Technical Notes

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Laser Gain Measurements in a Long Noncontoured Hypersonic Nozzle

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Introduction

THE performance of gas dynamic lasers is proportional to the population inversion created by the nonequilibrium expansion of the lasing gas through a nozzle. The population inversion is characterized by the small-signal gain coefficient G_0. Previous studies measured G_0 in constant area ducts located downstream of minimum length contoured nozzles.[1-3] Some of these studies have reported departures from theory at large distances from the nozzle throat ($200h^*$). Such departures have been attributed to viscous effects and weak shock patterns existing in constant area ducts. These observations and the interest in evaluating the nonequilibrium expansion of the CO_2-N_2-He system in a long, noncontoured nozzle motivated this investigation. By measuring the gain during the gas expansion in the supersonic section of the nozzle, the deleterious effects of shock wave patterns on G_0 were avoided. The viscous effects on G_0 were minimized through the use of relatively high characteristic Reynolds numbers Re_0.[4]

A shock tube[1,5,6] is used to provide a reservoir of hot, highly pressurized, vibrationally excited gas for subsequent expansion through the nozzle. A nonequilibrium population inversion is created when this shock-heated[7] gas expands through a double-wedge type nozzle mounted at the end of the shock tube.

Small-signal gain measurements are made at three different locations along the nozzle centerline for different reservoir conditions. Good agreement between experimental data and the analytical model was observed at the two first stations near the nozzle throat. At the station near the exit of the nozzle, the experimental results are below the theoretical curves.

Analytical Models

The nonequilibrium flow model developed by Glowacki and Anderson[8] was used. The model assumes a simplified vibrational kinetic mechanism for CO_2-N_2 and an inviscid one-dimensional flow of a thermally perfect gas in a supersonic nozzle. The original computer code version used H_2O as a catalyst and had to be modified[9] for use with He.

The temperature and pressure of the shock-heated gas is determined analytically[9] by solving Euler's equations in the region between the reflected shock wave and the nozzle throat. The solution of these equations is obtained assuming a choked flow at the nozzle throat and an equilibrium flow up to that location. The incident shock wave velocity and initial driven conditions are experimentally determined. The reservoir pressure is measured in every experiment and compared to the analytical one. The agreement is within 3%.

Experimental Apparatus

The shock tube used[9] is 70 mm in diameter; helium was used as the driver gas at pressures ranging from 5 to 65 atm. The driver tube was separated from the driven tube by a 0.5-mm-thick diaphragm. A commercial mixture of 6.6% CO_2, 54.1% N_2, 39.3% He was used as the test gas. The driven tube pressures were in the 20–60 mm Hg range. At the end of the shock tube, the driven section is separated from the hypersonic nozzle entrance by a scored Mylar diaphragm 0.025 mm thick. The nozzle exhausts into an evacuated (less than 10^{-1} Torr) dump tank in order to shorten the flow establishment time. Two ports in the driven tube, near the nozzle section, are instrumented with quartz piezoelectric pressure transducers. The one closer to the nozzle is used for determining the shock-heated gas pressure. A time interval counter connected to both pressure transducers (31.5 cm apart) measured the incident shock wave transit time. The shock tube was capable of generating reservoir pressures from 2 to 27 atm and reservoir temperatures from 800 to 2700 K. The useful test time was of the order of 300 μs.

A two-dimensional double wedge (sharp throat) nozzle was used to drive the nonequlibrium expansion of the gas mixture. The nozzle area ratio was 53 and the throat height h^* was 1.25 mm. The hypersonic section of the nozzle is 230 mm long; the subsonic portion is 3 mm long to improve the freezing of the CO_2-N_2 upper level. The stainless steel nozzle walls have a very good surface finishing to minimize flow disturbances. To permit G_0 measurements, the nozzle has three pairs of ports (35 mm in diameter) centered at 72, 130, and 187 mm downstream from the throat (Fig. 1). To minimize flow disturbances, the antireflection coated Ge windows are flush with the inner sidewall surfaces.

The gain coefficient was determined by measuring the increase in power of the probe beam between no flow and flow. The diagnostic laser is provided by a homemade CO_2 CW gas laser operating at 10.6 μm predominantly on the P(20) transition. The intensity was 0.1 W/cm^2, which is below the saturation intensity of the medium (1.0 kW/cm^2). The beam is mechanically chopped and then injected into the nozzle flow. After passing through the nozzle, the probe beam is diffused by reflection from a rough-surfaced aluminum plate to ensure coverge of the active area (1 mm^2) of the N_{2l} cooled HgCdTe detector. Both the infrared detector and the pressure signals are recorded by a digital oscilloscope. Then G_0 is determined from the expression $G_0 = (1/L)\ln I_{after}/I_{before}$, where L is 70 mm (nozzle width), and I_{before} and I_{after} are, respectively, the measured diagnostic laser beam intensities before and after crossing the active medium.

Presented as Paper 90-1511 at the AIAA 21st Fluid Dynamics, Plasma Dynamics and Lasers Conference, Seattle, WA, June 18–20, 1990; received July 19, 1990; revision received Oct. 2, 1990; accepted for publication Oct. 4, 1990. Copyright © 1990 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved.

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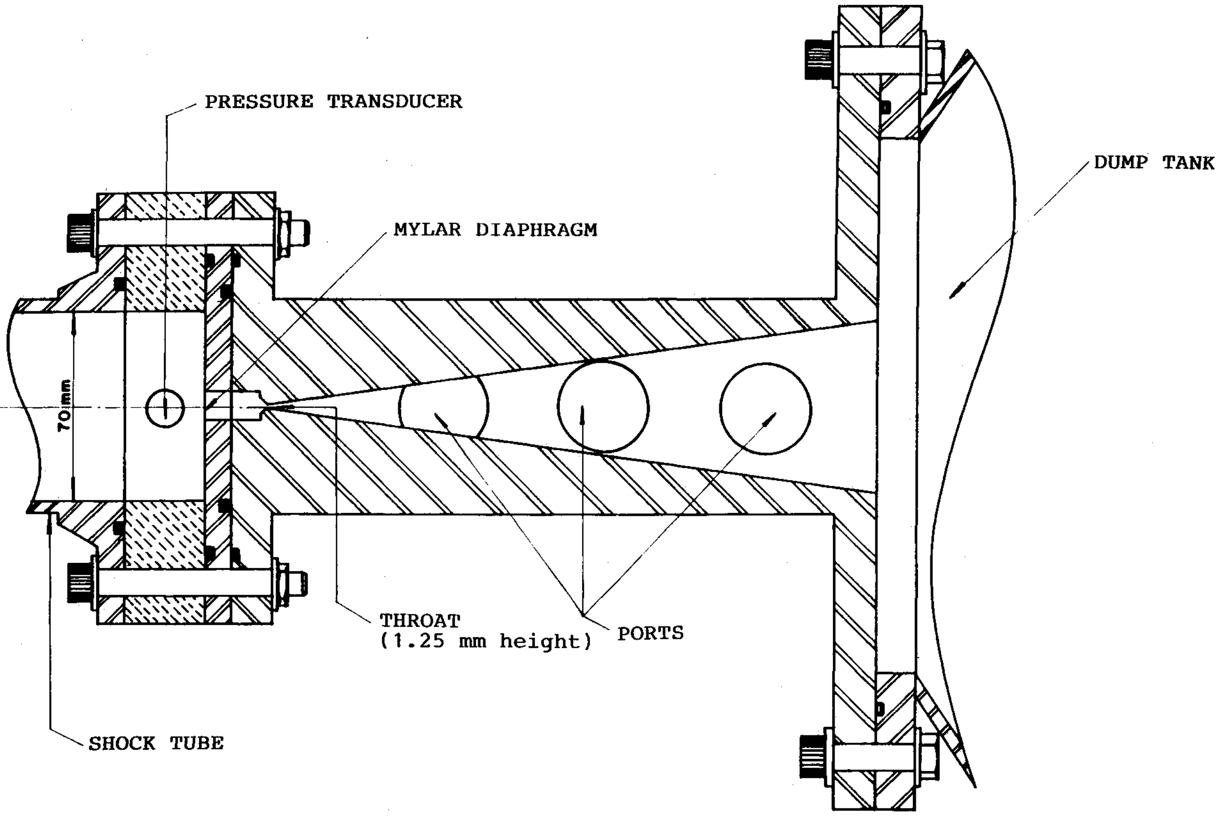

Fig. 1 Double-wedge nozzle and cavity arrangement.

Table 1 Test conditions and important parameters

Test no.	p_0, atm	T_0, K	p_0h^*, atm-cm	$Re_0 \times 10^5$	$G_{0,m}$, (m^{-1})
1	12.0	2000	1.50	0.7	0.91
2	13.5	1445	1.69	1.1	0.78
3	7.0	1500	0.88	0.6	0.88
4	23.0	1620	2.88	1.7	0.89
5	10.0	1820	1.25	0.6	0.94
6	11.0	1000	1.34	1.4	0.38

Results

Table 1 lists the reservoir pressure and temperature p_0 and T_0, the binary scale parameter p_0h^*, the characteristic Reynolds number[4] Re_0, and the measured peak gain values $G_{0,m}$.

According to Mitra and Fiebig,[4] the viscous losses on the small-signal gain are negligible when Re_0 is of the order of 10^5. From Table 1 it is seen that, for all of the test conditions, the characteristic Reynolds number is of the order of 10^5. Furthermore, due to the short duration of the flow, the cold wall assumption is valid. Such facts lead to the existence of very thin boundary layers. Under these circumstances, the viscous effects are highly attenuated. Another important observation is that the nozzle flow is shock-free. The reasons are 1) the continuous expansion of the gas in the double wedge type nozzle and 2) the back pressure in the dump tank being many times smaller than the nozzle exit pressure.

The measured small-signal gain profiles along the nozzle centerline and the computed values are shown in Figs. 2 and 3 for the conditions listed in Table 1. These figures show that the largest departures between theory and experiment occur far downstream from the nozzle throat. The best agreement in that region occurred when the lowest reservoir temperature (1000 K) was used (Fig. 3). For this case, the theory shows a decrease in the gain at points located far downstream from the nozzle throat. Such a trend is not observed in the other cases

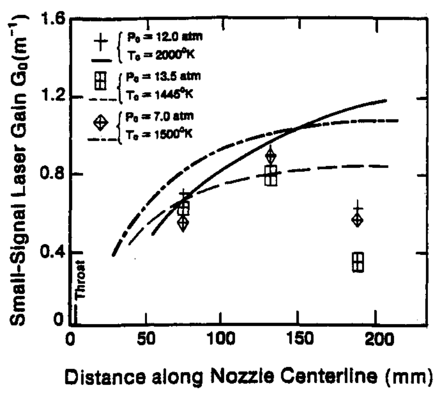

Fig. 2 Comparison between theoretical (lines) and experimental (points) small-signal laser gain profiles.

where higher temperatures were used. Since viscous and shock effects on the small-signal gain can be neglected in this experiment, they cannot be responsible for the drop of the experimental data below the theoretical prediction. A possible explanation is that a deactivation rate of the CO_2 (001) level is higher than that used in the analytical model. If this is the case, the discrepancies between theory and experiment in constant area duct G_0 measurements may not only be caused by flow disturbances but also by higher deactivation rates. As noted by Anderson,[1] the uncertainties in the kinetic rates can strongly affect the prediction of the small-signal gain.

Figures 2 and 3 show peak gains as high as $0.9\ m^{-1}$. Such values are comparable to those obtained by other authors, e.g., Anderson,[1,3] using minimum length contoured nozzles. Although these results are somewhat interesting, they are no surprise, since the theoretical model proposed by Anderson was quite capable of predicting the high gains throughout the nozzle. The only problem was the overestimation of the gain near the nozzle exit. To extend these results, a laser power extraction experiment[10] is being carried out by the authors.

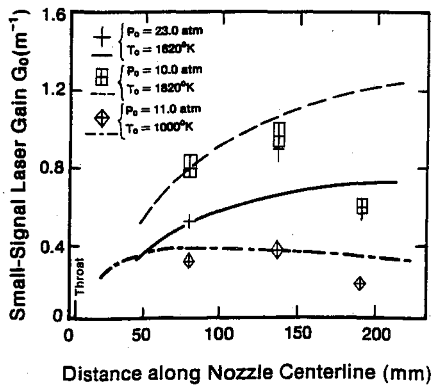

Fig. 3 Comparison between theoretical (lines) and experimental (points) small-signal laser gain profiles.

Conclusions

Small-signal gain measurements were conducted in a shock tube driven nonequilibrium expansion of a gas mixture containing 6.6% CO_2, 54.1% N_2, and 39.3% He at different reservoir conditions. The gain measurements were made at three locations downstream from the nozzle throat of a long double-wedge type hypersonic nozzle. The experimental results were compared with computer code predictions. The main results of this investigation are as follows:

1) Good agreement between the experimental data and the analytical predictions for the small-signal gain was obtained at the two stations closer to the nozzle throat.

2) Poor agreement between the experimental data and theoretical predictions for gain occurred at the station near the nozzle exit. At that location, the analytical model overestimates the actual gain. A possible reason could be the underestimation of the deactivation rate used by the theory.

3) Small-signal gain peaks of 0.9 m^{-1}, comparable with those obtained in minimum length contoured nozzles, were measured.

Acknowledgments

The authors wish to express their appreciation to the Brazilian Air Force for funding the present work. Particularly to Air Force Colonel Reginaldo dos Santos, director of the Instituto de Estudos Avançados, for his support and encouragement throughout this project. Thanks also to Sylvio Fish de Miranda for his valuable help at the laboratory during the tests. Acknowledgment is also due to Henry T. Nagamatsu and Leik N. Myrabo, from Rensselaer Polytechnic Institute, for their extremely useful advice and suggestions during the review of this work.

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Derivation and Testing of a One-Equation Model Based on Two Time Scales

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Introduction

TURBULENCE measurements indicate that large-scale energy generating eddies possess a development rate substantially different from that of small-scale dissipative eddies. This suggests using a model that treats these eddies separately, assigning each range its own time scale. In the present work, a one-equation model is developed wherein the velocity scale is determined from the solution of an equation for the turbulence kinetic energy and the length scale is found indirectly from two time scales assigned each to large and small eddies. The derivation of this model leads to an expression for the near-wall function f_μ used in low Reynolds number versions of the k-ϵ model. A backflow model[1] is applied in conjunction with the one-equation model for the treatment of detached flow regions. Several flow cases are calculated to test the performance of this turbulence model.

Model Formulation

To account separately for the large (energy producing) eddies and the small (dissipative) eddies, characteristic time scales are assigned to each. Thus, the large eddies are characterized by

$$t_k \sim k/\epsilon \tag{1}$$

where k is the kinetic energy of the turbulence $k = ½\overline{u_i'u_i'}$, and ϵ is the dissipation rate of k.

The small eddies are characterized by the Kolmogorov scale

$$t_\epsilon \sim \sqrt{\nu/\epsilon} \tag{2}$$

where ν is the kinematic molecular viscosity.

To determine these time scales, k and ϵ must be known throughout the flowfield. In the present work k is determined from the solution of a partially modeled version of the exact equation for turbulence kinetic energy

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho U_i k) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_i}\right] - \rho\overline{u_i'u_j'}\frac{\partial U_i}{\partial x_j} - C_k\frac{(\rho k)^2}{\mu_t} \tag{3}$$

Received Aug. 15, 1990; revision received Sept. 10, 1990; accepted for publication Sept. 18, 1990.

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