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# Studies on the Characteristics of the Gas-Dynamic Laser with Low $CO_2$-Concentration Medium by a Diaphragmless Shock Tube

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Abstract: A diaphragmless shock tube equipped with a supersonic nozzle section has been newly developed in order to experimentally study various basic characteristics of the $CO_2$ gas-dynamic laser under low-impurity conditions. This paper reports on the experimental studies of the characteristics of laser output power at wavelengths of about 10.6 μm with stagnation conditions behind reflected shock waves in the laser mediums as 0.3 $CO_2$ + 0.7 $N_2$ and 0.2 $CO_2$ + 0.8 $N_2$ under low and controllable concentrations of residual $H_2O$ and $H_2$.

1. Introduction: Conventional shock tubes (diaphragm-type) have been used in gas-dynamic laser (GDL) experiments [1-5] for compressing and pre-heating a gaseous mixture instantaneously to elevated temperatures and pressures and delivering it to a nozzle section by which the shocked mixture is turned into a laser medium (i.e., a population inversion is created) during the process of rapid cooling of the vibrationally excited mixture therein. However, in general the use of a conventional shock tube results in (a) uncontrollable amount of impurities as water vapour and hydrogen inside the shock tube because of the inevitable procedure of replacing a ruptured diaphragm with a new one for the following test shot, and (b) relatively low reproducibility of the conditions behind reflected shock waves (i.e., temperature and pressure). These two together have unfavourable effects on the processes important in the $CO_2$ GDL [6] (e.g., rates of vibrational energy transfer involved). A diaphragmless shock tube, based on the double piston-actuated concept reported by Oguchi et at. [7], has been recently developed [8-9] and designed to perform $CO_2$ GDL experiments under low- and controllable-impurity conditions as well as good degree of reproducibility of shock-wave conditions. In addition, since there is no necessity to undertake the procedure of diaphragm replacement mentioned above, the turn-around time to repeat test shots has been greatly shortened, which makes the rate of test shots per working hours possible to be increased. The paper reports on the experimental study of the effect of diluting $CO_2$ in $N_2$ on the magnitude of the laser output power by using the diaphragmless shock tube.

2. The experimental GDL design and its principle of operation: Figure 1 shows a schema of

the experimental GDL device driven by the newly developed diaphragmless shock tube. The reservoir of vibrationally excited mixture is provided by the shock tube (typical values of temperature behind reflected shock waves range from 1000 to 3000 K and the corresponding values of pressures reach up to 3 atm). Referring to Fig. 1, the auxiliary piston is quickly actuated when the high-pressure actuating gas at its rear is very rapidly purged by means of the fast-opening valve. As such a piston slides backwards, the high-pressure actuating gas at the rear of the main piston, which separates the driver-gas chamber (high-pressure region) from the shock tube (low-pressure region), is massively released through the orifices. This actuates the main piston which slides rapidly backwards driven by the high-pressure driver gas. Simultaneously, the driver gas discharges massively in the shock tube, thereby forming an incident shock wave therein. The detailed principle of operation of this diaphragmless shock tube is reported separately in Refs. [8,9].

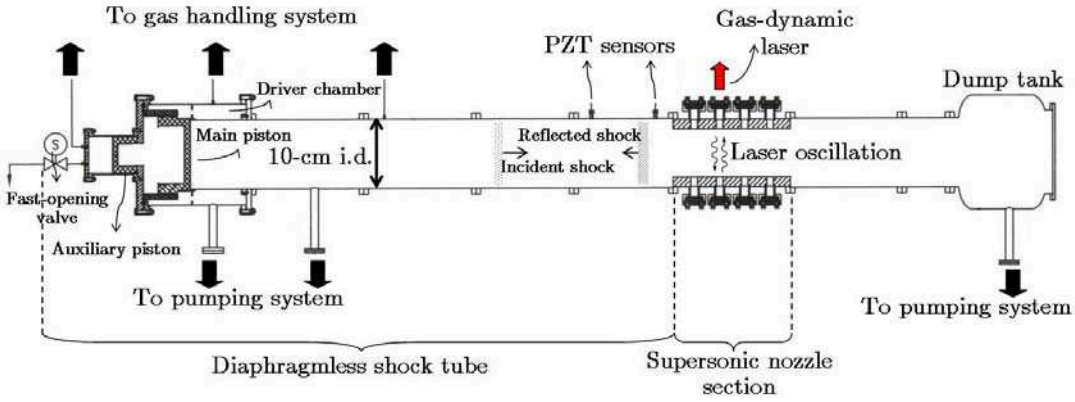


Fig. 1 – Overall drawing of the experimental GDL laser device driven by the newly developed diaphragmless shock tube (not to scale). Gas handling and pumping systems not illustrated.

The shock tube is 10 cm in i.d. and terminates with the end wall where the supersonic nozzle section is mounted (see Fig. 2a). The shock-heated mixture is delivered to the supersonic nozzle section for subsequent rapid expansion therein, where population inversion takes place. Such a section is instrumented for the measurement of laser output power available in the non-equilibrium flow in the resonator. Particularly, because of the large diameter of this shock tube, longer test times (i.e., time interval during which reservoir conditions behind reflected shocks are held) are expected to be achieved as well as longer laser durations. The dump tank placed behind the supersonic nozzle section serves to relax the supersonic flow to subsonic speeds. The temperature and pressure behind reflected shocks waves (denoted as $T_5$ and $P_5$, respectively) are routinely inferred from the measured velocity of the incident shock along with the Rankine-Hugoniot relations. The time interval between post-shock pressures

(see Fig. 2b) is used to derive the velocity of the incident shock wave. The gas handling system serves to handle and convey the high-pressure gases as actuating and driver gases and the low-pressure mixtures of which were used in the GDL experiments. The pumping system serves to pump down the entire experimental GDL device to acceptable low pressures before each and every test shot.

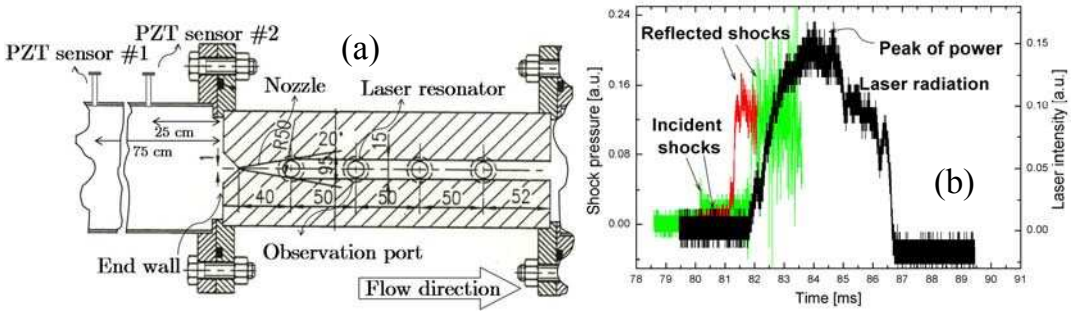


Fig. 2 – (a) End wall and supersonic nozzle section arrangement for the test shots, showing instrumentation and observation ports. (b) Time variation of post-shock pressures and laser intensity as detected during a test shot.

3. Results and Discussion: The gas composition was altered by changing the molar-fraction ratio of $CO_2$ to $N_2$ from 1:4 to 3:7 in the mixture. The role of $H_2O$ and $H_2$ in the kinetic of vibrational energy transfer [6] was believed to be negligible since the concentration of each in the evacuated shock tube relative to the amount of $CO_2$ supplied into the shock tube corresponded to typically 0.01 and 0.001 ppm by mass, respectively, and the content of both in the commercial $CO_2$-$N_2$ mixtures employed was stated as very low by the manufacturer. The laser radiation was extracted with the resonator (constituted of a concave, ZnSe-coated reflector mirror and a flat, ZnSe-coated output mirror with approximately 98 % reflectance for normal incidence at about 10.6 μm placed 14 cm apart) arranged perpendicularly to the flow direction at a fixed distance of 9 cm from the nozzle throat, and detected by a room temperature photo-detector sensitive to 10.6 μm. In Fig. 3a, it is clear that the maximum laser output power (at approximately 1750 K) for 0.2 $CO_2$ + 0.8 $N_2$ mixture initially at 0.39 kPa was relatively higher than that (at around 2150 K) for 0.3 $CO_2$ + 0.7 $N_2$ mixture initially at the same pressure. Examining Fig. 3b the values of laser output power for 0.2 $CO_2$ + 0.8 $N_2$ mixture at $P_5$ ranging from 0.1 and 0.5 atm appeared to be relatively higher than those for 0.3 $CO_2$ + 0.7 $N_2$ mixture within the same range of $P_5$. Thus, by diluting $CO_2$ in $N_2$ the laser output power can be enhanced. These experimental trends may be attributed in part to the following factors: (i) as the number of $N_2$ molecules present in the flow increases, the vibrational energy available to pump the laser levels of $CO_2$ increases since the energy provided by the reflected shock waves is primarily stored in $N_2$. As a result, the laser output

power is enhanced; (ii) the loss of vibrational energy stored in the vibrationally excited $N_2$ by means of collisions with $CO_2$ molecules, which have high efficiency in relaxing $N_2$ via translational-vibrational energy transfer, is lessened due to the decreasing number of $CO_2$ molecules present in the flow; and (iii) the relaxation of $CO_2$ in the upper laser level (001) of the asymmetric mode ($\nu_3$) via vibrational-vibrational collisions with $CO_2$ is reduced due to the decreasing number of $CO_2$ in the flow. Also, note that the optimum temperature seemed to decrease as the molar-fraction of $CO_2$ decreased. This may be associated to higher rates of dissociation of $CO_2$ due to lower partial pressures of this molecule relative to the total pressure of the mixture. Directions for future works include: GDL experiments with mixtures containing a higher He content and those with a lower $N_2$ content, and experiments on superposition of pulsed electric discharge in supersonic flow of the mixtures above.

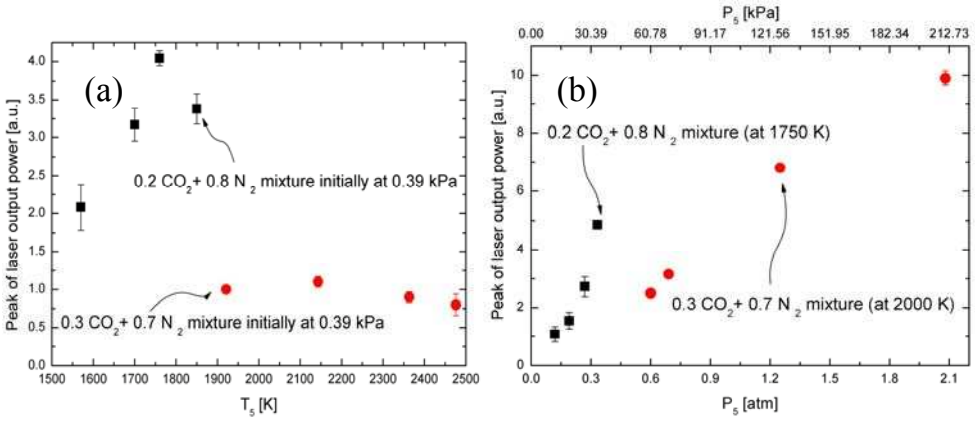


Fig. 3 – Variations of laser output power with (a) $T_5$ and (b) $P_5$ for 0.2 $CO_2$ + 0.8 $N_2$ and 0.3 $CO_2$ + 0.7 $N_2$ mixtures. Output laser diagnosed transversely to the flow and 9 cm downstream from the nozzle exit.

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