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WITHIN MULTIPLE NOZZLE ARRAYS.

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INVESTIGATION OF FLUID DYNAMIC INTERACTIONS
WITHIN MULTIPLE NOZZLE ARRAYS

DISSERTATION

Presented in Partial Fulfillment of the Requirements
for the Degree Doctor of Philosophy in the
Graduate School of The Ohio State University

by

James Joseph Komar, B.A.A.A., M.S.A.E.

* * * * *

The Ohio State University
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"Electron Beam Analysis of the Properties of Molecular Nitrogen and Nitric Oxide in the AFFDL 2-Foot Electrogasdynamics Facility," AFFDL-TR-74-8, February 1974.

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LIST OF SYMBOLS

Symbol

A	Area
c	Speed of light
d	Diameter or Distance
h	Planck's Constant
k	Boltzmann's Constant
$\dot{m}$	Mass flow rate
P	Pressure
$Q_V(T_V)$	Vibrational Partition Function
R	Specific Gas Constant
$S(T_V)$	Vibrational temperature correction factor
T	Temperature
x	Downstream distance

Greek Symbols

α	Nozzle half-angle, degrees
γ	Ratio of specific heats
δ	Boundary layer thickness
δ^*	Boundary layer displacement thickness
ν	Wave number

LIST OF SYMBOLS (Continued)

Subscripts

0	Stagnation or reservoir conditions
r	Rotational
v	Vibrational

Superscripts

*	Nozzle throat conditions
---	--------------------------

INTRODUCTION

Theoretical analyses of the chemical transfer and mixing gasdynamic lasers have progressed to a high level of sophistication. It may now be observed that continuing advancement of the state-of-the-art of such devices is more dependent upon experimental verification of many of the simplifying assumptions and proposed flow models inherent to those analyses than heretofore. In several experimental studies, attempts have been made to assess various fluid mechanical influences, such as instabilities, mixing layer gradients and turbulence levels. However, it appears no systematic experimental investigations have been made to establish relative fluid-mechanical influences in a configuration devoid of sophisticated injection techniques, complex chemical reactions and other interactions which complicate the verification of the assumptions inherent in more advanced theoretical analyses. Results of previous experimental efforts, while often answering specific objectives to which they were addressed, have invariably raised additional questions concerning very fundamental aspects of the investigations. Basic questions concerning mixing layer phenomena inherent to both chemical transfer and mixing gasdynamic lasers remain essentially unresolved.

A comprehensive research study has been undertaken,

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whose overall objective includes the characterization of the mixing layer, to permit assessment of relative influences of parameters such as turbulence scale, energy spectrum and density fluctuations, as examples. The specific results presented herein are concerned with the design and characterization of a simple, yet versatile experimental facility, establishing steady state gasdynamic flow properties, and verification of measurement techniques for subsequent application to investigations of the micro-structure of mixing shear layers. This study is concerned only with fluid-mechanical aspects of flowing gas lasers, and does not involve considerations of the lasing process.

A review of pertinent experimental investigations and a survey of work presently under investigation is presented in Chapter I. Chapter II discusses those flow field analyses required to carefully define the experiment. The equipment, instrumentation, and test conditions are described in Chapter III. Results and discussions of the data are presented in Chapter IV, including steady-state gasdynamic data, effects of fluctuating properties on the diagnostic measurements, and results of a shear layer analysis program. A summary of the conclusions drawn from this study is presented in Chapter V.

I. BACKGROUND

Supersonic chemical transfer lasers and mixing gas-dynamic lasers have been the subject of considerable research interest in recent years because of the potentially large power available from such systems. In a typical arrangement, shown in Fig. 1, for a chemical transfer laser (Refs. 1-7), a gas containing fluorine is heated and expanded through a multiple array of small nozzles to supersonic Mach numbers. Molecular hydrogen is injected into the flow at the nozzle exit and an exothermic chemical reaction occurs in the mixing layer between the H_2 and F atoms in the nozzle flow. Most of the heat of reaction is absorbed by the vibrational energy mode of the HF molecules formed and under proper conditions in a suitable cavity, these excited molecules can be made to lase.

For the more conventional gasdynamic laser (Fig. 1) utilizing N_2 , CO_2 and He, it has been found (Refs. 8, 9) that the inverted population distributions necessary for laser output were significantly reduced when complete pre-mixing of the constituents was used. The presence of He, CO_2 , and CO in the rapid gasdynamic expansion resulted in collisional deactivation of the excited nitrogen molecule, thus reducing the population inversion. Significant increases in output power were achieved when diluent molecules

were injected downstream of the rapid expansion nozzle (Ref. 10), but the flow quality, and thus optical coherence suffered greatly. Diluent gas injection in a manner similar to that used in the chemical transfer laser improved the situation somewhat (Ref. 11), but flow field interactions still were sufficiently strong to limit the applicability of the technique. These flow field interactions were primarily fluid mechanical in nature.

Fluid mechanics plays a dominant role in the process of obtaining laser radiation from the lasing cavity for both chemical and gasdynamic laser configurations. Mixing phenomena at the jet boundaries will influence the local species concentrations and density variations, which in turn determine the type of laser mode generated, as well as the optical quality of the lasing medium (Refs. 12, 13). The degree and scale of existing turbulence associated with the mixing phenomena will also have an important effect on the optical quality of the lasing cavity (Refs. 14, 15). Severe interactions between adjacent nozzle flows and gas injection in the mixing region can also create significant perturbations of the flow field. The investigation of the extent of both molecular and mechanical penetration of the injected gas into the inviscid nozzle flow is still considered to be state-of-the-art research for both chemical transfer and gasdynamic lasers.

There have been a number of investigations (e.g., Refs. 16 through 22) into the fluid mechanical mechanisms respons-

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ible for the mixing and turbulent structure of the flow fields in both chemical transfer lasers and mixing gas-dynamic lasers. Few of these appear to have attempted an assessment of basic mechanisms responsible for mixing in the laser cavity. In fact, theoretical analyses of certain aspects of multiple nozzle laser configurations have advanced at a much more rapid rate than have corresponding experimental efforts, as indicated, for example, by the availability of the engineering analysis "RESALE" computer code (Ref. 23) and more sophisticated Laser and Mixing Program (LAMP) codes developed by Lockheed Aerospace Corporation (Refs. 24-30).

Emphasis in these previous theoretical studies has been placed on detailed analyses of the reaction mechanisms in the fully mixed flow and the resulting effects on laser performance. The fluid mechanical details of the mixing process are usually handled by simple empirical correlations. Theoretical solutions for mutually interdependent mixed flow problems have been carried out using phenomenological models of mixing. For example, for the case of no mass injection, Thoenes and Ratliff (Refs. 31, 32) describe the parallel mixing problem with turbulent transport coefficients described by various eddy viscosity models. These models were developed from empirical correlations of axial decay rates or lateral gradients measured downstream of an initial mixing zone. Since most of the population inversion-producing reactions take place slightly downstream of the nozzle exit,

the applicability of these models may be subject to question.

In a recent series of papers by Mirels and co-workers (Refs. 33-36), a flame sheet model has been employed to account for mixing. In this case, streamlines containing the main nozzle flow and injected gas were assumed to intersect along a flame sheet defined by $Y_F = A(D\psi/u)$ where Y_F is the flame sheet ordinate, D is the diffusion coefficient, ψ is the axial coordinate, u is the flow velocity, and A is a scaling constant. Laminar and turbulent diffusion were both treated with this model by varying the scaling constant A over roughly an order of magnitude. However, the flame sheet approach masks all the fluid mechanical phenomena; lateral diffusion of reaction products across stream tubes was neglected and axial velocity and pressure were assumed constant throughout the flow field. No details of the mixing process were included. Clearly, mixing must take place first, followed by initiation of reactions which must not only produce inversions but chemically release heat, thereby increasing the temperature. The initial mixing rate determines the degree of reaction and is therefore a primary controlling parameter.

While simplified models appear adequate for examining certain characteristics of laser operation, significant performance improvements cannot be obtained nor can accurate scaling laws be developed until more representative mixing models are available. The influence of mixing is a first

order effect, but current knowledge of the mixing phenomena⁷ is limited and the mathematical models are usually based on empirical correlations. The universality of such correlations is unknown. Hence, detailed experimental studies of the mixing process, including an examination of turbulence structure (e.g. Refs. 37-38) are required before adequate models can be developed.

Experimental studies of chemical transfer lasers have generally emphasized overall laser performance rather than details of the fluid mechanical mechanisms responsible for the flow structure. Certain flow field measurements have been made, but generally only gross features of the flow field have been investigated. Results reported in Refs. 39-41 were obtained in a laser facility which employed many small nozzles. Because of the small size of the flow from the individual nozzles, the details of the mixing process could not be examined. Gross influences in the downstream flow based on steady-state values of pitot pressure, total temperature, and certain radiative characteristics were examined. Time-resolved measurements within the mixing region or in the laser cavity are virtually non-existent.

With the foregoing background material in mind, it is clear that definitive experimental studies of the structure of the mixing region are required before further refinements of existing theoretical models can be made. The experimental facility for such studies must be carefully designed to permit detailed examination of the important fluid

mechanical mechanisms. As previously cited, the use of many small nozzles is undesirable since the spatial extent of the resulting mixing region is extremely small and thus difficult to examine experimentally. With proper design, a facility consisting of only two nozzles can duplicate essential features of the pertinent mixing region and should provide sufficient spatial extent to allow detailed measurements within the mixing region. This approach has been undertaken with the objective of providing definitive measurements of pressure, translational and vibrational temperature, and number density across the mixing shear layer between two coplanar, supersonic expansion nozzles operating at a nominal Mach number of four with arc-heated nitrogen. The effects of geometric design parameters, such as those used in gasdynamic and chemical transfer lasers, have been investigated using a simplified wedge nozzle and a contoured, parallel flow nozzle. A description of flow field analyses accomplished during the design process, as well as discussions of the shear layer program and principle diagnostic method, the electron beam technique, are presented in Chapter II.

II. FLOW FIELD ANALYSES

A. NOZZLE DESIGN PROCEDURES

Contoured Nozzles: A widely used approach to designing nozzles for gasdynamic lasers assumes a fixed initial nozzle expansion angle nearly equal to the maximum allowed for the specified exit Mach number. However, extensive experimental studies (e.g., Refs. 42, 43) with two dimensional wind tunnel nozzles have shown that high flow quality is obtained at the nozzle exit only for expansion angles considerably less than the maximum allowable angle. While rapid expansions are required in gasdynamic lasers to achieve the population inversions necessary to obtain the maximum output power, flow uniformity within the laser cavity is required to obtain a good quality laser beam (c.f. Refs. 12-15). Russell (Ref. 44) points out that wall effects in the nozzle expansion are extremely important. Displacement thickness effects must be added to the inviscid core results to achieve the required flow conditions at the nozzle exit and additionally, boundary layer momentum defects can create wakes in the laser cavity of a multiple nozzle array. Also, total enthalpy defects will control wall heat transfer rates and thus influence overall facility cooling requirements. The foregoing boundary layer effects can induce flow disturbances

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in mixing gasdynamic lasers and significantly influence mixing layer losses for chemical transfer lasers.

Specification of a nozzle contour to provide uniform parallel flow at the nozzle exit was accomplished with a digital computer program which combined a method of characteristics solution for the inviscid flow and a calculation of the boundary layer properties employing the method of Cohen and Reshotko (Ref. 45). Program details are discussed in Appendix B. A conventional division of the flow field into several regions, as shown in Fig. 2, was employed. Region I is the transonic flow region which delivers source flow along the characteristic BP. Region II is assumed to consist of two-dimensional source flow with the source origin at Point O. Region III is the wave cancellation region and Region IV is the test region consisting of uniform parallel flow.

The axial Mach number distribution along AB may be specified to provide any desired wall shape in the transonic region. The downstream boundary of the source flow region, CP, and the upstream boundary of the test section, DF, are purposely separated on the axis to relieve the critical requirements for continuity of the second derivative of the wall coordinate at the inflection point, P. The inviscid nozzle contour obtained from the method of characteristic calculation was then modified for the boundary layer displacement thickness, computed from the Cohen-Reshotko program, to obtain the final wall contour. Numerical experi-

ments were performed to assess the influence of geometric variations in the nozzle design on the quality of the flow at the nozzle exit plane. Some results of these studies are discussed in Chapter IV.

The contoured nozzle was designed for a nominal Mach number of 4.0, using minimum length and boundary layer cut-off criteria. This Mach number was chosen as representative of the exit velocities used in present "third generation" chemical transfer lasers. Overall sizing of the nozzle was determined by the mass flow rate capability of the arc heater used, the anticipated resolution obtainable from proposed measurement techniques (probes and electron beam) and the machineability of the desired contours. A schematic drawing of the two nozzle array is shown in Fig. 3 and a photograph of the nozzle block assembly is presented in Fig. 4. Additional details of the nozzle hardware are discussed in Chapter III.

Wedge Nozzles: Many "second generation" chemical transfer laser facilities have utilized two-dimensional wedge nozzles, instead of the more sophisticated contoured nozzles. A decision was made to investigate the flow field of such nozzles in order to provide comparison data for correlation with other facilities, as well as to provide direct comparisons with the flow field data obtained from the contoured nozzle experiments. The flow field emanating from coplanar wedge nozzles results in a complicated mixing interaction region. Immediately downstream of the nozzle exits, an interaction

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shock grows in strength within the nozzle boundary layer as it leaves the nozzle wall and progresses into the wake region of the nozzle lip. The static temperature within the interaction region has been estimated to be as high as twice that of the undisturbed flow. Normally, only minor static pressure variations are anticipated in the interaction region. With these variations of parameters in mind, a nozzle design study for the wedge nozzles was accomplished.

The design procedure for the wedge nozzles was based upon a correlation presented by Russell (Ref. 44). Russell used the design simplifications discussed in Ref. 45 and similar solutions presented in Ref. 46 to arrive at a boundary layer displacement thickness correlation of the form

$$\left(\frac{\delta^*}{d}\right)_{\text{exit}} [P_0 d^* \sin \alpha]^{1/2} = f\left(\frac{A}{A^*}\right) \quad (1)$$

where the exact form of (δ^*/d) is dependent upon whether the flow is two or three dimensional and the value of the specific heat ratio, γ . The resulting nozzle half angle, α , for the wedge nozzles was 11.67 degrees, as obtained from an iterative computer program which accounted for existing nozzle block holder dimensions, throat heights and stagnation conditions. An accuracy of approximately $\pm 20\%$ is quoted for the design correlation, and the material presented in Chapter IV, Discussion of Results, will confirm this estimate, providing account is made for an error discovered in

13

the original correlation. This error in Eq. 1 is corrected by replacing d^* , the throat diameter, by throat radius, r^* .

B. SHEAR LAYER ANALYSES

Several numerical experiments were performed using a sophisticated computer program which permits the calculation of distributional properties for either laminar or turbulent two dimensional compressible shear layers. These numerical experiments were performed to provide insight into the nature of the wake region downstream of the coplanar nozzles. Extensive unpublished modifications of the program are due to Bodonyi, (Ref. 47) and a detailed description of the program has been provided in Appendix B. Only a brief summary is provided here.

The shear layer program is the result of an extensive analysis of comparative turbulence models by Burggraf (Ref. 48) and is capable of calculating laminar or turbulent, two-dimensional compressible or incompressible boundary layer flows along a body, or wakes and free shear layers. The adiabatic wall requirement of the original program was relaxed in the modifications due to Bodonyi, as was the requirement of fixed laminar and turbulent Prandtl numbers. Additionally, mass diffusion of a binary mixture is permitted subject to the assumption of unity Lewis number.

Closure of the momentum equation in the shear layer program for turbulent flow was achieved using the model of Glushko (Ref. 49), as described in considerable detail by Burggraf. Glushko assumed the eddy viscosity for a turbulent

boundary layer was a universal function of the turbulence Reynolds number, and was also independent of the pressure gradient. Because the turbulence Reynolds number depends on the kinetic energy of the turbulence and on the characteristic turbulence length scale, as well as on molecular viscosity, a differential equation covering the turbulence kinetic energy was formulated and solved, in addition to the continuity, momentum, and energy equations. The eddy viscosity dependence on turbulence Reynolds number and the variation of the characteristic length scale in the vertical coordinate were deduced from experimental results. In the energy and species continuity equations, expressions for the eddy conductivity and eddy diffusivity were obtained by relating turbulent heat and mass diffusion terms to the eddy viscosity model used in the momentum equation. In addition to mean velocity and total enthalpy profiles computed at each streamwise location, the species continuity equation for a binary nonreacting mixture was solved to yield mass fraction profiles in the boundary layer and wake.

Characteristics of wakes formed behind the nozzle exit were analyzed for typical reservoir conditions of the experiment. The nozzle boundary layer was assumed laminar and turbulent flow in the wake was allowed to vary depending upon the amount of initial turbulent kinetic energy assumed at the nozzle exit. It should be emphasized that results presented in Chapter IV are only for the far wake. Calculation of near wake properties is a topic of current research by

several investigators and may be accomplished, for example¹⁵ with the triple-deck structure of Stewartson and Messiter (Refs. 50, 51).

C. ELECTRON BEAM TECHNIQUE

Temperature and Density Measurements: Radiation intensities sufficient for accurate determination of gas properties in an arc-heated wind tunnel can be obtained with an electron beam. A narrow beam of electrons is projected across the flow, and the interaction of electrons with gas particles produces a column of radiation which is nearly coincident with the beam of electrons. High-beam voltages are required to obtain good spatial resolution in the measurements. Profiles of gas properties may be obtained by examining various points along the length of the beam.

When an electron beam is passed through the flow at the nozzle exit, radiation is observed due to bombardment of most species known to exist in the flow field. The radiation resulting from excitation of molecular nitrogen is of particular interest to this study. The predominant radiation due to excitation of molecular nitrogen is the first negative system of the ionized nitrogen molecule (N_2^+). The most intense band is the (0,0) band at $3914\overset{\circ}{\text{A}}$. Much experimental work, some of which has been summarized in Ref. 52, has been done with the first negative system in nitrogen to verify the applicability of the diagnostic technique. Extensive details of the methods are discussed in Refs. 53 and 54.

Briefly, when a high energy electron interacts with a nitrogen molecule, it may induce a transition to a higher electronic state of the neutral atom, or the electron impact may ionize the neutral atom to form an excited $(N_2^+)^*$ ion. This excited ion can then transfer its energy by either collision or radiation. The latter process occurs most frequently at low gas densities and results in the desired diagnostic radiation. The collisional process results in quenching of the radiation. A schematic diagram of this excitation-emission process is shown on the potential curves of Fig. 5. Also included is a symbolic equation describing the steps in the excitation-emission process.

For molecular nitrogen, it was assumed that excitation occurred with no perturbation of the rotational and vibrational population distribution in the ground electronic energy state. Since the Born approximation was assumed to apply, only those transitions which are allowed by optical selection rules were considered. Hence, both the excitation and emission transitions were assumed to be governed by the Franck-Condon principle. It must be pointed out that analysis of the radiation from the ion was used to infer properties of the neutral molecule. The technique examines neutral nitrogen, before being excited by the electron, not nitrogen ions.

It is assumed that the number of ground state N_2^+ ions in the flow field prior to excitation is negligible. Transitions between vibrational levels designated by the vibra-

tional quantum number, v , give rise to vibrational spectra,¹⁷ and rotational transitions within the vibrational levels result in the rotation-vibration spectra. Additional detailed information concerning the electron beam induced emission technique may be found in Ref. 55.

The rotational line structure of the $N_2^+(1-)(0,0)$ band is customarily used to determine the rotational temperature, T_R , of the gas. T_R was assumed to be identical to the gas static temperature. This assumption is valid since only a few collisions are required to equilibrate the rotational and translational energy modes. Under extreme conditions, such as a low density free jet expansion, rotational non-equilibrium may be observed. However, for the conditions of the studies reported here, equilibration of the translational and rotational degrees of freedom may be assumed.

The rotational line intensity analysis is presented in many references (e.g. Refs. 53, 56, 57) and need not be repeated here. It suffices to write the resultant equation for the relative intensity of a rotational line as

$$\frac{I_{K'K''}/I_0}{(K' + K'' + 1)[G]v^4} = -B_{N_0} K'(K' + 1) \frac{1.4385}{T_R} + \text{CONSTANT} \quad (2)$$

where K' and K'' are the rotational quantum numbers for the upper and lower states of the ion, respectively. B_{N_0} is the rotational constant for the ground state of the neutral

$$\log_{10} \left[\frac{I_{K'K''} / I_0}{(K' + K'' + 1)[G]v^4} \right] \text{ VERSUS } K'(K' + 1) \quad (3)$$

will have a slope equal to $-1.4385(.4343)B_{v_0}/T_R$. The term $[G]$ is a function of the rotational temperature, T_R , and $[G](v/v_0)^4$ can be obtained for $T_R = 50$ to $T_R = 1100^\circ\text{K}$ from tables found in Ref. 58. T_R must be assumed and an iteration performed until the assumed and calculated temperatures are equal to within a prescribed accuracy. The entire process can be translated easily into computer instructions for quick and accurate data reduction. The program can determine the slope from a least square fit of the data, thus removing any experimental bias. Using this well established technique, rotational temperature measurements can be made to within an accuracy of approximately 5%.

The ratios of intensities of two vibrational bands in the N_2^+ first negative system are determined by assuming that the populations of the vibrational energy levels of N_2 can be described by Boltzmann distributions with vibrational temperatures which need not be equal to the translational temperature. The ratio of intensities of two vibrational bands is given by

$$\frac{I_1}{I_2} = \left(\frac{\nu_1}{\nu_2} \right)^4 \frac{q_1}{q_2} \frac{\sum_{N_0} q_1(N_1', N_0) e^{-G(N_0)hc/kT_v}}{\sum_{N_0} q_2(N_2', N_0) e^{-G(N_0)hc/kT_v}} \frac{\sum_{N_2''} \nu_2^3 q(N_2', N_2'')}{\sum_{N_1''} \nu_1^3 q(N_1', N_1'')} \quad (4)$$

where q_1 and q_2 are the Franck-Condon factors for the emission transitions, $q(\nu_1', \nu_0)$ is the Franck-Condon factor for the excitation transition from the ν_0 vibrational energy level in the ground electronic state to the ν_1' vibrational level in the excited electronic energy state, and $G(\nu_0)$ is the vibrational term value in the ground electronic energy state.

From Eq. 4, the ratio of intensities of two bands in emission is a function only of the vibrational temperatures of the molecules in the ground electronic energy state. The ratios of intensities for molecular nitrogen is shown as a function of vibrational temperature in Fig. 6. The Franck-Condon factors employed to construct Fig. 6 are given in Ref. 59.

With the assumption of direct excitation, the vibrational temperatures may be determined by measuring the relative intensities of the vibrational bands and consulting curves similar to that of Fig. 6, corrected for specific instrument transfer functions. Such curves are presented and discussed in Chapter IV.

Relative number densities of molecular nitrogen were determined from the measured intensity of the (0,1) band of the N_2^+ first negative system at $4278\text{\AA}$. The relative N_2 number densities were evaluated from the measured band intensity with the procedures described in Ref. 59, that is,

$$N_{N_2} = \frac{\text{CONSTANT}}{j_b [S(T_v)/S(T_c)]} \cdot I_{(0,1)} \Big|_{\text{REL.}} \quad (5)$$

where $S(T_v)$ is given by (Ref. 59)

$$S(T_v) = \frac{\nu^4 q(N', N'')}{Q_v(T_v)} \frac{\sum_{N_0} q(N_0, N') e^{-\frac{G(N_0)hc}{kT_v}}}{\sum_{N''} q(N', N'') \nu_{N', N''}^4} \quad (6)$$

and $S(T_c) = S(T_v)$ at 300°K .

To evaluate the slope ratio, $S(T_v)/S(T_c)$, the vibrational temperature must be known. Since the vibrational temperature and number density data were taken simultaneously the slope ratio could be obtained directly from the measured vibrational temperature at each point and the results of Fig. 6 of Ref. 59. Since the number densities were relative based on a constant value of j_b , the beam current, it was decided they should be normalized with respect to the

inviscid freestream values of number density computed from²¹ the measured temperature and calculated free-stream pressure. Therefore the material presented will appear as local number density ratioed to free-stream number density.

Fluctuating Property Effects: The electron beam technique is effective in high speed, low density flows because it does not introduce the flow disturbances associated with the introduction of conventional wind tunnel probes. However, as pointed out by Lazdinis (Ref. 60), and others, the theory of the electron beam technique depends upon uniform steady flow in the test gas medium. If the properties of the medium are fluctuating, some question must be raised as to the effects of the flow perturbations on the measured temperature.

Most electron beam measurements rely on either photomultiplier or photographic techniques to determine the radiative intensity. As a rule, only the time-averaged intensities of the rotational lines are obtained and these are then ratioed to obtain average rotational temperatures. The method used by Weeks (Ref. 61) in his attempt to assess the effects of fluctuating properties assumed that the mean temperature ratio could be represented as $\overline{I_2/I_1}$. However, the spectral data are ordinarily obtained using the ratio $\overline{I_2}/\overline{I_1}$, and in general $\overline{I_2}/\overline{I_1}$ is not equal to $\overline{I_2/I_1}$. Also, since the rotational line intensity is in general dependent upon vibrational temperature and gas number density, an assessment of fluctuations in these properties on the time

averaged rotational temperature must be made.

A computer program similar to that of Ref. 60 was provided to analyze the potential effects of perturbations in density, rotational temperature, and vibrational temperature on the measured rotational temperature. The program was modified in order to permit operation on the existing data acquisition computer, but retained all of the essential elements of the development described in Ref. 60. A detailed description of the program is presented in Appendix B.

The program was utilized for conditions representative of the test section of the multiple nozzle array. A baseline case of $T_R = 500^\circ\text{K}$, and $T_V = 2000^\circ\text{K}$ was analyzed for number density fluctuations up to $\pm 15\%$ and T_R, T_V fluctuations as high as $\pm 60\%$. Results for the baseline case are discussed in Chapter IV.

III. EXPERIMENTAL PROCEDURE

A. APPARATUS

Facility: The facility used for this investigation was the arc heated vertical wind tunnel located in the Aeronautical and Astronautical Research Laboratory of The Ohio State University. The facility is shown in Fig. 7 and a schematic representation is presented in Fig. 8. The facility consists of an arc-heater, settling chamber, conical convergent-divergent nozzle, test cabin, diffuser, and vacuum pumping system. The wind tunnel is a continuous flow, free-jet type which has been operated with air, nitrogen and argon effluents. Only nitrogen was used for this study. A 2000 cu. ft. supply common to the primary and secondary mass flow systems was made up by manifolding nine dry nitrogen cylinders.

The effluent was heated by a continuous flow, direct current arc heater. The heater employed a hollow upstream cathode and a nozzle anode. The test gas was injected into the arc chamber in a swirling fashion to provide vortex stabilization of the arc column. An electromagnet at the cathode forced the upstream arc impingement point to remain at a fixed axial location and caused the arc to move rapidly over the electrode surface, thereby reducing electrode erosion. The anode arc impingement was fixed primarily by the mass flow rate through the heater. The arc heater had

been designed to provide a heated gas with a minimum of both electrode erosion and arc instability. Electrical power for the facility was supplied by two motor-generator sets with a maximum continuous power output of 1.14 megawatts.

After passing through the arc-heater, the test gas continued through a long plenum-transition reservoir, where temporal and spatial variations in gas properties were damped. The plenum reservoir included provisions for the mixing of cold test gas with the arc-heated gas to obtain temperatures more nearly representative of present chemical and gasdynamic mixing lasers. A bare-tube heat exchange grid was also included in the design of the plenum reservoir. These two features provided for additional adjustment of reservoir pressure and temperature, in conjunction with the variation of mass flow and power to the arc heater. Details of the cold gas mixing and heat exchanger effectiveness are discussed in Part C. of this chapter under Facility Characterization.

From the plenum reservoir the test gas entered a two-dimensional nozzle configuration, discussed in the next section, and then passed through an open jet test cabin to a water-cooled convergent-divergent diffuser system which was designed for high temperature flows. The diffuser exhausts to a multi-stage rotary-vane vacuum pumping station. Further facility details are discussed in Ref. 52.

Test Section: The mechanical configurations of the two nozzle shapes are shown in Fig. 9. Two configurations were

chosen to provide comparisons between the relatively easy-to-fabricate wedge flow nozzles, with their non-uniform flow, and the generally difficult-to-fabricate contoured nozzles which have reasonably uniform flow properties. The nominal design Mach number was 4.0 and the nozzle blocks were water-cooled to preserve dimensional integrity at high temperatures.

The wedge flow nozzle had an expansion angle near the maximum for the Mach number, within the geometric constraints of the nozzle block holder and mass flow rate capabilities of the arc-heater. The contoured nozzle was designed to minimum-length rapid-expansion criteria established by the flow field analysis (discussed in Chapter II) to provide uniform, parallel flow at the nozzle exit. The nozzles are each nominally one inch high at the exit and two inches wide.

The center nozzle element has been designed for ease of replacement to permit a variety of mixing layer injection schemes to be investigated. In addition, the nozzle block holder has been designed to permit rapid alteration of the nozzle array configuration for different Mach numbers or internal injection methods.

The test cabin was equipped with four instrumentation access ports. In the nominal operating configuration, one port was occupied by the impact pressure probe; the opposing access port was fitted with an optical grade quartz window and the two remaining ports utilized for the introduction and collection of the electron beam. The test cabin

was also fitted with a variable speed scanning optical table for temperature and density surveys using the electron beam.

Electron Beam Generator: With the electron beam, the rotational temperature, vibrational temperature, and concentration of molecular nitrogen can be measured at arbitrary locations within the flow. The rotational temperatures were obtained from analysis of the $N_2^+(0,0)$ band at $3914\overset{\circ}{\text{A}}$. The nitrogen vibrational temperatures were determined by measuring the relative intensities of the $N_2^+(0,1)$ and $(1,2)$ vibrational bands. The techniques of data interpretation have been described adequately elsewhere (c.f. Refs. 53, 55, 62) and will not be repeated here.

The electron beam was generated by a commercially available 19AYP4 television electron gun (provided by Bill Mason of Sylvania GTE, Ottawa, Ohio at a very crucial point in the experiment) with energies of about 15 KeV and beam currents from 100 μa to 1000 μa . The beam diameter was about 1 mm. at low densities and approximately 3 mm. at the higher densities. The relationship of the beam generator to the wind tunnel is shown schematically in Fig. 8. A detailed description of the beam generator and some of the unique operating procedures required are discussed in Ref. 52.

Data Acquisition System: The numerical results of the study described in the main body of this discussion were obtained with the Aeronautical and Astronautical Research Laboratory (AARL) data acquisition system and digital computer (Ref. 63).

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This system is employed for on-line data acquisition, facility control and data reduction, as well as conventional digital numerical processing when off-line. The overall system (Fig. 10) may be segregated into three separate functions: a) the analog to digital front-end devices; b) the mainframe computer, consisting of the central processor and executive control functions; and c) the related input/output devices necessary to control the flow of reduced and/or processed data.

The analog front end serves to interface continuous analog signals to the central processing unit in digital form. Analog signals enter the central laboratory patch panel, where they may then be routed to signal conditioning devices and converters. Two analog-to-digital converter systems are available: A/D multiplex converter system which will accept 16 differential high-level inputs with full scale voltages of ten volts at throughput rates of 100 KHz; and a medium speed multiplex converter system which will accept 16 differential low-level inputs with full scale voltages of one volt at throughput rates of 8 KHz. The latter system has eight program-controlled gain ranges, and is transformer coupled to allow high common mode voltages.

Eight pre-amplifiers are available for signal conditioning and ten bridge-balance and span control units are included to accommodate strain gage bridges. A 5 channel digital-to-analog (D/A) system is also available which can be used for transmission of various control signals. Part

of the D/A system is used to drive an analog X-Y plotter.²⁸

The central processing unit (CPU) is a Datacraft DC 6024/5 and consists of an arithmetic unit, control unit, interface elements for the magnetic core memory, and the input-output (I/O) channel interface. The CPU has a 0.95 microsecond full cycle time and a fixed word length of 24 bits. Current memory size is 32,768 words.

The input/output system, exclusive of the devices which comprise the analog front end, includes a cartridge disc system, magnetic tape drive, a card reader, a line printer, a teletype with paper tape capability, and a Tektronix 4010 data terminal providing graphic as well as alphanumeric display capabilities. The computer is interrupt oriented so that it responds quickly to data acquisition and reduction requests. It includes a sophisticated operating system which allows data acquisition computer programs to operate on an adjustable priority basis along with the housekeeping functions required to route data between the various physical devices.

B. INSTRUMENTATION

General: The wind tunnel was instrumented to record static and total pressures, mass flows, cabin wall temperature and inlet gas temperatures. Pressure measurements were obtained with variable reluctance differential pressure transducers. The plenum pressure transducer had a full scale range of 15 psid; the impact pressure probe a range of 0-2 psid; and the test cabin pressure transducer range was 0-0.1 psid. All

pressure transducers were connected to a vacuum reference which was held at approximately 5 μ Hg. The transducers were calibrated against a silicon oil micromanometer. Calibration results are discussed in Appendix A.

Primary (arc-heater) and secondary (cold gas injection) mass flow rates were monitored by measuring the differential pressure drop across a calibrated orifice plate. Discussion of the mass flow rate calibration may also be found in Appendix A. Primary mass flow rates varied between 0.004 and 0.010 lb_m/sec , while the secondary mass flow values varied from 0.010 to approximately 0.015 lb_m/sec .

Two copper-constantan thermocouples were used to monitor the test cabin temperature and the inlet gas temperature. A polynomial curve fit of the e.m.f. output as a function of applied temperature was made and the curve-fit coefficient included in the on-line data reduction program.

Optical Systems and Spectrometers: Rotational spectra resolution and integrated band intensities were obtained with a Jarrell-Ash 0.5 meter Ebert scanning spectrometer. Radiation from the electron beam was collimated by a 13 inch focal length, 2 1/2 inch diameter collimating lens and then refocused on the inlet slit of the spectrometer. An uncooled EMI 6256 photomultiplier was used with the half meter spectrometer. Photocurrent was measured and amplified by a Keithley Model 417 picoammeter. The output of the amplifier was input to the signal conditioning patch board of the on-line data acquisition computer for further signal analysis.

Rotational and vibrational temperatures, as well as density profiles across the mixing layer were obtained with dual 1/4 meter Jarrell-Ash spectrometers and a scanning optical system shown in Fig. 11. Two EMI 9558QC photomultiplier tubes were used to record the light intensity from either rotational lines or vibrational band heads. The phototube outputs were again amplified, in this case by Keithley Model 414 picoammeters, and the signal input to the data acquisition system.

Reference signals to account for the possibility of electron beam current fluctuations were taken directly across the meter drop of the beam current milliammeter and input to the signal conditioning network. This signal was used to normalize the recorded phototube output in the data reduction procedure.

To calibrate the instrument response of an optical system, the electrical response of the photomultiplier must be related to the actual intensity of the light falling on the collecting optics. The optical response of the spectrometers to a standard line source was examined as a function of wavelength, and specific slit transmission factors determined. A Xenon Pen-Ray lamp was used as the standard source at a nominal wavelength of $4624\text{\AA}$.

The actual choice for the slit locations in the (0,0) band for rotational temperature measurements was determined by several considerations. In order to maximize the signal to noise ratio, the slits were located near the intensity

peak within the band. The two slits had to be sufficiently³¹ separated, however, to exhibit acceptable sensitivity of the signal ratio to the rotational temperature. It was also desirable that the slit located in the tail of the band ($k' = 15$ in this case) not overlap the $N_2^+(1,1)$ band, and thus exhibit a dependency of signal ratio on vibrational temperature. An additional selection criteria was considered, based upon results from the fluctuating properties program. Slit locations were analyzed to establish which values of k' would least effect the rotational temperature determination if one or all of the properties (T_R, T_v , or N , the number density) were fluctuating. Considering each of the above factors, the spectral locations chosen for the two slits are shown in Fig. 12. The locations and approximate relative intensities of the P and R branch intensities at 300°K are also shown. No overlap of the (1,1) band is observed for the Channel II spectrometer.

An additional calibration was required to determine the overall spectral response of the optical system. The spectroscopically measured intensity of some species will, in general, not equal the actual intensity emitted from the source. This inequality may be due to absorption and reflection losses from optical components, spectral characteristics of photomultiplier tubes, and various electronic gain factors incurred when converting light intensity to voltage. For the electron beam fluorescence technique, relative intensities may be used. However, true relative intensities may not be

the same as the measured relative intensities. Constant factors cancel for relative intensity measurements but wavelength dependent factors may not, so a total system response to radiation at different wavelengths must be obtained. In the present study, rotational line intensities of the $N_2^+(0,0)$ band were measured over a narrow region ($<10\text{\AA}$) of the spectrum. Vibrational band wavelengths of the $N_2^+(1-)$ emission system varied over a range from 4200-4350 $\text{\AA}$. The wider range of observation required a relative sensitivity calibration for the wavelengths investigated.

The true intensity of a particular spectral feature is given by

$$I_{\text{true}} = A \cdot K \cdot C(\lambda) I_{\text{measured}} \quad (7)$$

where A is the electronic gain factor and K the overall attenuation factor. $C(\lambda)$ is a term which accounts for all the relative light losses which vary with wavelength. The true relative intensity of a rotational line or vibrational band is given by

$$\frac{I}{I_0}_{\text{true}} = A \cdot C(\lambda) \frac{I}{I_0}_{\text{measured}} \quad (8)$$

For the rotational temperature measurement the wavelength interval was narrow and $C(\lambda)$ was approximately constant. The intensities of the rotational structure were of the same order of magnitude so A was also constant. Hence, the measured relative intensities could be taken as true relative intensities and an arbitrary intensity scale used.

For the rotational temperature, values of $C(\lambda)$ were

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established by comparing line intensity ratios at 300°K (considered the standard temperature) with those predicted by theory for the specific instrument functions previously determined. Thus

$$C(\lambda) = C_{1,R} = \frac{I_{\text{ratio, theory}}}{I_{\text{ratio, measured}} \quad 300^\circ\text{K}} \quad (9)$$

A mild pressure effect was observed in the value of $C_{1,R}$, and therefore calibrations were made to account for the variation of $C_{1,R}$ with pressure. The results are shown in Fig. 13. A least squares fit of the data resulted in an equation of the form

$$C_{1,R} = 0.662 - .0362 P_{eq}[\text{mmHg}], \quad (10)$$

where P_{eq} is the equivalent pressure found by multiplying the measured pressure by the ratio of the standard temperature (300°K) to the gas temperature.

In order to account for day to day system sensitivity changes, as defined by a constant, C_2 , an NBS-type coiled filament tungsten standard lamp was permanently incorporated into the optical system to provide a reference intensity standard. The standard lamp was powered by a stable source capable of precise repeatability of the lamp current setting. The lamp setting and resultant optical system response were noted during the establishment of standard values at the beginning of the test series, and all subsequent data referenced to the standard values by the relation

$$C_2 = \left\{ \frac{\text{Current Value of Lamp Intensity}}{\text{Standard Value of Lamp Intensity}} \right\}^{-1} \quad (11)$$

Variations of the daily run constant, C_2 , were less than $\pm 2\%$ over the entire test sequence, resulting in very small corrections for optical system sensitivity changes.

The vibrational temperature calibration constant $C_{1,v}$, was determined in the same manner as the rotational constant, $C_{1,R}$, using the (0,1)/(1,2) band intensity ratio. The constant did not exhibit significant pressure effects, and a fixed value of 0.945 was used (Fig. 13). The same C_2 values were used for both rotational and vibrational temperatures within a given run. Thus the corrected intensity ratio was the product of the measured signal and the correction factors;

$$I_{\text{corr.},1} = C_{1,1} \cdot C_2 \cdot I_{\text{meas.},1} \quad (12)$$

where 1 refers to either rotational or vibrational temperature.

Data Acquisition Procedures: All pressure and temperature data were reduced on-line with the AARL Digital Computer and Data Acquisition System. For these tests, the medium speed, auto-ranging amplifier and analog-to-digital (A/D) converter system were employed. The A/D converter resolved each data signal to 11 digital bits plus a sign bit. Hence, the resolution of the converter was $\pm .0489\%$ of full scale. On the maximum gain range, this amounts to a resolution of

$\pm 2.4 \times 10^{-6}$ volts.

The data were obtained by scanning all data channels sequentially twenty times and averaging the recorded voltages for each channel. A single scan through the channels was accomplished in approximately 1.6 millisecond. A delay of 8.3 milliseconds between scans was employed so that all steady-state data represent averages over approximately 200 milliseconds. The individual samples for each channel were statistically analyzed to yield root-mean-square deviations expressed in terms of percent of the average reading.

For each data channel, the average voltage, percent root-mean-square deviations, and reduced average data (i.e. pressure or temperature, mass flow, photomultiplier output, etc.) were displayed on a cathode ray tube data terminal for operator inspection. The display was updated every 8 seconds. At the discretion of the operator, the results of a selected scan were saved for print-out at the conclusion of the run. In addition, the average results, all raw data used to compute the results, and appropriate run, date, and time identifiers were saved on magnetic tape.

Pitot pressure surveys across the test section were tained with an analog plotter driven by two digital-to-analog (D/A) converters. The raw pressure data were obtained and reduced to pressure ratio on-line and the results displayed on the plotter. The local probe position within the test section was determined from the voltages obtained from potentiometers connected to the probe drive mechanisms.

The reduced data for each point were recorded for later print-out and the raw and reduced data were recorded on magnetic tape.

C. TEST CONDITIONS

Facility Characterization: It was realized from the outset of this study that the gas temperature of the arc heater would be significantly higher than that used in second and third generation mixing lasers. For this reason, the plenum reservoirs were long and well cooled, for the purpose of damping spatial and temporal fluctuations, as well as extracting excess energy from the flow. Inasmuch as the arc heater and heat exchanger sections were of circular cross-section and the nozzle plenum square, an additional square transition section was added between the heat exchanger and the nozzle plenum. This transition section was also water cooled. In the nominal operating configuration, the total plenum length was approximately twenty inches or a 10:1 ratio of plenum length to total nozzle height.

Initial efforts to reduce the reservoir temperature centered on the injection of cold nitrogen in the region approximately six inches downstream of the arc heater exit. The plenum length downstream of this point was considered adequate to ensure thorough mixing of the hot and cold gas streams. This technique was successful in reducing the total gas temperature, but did not achieve the desired goal of 2000°K at 1/2 atmosphere total pressure. The line labeled "no heat exchangers" in Fig. 14 represents the mass

flow-total pressure variation for cold N_2 injection alone. A star on the figure represents the design goal. Subsequent runs were made with the addition of bare tube heat exchangers of the type shown in Fig. 15. The results for the heat exchanger runs are also presented in Fig. 14. Two heat exchangers were inadequate, and four lowered the temperature slightly below the desired design goal. Thus a combination of three bare tube heat exchangers and secondary mass addition downstream of the arc heater achieved the design goal of $2000^\circ K$ at $1/2$ atm. It was possible, in fact, to vary the temperature approximately $\pm 300^\circ K$ about the $1/2$ atm. design point by adjusting the secondary mass flow rate. The primary to secondary mass flow ratios varied between 0.444 to 1.0.

Reservoir Conditions: The reservoir total temperature was determined by the "sonic-orifice" method described in Refs. 64-66. Modifications of the technique for molecular nitrogen and an extensive error analysis are presented in Ref. 67. In this technique, it is assumed that the mass flow rate per unit area is a unique function of the reservoir pressure and temperature. If the flow can be considered one dimensional and isentropic, i.e. small boundary layer thicknesses, thermodynamic equilibrium, small changes of area with distance ($\frac{dA}{dx} \ll 1$) and negligible heat transfer, one can measure the mass flow rate, area of the throat and reservoir pressure to establish the reservoir temperature. An expression of the form (c.f. Ref. 68)

$$T_o = \gamma \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \frac{A^*2}{R} \left(\frac{P_o}{\dot{m}} \right)^2 \quad (13)$$

can be derived for one dimensional, isentropic flow. In general, correction for the discharge coefficient, C_D , is required to account for the effects of throat radius of curvature, sonic line curvature, as well as boundary layer and wall temperature effects. Referring to Ref. 69, a value of $C_D = 0.95$ is obtained for the throat Reynolds number of the design condition ($Re_t = 1728$). Substitution of the appropriate dimensional conversion factors and molecular constants for nitrogen, yields a relationship of the form

$$T_o [^\circ K] = 2.4529 \left(\frac{P_o}{\dot{m}} \right)^2 \left[\frac{\text{atm. sec}}{\text{lb}_m} \right] \quad (14)$$

A reasonably large sampling of operating data over a temperature range of approximately 1700°K to 4400°K was analyzed for combinations of P_o and $\dot{m}$. Reservoir temperatures were calculated using a modified version of the Cornell nozzle flow program (Ref. 70) and the experimental data fitted by a linear regression using $(P_o/\dot{m})^2$ and T_o as the dependent and independent variables, respectively. The results are presented in Fig. 16, including the regression analysis coefficients. The slope obtained was 2.4543, or + 0.05% difference from the slope predicted by the one dimensional analysis. However, when weighted potential errors in the measurement of P_o and $\dot{m}$ were considered

(c.f. Appendix A), the possible error in the T_0 measurement³⁹ increased to + 4.36 or - 4.15%. For purposes of estimating T_0 values, the correlation was considered adequate. Where additional accuracy (consistent with the initial assumptions of the method) was required, the nozzle flow computer program was used.

IV. DISCUSSION OF RESULTS

A. NOZZLE DESIGNS

Contoured Nozzles: Numerical experiments were performed to determine the influence of geometric configuration and flow-field parameter variations on the uniformity of flow at the nozzle exit plane. The influence of initial flow expansion angle was examined by varying the angle at the throat from 5 to 40 degrees and determining resultant nozzle lengths. The effective nozzle length as a function of initial expansion angle is shown in Fig. 17. Effects of specific heat ratio, γ , were reasonably pronounced, but more significantly, there was little change in the total nozzle length accompanying a decrease from the maximum theoretical expansion angle as much as five degrees. This five degree decrease in expansion angle can significantly relieve the requirement for a smooth transition in the nozzle coordinates near the inflection point, as discussed in Chapter II.

Additional reductions in overall nozzle length were achieved when the boundary layer calculations were combined with the inviscid analysis. These analyses showed a minimum length existed, where further expansion of the flow in the x direction resulted in a growth rate of the boundary layer greater than geometric expansion rate, thus ultimately resulting in the boundary layer completely filling the nozzle.

The boundary layer cut-off point, referred to in Chapter II, is the intersection of the upstream test section boundary, (line DF in Fig. 2) with the outer edge of the boundary layer. Further increased in axial nozzle length beyond this point result in diminished test section size.

Nozzle exit boundary layer thicknesses, as predicted by the combined inviscid-viscid program, are presented in Fig. 18, for a wall temperature of 294°K . Variations in boundary layer and displacement thickness, as functions of temperature, were less than five percent over a range of stagnation temperatures from 1300°K to 2300°K . Discussions of measured pressure and temperature profiles are presented in subsequent sections.

Wedge Nozzles: The data obtained from pitot pressure calibrations of the wedge flow nozzles resulted in Mach number profiles which were consistent with a source flow nozzle; however, the exit Mach number was greater than expected. The design Mach number was 4.0 and in spite of the reasonably small difference (4-6%) between the measured and predicted values, a review of the design was undertaken. The difference may be accounted for if one examines the detailed form of the wedge flow correlation cited in Equation (1). The value d^* appears as a square root, but the factor of two necessary to reduce the throat height to throat "radius" for the correlation was not included in Russell's original correlation. When account is made for this difference, the predicted and measured values agree exactly (which may indeed

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have been fortuitous). Subsequent discussions with Russell on this point confirmed the absence of the factor of two. All other aspects of the measured and predicted values for the wedge nozzles were consistent with this observation, as will be borne out in discussions of pressure and temperature profiles.

B. STEADY STATE GASDYNAMIC DATA

Pitot Pressure Profiles: Representative pitot pressure profiles for the wedge flow nozzles are shown in Fig. 19. A nominal Mach number of 4.25 was obtained from the impact pressure ratio, P_{t2}/P_o , at the 11/32 in. station downstream and a value of 4.52 was computed for the Mach number at the 1-11/32 in. station. One impact pressure trace was obtained immediately downstream of the nozzle exit (.027 in.) and the calculated Mach number was 4.16. The Mach number gradient for the wedge flow nozzles was $0.26 \pm .02$ per inch. Values of impact pressure ratio at the 2-11/32 in. station were not used to determine Mach number, since the pressure traces showed no regions of uniform flow. This observation was confirmed by electron beam flow visualization photographs taken during the wind tunnel run. The photographs showed the wave system generated by the required flow turning at the nozzle exit had processed all of the gas seen by the impact pressure probe, and therefore altered the nominal freestream properties. The successive pressure traces of Fig. 19 also show the region of uniform flow rapidly decreasing as downstream distance is increased.

Several spanwise pitot pressure surveys were taken across the two inch width of the south nozzle, through the center of the uniform flow region at $11/32$ in. These surveys were taken to verify the two-dimensionality of the flow field in the spanwise direction. One such pressure trace and the corresponding Mach number profile is shown in Fig. 20. While the centerline Mach number distribution appears peaked, the overall variation is of the order of one percent. However, this small variation in Mach number can have a significant effect on the interpretation of rotational temperature data.

Representative pitot pressure traces for the contoured nozzles are shown in Fig. 21. One immediate fact stands out; the strength of the wave system emanating from the vicinity of displacement thickness at the nozzle exit is considerably diminished. This result was not entirely unexpected, in that one of the reasons for including the contoured nozzles in the experimental program was anticipated smoother transition of the wall boundary layers into the wake region downstream of the nozzle exit. Flow uniformity of the contoured nozzles was not as good as was anticipated. The difference between design Mach number (4.0) and the measured value (4.45) is much too great to be attributed to experimental error.

Temperature Measurements: It was not clear during the initial planning stages of the experiment whether the two line ratio rotational temperature measurement technique, described in Chapter II, would be valid for the range of

pressure-temperature conditions required. Rotational temperature measurements are customarily made by plotting the intensity of the R branch of the N_2^+ First Negative (0,0) band as a function of wavelength and then reducing the data to a line-slope plot of the form defined by Eq. 3. This procedure is a time consuming process and permits acquisition of only one temperature point per rotational scan. Since temperature profiles across the mixing layer between the two nozzles were desired, an extensive analysis of the feasibility of the two line method was made.

Instrument function calibrations for the quarter-meter spectrometers were made using the procedures described in Chapter III, and these results used as input data for a computer program to predict the temperature-intensity ratio relation. Numerical experiments were performed in which the slit locations of the two spectrometers were varied, accounting for slit transmission bandwidth, in order to maximize signal response and measurement sensitivity. Once a suitable combination had been determined, the fluctuating properties program described in Chapter II (and in more detail in Appendix B) was used to examine the response of the line pair to fluctuations in rotational and vibrational temperatures, as well as number density. Maximum sensitivity and minimum fluctuation perturbation was obtained when the $k'_1 = 7$, $k'_2 = 15$ line pair was used. The temperature intensity solutions are shown in Fig. 22 for various k' combinations using the $k' = 7$ line as the least affected by

fluctuations.

The method of using vibrational band head ratios for the measurement of vibrational temperature, as opposed to using integrated vibrational band intensities, is reasonably well established (Refs. 54, 59, 60). This method permits reasonably instantaneous determination of the vibrational temperature with the aid of the on-line digital data acquisition/reduction computer. The use of integrated vibrational band intensities for vibrational temperature determination was clearly too slow for the required temperature profiles, and therefore a similar computer analysis of the band head intensity ratio method was accomplished. The results of the intensity ratio of the (0,1) and (1,2) bands of $N_2^+(1-)$ as functions of vibrational temperature are shown in Fig. 23. The resulting vibrational temperature is dependent upon rotational temperature, since slit bandwidths permitted band overlap when centered on the band heads. This fact dictated the need for the on-line data reduction capability of the digital computer.

Verification of the acceptability of these measurement techniques was accomplished with a half-meter scanning monochromator. The half-meter spectrometer was positioned so that radiation from the electron-beam excitation of the wind tunnel flowfield could be directed to either the quarter-meter or half-meter optical systems. A conventional rotational line-slope plot was generated for several positions within the flowfield, and integrated vibrational band

intensities collected for the same positions. These data were then compared with continuously scanned data obtained with the quarter-meter spectrometers during the same wind tunnel run. In a typical set of data, the temperature determined at the centerline of the mixing region for the quarter-meter spectrometers was 373°K , whereas the temperature measured by the line-slope technique was 411°K . When corrected for differences in total temperature, the quarter-meter data were increased to 392°K , or 19°K below the half-meter data. This amounts to a difference of 4.55% low. Similar comparisons for the vibrational temperature data gave a temperature of 1920°K for the half-meter and 2157°K for the quarter-meter spectrometers. Corrected for stagnation temperature differences, the quarter-meter indicated temperature was 2057°K , or approximately 7.1% high. Other check cases gave comparable differences in temperature. These differences of temperature are considered to be well within the bounds of attainable accuracy for the electron beam technique and gave confidence in the selected measurement techniques for the mixing layer temperature profiles.

A set of rotational temperature profiles for the wedge nozzles are presented in Fig. 24. These profiles correspond to the impact pressure traces given in Fig. 19. It may be observed that the temperature profile exhibits the temperature increase expected in the vicinity of the mixing layer, although the peaks are much less than predicted by the shear layer program (further observations on these differences are

presented in Section D of this Chapter). A summary of freestream rotational temperatures measured for both wedge and contoured nozzles is presented in Fig. 25. Temperatures as functions of downstream distance are displayed as well as the inviscid predictions of how temperature should decrease as a function of increasing distance. Agreement between the observed and predicted data is reasonably good, though data scatter is approximately $\pm 10\%$. The scatter appears to increase with downstream distance, leading to the supposition that wave system location may have an effect on the results. The difference in temperature gradient between the wedge and contoured nozzles is expected, since the wedge flow nozzles exhibited a significant Mach number gradient. The contoured nozzle pitot pressure profiles showed only a very small Mach number gradient existed.

Vibrational temperatures corresponding to the cases presented in Figs. 19 and 24 are shown in Fig. 26. Reasonably pronounced decreases of vibrational temperature are observed as the centerline of the wake region is approached. It may also be observed that peaks in vibrational temperature distributions occur in the vicinity of the impact pressure profiles maximums. Freestream vibrational temperature measurements are summarized for both wedge and contoured nozzles in Fig. 27. No significant difference is observed between the vibrational temperatures obtained for the two different nozzle configurations. It appears, in fact, that the vibrational temperature has frozen at some value very close to

that predicted for the nozzle throat.

To check the effects of vibrational temperature freezing, a computer program based on the calculations of Hurle, Russo and Hall (Ref. 71) was written to examine vibrational relaxation effects. Vibrational relaxation rate equations cited by Sebacher (Ref. 72) and Anderson (Ref. 73) were believed the most reliable to data and comparisons were made for the specific nozzle profiles used in this experiment. Results correlated well with both cited rate equations, as shown in Fig. 28, with the results of Anderson correlating more closely with the experimental measurements. In the temperature range of interest for this experiment, a maximum difference of approximately six percent occurred between the rate given by Sebacher, i.e.

$$\tau_p = 3.4(10^{-2})\exp(195T^{-1/3})\text{atm.sec} \quad (15)$$

and that of Anderson, given by

$$\tau_p = 9.95(10^{-9})\exp(93T^{-1/3})\text{atm.sec} \quad (16)$$

where T is given in °K.

Further discussions of the profiles of temperature, pressure and number density in the vicinity of the mixing layer are presented in Section D of this Chapter.

C. FLUCTUATING PROPERTY EFFECTS

In a recently published paper by Lazdinis (Ref. 60), effects of fluctuations on measured rotational temperature,

using the electron beam technique, are discussed in detail. For the conditions of the experiment described herein, with rotational temperature of the order of 500°K and vibrational temperature approximately 2000°K, a 20% r.m.s. fluctuation in vibrational temperature will cause no significant change in the measured rotational temperature. Results shown in Fig. 29, as reproduced from Ref. 60, reflect the negligible temperature change. If, however, vibrational temperature fluctuations are coupled with a significant perturbation in rotational temperature, e.g. $\pm 30\%$, the mean rotational temperature may be reduced by as much as 20 to 25°K, as shown in Fig. 30. If the rotational temperature is increased to 750°K, much more significant changes in ΔT_r occur, as may be seen in Fig. 31. This trend emphasizes the necessity of accounting for fluctuations as the translational temperature of the flowfield increases. These results may explain observed temperature differences between theory and experiment. However, verification required additional time resolved data gathering equipment, which was not available during the course of this study.

The fluctuating property computer program was useful in establishing the proper choice of rotational line pairs and should prove to be of further value when time-resolved data are gathered in the future.

D. MIXING LAYER RESULTS

Temperature, pressure and number density profiles, in addition to those presented in Section B, were obtained for

the cases of nitrogen and helium injected into the wake region between the two nozzles. The injection technique was similar to that used by Shackleford, et al. (Ref. 16) and consisted of a 0.065 in. stainless steel hypodermic tube with twenty-one 0.020 in. diameter holes drilled through one side. The holes were spaced every 0.10 in. for a total width of 2.0 in. and the tube was installed in the land region between the two nozzles.

Injected gas flow rates were measured with an Airco nitrogen flow meter having a full scale capacity of 80 S.C.F.H. at 30 psig. The nitrogen injection flow rate was fixed at 40 S.C.F.H., which corresponded to $8.67 (10^{-4}) \text{ lb}_m/\text{sec}$. This flow rate amounts to approximately 5.8% of the mass flowing through the two nozzle array. The helium flow rate was also held at 40 S.C.F.H., which is equivalent to $1.24 (10^{-4}) \text{ lb}_m/\text{sec}$. or approximately 0.83% by mass of the total nitrogen flow rate through the nozzles.

Pitot pressure profiles for the wedge nozzles are presented in Figs. 32 and 33 for nitrogen and helium injection, respectively. The pressure profiles show the presence of a double shock wave structure in the nitrogen injection case and this structure has been modelled in Fig. 34 with measurements taken from photographs and the pressure profiles. The wave at 5.6° from the centerline represents the position of the wave structure for no nitrogen injection. For nitrogen injection, the free jet plume from the injection tube interferes with the shear layer leaving the nozzle wall and

strengthens the first wave. The second wave appears to be⁵¹ the result of the inability of the flow that has been processed by the first wave to negotiate the turning required at the "barrel" shock in the injection plume. These wave systems are quite pronounced in flow visualization photographs of the region and have also been observed in the rotational and vibrational temperature profiles.

The helium injection case does not appear to produce the pronounced double wave structure in the wedge flow nozzles, but the effect is observed to a lesser degree for the contoured nozzles. The shear layer is not as wide for the contoured nozzles as for the wedge case, and is therefore more likely to be perturbed by the gas injection.

Temperature data for the centerline axial positions are presented in Figs. 35 and 36. The rotational temperature data of Fig. 35 show an increased value of rotational to total temperature ratio for the non-injection case, and consistently lower ratios for those cases where gas is injected in the land region. Predicted temperature decay variations obtained from the shear layer analysis program for the non-injection case are shown as solid lines.

Temperature profiles, as predicted by the shear layer analysis program, are shown in Fig. 37 for a case representative of the experimental conditions investigated here. The predicted centerline temperature of 1.4 times the freestream temperature is approximately 24% higher than the observed temperature; however, the shear layer program does not

account for the finite land width, which is of the order of five momentum thicknesses. This width should have the effect of broadening the temperature profile, since energy will be transferred from the shear layer to the slower speed flow along the land centerline. Thus, the agreement between theory and experiment is reasonably good considering the approximations involved.

Vibrational temperature ratios, T_v/T_0 are shown in Fig. 36. For no gas injection, the land temperatures are consistently lower than the free stream vibrational temperatures. When nitrogen is injected in the land region, a significant reduction in vibrational temperature is realized. This reduction is most likely the result of the increased energy transfer due to vibration-vibration and vibration-translation collisions, as well as the mixing of the hot gas with the incoming cold (300°K) gas.

The vibrational temperature reduction of the nitrogen in the land region during helium injection is less pronounced than in the nitrogen-nitrogen case. There is evidence, in fact, as shown in Fig. 38, that suggests vibrationally hot nitrogen is being entrained by the free jet expansion, since peaks in the vibrational temperature profile occur. It was felt that possibly the vibrational temperature measurement was being contaminated by atomic line radiation from the helium, but analysis showed there were no potential line sources in the wavelength region of the vibrational band. Subsequent examination by spectral

analysis with the half meter spectrometer failed to reveal any atomic line radiation in the vicinity of either vibrational band head. The exact cause of the temperature peaks is still unresolved; however, the possibility of spectral contamination and/or entrainment should be investigated further.

Analysis of the relative number density profiles taken at two stations for the contoured nozzles revealed an anticipated decrease in nitrogen number density when helium was injected, but the decrease amounted to only some 12-15%. This would seem to imply that the nitrogen is either diffusing inward, being entrained or both. Further definitive experiments are required before the matter can be resolved. Comparative relative number density profiles are shown in Figs. 39 and 40 for the $x = 11/32$ in. and $1-11/32$ in. stations respectively. Both figures reflect slight preferential injection to the south nozzle due to a misalignment of the injection tube. The results are consistent with the simultaneously observed temperature and pressure profiles.

V. CONCLUSIONS

A combined inviscid-viscid computer analysis has shown that the initial throat turning angle of rapid expansion flowing gas laser nozzles can be reduced without significant increases in overall nozzle length or decreases in nozzle exit flow uniformity.

The applicability of the two line ratio rotational temperature measurement technique has been verified for the conditions studied and provided a continuous temperature profile in a reasonably short period of time without significant loss of accuracy. In addition, vibrational temperature measurements across the shear layer between two supersonic, high temperature coplanar nozzle flows have been made for cases which include the injection of similar and dissimilar gases in the shear layer region. These measurements are unique and should provide valuable baseline data for subsequent fluctuating property measurements in the shear layer.

While pitot pressure measurements provided valuable insight into the structure of various portions of the flow, as well as to locations of shock waves caused by flow turning at the nozzle exit and gas injection in the shear layer, it

is concluded that a much smaller impact probe would be valuable when probing the structure of the boundary layers, free shear layers and mixing layers. The present probe, whose tip diameter was of the order of the land width between the coplanar nozzles, had a tendency to integrate pressure effects over the width of the tip, resulting in the loss of detailed flow structure.

When comparing contoured and wedge flow nozzles, it was found that the contoured nozzles exhibited a lower temperature gradient in the shear layer region for both rotational and vibrational temperature. Also, the shock strength of the flow turning at the nozzle exit was lower than that exhibited in the wedge flow nozzles. This difference in flow properties immediately downstream of the nozzle exit will have an important effect on flow lasers which depend upon shear layer injection and rapid mixing.

Results of comparisons between theoretical shear layer profiles and experimental measurements are sufficiently encouraging to warrant further efforts to model the mixing layer in conjunction with the developed pressure, density and temperature profiles. In addition, further work towards comparison with other investigators' predictive methods should prove instructive.

The agreement of observed vibrational temperatures with those predicted using the relaxation rates cited by Anderson was excellent. This agreement provides additional confidence in the band head intensity ratio method for vibrational

temperature measurements.

An anomolous peak in vibrational temperature profiles of the mixing layer occurred when helium was used as the injected gas. If, in fact, this peak is caused by the entrainment of gases from the shear layer across the free jet expansion region, it could have a significant effect on the design of flow lasers, possibly leading to more rapid and efficient mixing in the shear layer.

APPENDIX A

INSTRUMENTATION CALIBRATION PROCEDURES

I. PRESSURE TRANSDUCERS

Pressure measurements were accomplished with either Pace or Validyne variable reluctance transducers in conjunction with a carrier demodulator unit. The carrier demodulator provides the transducer an isolated carrier excitation of 5 volts r.m.s. at 5 KHz. The transducer output, which is proportional to the physical input, was amplified, demodulated and filtered to produce a D.C. output of one volt. The one volt output was determined by the input requirements of the real time processor of the data handling system.

The pressure transducers were calibrated by recording the output of the transducer/carrier demodulator system as a function of a known pressure value. Pressure values were determined with Meriam Instrument Corporation micromanometers or manometers, depending upon the range calibrated. Output of the carrier demodulator was read on a Digitec digital voltmeter. The meter was readable to 3 1/2 digits and had a reported accuracy of $\pm 0.05\%$ of reading plus or minus one digit. Recorded voltage as a function of applied pressure was input to a computer program and the slope of the transducer output determined in volts per p.s.i. applied. These

slopes were then used in the data reduction program previously described. Values from the computer program for calibration accuracy, standard estimate of error and correlation coefficients for each pressure transducer used are presented in Table 1.

II. MASS FLOW RATE CALIBRATIONS

Two mass flow systems were used in the operation of the wind tunnel for this experiment. The primary system was used to supply nitrogen to the arc-heater. The secondary system was used to supply cold nitrogen to the mixing chamber in order to establish the desired operating temperature and pressure in the plenum of the multiple nozzle array.

A pumped sphere system similar to that described in Ref. 62 was used for calibrations and is shown schematically in Fig. 41. Calibrations were performed with all equipment in the same configuration as would be utilized during a wind tunnel run, with the exception that the tunnel supply lines were fed to a four-way vent valve.

The measurement of the mass flow rate was determined by establishing a given pressure rise, ΔP , in a measured time, Δt , for a given gas, calibrated sphere volume, and recorded temperature, T . These parameters were used to solve the equation

$$\dot{m} = \frac{dm}{dt} = \frac{\Delta P}{\Delta t} \frac{V}{RT}, \quad (17)$$

where $\dot{m}$ is the mass flow rate, V is the calibrated sphere volume and R is the gas constant for molecular nitrogen.

Substitution of appropriate units and constants yields a calibration equation of the form

$$\dot{m} = 7.147 \frac{\Delta P}{T \Delta t} \left[\frac{\text{lb}_m}{\text{sec}} \right], \quad (18)$$

where the units are ΔP in psia, Δt in seconds and T in $^{\circ}\text{R}$.

A brief description of the technique is provided. Details are provided in Ref. 62. Referring to Fig. 41, initial conditions for the fore and back pressure regulators were set up and the desired flow rate through the differential pressure orifice established. The four way valve was initially in the vent position. Once the sphere was evacuated and initial temperature and pressure recorded, the valve was placed in the calibrate position and the calibrated volume filled to the predetermined value of either time or pressure. Final readings of time, pressure and temperature were made, after an appropriate equilibration interval, and the sphere subsequently evacuated for the next calibration point. This procedure was repeated at appropriate intervals until each calibration point had been examined at least twice. These data were reduced using a least squares linear regression and the slope, intercept, correlation coefficient, standard error of estimate and percentage r.m.s. error established. The procedure was repeated for each mass flow system (primary and secondary) and the data are shown in Figs. 42 and 43. Results obtained from the computer program are presented in tabular form on each of the figures. The techniques described are capable of attaining accuracies

in mass flow rate of better than 1% of full scale reading.

An extensive error analysis of the foregoing procedure is presented in Ref. 74.

APPENDIX B

SUMMARY OF COMPUTER PROGRAMS

I. METHOD OF CHARACTERISTICS NOZZLE DESIGN PROGRAM

The program developed for this study is a modification of a three dimensional method of characteristics program developed at The Aeronautical and Astronautical Research Laboratory. The original version of the program included the effects of transverse curvature and other effects concerned with three dimensional aspects of nozzle design, which were removed or modified to suit the requirements of the two dimensional nozzle design. This discussion describes the input variables required and a tabulation of the output results. It is in no sense meant to be a users manual for operation of the program, but rather a guide to interpretation of the required input variables and output results.

Certain physical and geometric constraints on the nozzle design were established before numerical experiments were begun. These included the pumping capacity of the wind tunnel vacuum system, the operating constraints of the arc-heater, size limitations of instrumentation access to the existing wind tunnel test cabin, and nominal scaling laws

concerning nozzle aspect ratios, throat sizes, entrance and exit angles, and so on. Once the general sizing of the nozzle block configuration was established, effects of varying flow parameters were investigated in a systematic manner. Some of the results have been discussed previously in Chapter IV. The required input variables for the two dimensional method of characteristics program, as well as their dimensional units are tabulated in Table 2. Control Integers and their functions are described in Table 3. The pertinent output heading parameters are tabulated in Table 4.

The actual coordinates of the nozzle design were determined by using the results of the method of characteristics program as input data for the boundary layer program. Either laminar or turbulent calculations could be made. Laminar computations were accomplished with a program based on the method of Cohen and Reshotko. This method is discussed in detail in Ref. 45. Should initial conditions warrant a turbulent boundary layer computation, the correlations of Burke and Bird, described in Ref. 75, were included in the program. The stagnation conditions of this experiment precluded any such consideration. The boundary layer program used the physical dimensions of the method of characteristics program as the coordinates of the boundary layer displacement thickness and then converted the appropriate dimensions for wall position and boundary layer edge coordinates. The actual nozzle dimensions were dictated by the boundary layer cut-off criteria previously described.

II. ELECTRON BEAM FLUCTUATING PROPERTY PROGRAM

The program used to predict the effect of fluctuating properties on the measured rotational temperature is a modified version of a program developed by Lazdinis (Ref. 60). In this method, it has been assumed that three variables influence the measurement of rotational temperature; i.e. the number density of the gas, N ; the vibrational temperature, T_v ; and the rotational temperature, T_R . These variables may be expressed at any instant of time by the sum of a mean value and a fluctuating value. Thus we may represent the variables as

$$\begin{aligned} N &= \bar{N} \pm N' \\ T_v &= \bar{T}_v \pm T_v' \\ T_R &= \bar{T}_R \pm T_R' \end{aligned} \tag{19}$$

where the prime notation indicates the fluctuating component of the variable.

The instantaneous value for the intensity of a rotational line is expressed in a Taylor series expanded about the mean value of T_R , T_v and N , in the manner suggested by Weeks (Ref. 61). If the series is truncated to second order and the time average taken, it is found that first order fluctuation terms do not appear and the resulting expression is of the form

$$\begin{aligned}
\bar{I}_{k_1} = I_{k_1}(\bar{N}, \bar{T}_v, \bar{T}_R) + \frac{1}{2} \left\{ \left(\frac{\partial^2 I_{k_1}}{\partial N^2} \right) \langle N'^2 \rangle + \right. \\
\left(\frac{\partial^2 I_{k_1}}{\partial T_v^2} \right) \langle T_v'^2 \rangle + \left(\frac{\partial^2 I_{k_1}}{\partial T_R^2} \right) \langle T_R'^2 \rangle + 2 \left[\left(\frac{\partial^2 I_{k_1}}{\partial T_v \partial N} \right) \langle T_v' N' \rangle \right. \\
\left. \left. + \left(\frac{\partial^2 I_{k_1}}{\partial T_v \partial T_R} \right) \langle T_v' T_R' \rangle + \left(\frac{\partial^2 I_{k_1}}{\partial T_R \partial N} \right) \langle T_R' N' \rangle \right] \right\}
\end{aligned}
\tag{20}$$

where the symbol $\langle \rangle$ has been used to represent a time average.

The problem reduces to the evaluation of the various first and second order derivatives of I_{k_1} as functions of N , T_v and T_R . The expression for I_{k_1} is given by

$$\begin{aligned}
I_{k_1} = \frac{C v_{k_1}^{-4} f(0,0) \left(\frac{k_1}{2k_1+1} \right) N}{\sum_{N''} f(0, N'') \frac{k_1 v_R^3 + (k_1+1) v_P^3}{(2k_1+1)}} \times \\
\sum_{N_0} \left\{ \frac{f(0, N_0) H(N_0, T_R, k_1) e^{-\frac{G(N_0) h c}{k T_v}}}{Q_{vib}(T_v) \cdot Q_{rot}(N_0, T_R)} \right\}
\end{aligned}
\tag{21}$$

for the k_1 rotational line of the (0,0) vibrational band of the First Negative System of N_2^+ . The constant C represents

a calibration constant, which is a function of the optics system, electronics equipment response and instrument response functions. The term $q(0,0)$ and $q(0,v_0)$ are the emission and excitation Franck-Condon factors. These factors are the only required input data to the computer program.

Simplification of equation (21) leads to an expression of the form

$$I_{k_1} = X_{k_1} N \sum_{v_0} q(0, v_0) F_1(k_1, T_R, v_0) F_2(T_V, v_0) \quad (22)$$

where explicit forms for X , F_1 and F_2 are defined in Ref. 60. The foregoing expression is further simplified by defining normalized values of the fluctuating properties in the following manner;

$$\begin{aligned} \epsilon_1 &= T'_V / \bar{T}_V \\ \epsilon_2 &= T'_R / \bar{T}_R \\ \epsilon_3 &= N' / \bar{N} \end{aligned} \quad (23)$$

To eliminate the calibration constant in equation (21), the intensity, $\bar{I}_{k_1}$, is ratioed to an intense rotational line, I_{k_2} , in the spectrum, resulting in an expression which does not explicitly depend upon the number density, N . There is, however, an implicit dependence of $\bar{N}$, since ϵ_3 has been defined as $N' / \bar{N}$.

Having established the intensity ratio, I_{k_1} / I_{k_2} , a line-slope method for determining rotational temperature was implemented by iterative solution. The iteration was necessary

because Q_{ROT} and G in equation (21) are both dependent on T_R , the rotational temperature. The computer program performed the iterations as functions of a parametric variation on the perturbation quantities ϵ_1 , ϵ_2 and ϵ_3 for specified T_R and T_v values. Some of the results, as they pertain to the experimental conditions of this study, are presented in Chapter IV.

III. SHEAR LAYER ANALYSIS PROGRAM

The shear layer program used for this study is a modification of Burggraf's generalized shear analysis program (Ref. 48) as accomplished by Bodonyi (Ref. 47), to whom the author is indebted.

The shear layer program computes the distributions of the properties of a turbulent or laminar, two-dimensional compressible or incompressible boundary layer developed along an arbitrary body. It is also capable of computing wake flows and free shear layers. The program in its original form only treated adiabatic flows with laminar and turbulent Prandtl numbers equal to one. In its present form, the requirement of an adiabatic wall has been relaxed, and constant but otherwise arbitrary, laminar and turbulent Prandtl numbers are permitted. In addition, mass diffusion of a binary mixture has been included in the formulation of the problem, based on the assumption of unity Lewis number. Specific details of the analysis are found in Ref. 48 and will not be repeated here.

The equations discussed were programmed in FORTRAN and run on IBM 370, Models 158 and 165, digital computers for a variety of flow conditions. In a typical application, the wall was divided in 70 X-steps and the wake approximately 90 X-steps; the thickness of the boundary layer was divided into 150 Y-steps, and it was found that convergence of the solution to five decimal places occurred in approximately 15 iterations for each X-station. Typical computer run times were about 2-3 minutes, depending on flow conditions.

For current applications, laminar boundary layer calculations were carried out along the nozzle surface and resulting solution profiles determined at the trailing edge of the nozzle. The program was then restarted using the above data as initial conditions and the solution continued downstream into the wake, assuming transition to turbulent flow occurs immediately downstream of the trailing edge. Modifications for the nozzle lip shock location were made, in order to provide realistic input conditions for the wake calculations.

The required input variables for the program are tabulated in Table 5.

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PRESSURE	TRANSDUCER TYPE/RANGE	SLOPE (psid/volt)	CORRELATION COEFFICIENT	STD. ERROR* OF ESTIMATE (psid)	PERCENTAGE R.M.S. ERROR
Plenum	Whittaker KP15/0-20 psid	20.1061	0.9999	± 0.076	± 0.380
Impact (Pitot)	Pace PID/0-2 psid	1.9682	0.9999	± 0.0050	± 0.254
Primary Mass Flow	Pace IP15/0-30 psid	30.3716	0.9999	± 0.0464	± 0.153
Secondary Mass Flow	Validyne DP15/0-1 psid	1.0071	0.9999	± 0.0013	± 0.129
Cabin Static	Pace PID/0-0.1 psid	0.0998	0.9999	± 0.0003	± 0.301
Mass Flow Calibration	Validyne KP15/0-5 psid	4.8992	0.9999	± 0.0105	± 0.215

*STD. ERROR OF ESTIMATE = R.M.S. OF PRESSURE DEVIATIONS ABOUT LEAST SQUARES FIT OF DATA.

TABLE 1. PRESSURE TRANSDUCER CALIBRATION DATA

VARIABLE	DESCRIPTION	UNITS
S26	72 Columns of Hollerith Data	-
T ₀	Stagnation Temperature	°R
P ₀	Stagnation Pressure	atm.
R	Specific Gas Constant	ft ² sec ⁻² °R ⁻¹
T _w	Wall Temperature	°R
P _r	Prandtl Number	-
FE1D	Subsonic Inlet Half-Angle	deg.
D ₀	Initial Entry Height (Total)	ft.
DSB	Initial Step Size in S.	-
γ	Ratio of Specific Heats	-
D _e	Final Exit Height (Total)	ft.
FE2D	Wall Half-Angle at Inflection Point	deg.
PP1 PP2	Powers governing x-spacing on transonic and supersonic axis, respectively	-
EMF	Final Mach Number	-
ED	Number of nozzle exit heights between source flow and test sections start on axis	-
DS	Throat Height (Total)	ft.
ABL	Constant in linear fit of N vs. n in Cohen-Reshotko Method	-
AA-AE	Coefficients for the Burke-Bird Turbulent Boundary Layer Correlation Ref. 75.	-

TABLE 2. METHOD OF CHARACTERISTICS INPUT VARIABLES

VARIABLE	VALUE	DESCRIPTION
IADJ	0	Specified Net Size
	1	Automatic Net Sizing
MN1	var.	No. points on first transonic characteristic
MN2	var.	No. points on first supersonic characteristic
NN1	var.	No. points on transonic axis if IADJ = 0
		Minimum no. points on transonic axis if IADJ = 1
NN2	var.	No. points on supersonic axis if IADJ = 0
		Minimum no. points on supersonic axis if IADJ = 1
NP	var.	No. points on test section characteristic if IADJ = 0. Minimum no. points on test section characteristic if IADJ = 1
IPRINT	var.	Increment between print out of characteristics (less than zero gives only the wall values)
ICASE	1	Specified M_{exit} and exit height
	2	Specified throat and exit height

TABLE 3. METHOD OF CHARACTERISTICS PROGRAM CONTROL INTEGERS

VARIABLE	VALUE	DESCRIPTION
IBL	0	No boundary layer calculation.
	1	Call boundary layer load module.
ILAM	1	Laminar boundary layer calculation using Cohen-Reshotko Method.
	2	Turbulent boundary layer calculation using Burke-Bird correlation.
ITRANS	1	Linear Mach no. distribution upstream of source flow.
	2	Source flow on the entire transonic axis.

TABLE 3. (Continued)

VARIABLE	DESCRIPTION	UNITS
MACH	Mach Number	-
XWALL	X Wall Coordinate	in.
YWALL	Y Wall Coordinate	in.
DEL*	Displacement Thickness	in.
XEDGE	X B.L. Coordinate	in.
YEDGE	Y B.L. Coordinate	in.
DEL	Boundary Layer Thickness	in.
XCORE	δ^* X Coordinate	in.
YCORE	δ^* Y Coordinate	in.
N	Correlation Coefficient	-
T/T ₀	Static Temperature Ratio	-
PT2/P0	Pitot Pressure Ratio	-
P/P0	Static Pressure Ratio	-
HTR	Transformed Form Factor, δ^*/θ	-
VEL	Velocity	ft/sec.
TH1D	θ/δ	-

TABLE 4. NOZZLE DESIGN OUTPUT PARAMETERS

VARIABLE	DESCRIPTION
REY	Reynolds number based on reference conditions
MREF	Reference state Mach number
GAMMA	Ratio of specific heats: $\gamma = C_p/C_v$
OMEGA	Power law exponent for the viscosity - temperature relation i.e., $\mu/\mu^* = (T/T^*)^{\text{omega}}$
NY	Number of grid points across the B.L.
NYZ	Number of grid points below $Y = 0$. Set $NYZ = 1$ for solid wall or symmetric wake
KCON	Axial location counter (X_{KCON}) at which mass fraction computations begin
IREAD	Set = .TRUE. if initial profiles are to be read via punched cards; otherwise set equal to .FALSE.
IPUNCH	Set = .TRUE. if data is to be punched at specified X-station
K2	Axial location counter (X_{K2}) at which computations are stopped
KWALL	Axial location counter (X_{KWALL}) defining the last point on the body. For $K > KWALL$ computations are for wake flows or free shear layer flow
KLAST	Axial location counter (X_{KLAST}) defining the last X-station
KTRANS	Axial location counter (X_{KTRANS}) defining the X-station at which transition to turbulence occurs
KPUNCH	Axial location counter (X_{KPUNCH}) at which data are punched

TABLE 5. INPUT DATA REQUIRED FOR SHEAR COMPUTER PROGRAM

VARIABLE	DESCRIPTION
POWER	Exponent on YSCALE function (YSCALE = X ^{POWER}). Purpose is to minimize the growth of the boundary layer in the transformed plane. Using YSCALE the thickness of the boundary layer is kept relatively constant for all X-stations. Set POWER = 1/2 for laminar flow and = 4/5 for turbulent flow
TGRAD	Set = .TRUE. if heat transfer occurs at wall; adiabatic wall or wake set = .FALSE.
LAMNAR	Set equal to .TRUE. for no turbulence at all. Otherwise, set .FALSE. (on the solid boundary - only)
PARM	Coefficient of the initial profile defining the variation of the turbulence kinetic energy across the boundary layer. $\text{PHI} = \text{PARM} * r / S * e^{(1-\text{ARG})}$. Generally PARM = 1×10^{-5}
XX(K)	Axial locations for finite difference solution. Note that intervals need not be of equal width
XGRAF	Axial locations at which complete output is printed out
XWAKE	Axial locations at which complete output is printed out in the wake
UE(K)	Axial distribution of velocity at the edge of the boundary layer (specify in data statement as US)
HE(K)	Axial distribution of total enthalpy at the edge of the boundary layer (specify in data statement as HS)
SC	Schmidt number; currently restricted to a value of SC = PR since the Lewis number (Le) must be equal to 1 for the energy equation in its present form (SC = PR/Le)

TABLE 5. (Continued)

VARIABLE	DESCRIPTION
PR,PRT	Laminar and turbulent Prandtl numbers
HWALL	Total enthalpy at the wall normalized with respect to $H^*. HWALL = T_{WALL}/T^*[1 + \frac{\gamma-1}{2} M^2]^{-1}$
SUBROUTINE SPECIE	
S(L)	For K = KCON, specify the distribution of S across the boundary layer; i.e., prescribe the initial profile for mass fraction of species i.
CIE(K)	Axial distribution of mass fraction of species i at the edge of the boundary layer
SUBROUTINE VISCOS	
LAMBDA	Scale factor used in defining the eddy-diffusivity in terms of the eddy viscosity: $\epsilon_D = \epsilon(LAMBDA \cdot r)$

TABLE 5. (Continued)

Chemical Diffusion Mixing Laser

Downstream Mixing Gasdynamic Laser

Figure 1. Schematic of Mixing Gas Lasers

Figure 2. Method of Characteristics Nozzle Geometry

Figure 3. Test Section Schematic

Contoured

Wedge

Figure 4. Nozzle Blocks and Holder

Figure 5. Diagram and Schematic of Excitation-Emission Process

Figure 6. Ratios of Various Band Intensities as a Function of Vibrational Temperature

Figure 7. The Mixing Jet Flow Facility

Figure 8. Schematic of Mixing Jet Flow Facility

Wedge Nozzle Configuration

Contoured Nozzle Configuration

Figure 9. The Multiple Nozzle Arrays

Figure 10. Data Acquisition and Digital Computer System

Figure 11. Spectrometers and Optical System

Figure 12. Slit Locations for Spectrometers

Figure 13. Pressure-Temperature Calibration Factors

Figure 14. Effects of Secondary Mass Injection and Heat Exchange on Reservoir Conditions

Figure 15. Typical Heat Exchanger Element

Figure 16. Reservoir Temperature as a Function of Mass Flow Parameter

Figure 17. Inviscid Effects on Nozzle Geometry

Figure 18. Predicted Boundary Layer Parameters

Figure 19. Pitot Pressure Profiles-Wedge Nozzles

Figure 20. Spanwise Pitot Pressure and Mach Number Distribution

Figure 21. Pitot Pressure Profiles-Contoured Nozzles

Figure 22. Rotational Temperature as a Function of Intensity Ratio

Figure 23. Vibrational Temperature as a Function of Intensity Ratio

Figure 24. Rotational Temperature Profiles

Figure 25. Freestream Static Temperature Variation

Figure 26. Vibrational Temperature Profiles

Figure 27. Freestream Vibrational Temperature Variation

Figure 28. Comparison of Measured and Predicted Vibrational Relaxation Temperatures

Figure 29. Rotational Temperature Fluctuation Effects (Ref. 60)

Figure 30. Perturbation Effects at $\bar{T}_R = 500$ °K

Figure 31. Perturbation Effects at $\bar{T}_R = 750$ °K

Figure 32. Pitot Pressure Profiles For Nitrogen Injection

Figure 33. Pitot Pressure Profiles For Helium Injection

Figure 34. Shock Wave Positions For Nitrogen Injection in the Shear Layer

Figure 35. Centerline Static Temperature Variation

Figure 36. Centerline Vibrational Temperature Variation

Figure 37. Comparison of Measured and Predicted Shear Layer Temperature Distributions

Figure 38. Vibrational Temperature Peaks for Helium Injection

Figure 39. Nitrogen Relative Number Density Profiles - Contoured Nozzle, 11/32 in. Downstream

Figure 40. Nitrogen Relative Number Density Profiles - Contoured Nozzle, 1 11/32 in. Downstream

SYMBOL KEY	
BG - Barton Gauge	PT - Pressure Transducer
BPR - Back Pressure Regulator	RCV - Remote Control Valve
D/P - Differential Pressure Orifice	TC - Thermocouple
FPR - Fore Pressure Regulator	VT4 - Wind Tunnel Supply Manifolds

Figure 41. Dual Mass Flow Monitoring and Calibration Systems

Figure 42. Primary Mass Flow Rate Calibration

Figure 43. Secondary Mass Flow Rate Calibration