}\right)\;, \qquad \mathbf{j}_{tc_i} = -a\rho\nu_t\nabla c_i\;.$$

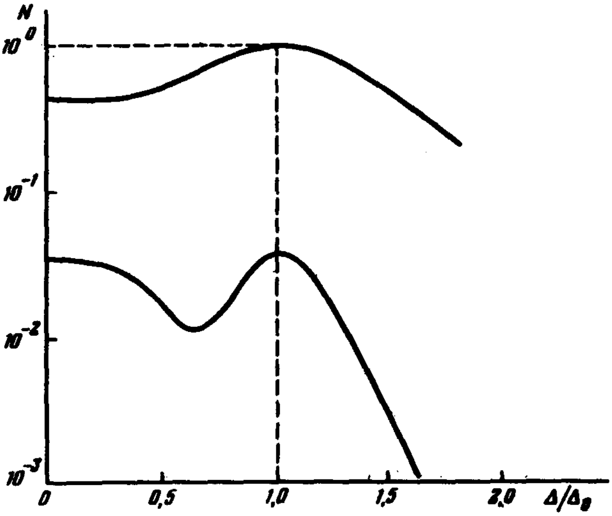

FIG. 1

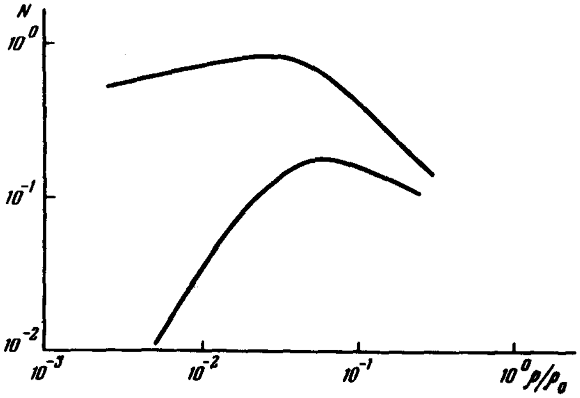

FIG. 2

Figure 1 shows in relative units the neutron yield from a target with different shell thicknesses obtained from both ideal calculations and those which allow for a possibility of low agitation. Figure 2 shows the similar dependence of the neutron yield on the initial gas density for a target with shell thickness $\Delta = 3\ \mu\text{m}$. The only unstable quantity in the aforementioned calculations was the internal boundary of the glass shell at a time when the latter is decelerated in the vicinity of the maximum compression of D-T gas. The attendant turbulent mixing of shell material with the D-T fuel encompasses there entire fuel mass. Flow in the remaining regions under compression remains stable, including a boundary between the evaporated and unevaporated parts of the shell. The absence of agitation at a boundary of the unevaporated portion of the shell was determined by selection of an appropriate shape of the temporal function of laser output energy. Clearly, effect of the turbulent mixing on target characteristics may be very significant. Moreover, this effect is characterized not only by a considerable reduction in the absolute neutron yield but also by a modified dependence of the neutron yield on the initial target parameters.

In conclusion, we should note that the nature of results presented in this article is basically qualitative. The solution of a question concerning the derivation of concrete calculated quantitative data requires further effort that pertains to the determination of the degree of applicability of the semi-empirical model of turbulent mixing used to calculate target compression. Nevertheless, it seems certain that in the target calculations a possibility of flow agitation must be taken into the consideration as one of the basic factors that may substantially influence the neutron yield from a target, the required laser energy for the ignition, and the energy yield from the target.

[1)] As is known, flow is unstable if the following inequality holds: $\nabla P \nabla \rho < 0$, where P is pressure and ρ is density.

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[1] K.A. Brueckner, P.M. Campbell, and R.A. Grandey, Nuclear Fusion **15**, 471 (1975).

[2] V.V. Andronov, S.M. Bakhrakh, E.E. Meshkov, V.N. Mokhov, V.V. Nikiforov, A.V. Pevnitskiĭ, and A.I. Tolshmyakov, Zh. Eksp. Teor. Fiz. **71**, 806 (1976) [Sov. Phys. JETP **44**, 424 (1976)].