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STUDY ON N₂/CO₂ MIXING GASDYNAMIC LASER BY MEANS OF SYNCHRONIZED OPERATION OF TWO SHOCK TUBES

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Résumé.- On expérimente l'obtention de GDL par mélange de N₂ et de CO₂ à l'aide d'un bec à écran conçu pour un mélange supersonique aval, par utilisation synchronisée de deux tubes de choc séparés. Les distributions de gain mesurées sont comparées à une estimation fondée sur une analyse simplifiée quasi unidimensionnelle.

Abstract.- The experiment on N₂/CO₂ mixing GDL is conducted using a screen nozzle, contrived to make supersonic downstream mixing, by means of a synchronized operation of two separate shock tubes. The measured gain distributions are compared with an estimate based on simplified, quasi one-dimensional analysis.

Introduction

In this paper we concern a N₂/CO₂ mixing GDL experiment. It has already been demonstrated by previous investigators1–11 that a mixing GDL is one of the promising and powerful methods transcending a gain limit pertinent to a conventional premixed GDL; notably, comprehensive reviews should be referred to Refs. 9 and 11. So far as thermal excitation of the donor gas N₂ is concerned, the shock tube is one of the most useful means, because of the feasibility to cover a wide range of flow conditions.

Regarding the mixing of CO₂ (+ He) with a donor gas N₂, various schemes for the injection of CO₂ into a supersonic nozzle of N₂ have been noticed and/or contrived; for example, a normal throat injection from wall or slotted tube vertically mounted at the nozzle throat,3,4 a downstream screen nozzle injection with sonic nozzle of CO₂,5 and further a supersonic downstream injection by screen nozzle.6 In any scheme, however, the gasdynamics pertinent to mixing processes above mentioned is so intricate that simplified assumptions could be involved in any analysis; otherwise, the description of the relevant flow phenomena must largely rely on the experimental evidences.

As a mixing scheme of our experiment is chosen a screen nozzle which proved to yield high gain. This screen nozzle enabled us to make a supersonic downstream mixing of a donor gas with CO₂ with or without catalyst He. The screen nozzle is rather fixed in configuration and designed to comprise of simple conical nozzles, because optimization of the nozzle configuration is not our primary purpose. This paper aims to clarify some of fundamental characteristics of N₂/CO₂ mixing GDL, associated with supersonic downstream mixing over a wide range of stagnation conditions of the component gases.

Experimental Apparatus

This experiment was conducted by a synchronized operation of two shock tubes, which produce separate stagnant conditions for each gas. These two tubes have quite the same driving mechanism, which is illustrated in Fig. 1. The diaphragm of an ordinary shock tube is replaced by a free piston which is contrived to quickly move back and forth
following the movement of an auxiliary free piston. The auxiliary piston can be moved by on-off switching of small magnetic valve, equipped outside of the compression chambers. Consequently, the operation of each tube can be made simply by a snap action. Both feasibility and reproducibility of the operation is quite satisfactory, as previously reported in Refs 12, 13. Thus, the synchronized operation of these two tubes was easily achieved by electric control of the respective magnetic valves.

![Fig. 1 Schematic diagram of driver sections.](image1)

The shock tubes are different from each other in dimension; the tube for a donor gas $\text{N}_2$ has a driven section of 50 mm in inner diam. and 5,500 mm in length with the following 20x80 mm square cross section, and the other for $\text{CO}_2$ has a driven section of 20 mm in inner diam. and 5,000 mm in length. The terminal section of the $\text{CO}_2$ tube is connected with the screen nozzle through a straight tube, and initially separated by insertion of a polyethylene diaphragm, thin enough to break at arrival of the shock wave, in a port of the connection tube (Fig. 2).

![Fig. 2. Test section.](image2)

The screen nozzle is installed within the square cross section (20x80 mm) and the laser cavity is followed with the same cross section downstream of the nozzle exit. The windows for optical observation as well as gain measurement are mounted flush with the side walls of the cavity. In Fig. 3 is shown the schematics of the screen nozzle. Since, in the experiment, the optimization of the nozzle configuration was not aimed, a simple geometry which consists of conical supersonic nozzles was chosen; that is, one row of 6 nozzles for $\text{CO}_2$ sandwiched with two rows of 8 nozzles for $\text{N}_2$. No separation diaphragm was used, because of the small area ratio of throat to cross section 5%; this assured further feasibility of the operation, though a slight loss in flow duration was incurred.

![Fig. 3. Screen nozzle.](image3)

**Operation and Experimental Conditions**

The driver gas was helium, which was charged from 6 up to 20 atm for the tube of a donor gas $\text{N}_2$ and from 5 to 10 atm for the tube of $\text{CO}_2$. Regarding driven pressure, a donor gas $\text{N}_2$ was filled at
a pressure from 20 to 50 Torr, while the CO$_2$ was filled at a pressure from 200 to 400 Torr.

The pressure was measured by means of piezoelectric pressure gauges mounted at appropriate locations close to the end wall (or the front face of screen nozzle). The incident shock speed was recorded on the time counters detecting shock arrival by pressure gauges. In Fig. 4 is shown an example of pressure records, either of which is that for a donor gas just ahead of the front face of screen nozzle or that for CO$_2$ just ahead of the end wall. We can see from this figure that a satisfactory synchronization of two shock tubes is achieved. In fact, the operation was capable of making the difference in arrival times of both incident shock waves less than about 2 $\times$ $3 \times 10^{-2}$ $\mu$s.

Since the flow duration estimated from the pressure history were about 2 msec for a donor gas N$_2$ and about 4 msec for CO$_2$, the achieved synchronization was tolerable for the measurement of any lasing performance. Apparently, this must be further improved if longer driven tubes are available to use.

The stagnation temperatures were estimated from the ideal reflected shock relation using the measured incident shock speeds. The experimental conditions regarding the stagnation pressure and temperature are summarized as follows:

- $2 \text{ atm} < p_b^S < 6 \text{ atm}$, $500^\circ \text{K} < T_b^S < 2400^\circ \text{K}$
- $2 \text{ atm} < p_C^S < 5 \text{ atm}$, $700^\circ \text{K} < T_C^S < 2300^\circ \text{K}$
- $5 \text{ atm} < p_N^S < 10 \text{ atm}$, $1800^\circ \text{K} < T_N^S < 3500^\circ \text{K}$

where $p$ and $T$ are pressure and temperature at stagnation, respectively, and the subscripts N, C, and CH refer to the test gases N$_2$, CO$_2$, and mixture of CO$_2$/He, respectively. It is noted that no dissociation occurs for either CO$_2$ or N$_2$ over this experimental condition.

Measurement of Small Signal Gain Coefficient

The small signal gain $G$ was determined from the intensity increment of the beam which was produced by an electrically pumped CW CO$_2$ laser. The beam homogeneously scattered by reflection upon a diffusive aluminium mirror was set to pass through Ge windows, so that the beam intensity was measured by a dewar-type Hg-Cd-Te photoductive infrared detector. The measurement scheme for small signal gain is illustrated in Fig. 5. Care was taken for protection of the Hg-Cd-Te infrared detector; for example, a shutter was inserted in a beam path to avoid unnecessary exposure of the detector to the continuous beam, and also a Ge transmitter was inserted in front of the detector in order to attenuate the beam intensity.

Since the test time was comparatively short,
the beam intensity prior to the flow start or non-
arrival of the lasing media indicated no appreci-
able change during the test time. Therefore, this 
initial intensity was able to regard as the undis-
turbed beam intensity $I_0$. In Fig. 6 an example of 
the beam signal is shown together with the pressure 
history at the end of the CO$_2$ tube. The flow in a 
cavity is estimated to start after at most a few 
hundreds microseconds from arrival of the incident 
shock wave at the end of the CO$_2$ tube (the initial 
rise of the pressure in Fig. 6). It is noted that 
the maximum of gain is achieved with some delay 
from the flow start. This was also confirmed not 
to be caused by mismatch in operation of the two 
tubes. The gain distributions along the center ax-
is as well as lines normal to the axis were measur-
ed at window locations downstream of the nozzle 
exit.

![Fig. 6. Gain signal and pressure of CO$_2$ tube.](image)

Simple Estimate by Quasi One-Dimensional Analysis 
- for Comparison with Experiment -

So far there have been worked out many investi-
gations on the screen nozzle of a single gas from 
a viewpoint of the application to wind tunnel or 
other fluid machinery. Recently, for gasdynamic 
laser application Russell et al$^{14}$ developed an ela-
borate analysis of the screen nozzle flow, taking 
into account of the viscous effects. Cassady et 
all$^{11}$ extensively applied it to an estimate of the 
laser performance for the mixing GDL using a screen 
nozzle similar to the present one, and showed a 
reasonable agreement of the estimate with their 
experiment. Even in these elaborate analyses, the 
flow behavior in the mixing region is not dealt 
with. This is mainly because the mixing processes 
of viscous flows mismatched in velocity and tempe-
rature are much intricate for the straightforward 
analysis.$^{15}$ In addition, the outgoing disturbances 
from the nozzle exit are also untractable without 
any semi-empirical considerations.

Regarding the mixing GDL flow analysis, more 
simple analysis was done by Soloukhin et al$^9$ for 
the mixing nozzle scheme, in which the secondary 
sonic jet is injected at the throat or from the 
side wall of a primary nozzle flow of a donor gas. 
In their analysis, one of the most simplifying ass-
sumptions is that of an instantaneous mixing. Despite 
such a simple analysis, the estimate was shown to 
be in a reasonable agreement with their own experi-
ment.

In this paper, for the present mixing GDL flow 
we performed a simple analysis of flows, which pro-
vides an estimate of the lasing performance or 
small signal gain. As in Reference 9, the analysis 
is based on the assumption of the quasi one-dimen-
sionality, instantaneous mixing at the nozzle exit 
and negligible viscous effects. Apparently, the 
above assumptions reduce the analysis to a great 
deal of simplification. Regarding a chemical kinet-
ics involved, the vibrational energy relaxation 
processes are followed by the three-mode model, in 
which each mode is in local equilibrium as harmonic 
oscillator, and chemical equilibrium establishes at 
each throat of the screen nozzle.
Once the stagnation condition of each component gas \( N_2 \) or \( CO_2 \) (+ He) and the geometry of nozzles are prescribed, a set of governing equations can be integrated from the throat to the exit, separately for each nozzle. Since the instantaneous mixing just at the nozzle exit is assumed, the flow properties at the nozzle exit after mixing are determined from the algebraic conservation equations, in which all the vibrational temperatures pertinent to each mode are assumed to remain unchanged across the mixing layer. With the flow properties after mixing, thus obtained at the exit, the governing equations are also integrated through the cavity from the exit toward downstream. The estimate of small signal gain obtained by the above analysis will be compared with the present experiment.

Results and Discussion

In Fig. 7 is shown the distribution of small signal gain coefficient \( G \) \((1/m)\), measured at several locations along the center axis from the nozzle exit toward downstream. Two kinds of measurement data are plotted for a fixed stagnation condition of a donor gas \( N_2 \); namely, one is for the case of mixing with pure \( CO_2 \) and the other for the case of mixing with a mixture \( CO_2/He \). For comparison, the estimates, obtained by the simple analysis in the previous section, are also plotted in the same figure. It follows from the figure that the effect of catalyst He is not so appreciable on an achieved maximum gain but the decrease in gain toward downstream is suppressed by addition of the catalyst.

Further, for cases of a mixture \( CO_2/He \), the simple estimate of \( G \) is rather lower than the measured data. This is likely to be mainly due to the fact that, as shown later, the gain \( G \) on the axis takes the maximum in the distribution along a line normal to the axis. It also follows from the figure that the gain distribution of a qualitative behavior is reasonably similar to that from the simple analysis.

For the case of pure \( CO_2 \), however, there appears a great discrepancy of the estimate from the data. As previously mentioned, the present estimate is based upon the neglection of loss due to the viscosity as well as disturbances, along with an ideal mixing. Therefore, the estimate thus obtained must lead an overestimate of the gain. Nevertheless, for the case of pure \( CO_2 \), the data indicate the gain much greater than the estimate. Physical explanation on this discrepancy must remain in future study.

The gain distributions over lines normal to the axis were measured at several stations from the nozzle exit toward downstream. The data are shown in Fig. 8, where \( x \) is measured along the nozzle exit toward downstream and \( y \) normal to it. As ex-

Fig. 7. Gain distribution along center of cavity.

Fig. 8. Gain distributions normal to flow.

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pected, the maximum gains occur on the axis \( y = 0 \) and a steeper profile at the station closer to the nozzle exit becomes plateau toward downstream. The experimental condition for the data shown in Fig. 8 was the same as that shown in Fig. 7. In these measurements, the area ratio of \( \text{CO}_2 \) nozzle was 1.8 with the throat of 3 mm in diam. (see Fig. 3), so that the mole fraction of \( \text{CO}_2 \) was comparatively larger; equivalent mole fraction was \( 56\text{N}_2/44\text{CO}_2 \) or \( 53\text{N}_2/19\text{CO}_2/28\text{He} \), respectively, for pure \( \text{CO}_2 \) or \( \text{CO}_2/\text{He} \) injection.

In order to elucidate the effect of the stagnation conditions on the achieved gain, the gain measurement was conducted at a fixed reference station which is located on the center axis of 97 mm downstream from the nozzle exit, in variation of \( \text{N}_2 \) stagnation condition for a fixed \( \text{CO}_2/\text{He} \) stagnation condition, and vice versa. The results are summarized in Figs. 9 and 10, together with the estimate obtained by the simple analysis previously mentioned. A stagnation condition is specified by a set of temperature and pressure. In variation of stagnation condition of \( \text{N}_2 \) (or \( \text{CO}_2 \)), not only temperature but pressure varied, so that the equivalent mole fraction after the mixing also varied. Thus the equivalent mole fraction \( \psi_N \) of \( \text{N}_2 \) is plotted vs the stagnation temperature \( T^S \). The optimum gain appears to depend sensitively on the \( \text{CO}_2/\text{He} \) stagnation condition than on the \( \text{N}_2 \) stagnation condition, except higher temperature region (\( T^S > 2.5 \times 10^3, T^S_{\text{CH}} > 1.5 \times 10^3 \)). It can also be seen that the present estimate provides a good agreement with the experiment.

Finally, in this experiment an advantage of this type of mixing GDL was confirmed in comparison with a conventional premixed GDL, though the geometry of the nozzle was not necessarily an optimized one. The simple estimate based on the assumptions of quasi one-dimensionality, instantaneous mixing, and neglection of viscosity as well as disturbances is shown to simulate at least qualitative behavior of small signal gain, so far as the catalyst \( \text{He} \) is contained in lasing media \( \text{CO}_2 \). For cases of no catalyst, however there appears a great discrepancy of the simple estimate from the data. Physical explanation on this discrepancy remains in future study.
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