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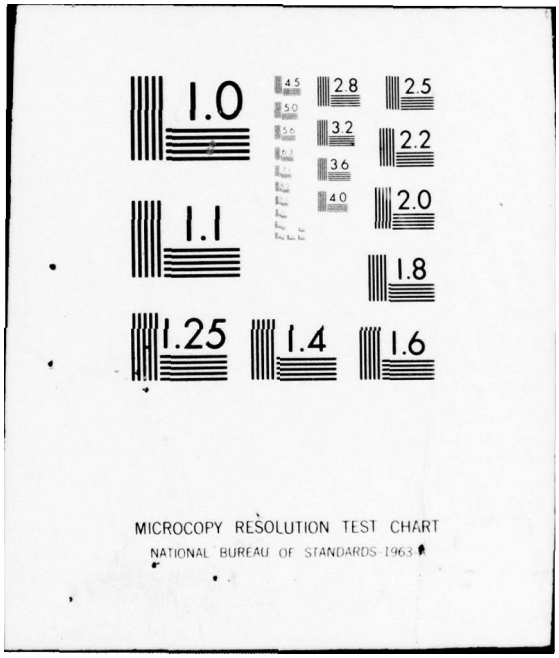
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Boundary Layer Effects in Chemical Laser Nozzle Inlet

Aerophysics Laboratory
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8 November 1977

Interim Report

APPROVED FOR PUBLIC RELEASE:
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Prepared for

NAVAL RESEARCH LABORATORY
Washington, D. C. 20390

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This interim report was submitted by The Aerospace Corporation, El Segundo, CA 90245, under Contract No. F04701-77-C-0078 with the Space and Missile Systems Organization, Deputy for Advanced Space Programs, P.O. Box 92960, Worldway Postal Center, Los Angeles, CA 90009. It was reviewed and approved for The Aerospace Corporation by W. R. Warren, Jr., Director, Aerophysics Laboratory. Lieutenant Dara Batki, SAMSO/YCPT, was the project officer for Advanced Space Programs.

This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: SAMSO-TR-77-212	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): BOUNDARY LAYER EFFECTS IN CHEMICAL LASER NOZZLE INLET	5. TYPE OF REPORT & PERIOD COVERED: Interim rept.
6. PERFORMING ORG. REPORT NUMBER: TR-0078(3725)-1	
7. AUTHOR(s): Harold Mirels and Shaowen W. Liu	8. CONTRACT OR GRANT NUMBER(s): F04701-77-C-0078
9. PERFORMING ORGANIZATION NAME AND ADDRESS: The Aerospace Corporation, El Segundo, Calif. 90245	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS: Naval Research Laboratory, Washington, D.C. 20390	12. REPORT DATE: 8 November 1977
	13. NUMBER OF PAGES: 27 (12) 31p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): Space and Missile Systems Organization, Air Force Systems Command, Los Angeles Air Force Station, P.O. Box 92960, Worldway Postal Center, Los Angeles, California 90009	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

CW Chemical Laser
Reacting Flows
Nozzle Wall Boundary Layer
Fluorine Atom Surface Recombination

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Fluorine atom recombination and heat loss to the wall are investigated in the inlet and supersonic expansion region of typical CW chemical laser nozzles. It is concluded that the major losses occur in the inlet section. Expressions given for estimating these losses are based on zero pressure gradient flows with unit Prandtl and Schmidt numbers. For typical geometries, a plenum temperature $T_o = 1500^\circ K$, and plenum pressures in the range $1 \leq p_o$, atm ≤ 10, the reduction of total enthalpy at the downstream end of the inlet section varied

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19. KEY WORDS (Continued)

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from about 10% to 30%. The reduction within the actual boundary layer mass flow is approximately 40% for a boundary layer thickness defined such that $u/u_e = 0.9$, where u and u_e denote local and free-stream velocities, respectively. It is concluded that these losses should be considered when CW chemical laser performance is being estimated or analyzed.

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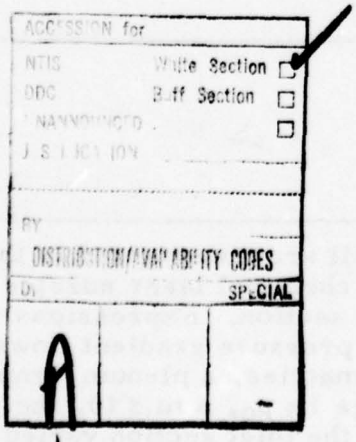

CONTENTS

FIGURES

INTRODUCTION

A typical CW HF(DF) chemical laser nozzle is illustrated in Fig. 1. Typical dimensions and flow conditions, based on the data of Wilson and Hook,[1] are as follows:

$h = 0.1$ cm	$w_t = 0.005$ cm
$L_{ex} = 0.3$ cm	$T_o = 1500°K$
$L_i = 0.5$ cm	$p_o = 10$ atm
$w_{ex} = 0.08$ cm	$M_{ex} = 6$
$w_i = 0.05$ cm	$p_{ex} = 10$ Torr

Studies of the chemical laser diffusion/reaction region,[2] under diffusion limited operation, have indicated that chemical efficiency of these lasers is inversely proportional to $(pw)_{ex}$, where p_{ex} and w_{ex} are the static pressure and semichannel width at the exit of the oxidizer nozzle, respectively. It is of interest, therefore, to reduce nozzle lateral scale in order to improve laser efficiency, particularly at high-pressure operation. However, the reduction of nozzle lateral scale, without a corresponding decrease in axial scale (for structural reasons), increases wall boundary layer effects. In particular, the effects of surface recombination of F atoms, shear, and heat transfer on nozzle exit flow profiles are enhanced.

Recombination effects in chemical laser nozzles were studied by Ferrell, Kendall, and Tong.[3] Numerical integration was used to investigate several nozzle configurations for a fixed set of initial flow conditions. It was concluded that most of the recombination occurred at and upstream of the throat,

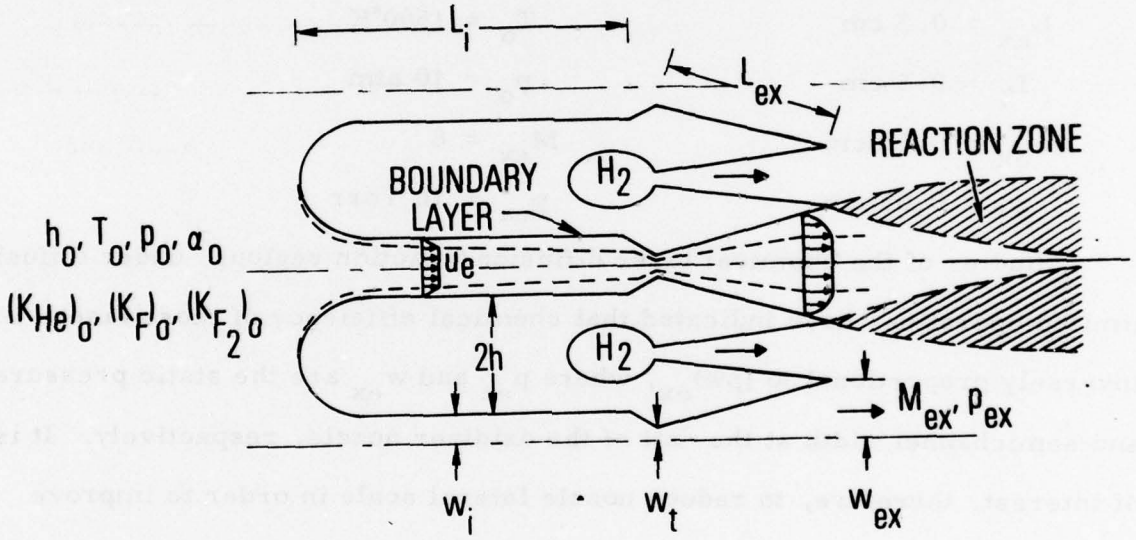

Fig. 1. CW Chemical Laser Nozzle Geometry and Flow

as would be expected from physical (i.e., unit Reynolds number) considerations. A 20% reduction in initial dissociation level was deduced for a baseline case.

The purpose of the present study is to provide simple analytic expressions for estimating fluorine recombination and other boundary layer properties in the inlet region of a chemical laser nozzle. The inlet region is idealized as having a uniform cross-sectional area and a sharp leading edge (Fig. 2). The analytic estimates for inlet boundary layer development are based on zero pressure gradient results for flows with unit Prandtl and Schmidt numbers and a linear viscosity-temperature relationship.[4] The nozzle surface is assumed to be fully catalytic, as discussed in Appendix A, and gas phase recombination is neglected. Boundary layer effects in the supersonic expansion region of the nozzle are estimated in Appendix B and are compared with the corresponding effects in the inlet region.

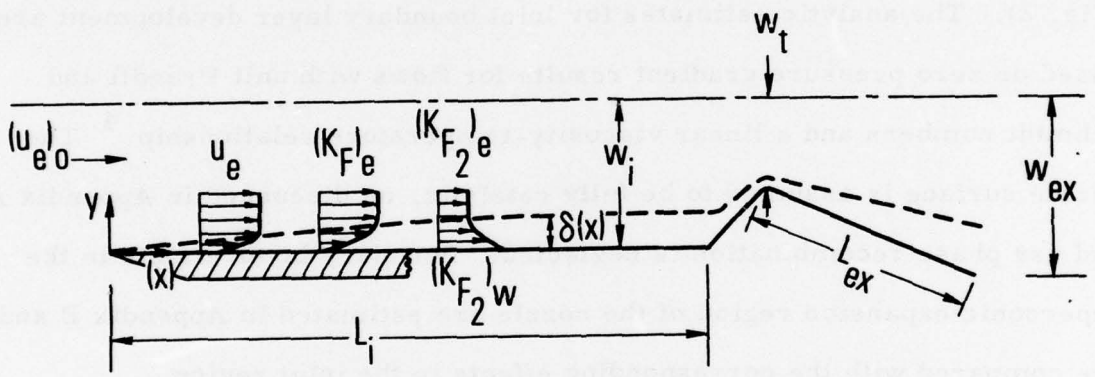

Fig. 2. Idealized Model of CW Chemical Laser Nozzle

ANALYSIS

Integral properties of the boundary layer in the idealized inlet of Fig. 2 are first noted. Analytical estimates for these properties are then presented.

INTEGRAL PROPERTIES

It is assumed that the thickness of the boundary layer δ is smaller than the semichannel width w_i. The mass, momentum, enthalpy, and fluorine atom defect thickness at each station x are defined, respectively, by

$$\delta^* = \int_o^\delta \left(1 - \frac{\rho u}{\rho_e u_e}\right) dy \tag{1a}$$

$$\theta = \int_o^\delta \frac{\rho u}{\rho_e u_e}\left(1 - \frac{u}{u_e}\right) dy \tag{1b}$$

$$\delta_E = \int_o^\delta \frac{\rho u}{\rho_e u_e}\left(1 - \frac{h}{h_e}\right) dy \tag{1c}$$

$$\delta_F = \int_o^\delta \frac{\rho u}{\rho_e u_e}\left[1 - \frac{K_F}{(K_F)_e}\right] dy \tag{1d}$$

where $h \equiv C_p T + u^2/2$ is the local total enthalpy and ρ, u, T, K_F denote mass density, velocity, temperature, and fluorine atom mass fraction. Subscript e denotes local properties external to the boundary layer.

With $\delta < w_i$, the upper limit of the above integrals can be replaced by w_i. Let subscript e, o denote local free-stream properties at x = o and subscript o denote plenum (stagnation) conditions (Fig. 1). Mass continuity indicates

$$\frac{(\rho u)_{e,o}}{(\rho u)_e} = 1 - \frac{\delta^*}{w_i} \tag{2}$$

The mass fraction of atomic fluorine, K_F, is assumed to remain constant (frozen) in the region external to the boundary layer. Thus

$$\alpha_o = \left(\frac{K_F}{K_F + K_{F_2}}\right)_o = \left(\frac{K_F}{K_F + K_{F_2}}\right)_e \tag{3}$$

where α_o denotes the dissociation level in the plenum. Let $\bar{\alpha}$ denote the average dissociation level (on a mass flux basis) at each station x, namely

$$\bar{\alpha} \equiv \int_o^{w_i} \rho u K_F \, dy / \{[\rho u (K_F + K_{F_2})]_{e,o} w_i\} \tag{4}$$

and let $\Delta\alpha \equiv \alpha_o - \bar{\alpha}$ denote the departure of $\bar{\alpha}$ from the initial value α_o. Note that Eqs. (1a) and (1d) can be written as

$$\delta^* = w_i - \int_o^{w_i} \frac{\rho u}{\rho_e u_e} dy$$

$$\delta_F = w_i - \delta^* - \int_o^{w_i} [(\rho u K_F)/(\rho u K_F)_e] dy$$

If follows from Eqs. (2) through (4) that

$$\frac{\Delta\alpha}{\alpha_o} = 1 - \frac{(\rho u\, K_F)_e}{(\rho u\, K_F)_{e,o}} \frac{\int_o^{w_i} \rho u\, K_F\, dy}{w_i\, (\rho u\, K_F)_e}$$

$$= 1 - \frac{w_i - \delta^* - \delta_F}{w_i - \delta^*} = \frac{\delta_F}{w_i - \delta^*} \qquad (5a)$$

If $\bar{\alpha}_{BL}$ represents the average dissociation level in the boundary layer

$$\bar{\alpha}_{BL} \equiv \int_o^{\delta} \rho u\, K_F\, dy / [(K_F + K_{F_2})_{e,o} \int_o^{\delta} \rho u\, dy]$$

and $\Delta\alpha_{BL} \equiv \alpha_o - \bar{\alpha}_{BL}$ represents the departure of the boundary layer dissociation level from the initial value, it follows that

$$\frac{\Delta\alpha_{BL}}{\alpha_o} = \frac{\delta_F}{\delta - \delta^*} \qquad (5b)$$

A suitable choice for δ is discussed later [i.e., Eq. (10c)]. Similarly, if $\bar{h}$ denotes the average value of h at any station and $\bar{h}_{BL}$ denotes the average value of h in the boundary layer, then, noting $h_e = h_o$, we obtain

$$\frac{\Delta h}{h_o} \equiv \frac{\bar{h}}{h_o} - 1 = \frac{\delta E}{w_i - \delta^*} \tag{6a}$$

$$\frac{\Delta h_{BL}}{h_o} \equiv \frac{\bar{h}_{BL}}{h_o} - 1 = \frac{\delta E}{\delta - \delta^*} \tag{6b}$$

The ratio of the mass flow in the boundary layer $\dot{m}_{BL}$ to the total mass flow m is

$$\frac{\dot{m}_{BL}}{\dot{m}} \equiv \frac{\int_o^\delta \rho u \, dy}{(\rho u)_{e,o} w_i} = \frac{\delta - \delta^*}{w_i - \delta^*} \tag{7}$$

Finally, the net heat transfer to the walls of each semichannel, up to station x, is denoted Q and can be expressed

$$Q = \int_o^x (-q_w) dx \tag{8a}$$

where

$$-q_w = \left(\frac{k}{C_p} \frac{\partial h}{\partial y} + \rho \mathcal{D} \Delta H \frac{\partial K_F}{\partial y} \right)_w \tag{8b}$$

Here, the first term on the right side of Eq. (8b) denotes the local heat transfer to the wall by thermal conduction; the second term denotes the local rate of energy addition due to diffusion of F atoms to the wall. The latter recombine at the wall and liberate energy in the amount of ΔH per unit mass of F atoms. Direct integration of the conservation equations yields the relations between the integrals, as defined in Eq. (1), and their respective surface fluxes. In particular

$$\frac{d\delta_E}{dx} = \frac{1}{\rho_e u_e h_o} \left(\frac{k}{C_p} \frac{\partial h}{\partial y} \right)_w \tag{8c}$$

$$\frac{d\delta_F}{dx} = \frac{1}{\rho_e u_e (K_F)_e} \left(\rho \mathcal{D} \frac{\partial K_F}{\partial y} \right)_w \tag{8d}$$

which result in the following expression for the net energy flux to the walls, up to station x

$$\frac{Q}{w_i h_o (\rho u)_e} = \frac{\delta_E}{w_i} + \frac{(K_F)_e \Delta H}{h_o} \frac{\delta_F}{w_i} \tag{8e}$$

where $\Delta H = 1.66$ kcal/g_F and $h_o = 1.24 \times 10^{-3}\ T_o$ kcal/g for a plenum gas that is primarily helium.

FLAT PLATE ESTIMATES

In general, numerical solutions of the boundary layer equations are needed in order to determine local values of δ, δ^*, δ_F, δ_E, and θ. Existing flat plate solutions can be used, however, if it is assumed that the Prandtl number ($Pr = \mu C_p/k$) and Schmidt number ($Sc = \mu/\rho\mathcal{D}$) equal 1, that the pressure gradient is negligible (i.e., $\delta^*/w_i \ll 1$), that wall species concentrations and wall temperature are constant, and that there is no gas phase recombination. It follows that normalized velocity, total enthalpy, and species distributions are identical. [For example, see Dorrance, Eqs. (2-103) and (2-104),[5] or Hayes and Probstein, Eqs. (8.3.3) and (8.3.4).[6]] Thus

$$\frac{u}{u_e} = \frac{h - h_w}{h_o - h_w} \simeq \frac{K_i - K_{i,w}}{K_{i,e} - K_{i,w}} \tag{9a}$$

where K_i denotes the mass fraction of species i and subscript w denotes wall conditions. It also follows that (note that $h_w/h_o = T_w/T_o$)

$$[1 - (K_{F,w}/K_{F,e})]^{-1}\ \delta_F = [1 - (T_w/T_o)]^{-1}\ \delta_E = \theta \tag{9b}$$

This property of the similarity profiles can be readily shown by direct substitution of the linear transformation of Eq. (9a) into Eqs. (1b) through (1d).

The recombination of F atoms at the wall creates F_2, which diffuses away from the wall. From conservation of mass, the concentration of F_2 at the wall is found from

$$K_{F_2,w} = K_{F,e} + K_{F_2,e} - K_{F,w} \tag{9c}$$

In typical chemical laser nozzles, the wall can be considered fully catalytic, $K_{F,w}/K_{F,e} << 1$. The validity of this assumption is examined in Appendix A. Finally, it is assumed that $\mu \sim T$.‡

The resulting expressions for the various boundary layer thickness at $x = L_i$ are then [4]

$$\left(1 - \frac{K_{F,w}}{K_{F,e}}\right)^{-1} \delta_F = \left(1 - \frac{T_w}{T_o}\right)^{-1} \delta_E = \theta = 0.664 \left(\frac{\mathscr{D}_e L_i}{u_e}\right)^{1/2} \tag{10a}$$

$$\delta^* = \left(\frac{\mathscr{D}_e L_i}{u_e}\right)^{1/2} \left[1.72 \frac{T_w}{T_e} + 0.332(\gamma - 1)M_e^2\right] \tag{10b}$$

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‡The effect of $\mu \sim T^\omega$, $\omega \neq 1$ can be accounted for by the use of a mean reference temperature.[6] Because this effect is relatively small for the inlet region (on the order of 10%), it is neglected herein.

$$\delta = \left(\frac{\mathscr{D}_e L_i}{u_e}\right)^{1/2} \left[A + \delta^* \left(\frac{u_e}{\mathscr{D}_e L_i}\right)^{1/2}\right] \qquad (10c)$$

$$\left(1 - \frac{K_{F,w}}{K_{F,e}}\right)^{-1} \frac{\Delta\alpha_{BL}}{\alpha_o} = \left(1 - \frac{T_w}{T_o}\right)^{-1} \frac{\Delta h_{BL}}{h_o} = \frac{0.664}{A} \qquad (10d)$$

where $\mathscr{D}_e$ is the local free-stream value of the diffusion coefficient and γ is the ratio of specific heats. The value of A depends on the definition of the boundary layer edge. In particular (from Stewartson,[4] with $A \equiv \sqrt{2}f$)

$$1.7 \leq A \leq 3.3 \qquad \text{for} \qquad 0.90 \leq u/u_e \leq 0.99$$

The value A = 1.7, corresponding to $u/u_e = 0.90$, will be used herein to characterize boundary layer thickness. For A = 1.7, Eq. (10d) becomes

$$\left(1 - \frac{K_{F,w}}{K_{F,e}}\right)^{-1} \frac{\Delta\alpha_{BL}}{\alpha_o} = \left(1 - \frac{T_w}{T_o}\right)^{-1} \frac{\Delta h_{BL}}{h_o} = 0.39 \qquad (11)$$

Equations (10) and (11) are valid for $\delta/w_i \leq 1$ and, because pressure gradient was neglected, for $\delta^*/w_i << 1$. Neglecting terms of order δ^*/w_i, compared with 1, in Eqs. (5) through (7) and substituting into Eq. (10) yields

$$\left(1 - \frac{K_{F,w}}{K_{F,e}}\right)^{-1} \frac{\Delta\alpha}{\alpha_o} = \left(1 - \frac{T_w}{T_o}\right)^{-1} \frac{\Delta h}{h_o} = \frac{0.664}{w_i}\left(\frac{\mathscr{D}_e L_i}{u_e}\right)^{1/2} \qquad (12a)$$

and, for A = 1.7

$$\frac{\dot{m}_{BL}}{\dot{m}} = \frac{1.7}{w_i}\left(\frac{\mathscr{D}_e L_i}{u_e}\right)^{1/2} \qquad (12b)$$

Equations (10) through (12) can be used to estimate boundary layer effects provided $\delta^*/w_i << 1$ and $\delta/w_i \leq 1$.

It is convenient to express $(\mathscr{D}_e L_i/u_e)^{1/2}/w_i$ in terms of plenum conditions (denoted by subscript zero) and nozzle geometry. It can generally be assumed that $M_e^2 << 1$ in the inlet region. Isentropic flow conditions indicate

$$T_e/T_o = a_e/a_o = p_e/p_o = 1 + O(M_e^2) \qquad (13a)$$

$$u_e/a_o = \left(\frac{2}{\gamma+1}\right)^{(\gamma+1)/[2(\gamma-1)]} \frac{w_t}{w_i}\left[1 + O(M_e^2)\right] \qquad (13b)$$

$$= \frac{9}{16}\frac{w_t}{w_i}\left[1 + O(M_e^2)\right] \qquad (\gamma = 5/3) \qquad (13c)$$

where w_t is the throat semiwidth. [Equations (13b) and (13c) neglect the boundary layer displacement thickness at the throat.] The diffusion

coefficient will be approximated by the value for a binary mixture of helium and fluorine atoms, which can be expressed (from the results of Brokaw[7])

$$\mathscr{D}_e = 0.78 \times 10^{-4}\, T_e^{1.65}/p_e \qquad \text{cm}^2/\text{sec} \tag{14}$$

where T_e and p_e are expressed in terms of kelvin units and atmospheres, respectively. Further, assume that the free-stream flow is monatomic ($\gamma = 5/3$) and consists primarily of helium (i.e., $a_o/\sqrt{T_o} = 5884$). It follows, by direct substitution of the latter relations [Eqs. (13) and (14)], that

$$\frac{0.664}{w_i}\left(\frac{\mathscr{D}_e L_i}{u_e}\right)^{1/2} = 1.02 \times 10^{-4}\left[\frac{T_o^{1.15}}{p_o w_t}\frac{L_i}{w_i}\right]^{1/2} \tag{15}$$

where T_o, p_o, w_t are expressed in kelvin units, atmospheres, and centimeters, respectively. Equation (15) permits the rapid estimate of boundary layer properties in chemical laser inlet sections. The variation of $\Delta\alpha/\alpha_o$ and $\Delta h/h_o$ with $p_o w_t$ is given in Fig. 3 for $5 \le L_i/w_i \le 40$ and $0.01 \le p_o w_t$, atm-cm ≤ 0.1. In this range, $\Delta\alpha/\alpha_o$ and $\Delta h/h_o$ vary from about 0.05 to 0.40.

For the typical chemical laser nozzle dimensions and flow conditions in the Introduction (i.e., $p_o w_t = 0.05$ atm-cm, $L_i/w_i = 10$), Fig. 3 indicates that $\Delta\alpha/\alpha_o = 0.10$ for a fully catalytic wall and $\Delta h/h_o = 0.10$ for $T_w/T_o << 1$. These losses vary as $(p_o)^{-1/2}$ so that the losses would be $\Delta\alpha/\alpha_o = \Delta h/h_o =$

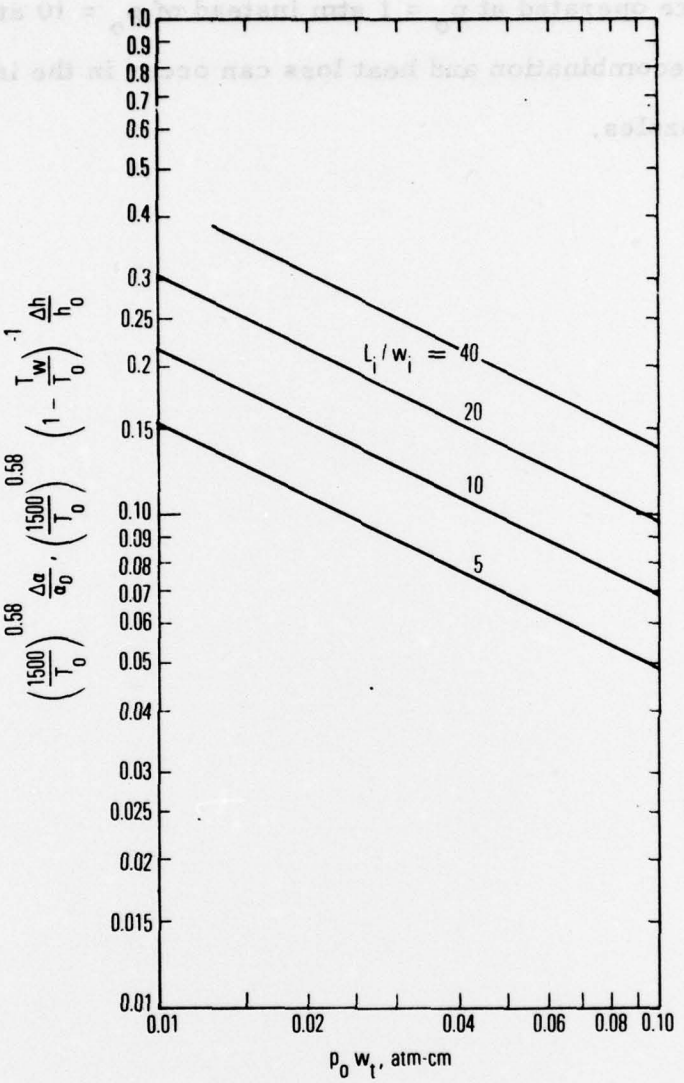

Fig. 3. Mass Averaged Reduction in Dissociation Level and Total Enthalpy at Downstream End ($x = L_i$) of Inlet Section. Solution valid for $\delta/w_i = 2.6(1 + T_w/T_o)(\Delta\alpha/\alpha_o) \leq 1$, $\delta^*/w_i = 2.6(T_w/T_o)(\Delta\alpha/\alpha_o) \ll 1$. Solution for $\Delta\alpha/\alpha_o$ assumes fully catalytic wall.

0.30 if the laser were operated at p_o = 1 atm instead of p_o = 10 atm. Thus, significant F atom recombination and heat loss can occur in the inlet region of chemical laser nozzles.

CONCLUSION

Wall boundary layer losses in the supersonic expansion region are discussed in Appendix B. It is concluded that for typical geometries, the major reduction in dissociation level and total enthalpy occurs in the inlet section, which is in accord with the results of Ferrell, Kendall, and Tong.[3]

It should also be noted that $\Delta\alpha/\alpha_o$ and $\Delta h/h_o$ represent quantities which are averaged over the entire mass flow. Based on the boundary layer mass flow only, the decrease in dissociation level and total enthalpy is considerably larger (i.e., for A = 1.7, $\Delta\alpha_{BL}/\alpha_o = 0.39$). Diffusion-type chemical lasers generally utilize only a portion of the oxidizer flow to create excited HF/DF.[2] The portion of the oxidizer flow that is used is, in fact, the flow within the wall boundary layer, because it is this flow that first comes into contact with the fuel (H_2/D_2) stream. Therefore, decreases in fluid properties based on total mass flow (i.e., $\Delta\alpha/\alpha_o$, $\Delta h/h_o$) underestimate the decrease for the flow actually participating in the lasing process and consequently underestimate the effect of the inlet on laser performance.

It is clear that F atom recombination and thermal losses in the inlet section of CW chemical laser nozzles can have a significant effect on the dissociation level and average static temperatures (and chemical rates) in the lasing region. These effects should therefore be considered when laser performance is predicted or experimental data are analyzed.

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APPENDIX A

VALIDITY OF CATALYTIC WALL ASSUMPTION

It was stated that the chemical laser nozzle wall can generally be considered fully catalytic ($K_{F,w}/K_{F,e} << 1$). The validity of this assumption is examined herein.

The wall concentration of F atoms is established by equating the rate of surface recombination of F atoms to the rate at which F atoms diffuse to the surface. Thus[5]

$$(\rho K_F)_w \, k_R = (\rho \mathscr{D} \partial K_F / \partial y)_w \tag{A-1}$$

where k_R is the surface recombination rate coefficient in cm/sec. For uniform free-stream conditions, $(\rho \mathscr{D} \, \partial K_F/\partial y)_w = (\rho u K_F)_e \, d\delta_F/dx$. Thus, using Eq. (10a) with L_i replaced by x, we obtain

$$\left(1 - \frac{K_{F,w}}{K_{F,e}}\right)^{-1} \frac{K_{F,w}}{K_{F,e}} = 0.332 \, \frac{\rho_e u_e}{\rho_w k_R} \left(\frac{\mathscr{D}_e}{u_e x}\right)^{1/2} \tag{A-2}$$

Equation (A-2) indicates that $K_{F,w}$ varies with x, which violates one of the assumptions leading to Eq. (9a). However, this variation has a negligible effect on Eq. (9a) when $K_{F,w}/K_{F,e} << 1$, as will be shown to be the general case. [For $K_{F,w}/K_{F,e}$ not small, Eq. (A-2) can be used to provide an approximate estimate for the value of $K_{F,w}/K_{F,e}$ at $x = L_i$]. For a helium-fluorine mixture and $M_e^2 << 1$, the value of $K_{F,w}/K_{F,e}$ at $x = L_i$ is found from

$$\left(1 - \frac{K_{F,w}}{K_{F,e}}\right)^{-1} \frac{K_{F,w}}{K_{F,e}} = \frac{0.169}{k_R} \frac{T_w}{T_o} \frac{w_t}{w_i} \left(\frac{T_o^{1.65}}{p_o w_t} \frac{L_i}{w_i}\right)^{1/2} \qquad \text{(A-3)}$$

Substitution of typical values of the variables ($T_w/T_o = 0.5$, $p_o w_t = 0.05$, $T_o = 1500°K$, $L_i/w_t = 100$, $L_i/w_i = 10$) into Eq. (A-3) yields

$$\left(1 - \frac{K_{F,w}}{K_{F,e}}\right)^{-1} \frac{K_{F,w}}{K_{F,e}} = \frac{5.0}{k_R} \qquad \text{(A-4)}$$

Estimated values of k_R[5] are $5 \times 10^2 \leq k_R$ for metal surfaces, $10 \leq k_R \leq 5 \times 10^2$ for oxide surfaces, and $k_R \leq 10$ cm/sec for Pyrex glasses. Inasmuch as chemical laser nozzles are metallic but surface oxidized by the fluorine passivation process, a value of k_R in the range 10^2 to 10^3 seems reasonable. Equation (A-4) then indicates $K_{F,w}/K_{F,e} << 1$, and the surface may therefore be considered fully catalytic.§

§A study was made recently by E. J. Jumper, C. J. Ultee, and E. A. Dorko ("Determination of the Surface Recombination Coefficients for a Stream of Fluorine Atoms in an Inert Gas Diluent," private communication). This study provides estimates of the variation of wall recombination coefficient with wall temperature for the case of a helium fluorine mixture and a nickel wall. The results indicate that $k_R \leq 500$ cm/sec for $T \leq 400°K$ and $k_R = 50$, 10, 1, and 0.1 cm/sec for $T = 450°$, $500°$, $550°$, and $650°K$, respectively. Hence, from Eq. (A-4), the typical chemical laser inlet section may be considered fully catalytic for temperatures less than about 450°K.

It should be recalled that gas phase recombination was neglected. Wall cooling ($T_w/T_o << 1$) tends to induce gas phase recombination near the wall. A cooled wall, therefore, represents a sink for F atoms due to both gas phase and surface recombination. When a cooled wall is not quite fully catalytic, the assumption of a fully catalytic wall ($K_{F,w}/K_{F,e} << 1$) and no gas phase recombination provides a reasonable estimate of the net effect of surface and gas phase recombination.

APPENDIX B

BOUNDARY LAYER EFFECTS IN SUPERSONIC EXPANSION REGION

A rough estimate of boundary layer effects in the supersonic expansion region can be obtained by using an "equivalent flat plate" formulation. The boundary layer at the exit of the supersonic nozzle is found by assuming a zero pressure gradient flow over a plate of length L_{ex} (Fig. 1) with free-stream conditions corresponding to those at the nozzle exit (denoted by subscript ex). Initial defects of momentum, energy, and atomic species are neglected. Equation (10) then applies with $(\mathscr{D}_e L_i/u_e)^{1/2}$ replaced by $(\mathscr{D}_{ex} L_{ex}/u_{ex})^{1/2}$. The results are of interest primarily for comparing the relative importance of the inlet and exit regions with regard to heat and F atom loss.

With hypersonic exit conditions assumed, isentropic flow relations indicate

$$\frac{T_o}{T_{ex}} = \left(\frac{p_o}{p_{ex}}\right)^{(\gamma-1)/\gamma} = \frac{\gamma-1}{2} M_{ex}^2 [1 + \mathcal{O}(M_{ex}^2)] \qquad \text{(B-1)}$$

If the effect of boundary layer displacement thickness at the throat and at the nozzle exit is neglected

$$\frac{w_{ex}}{w_t} = \left(\frac{\gamma-1}{\gamma+1}\right)^{(\gamma+1)/[2(\gamma-1)]} M_{ex}^{2/(\gamma-1)} [1 + O(M_{ex}^2)] \qquad \text{(B-2)}$$

For a helium-fluorine mixture with $\gamma = 5/3$, $a_o/\sqrt{T_o} = 5884$, and $\mathscr{D}_{ex}$ given by Eq. (14), the exit Reynolds number can be expressed

$$\frac{0.664}{w_{ex}}\left(\frac{\mathscr{D}_{ex} L_{ex}}{u_{ex}}\right)^{1/2} = 1.46 \times 10^{-4}\left(\frac{T_o^{1.15}}{M_{ex}^{1.3}} \frac{1}{p_o w_t} \frac{L_{ex}}{w_{ex}}\right)^{1/2} \qquad \text{(B-3)}$$

The ratio of supersonic nozzle F atom loss to inlet region F atom loss is then

$$\frac{(\Delta\alpha)_{ex}}{(\Delta\alpha)_i} = 1.43\left(\frac{L_{ex}/w_{ex}}{L_i/w_i} \frac{1}{M_e^{1.3}}\right)^{1/2} \qquad \text{(B-4a)}$$

$$\doteq 0.3 \qquad \text{(B-4b)}$$

Equation (B-4b) assumes $L_{ex}/w_{ex} \doteq 4$, $L_i/w_i \doteq 10$, and $M_e \doteq 6$. Equation (B-4) tends to overestimate F atom losses in the supersonic expansion region, because the considerable initial F atom defect at the start of the expansion process is neglected.

It may be concluded that the major decrease in dissociation level occurs in the inlet region.[¶] Similarly, the major loss in thermal energy ($\Delta h/h_o$)

[¶] The flux of F atoms and heat to the wall, in the vicinity of the throat, is relatively high. However, because of the small extent of the throat region, the losses in this region are probably less important than those in the inlet.

occurs in the inlet region. However, the momentum defect at the downstream end of the supersonic expansion is probably caused primarily by the supersonic nozzle wall boundary layer, inasmuch as the initial momentum defect, at the start of the supersonic expansion, is small (because of the large favorable pressure gradient in the vicinity of the throat).

ABBREVIATIONS AND SYMBOLS

a = speed of sound

A = constant defined in Eq. (10)

C_p = heat capacity at constant pressure

$\mathscr{D}$ = diffusion coefficient

h = total enthalpy; spacing between nozzle inlets

ΔH = heat of recombination

k = thermal conductivity

k_R = surface recombination rate coefficient

K_i = mass fraction of species i

L = lengths

$\dot{m}$ = mass flow rate

M = Mach number

p = static pressure

Pr = Prandtl number

q_w = local heat transfer at the wall

Q = net heat transfer to the wall

Sc = Schmidt number

T = static temperature

u = axial velocity

w = semichannel width

x = axial coordinate

y = lateral coordinate

α = dissociation level

γ = ratio of specific heats

δ = boundary layer thickness

δ^* = displacement thickness

δ_E = enthalpy defect thickness

δ_F = fluorine atom defect thickness

θ = momentum thickness

μ = viscosity coefficient

ρ = mass density

ω = viscosity-temperature exponent, $\mu \sim T^{\omega}$

Subscripts

BL = average in the boundary layer

e = external to the boundary layer (free stream)

ex = exit of nozzle

e,o = local free-stream value at x = 0

i = inlet of nozzle

o = plenum condition; initial value

t = nozzle throat condition

w = wall condition

Superscript

$(\bar{})$ = average value

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