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Population Inversion/Laser Oscillation Caused by Relaxation Time Difference with a Newly Developed Non-Diaphragm Shock Tube and a Supersonic Nozzle Flow

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Abstract: A large diameter, diaphragmless shock tube equipped with a supersonic nozzle section has been newly developed in order to study experimentally various basic characteristics of the gas-dynamic laser. During a series of recent experiments with such a device the population inversion of the vibrational levels of CO_2 in a supersonic flow of shocked gaseous mixture of CO_2-N_2 was successfully achieved. In addition, an analysis of the pulsed 10.6-μm laser radiation (single-shot) generated by this population inversion is provided.

1. Introduction: Since the first experiment with carbon dioxide gas-dynamic laser reported in 1969 by Kuehn and Monson [1], such a device has been of both basic and applied interest in view of high-power gas lasers. The gas-dynamic laser device of Kyushu University (Kyudai GDL) consists of a newly developed large diameter, diaphragmless shock tube [2, 3] with a supersonic nozzle section mounted in the end wall of the shock tube intended for a full investigation of several GDL-related issues [4, 5]. This shock tube has the potential to offer various advantages over the diaphragm-type shock tubes, particularly in terms of GDL research, such as (a) significant reduction of inflow of impurities (H_2O, mainly) from atmosphere since there isn't the necessity of replacing the ruptured diaphragm shot by shot, (b) a higher degree of reproducibility of shock wave Mach numbers (for identical initial conditions) because of non-ideal shock formation-free, or rather non-ideal diaphragm breakage-free, etc. In addition, the large inner diameter of about 10 cm of this shock tube minimizes somehow incident-shock attenuation caused by the effects of viscosity. Next, a brief description of the design and operation of the Kyudai GDL is provided as well as a progress report on some of the recent experiments with CO_2-N_2 gas-dynamic laser action at 10.6 μm attained using such a device.

2. The Kyudai GDL design and operation: Figure 1 shows a schema of the large diameter, diaphragmless shock tube, which is utilized to produce a reflected shock wave responsible for generation of a hot and high pressure mixture of gases, together with the supersonic nozzle section from which the shocked gaseous mixture is very rapidly expanded (rapid cooling). A dump tank is placed behind the nozzle section in order to shock down the supersonic flow to subsonic speeds.

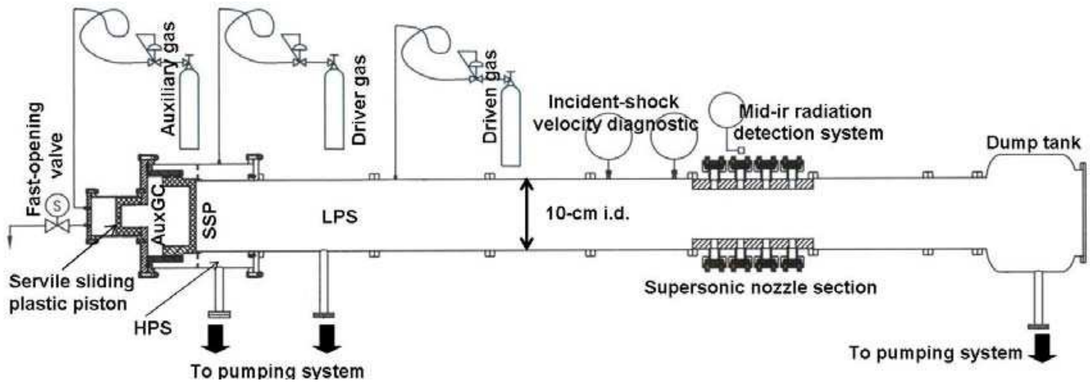

Fig. 1 – Overall drawing of the Kyushu University gas-dynamic laser, Kyudai GDL.

The entire device is made of stainless steel, assembled with its axis aligned in a horizontal direction, and rigidly fixed on a massive steel base. The shock tube comprises a volumetric driver gas chamber or high-pressure section (HPS) and a long, 10-cm i.d. driven gas tunnel or low-pressure section (LPS) separated from each other by a diaphragm-like sliding plastic piston (SPP) in place of a conventional diaphragm (see Fig. 2). Both sections are evacuated to a vacuum of about 10^{-2} Pa by a pumping system for a few minutes between two consecutive test shots. The key features of the supersonic nozzle section employed in the test shots are shown in Fig. 3(a). On the Kyudai GDL, both stagnation temperature and pressure (T_5 and P_5, respectively) are routinely inferred from the incident-shock velocity, which is measured via two piezo-electric pressure sensors located on the wall of the LPS 50 cm apart and a host oscilloscope for fast-signal acquisition, along with the Rankine-Hugoniot equation. Such host oscilloscope is triggered by an automatic synchronization system at a pre-selected time (within 60-80 ms) after the start of the shock wave formation (described next). The scheme for formation of shock waves for the Kyudai GDL is as follows: (i) high-pressure auxiliary gases, nitrogen (N_2) or helium (He), are used for the pressurization of an auxiliary gas chamber (AuxGC), (ii) as the whole AuxGC is pressurized, due to the auxiliary gas inflow (from left to right in Fig. 2(a)) through a low conductance, 1-mm pinhole in a servile sliding plastic piston, that diaphragm-like sliding plastic piston slides towards the right side to seal a passage between the HPS and the LPS (see Fig. 2(a)), (iii) since the pressure of the driver gas (helium) introduced next into the HPS is slightly lower than the auxiliary gas pressure in the AuxGC, the driver gas is then sealed in the HPS with the SPP, (iv) upon a fast evacuation of only a portion of the auxiliary gas from the posterior part of that servile piston by means of a fast-opening valve (see Fig. 2(b)), the servile piston rapidly backs, allowing the rest of the auxiliary gas to escape massively through various high conductance orifices on the AuxGC open to the ambient air, and (v) at last, because of this quick pressure imbalance, the SPP rapidly backs, opening that passage for the driver gas (see Fig. 2(c)) and thereby forming a shock wave.

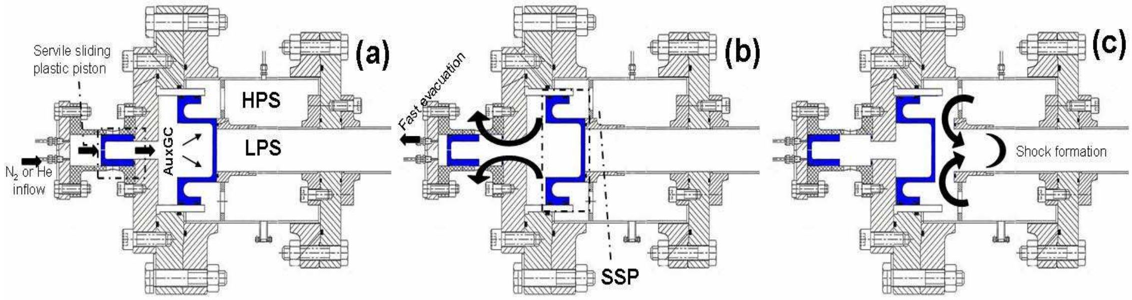

Fig. 2 – Principles of shock wave formation for the diaphragmless shock tube: (a) sealing mode via auxiliary gas inflow, (b) fast evacuation of auxiliary gas, and (c) shock wave formation.

3. Preliminary Results and Discussion (CO_2-N_2 Laser Action at 10.6 μm): The CO_2-N_2 gaseous mixture (mol fraction of 0.2 CO_2 + 0.8 N_2) at a total pressure ranging from 2 to 6 × 10^{-3} atm was compressed and heated by the reflected shock wave to roughly 0.1-0.6 atm and 1500-1900ºK, respectively at the end wall of the LPS, and rapidly expanded through the supersonic nozzle. The attainment of the population inversion of the vibrational levels of the CO_2 by means of that non-equilibrium flow was indirectly inferred by the detection of a mid-infrared laser radiation output at 10.6 μm. This was performed with (a) an 14-cm-optical path ir laser cavity arranged perpendicularly to the flow direction and 9 cm or so from the nozzle throat, where a flat reflector of germanium and a 50-cm radius spherical mirror are placed on both sides of the nozzle section (see Fig. 3(a)), (b) a room temperature ir photodetector sensitive to 10.6 μm, and (c) the host oscilloscope. Figure 3(b) shows a typical waveform of the power of the laser output at 10.6 μm registered during the test shots. Laser action duration (measured FWMH) was detected for about 1.5 to 4.5 ms. The dependence of the laser output power (peak power) on the stagnation conditions, i.e. T_5 and P_5 was investigated (see Fig. 4) and has shown to be in strict accordance with the literature. Further steps towards these studies will be as follows: (a) the laser action features in high stagnation

pressure region for the gaseous mixture with a higher He content and those for a lower N_2 content, (b) experiments with simultaneous addition of He and water to the gaseous mixture, (c) the effects of the supersonic nozzle design and the laser cavity configuration, and (d) experiments with rapid cooling accompanied by conventional electric discharge.

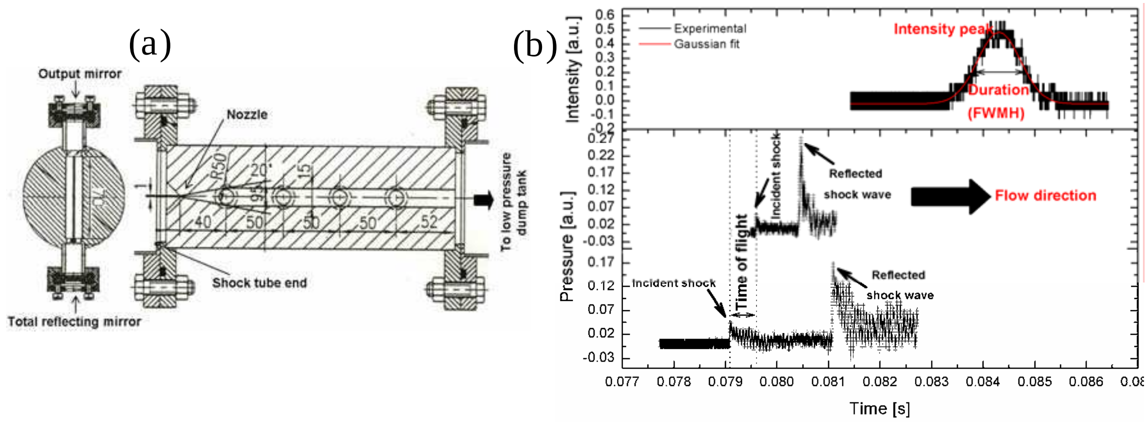

Fig. 3 – (a) supersonic nozzle section-infrared laser cavity assembly. (b) Sample of pressure histories (at the bottom) and 10.6-µm laser radiation (at the top).

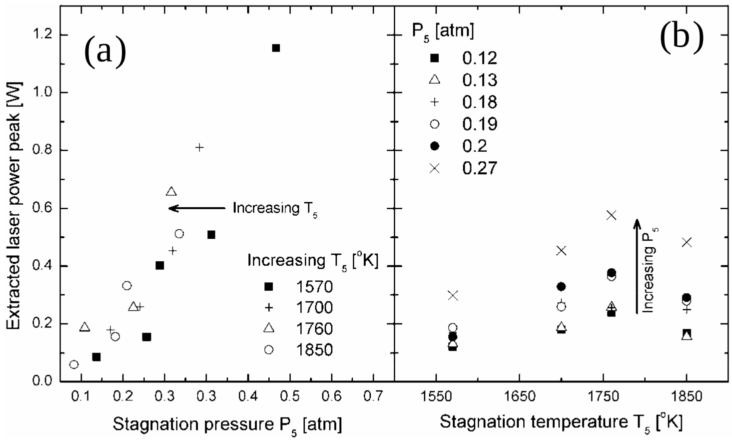

Fig. 4 – Peak power output of the 10.6-µm laser radiation vs. (a) the stagnation pressure (P_5) and (b) the stagnation temperature (T_5).

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