Technical Notes

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Laser-Induced I_2 Fluorescence Measurements in a Chemical Laser Flowfield

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Introduction

SINCE the advent of cw flowing chemical lasers, a persistent problem has been the difficulty of understanding the mixing phenomena in the fluid-dynamic flowfields. Indeed, efficiencies of cw chemical lasers are controlled in great part by mixing.[1] Excellent review articles[2,3] have appeared in which the problems and progress associated with understanding of the fluid-dynamic mixing process have been presented.

There has been a considerable amount of effort in recent years developing new nonintrusive techniques and also applying well-established techniques to interrogate the flowfields in chemical lasers. Some of the methods which have been applied are chemiluminescence and Schlieren photography,[4] coherent anti-Stokes Raman scattering (CARS),[5,6] laser doppler velocimetry (LDV),[7,8] and index of refraction studies.[9] All of these techniques have been used to probe the flowfields in order that phenomena such as density gradients and particle velocity resulting from the various mixing processes might be understood. One usually attempts to use the data obtained to construct a map of the flowfield in the laser and better understand the mixing process.

While extremely useful, all of these techniques have some inherent problems and difficulties. Chemiluminescence and Schlieren photographs, while yielding visual information of the flowfields, suffer from a lack of spatial resolution. CARS and LDV methods are spatially very sensitive and excellent resolution is possible. However, both of these methods require extremely expensive and sophisticated equipment. Even index of refraction experiments require the use of interferometric techniques.

The recent introduction of laser induced fluorescence (LIF)[10-12] as a diagnostic has opened up a new field for nonintrusive flowfield diagnostics. Daily and Chan[10] reported results of Na LIF in flames in 1977. More recently, Wrobel and Pratt[11] described some LIF experiments in a turbulent propane flame. NaCl crystals were seeded into the flame and a tunable dye laser excited the Na vapor which subsequently fluoresced at ~ 5900 Å and data on the flow were obtained. Levy et al.[12] used LIF to look at molecular structure in supersonic jets at extremely low temperatures. In their experiment, NO_2 and I_2 were seeded into a helium jet and a laser induced fluorescence was observed as the gas was expanded to near 0 K.

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In this paper, we describe a similar LIF experiment performed in the flowfield of a 1-kW supersonic chemical laser. Molecular iodine vapor was injected into the cavity and caused to fluoresce by argon ion (Ar^+) laser excitation.

Experiment

A schematic of the experimental arrangement is shown in Fig. 1. A 2-liter stainless steel vessel, 25% filled with I_2 crystals, was connected directly to the secondary He feed supply of a CL-II nozzle. (A detailed description of the CL-II nozzle is shown in Fig. 2.) The I_2 was not heated and number density of I_2 in the cavity was estimated to be ~ 1 m Torr.

The laser cavity was modified with viewing windows on top of the cavity so that the nozzle array and flowfield could be observed perpendicular to the optical axis. Also, for one run, the turning mirror M_2 was replaced with a dichroic mirror to allow viewing along the optical axis of the chemical laser.

The probe laser was a Spectra-Physics Model 170-03 argon-ion laser equipped with an intracavity etalon. Although not essential, the etalon increases the sensitivity of the technique by enhancing the I_2 fluorescence.

There is a fortuitous match between strong I_2 absorption and the 5145 Å line of the Ar^+ laser. This absorption is from the $v''=0$ level of the $X^1\Sigma$ state to the $v'=43$ level of the $B^3\Pi o$ state. In a typical run, the Ar^+ laser was properly

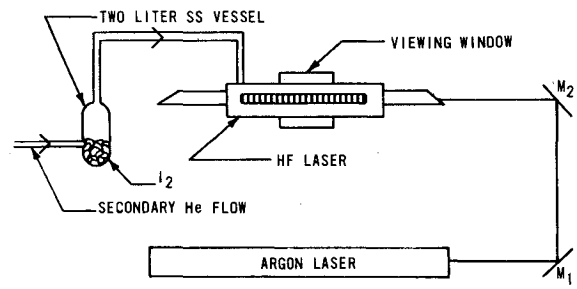

Fig. 1 Schematic of the experimental arrangement.

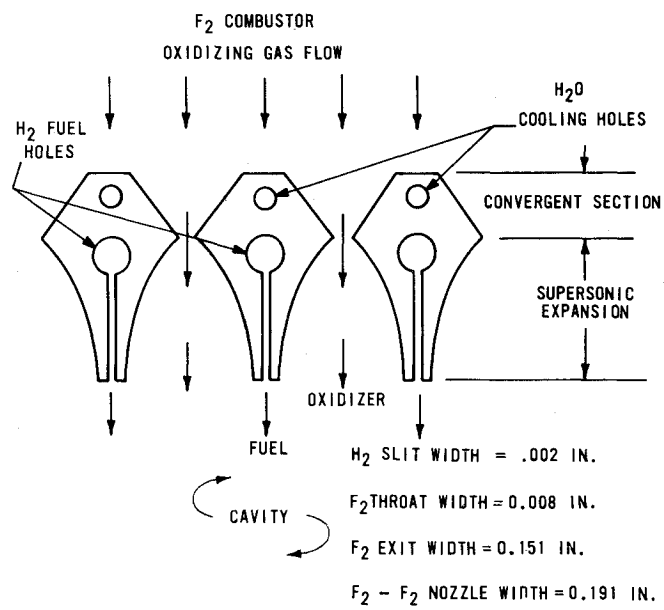

Fig. 2 Detailed description of the CL-II nozzle.

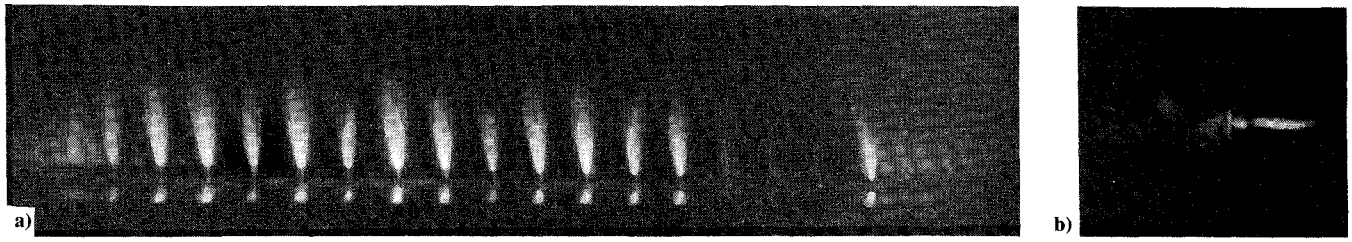

Fig. 3 Visible fluorescence from I_2 $(B-X)$ as viewed a) perpendicular to the optical axis and b) along the optical axis.

tuned by maximizing the fluorescence in a sealed glass cell containing I_2 vapor. The laser was stable enough that further tuning was not required.

The Ar^+ beam was directed into the chemical laser cavity along the optical axis by a focusing optical train. The spot size in the cavity was a fraction of a millimeter, although tighter focusing could have been done, thus increasing the spatial resolution. The Ar^+ beam could be translated into two dimensions, up and down the nozzle face, at a single position in the flow direction, and also downstream from the nozzle face. Hence, the flowfield could be visually mapped out with high spatial resolution.

A convenient feature of the $B^3\Pi o$ state of I_2 is that the lifetime of the $v'=43$ and nearby v' levels are on the order of a few microseconds. (The originally excited v' level will be somewhat relaxed to other v' levels by collisions before emission.) A lifetime of a few microseconds is nearly ideal to use as a tracer in the supersonic flowfields in which velocities of 10^5 cm/s are typical. This means that the fluorescing I_2 would "light up" a region downstream of the excitation point of ~ 1 cm. It is important to note that the region of excitation is defined by the spot size of the laser which is variable as described earlier.

He gas with the I_2 vapor was injected into the flowfield through the secondary nozzles. The Ar^+ laser beam was positioned in the flowfield and photographs were taken. The majority of photographs were taken with the laser operating in the cold-flow condition in which no F_2 was added in the combustor. Hot-flow conditions were imitated using N_2 and He gases. Some tests were performed using actual hot-flow runs. In these runs, the I_2 fluorescence was essentially absent because the I_2 was rapidly reacted away via the reaction $F+I_2 \rightarrow IF+F$. There was some evidence of additional visible LIF, possibly $IF(B-X)$, but this warrants further investigation for confirmation. This will be discussed in a subsequent paper.

Results and Discussions

Typical results of our effort are summarized in Fig. 3. The right portion of this photograph shows the visible fluorescence from I_2 $(B-X)$ as viewed perpendicular to the optical axis through the top of the cavity. The left portion of the picture emphasizes the extremely narrow region (slit) that is fluorescing in the optical axis direction. The left picture was obtained by means of looking through the dichrocic mirror (M_2) down the optical axis of the chemical laser, collinear to the Ar^+ beam. The fluorescence downstream from the Ar^+ beam is observed to be well defined and remains approximately the width of the Ar^+ beam. In all of these photographs, the Ar^+ laser excited a region at the nozzle exit plane.

The first remark one can make about photograph 3a is that of flow nonuniformity. This particular nozzle bank has a severe nonuniformity problem and actually some of the secondary nozzles are not flowing. Figure 3 was obtained with the Ar^+ laser intersecting the nozzle plane one-half way up in the vertical direction. By redirecting the beam higher in the cavity, the clogged nozzles were observed to flow much better. This demonstrated the high degree of spatial resolution since the nozzle was shown to have severe nonuniformities in flow over small dimensions, <1.5 mm, in the vertical direction. By directing the Ar^+ beam up and down in the vertical direction and in the downstream direction, the entire flowfield was mapped out. The nonuniformities of the flowfield caused by the nozzle seen at the nozzle plane in Fig. 3 continued far downstream, ~ 5 cm, and the gradients in the vertical direction seen at the nozzle plane also persisted.

Chemiluminescence photographs of the flowfield taken perpendicular to the optic axis indicated no such nonuniformities, because any such photos only give spatially integrated particle density data. Consequently, vertical density gradients caused by the nozzle are completely washed out. The amount of iodine actually injected into the flowfield is only a small fraction of the He carrier gas. Thus, potential mixing problems caused by the massive I_2 injection are minimized. Visual examination of the fluorescence indicated no changes in the flow structure as the I_2 flow was reduced to zero; the only change was that the entire fluorescence intensity became weaker.

Table 1 Potential seeding candidates for study of hot flows in chemical lasers[a]

Seed molecule	Emitter	λ pump, Å	λ fluorescence, Å
Popop dye vapor	Popop	3371 (N_2 laser)	3930
SiH_4	SiF	4240 (dye laser)	4400
H_2S	S_2	3000 (dye laser)	4500-5000
I_2	IF	4965 (Ar laser)	5000-7000
		4780 (dye laser)	5000-7000

[a] The type of pump laser and some pump wavelengths are shown as well as expected fluorescence wavelengths.

Conclusions

These results demonstrate that LIF can be applied successfully to study mixing zones in chemical laser cavities. Nozzle performance can be evaluated quickly and accurately. It is important to note that LIFS is not specific to iodine. Other species which can be made to fluoresce, such as sodium vapor, could be injected instead of I_2. Then, by use of a dye laser, visual fluorescence could be seen. By using several different species of different mass, one could study the mixing process with high accuracy and resolution. A list of possible species that could be injected into adjacent nozzles is given in Table 1. The mixing phenomena could be studied in color. One of the least understood mixing methods used in cw chemical lasers is that of trip jets. These are jets of secondary gas injected into the primary and secondary nozzles near the nozzle exit plane and are used to enhance the mixing process. A fluorescent species seeded into the trip jets could be used to better understand to what extent this process enhances mixing. By using black and white photography and a microdensitometer relative density gradient data with high resolution can also be gained. The spatial resolution of this technique is limited only by the spot size of the Ar^+ laser, which can be focused to diameters of a few microns.

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Transonic Shock/Boundary-Layer Interaction Subject to Large Pressure Fluctuations

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Nomenclature

c	= chord length
c_p	= pressure coefficient $p-p_1/\frac{1}{2}\rho_1 U_1^2$
c_p^*	= pressure coefficient at $M=1$
f	= frequency, Hz
$F(n)$	= contribution to $\tilde{p}^2/q^2$ in frequency band Δn
$\sqrt{n(F(\ ))}$	$=p/q(\epsilon)^{1/2}$
M	= Mach number
n	= frequency parameter fw/U_1
p	= pressure
q	= freestream dynamic pressure $\frac{1}{2}\rho U_1^2$
R_θ	= momentum thickness Reynolds number $U_1\theta/\nu$
U_1	= freestream velocity
u	= local velocity
w	= tunnel width
X_s	= shock position
θ	= boundary-layer momentum thickness $= \int_0^\infty \rho u/\rho_1 U_1 (1-\rho u/\rho_1 U_1)\,dy$
ϵ	= analyzer bandwidth ratio $\Delta f/f$
ν	= kinematic viscosity

Superscript

$(\tilde{\ })$	= root-mean-square value

Subscript

1	= freestream conditions

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Introduction

A RECENT Note[1] showed that for attached subsonic and transonic boundary layers with small pressure gradients the turbulence within the boundary layer is influenced by the external pressure fluctuations, but that the corresponding changes in the mean properties of the boundary layer are fairly small. The influence of pressure fluctuations on a boundary layer with a shock interaction, however, is not understood. Robertson's experiments on a missile body[2] showed strong effects of pressure fluctuations on the shock/boundary-layer interaction. The shock wave oscillations were strongly correlated with the freestream pressure fluctuations. The levels of pressure fluctuations in the tunnel during the tests were within the range $\tilde{p}/q = 0.7$-1.2%. The work of Ross and Rohne[3] on a supercritical airfoil with smaller freestream noise levels ($\tilde{p}/q = 0.35$-0.6%) showed no effect of pressure fluctuations on the shock separation and trailing-edge pressure coefficient. However, even these low-noise levels changed the boundary-layer transition. This Note presents some information obtained on a transonic shock/turbulent boundary-layer interaction subject to pressure fluctuations from 0.6% to 1.5%.

Tests

The tests were made in the 101×101 mm transonic tunnel at The Queen's University of Belfast. The model was a half-double wedge-shaped airfoil of 9% thickness with an aspect ratio of 1, giving a blockage of 9.0% set on the tunnel roof. The R_θ of the turbulent boundary layer at the leading edge of the model was about 10^4. Pressure fluctuations were varied by changing the number of slots in the floor of the tunnel and partially or fully closing the slots with perforated screens without significantly changing the mean pressure distribution in the tunnel in the presence of the model.

The freestream pressure p_1 was measured two chords upstream of the model. An adjustable choke downstream of the test section was used to set any desired freestream Mach number. Measurements were made of pressure distribution on the model for several shock strengths and, for a fixed shock position, of the boundary-layer mean and turbulence velocity profiles at the trailing edge. The boundary-layer separation and reattachment points were established by the china clay technique.

Results

Figure 1 shows typical spectra at $M=0.78$ of the pressure fluctuations for the three test conditions. The peak value of $\sqrt{nF(n)}$ vary from 0.6×10^{-2} to 1.8×10^{-2}. These values of $\sqrt{nF(n)}$ are, respectively, typical of pressure fluctuation levels that exist in rather noisy and very noisy ventilated