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HEAT LOSSES IN THE PLENUM CHAMBER OF A GASDYNAMIC LASER BY SIMULATION IN A SHOCK TUBE

O. V. Achasov, Ya. Blaga,
and N. A. Fomin

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It is shown that the heat losses in the plenum chamber of gasdynamic laser simulated in a shock tube do not significantly affect the operating conditions of the laser apparatus under investigation.

Experience in the use of shock-tube techniques in high-temperature gas dynamics in chemical physics has served as the basis for developing pulsed gasdynamic laser systems which practically completely simulate the working conditions in stationary apparatuses with thermal pumping and with subsequent adiabatic expansion of the working mixture in a nozzle [1]. Using the shock wave, we can heat a previously prepared working mixture of gases, fairly rapidly and uniformly over the volume, to a temperature of thousands (or even tens of thousands) of degrees. Using the reflection of the shock wave from the closed end of the tube, we can easily similate the necessary "static" state of the gas in the plenum chamber of the stationary apparatus; the final state of the apparatus after two shock compressions is uniquely specified by velocity of the shock wave and the initial gas pressure. If in the end face of the shock tube we mount a supersonic nozzle with a critical cross section much smaller than the cross section of the main channel of the tube, the final state of the gas will differ little from the state behind the reflected plane wave.

However, the final state of the gas in the plenum chamber of a gasdynamic laser may vary with time as a result of heat losses to the walls of the apparatus. At the same time, the output characteristics of the gasdynamic laser (amplification factor, power output) depend substantially on the thermodynamic state of the working medium, and in particular on the gas temperature in the plenum chamber. From the data shown in Fig. 1 it can be seen that a 10% change in the temperature of the working gas results in a change of 5-7% in the amplification factor, which inevitably affects the operating conditions of the laser apparatus.

The purpose of the present study is to determine the amount of the heat losses in the plenum chamber of a gasdynamic laser with mixing, simulated in a shock tube, and to estimate the effect of these losses on the parameters of the system.

We consider the heat losses into the end face and the lateral surface of the shock tube, starting from the time $t = 0$, when the shock wave is reflected from the end face. Suppose that the temperature of the tube walls is T_0 and the temperature of the gas behind the front of the reflected shock wave is T_1. The motionless gas behind the front of the reflected shock wave, moving at velocity D, will be considered a semibounded body, and the temperature at its boundary will be taken to be T_0; this leads to results which are somewhat too high, since we have not taken account of the thermal resistance of the shock-tube walls. Then [3] the amount of heat transferred in time t through the end face and the lateral surface can be written as follows:

$$\Delta Q_T = \frac{1}{2}\sqrt{\pi\lambda c_p\rho}\,(T_1 - T_0)\,d^2\sqrt{t}\,, \qquad \Delta Q_C = 2\sqrt{\pi\lambda c_p\rho}\,(T_1 - T_0)\,Ddt\sqrt{t}\,.$$

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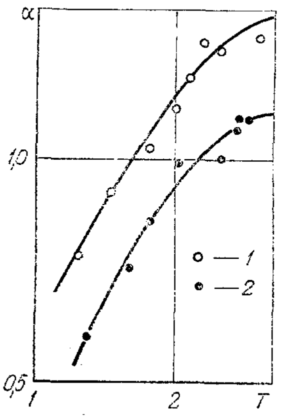

Fig. 1

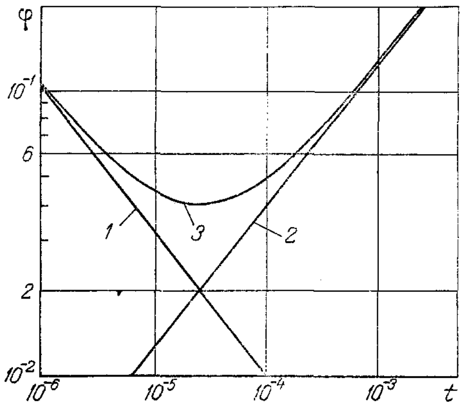

Fig. 2

Fig. 1. Experimental data showing the variation of the amplification factor of a gasdynamic laser with mixing, α, m^{-1}, as a function of the temperature T, kK, according to the data of [2]. The excited gas in the plenum chamber is: 1) nitrogen; 2) air.

Fig. 2. Contribution of the heat losses through the end face (1) and the lateral surface (2) to the total losses (3) as a function of time. $\varphi = fd/A$, $\sec^{1/2}$, $b = 10^{-4}$ sec.

The enthalpy of the gas heated in the reflected wave is:

$$H = h\rho \frac{\pi d^2}{4} Dt.$$

Then the relative heat losses can be expressed as follows:

$$f = \frac{\Delta Q_\Sigma}{H} = \frac{2\sqrt{\lambda c_p}}{h\sqrt{\rho\pi}} (T_1 - T_0)\left(\frac{1}{D\sqrt{t}} + \frac{4\sqrt{t}}{d}\right).$$

If we introduce the parameter $b = d/D$, the above expression becomes

$$f = \frac{A}{d}\left(\frac{b}{\sqrt{t}} + 4\sqrt{t}\right).$$

As can be seen, at the initial instant of time the relative heat losses through the end face are much higher than the losses through the lateral surface of the shock tube, but after ∿100 μsec (for $b = 10^{-4}$ sec) the losses through the lateral surface will become decisive, and the value of the relative heat losses will be minimal for time $t = b/4$ after the reflection of the shock wave (Fig. 2).

Figure 3 shows the variation with time of the relative heat losses for different values of b, where it is assumed that the velocity of the reflected shock wave remains constant. For experiments in the simulation of gasdynamic lasers in shock tubes we have a characteristic value of $b \simeq 10^{-4}$ sec. For such values of b, up to $t \sim 10^{-3}$ sec, the heat losses do not exceed 3%. When we conducted experimental investigations using shock-tube techniques, the characteristic time was equal to 10^{-5}–10^{-3} sec.

Thus, in the simulation of the operation of gasdynamic lasers in shock tubes, the heat losses through the surface of the shock tube may be disregarded; this results in an error of no more than 3%. Naturally, all of the foregoing is inapplicable to certain systems with quasicontinuous action (e.g., to lasers pumped by means of an explosion in an enclosed space, with subsequent escape of the heated gas through a nozzle), since in this case the relative heat losses will increase $\sim t\sqrt{t}$ because the volume of the heated gas, and therefore its enthalpy, will not increase, unlike the case of a reflected shock wave.

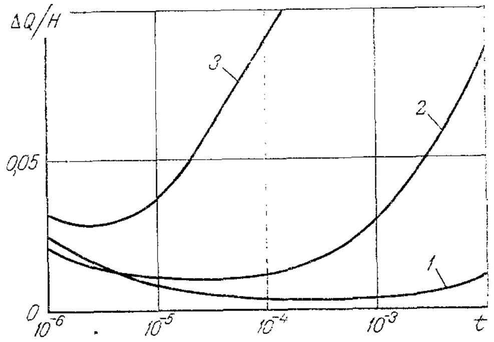

Fig. 3

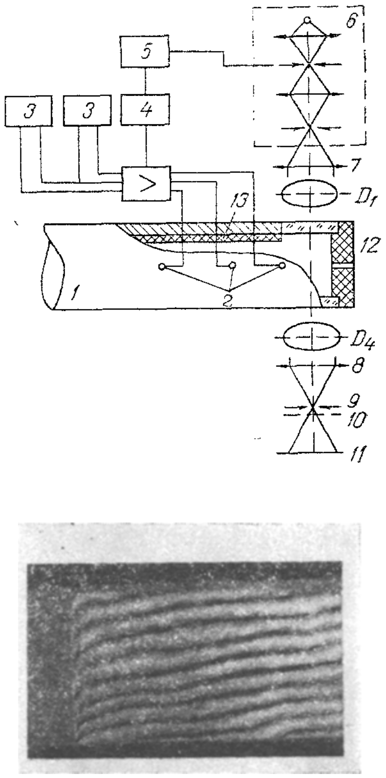

Fig. 4

Fig. 3. Relative heat losses as a function of time for values of $b = 10^{-3}$ (1), 10^{-4} (2), 10^{-5} sec (3).

Fig. 4. Schematic of the experimental apparatus and a typical interferogram: 1) shock-tube channel; 2) heat-flux sensors; 3) device for measuring time intervals; 4) delayed-pulse generator; 5) ignition unit; 6) pulsed light source; 7) collimator; D_1, D_4) interferometer mirrors; 8) focusing lens; 9) diaphragm; 10) filter; 11) Polaroid camera; 12) replaceable reflecting insert; 13) polyvinylchloride bushing.

In order to visualize the temperature field behind the reflected shock wave, we made a series of interferometer measurements.* The measurements were made by means of a Mach—Zender interferometer with a compensation chamber in which the density of the gas was kept close to the density behind the reflected shock wave. A schematic of the experiment is shown in Fig. 4. The light source used was a pulsed argon arc lamp (duration of pulse 500 nsec). The velocity of the shock wave was recorded on two time-interval measuring devices, using the measurement of the time intervals between the signals from three film sensors for recording the heat flux, set up on a different base. One of the sensors triggered a delayed-pulse generator, which was used for synchronizing the light source with the recording apparatus. The parameters of the gas behind the front of the incident and reflected shock wave were determined by the usual method on the basis of the velocity of the incident shock wave.

All the measurements were made with nitrogen, which is generally used as the energy-accumulating gas in a gasdynamic laser, with selective thermal excitation and mixing in the supersonic flow.

The intensity of the shock wave was taken to be such that $T \simeq 2600°K$, with $A = 0.226\ m^{-1} \cdot sec^{-1/2}$ (the value of λ was taken from [4]). In order to estimate the contribution made to the total by the heat loss through the end face and the lateral surface, we varied the material of the lateral surface and the end face as follows: end face — 1) Teflon; 2)

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*The experimental investigations were carried out at the Thermomechanics Institute of the Czechoslovakian Academy of Sciences, Prague.

aluminum; lateral surface — 1) polyvinylchloride; 2) steel. As a result, it was found that in all the variants the temperature of the gas behind the front of the reflected shock wave remains practically constant for time $t \sim 10^{-3}$ sec, after which the contact surface enters the zone of investigation. As an illustration of this fact, we show a typical interferogram in Fig. 4 ($t = 560$ μsec).

Thus, on the basis of the estimates made and of our series of interferometer investigations, we can conclude that in the simulation of gasdynamic lasers in shock tubes, the heat losses through the surface of the shock tube do not significantly change the thermodynamic state of the working gas heated and compressed in the shock wave.

NOTATION

d, shock-tube channel diameter, λ, thermal conductivity; c_p, specific heat capacity at constant pressure; ρ, density; h, specific enthalpy.

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