CO_2 MIXING GASDYNAMIC LASER WITH EMITTING MOLECULES FORMED IN THE REACTING $CO-O_2-H_2$ MIXTURE

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The measured values of the gain in a supersonic stream of a gasdynamic laser with emitting CO_2 molecules formed in the reacting $Co-O_2-H_2$ mixture are reported.

One of the simplest ways of producing a laser active medium is the gasdynamic method, in which thermal energy is converted directly to the energy of coherent radiation. It is implemented in gasdynamic lasers (GDL's) which have a number of significant advantages over other flowing-gas lasers [1-4]. It is possible in principle in such a system to achieve lasing in the combustion products of common fuels (carbon monoxide, hydrocarbons, etc.); the energy of the exothermic chemical reactions is converted to thermal energy in the first stage and then, after expansion in a supersonic nozzle, to coherent radiation energy. Studies [5-7] have demonstrated that chemical reactions can be combined with rapid adiabatic cooling of the reaction products to obtain inverse flows. Thus far chemical pumping of vibrations of CO_2 molecules has been recorded in GDL's operating on $CO-O_2$ [8-10], N_2O-CO [11-19], N_2O-CO_2 [20], and C_3H_8-air [21] reacting mixtures. In our work we studied the inverse properties of a gasdynamic laser with mixing, in which emitting CO_2 molecules are formed in the $CO-O_2-H_2$ reacting mixture.

A quasicontinuous mixing GDL was built on the basis of a shock tube with a nozzzle [4]. The low-pressure channel of the shock tube had an inner cross section of 0.05 × 0.05 mm and a length of 4.2 m. As the high-pressure chamber we used a solenoid starter valve, whose operating time was $2 \pm 0.1 \cdot 10^{-3}$ sec and remained constant at a driver-gas (He, H_2) pressure of up to 4 MPa. The operating voltage, ensuring operation of the high-pressure chamber at various initial pressures, varied from 3 to 5 kV.

The quasi-steady phase of adiabatic efflux, compressed to a pressure of 0.3-3 MPa, behind the reflected shock wavefront of the gas at $(1-5) \cdot 10^{-3}$ K lasted for 10^{-3} sec. The section with the nozzle was separated from the main channel of the shock tube by a thin copper diaphragm with a notch and was pumped down to ensure rapid formation of the flow ($\sim 10^{-4}$ sec) and substantially increased the efflux time. The gas flow from the nozzle entered a vacuum chamber with a volume of 0.1 m^3, which had been pumped down along with the nozzle section to a pressure of 10 Pa prior to the experiment. The influx of atmospheric air into the shock tube was less than 10^{-4} Pa·sec^{-1}. The state of the gas in the forechamber behind the incident and reflected shock waves was calculated from the measured velocity of the shock wave, using a data bank on the enthalpy of the gases studied. The velocity of the shock wave was measured on two bases by the intervals of time between passages of the wavefront, using piezoelectric pressure transducers. Precalibrated piezoelectric transducers were also used for direct measurements of the pressure behind the incident and reflected shock wave fronts.

An automatic system, whose block diagram is shown in Fig. 1, was used to acquire and process information in our experiments with shock tubes. The system consists of CAMAC equipment program-controlled by an Élektronika MS 1201.01 microcomputer.

The recording system is actuated when the first piezoelectric pressure transducer TR_1 is triggered. Similar transducers TR_2-TR_4 record the time when the shock wavefront passes. To prevent misoperation of the system signals from the pressure transducers are transmitted through a threshold signal conditioner to the synchronizer module. The pressure behind the incident and reflected shock wavefronts is measured with piezoelectric transducer TR_5. The

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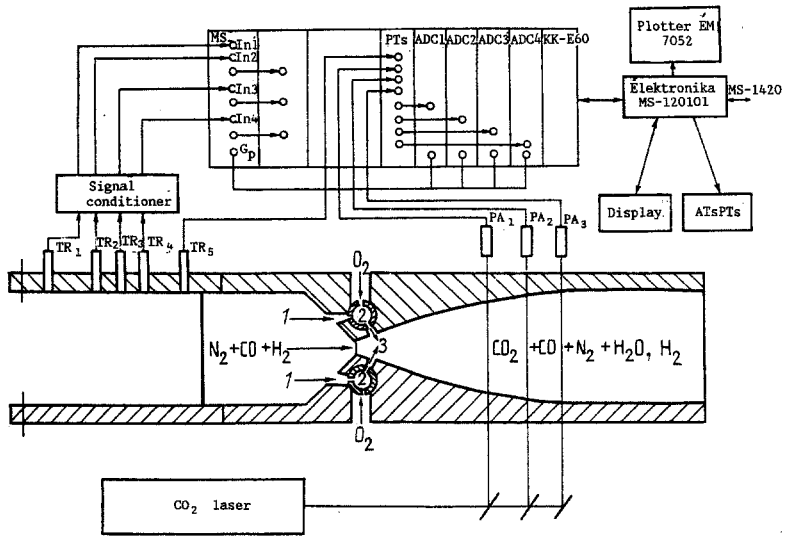

Fig. 1. Experimental system.

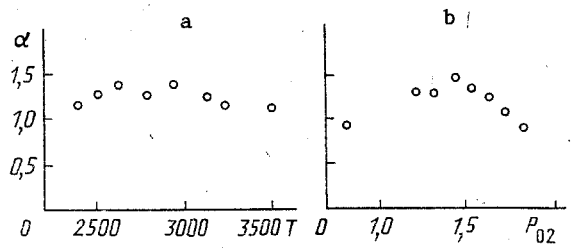

Fig. 2. Dependence of the gain of the R 16 line on the stagnation temperature in the forechamber (a) and pressure of injection of a 1:3 CO_2–He mixture (b). α, m^{-1}; T, K; P_{02}, MPa.

unit for measuring the light from the probing CO_2 laser is recorded by means of cooled FSG-22A photoresistors (Ge–Au) with preamplifier circuits PA1-PA3. Similar signals from pressure transducer TR_5 and the photoresistors are sent to a four-channel amplifier with a programmable gain, whose value is set discretely in the range 1-128 and is equal to an integral power of 2. The amplified signals are fed to the inputs of 8-digit analog-digital converters (ADC's) with a minimum conversion time of 3 μsec. Each ADC has a 4K buffer, which is filled with the results of the input-signal conversion and then can be read into the microcomputer. The simultaneous triggering of all ADC's is ensured by a train of pulses, generated in the synchronizer module.

The operation of the CAMAC module is controlled by the microcomputer through the KK-E60 crate controller. The operating system and the control program are loaded into the microcomputer memory along communication links through SPI-15 interface cards from the central SM-1420 minicomputer. The use of this automatic system in shock-tube experiments ensures reliable synchronous triggering of the apparatus and equipment and accuracy of 1.0% in measurements of the electrical signals from the primary transducers.

The schematic of the nozzle unit of the mixing GDL studied is shown in Fig. 1. The CO–N_2–H_2 mixture heated behind the reflected shock wave is divided into two streams: one enters the mixing region and the other enters into the supersonic part through the critical section of the nozzle. At the same time room-temperature molecular oxygen is fed from the fast solenoid valve into the mixing region, where carbon monoxide is oxidized and CO_2 molecules are formed in chemical reactions. The CO combustion products pass through supersonic conical apertures (the Mach number of the injected stream is M = 2) to enter the supersonic part of the nozzle unit, where secondary mixing takes place with CO–N_2–H_2 coming from the forechamber. The mixing is organized at the place where the Mach number of the main stream is 2. The nozzle has an expansion ratio of 30 and a critical section of 1 mm. The gain α was measured in a channel of constant cross section at a distance of 0.09 m from the critical

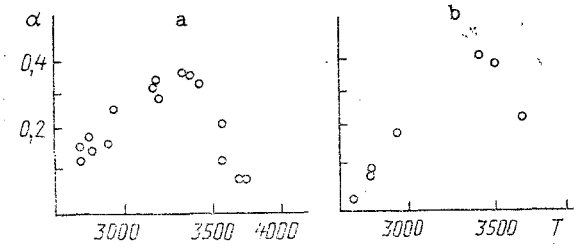

Fig. 3. Dependence of the gain on the stagnation temperature for a mixture 0.49 CO + 0.5 N_2 + 0.01 H_2 at P_{01} = 0.7 MPa, T_{02} = 300 K, P_{02} = 0.8 MPa (a) and 0.4 CO + 0.5 N_2 + 0.1 H_2 at P_{01} = 0.6 MPa, T_{02} = 300 K, P_{02} = 0.8 MPa (b); injected gas O_2.

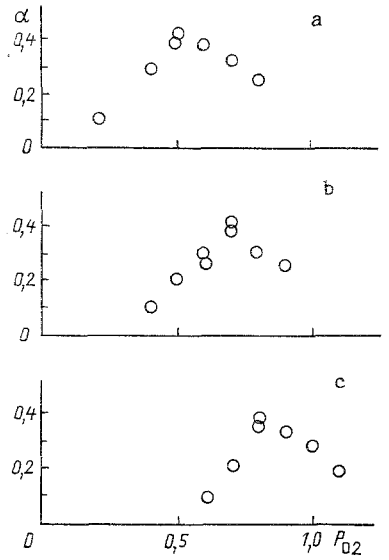

Fig. 4. Dependence of the gain on the oxygen injection pressure (T_{02} = 300 K): a) mixture 0.49 CO + 0.5 N_2 + 0.01 H_2 (T_{01} = 3300 K, P_{01} = 0.7 MPa); b) mixture 0.48 CO + 0.48 N_2 + 0.04 H_2 (T_{01} = 3100 K, P_{01} = 0.7 MPa); c) mixture 0.4 CO + 0.5 N_2 + 0.1 H_2 (T_{01} = 3500 K, P_0 = 0.6 MPa).

section of the nozzle. As the probing radiation we chose the R16 line of the 001-100 transition of a CO_2 laser spectrograph (lasing wavelength λ = 10.3 μm). The use of the R16 line of the CO_2 laser spectrograph allows us to disregard the contribution of the "hot" transitions to the value of the measured gain [22].

The efficiency of the gasdynamic system was tested in experiments with a GDL with mixing of nonreacting streams. A 1:3 CO_2–H_2 mixture was injected. From the results of gain measurements shown in Fig. 2, we see that the values attained by the gain in a GDL with two-stage mixing reach 1.4 m^{-1}, which indicates highly efficient mixing of the streams and the freezing of the vibrational energy.

Some results of our experimental studies of the amplifying characteristics of a mixing gasdynamic laser with the formation of emitting CO_2 molecules in a reacting CO–O_2–H mixture are shown in Figs. 3 and 4. The experiments were carried out for three compositions in the forechamber: 1) 0.49 CO + 0.5 N_2 + 0.01 H_2, 2) 0.48 CO + 0.48 N_2 + 0.04 H_2, and 3) 0.4 CO + 0.5 N_2 + 0.1 H_2. As follows from Fig. 3, the maximum gain for mixtures with a low (1%) or high (10%) content of molecular hydrogen is reached at practically the same temperatures in the forechamber: 3300 ± 200 K. "Shifting" the experimental dependences $\alpha(P_{02})$ to higher pressures, which means higher flow rates of molecular oxygen being mixed in while the hydrogen concentration in the mixture increases (Fig. 4), confirms the conclusion of [15] that additions of hydrogenous impurities substantially affect the chain oxidation of carbon monoxide.

Since the kinetics of the chemical reactions in a CO–O_2–H_2–N_2 mixture is a determining factor in the efficient operation of the proposed GDL scheme, we made experimental studies of the ignition period. The experiments were performed on a pulsed gasdynamic stand based

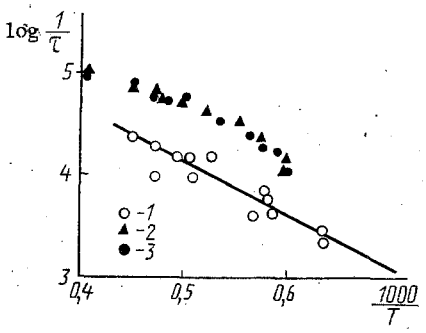

Fig. 5. Dependence of the ignition period on the temperature T_{01}: 1) 40% CO + 45% N_2 + 10% O_2 + 5% H_2; 2) 10% O_2 + 20% CO + 69% AR + 1% H_2 [23]; 3) 20% O_2 + 10% CO + 69% AR + 1% H_2 [23].

on a shock tube in the Thermodynamics Laboratory at the Institute of Thermomechanics, Czechoslovak Akademy of Sciences, Prague. The diameter of the shock tube was $5 \cdot 10^{-2}$ m and the lengths of the high-pressure and low-pressure sections were 1 and 6.2 m, respectively. The high-pressure and low-pressure sections were separated by aluminum diaphragms, mounted in a sealing clamp. The low-pressure section was evacuated to 10^{-3} Pa by two fore and diffusion pumps. Hydrogen was used as the driver gas.

The velocity of the shock wave was measured on two bases by two thin-film heat-flux sensors on the basis of the interval of time between passages of the shock wave. The ignition period of a 45% N_2 + 40% CO + 10% O_2 + 5% H_2 mixture in the parameter range of interest for GDL studied (temperature 1500-2500 K, pressure 0.55 + 0.03 MPa) was determined by the standard method on the basis of the recorded pressure in the mixture with a piezoelectric pressure transducer, set up at the end of the shock tube, and the recorded infrared radiation in the spectral region 4.3 ± 0.05 μm. Measured values of the ignition period are shown in Fig. 5, along with results of experimental studies on the effect of hydrogen molecules on the ignition period of a mixture containing CO, O_2, and AR molecules [23]. The slight increase in the ignition period of a mixture containing nitrogen molecules is apparently due to the effect of vibrational energy exchange on the kinetics of the chemical reactions of the oxidation of CO as well as the competing process in which oxygen is expended on the formation of nitrogen oxides.

As follows from these results, when the reacting mixture is at a temperature ~1500 K, which is attainable in the mixing and reaction zone at typical values of the GDL-stream-mixing parameters in the nozzle apparatus, the ignition period is comparable with the time of quasisteady efflux of a "plug" heated and compressed behind the front of the gas shock wave and, therefore, is also comparable with the feed time of the CO + N_2 + H_2 mixture into the reaction.

In summary, experimental studies have shown that a mixing gasdynamic laser with the formation of emitting CO_2 molecules in a reacting CO–O_2–H_2 mixture is realized in the proposed scheme. We must point out that when the temperature of the N_2–CO–H_2 stream reaches 2000-3000 K, oxidant is fed at room temperature, causing the temperature in the reaction zone to decrease. In this case, however, the measured gain for the R16 line of the 00°1-10°0 transition of the CO_2 molecule reaches $\alpha = 0.4$ m^{-1}. For further investigation of the efficiency of the proposed gasdynamic laser scheme it is desirable to carry out experiments with the quasistationary phase of the efflux considerably exceeding the ignition period of the mixture under study; this can be accomplished on equipment of the shock tube type by raising reaction zone temperature, i.e., by feeding a hot oxidant, or by using continuous-operation equipment or pulsed stands with a substantially longer (>2 msec) quasisteady phase of efflux.

NOTATION

Here α is the weak-signal gain; M is the Mach number; P_{01} is the stagnation pressure; T_{01} is the stagnation temperature; P_{02} is the pressure of the injected stream; T_{02} is the temperature of the injected stream; λ is the probing laser wavelength; and τ is the mixture ignition period.

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