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THE PRODUCTION OF POPULATION INVERSIONS
BY INJECTING NEON INTO AN ARC-HEATED
RAPIDLY-EXPANDING HELIUM PLASMA

by

James V. Dalton

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
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May, 1971
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<th>Description</th>
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<tr>
<td>$A_{n,m}$</td>
<td>Probability of spontaneous emission from level n to level m</td>
<td>sec$^{-1}$</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>Angstrom</td>
<td>$10^{-8}m$</td>
</tr>
<tr>
<td>$a_o$</td>
<td>Speed of sound of gas</td>
<td>cm/sec</td>
</tr>
<tr>
<td>$E_I$</td>
<td>Ionization Potential</td>
<td>ev</td>
</tr>
<tr>
<td>$E_n$</td>
<td>Energy of level n</td>
<td>ev</td>
</tr>
<tr>
<td>$g_n$</td>
<td>Degeneracy of energy level n</td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>Planck's constant</td>
<td>$6.6 \times 10^{-27}$ erg-sec</td>
</tr>
<tr>
<td>$I_{n,m}$</td>
<td>Intensity of radiation due to transition from level n to level m</td>
<td>watts/cm$^3$</td>
</tr>
<tr>
<td>$I(r)$</td>
<td>Radial intensity distribution</td>
<td>watts/cm$^3$</td>
</tr>
<tr>
<td>$J(y)$</td>
<td>Observed intensity distribution</td>
<td>watts/cm$^2$</td>
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<tr>
<td>$k$</td>
<td>Boltzmann's constant</td>
<td>$1.38 \times 10^{-16}$ erg/molecule-°K</td>
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<tr>
<td>$m$</td>
<td>Mass flow rate</td>
<td>gram/sec</td>
</tr>
<tr>
<td>$m_e$</td>
<td>Mass of electron</td>
<td>$9.1 \times 10^{-28}$ g</td>
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<tr>
<td>$N_e$</td>
<td>Number density of free electrons</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>$N_{He}$</td>
<td>Number density of helium ions</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>$N_n$</td>
<td>Number density of atoms having an electron in excited level n</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>$N_0$</td>
<td>Total density of atoms</td>
<td>cm$^{-3}$</td>
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$P_o$ Pressure in arc chamber dynes/cm$^2$

$R$ Helium gas constant $4.15 \times 10^7$ erg/gm$^{-9K}$

$T$ Temperature $^oK$

$T_e$ Temperature of free electrons $^oK$

$T_o$ Temperature in arc chamber $^oK$

$Z$ Atomic partition function

$\gamma$ Ratio of specific heats $C_p/C_V$

$\lambda$ Wavelength Angstroms

$\mu$ Micron $10^{-6}m$

$\nu$ Frequency sec$^{-1}$

$x$ Similarity parameter $x/a_0 t$

$\rho$ Density dynes/cm$^3$

$\rho_o$ Density of atoms in arc chamber dynes/cm$^3$

$\tau$ Radiative lifetime sec

Subscripts

e Electron

n Electronic energy level

$n, m$ Radiative transition from upper level $n$ to lower level $m$
CHAPTER I
DISCUSSION

A helium-neon gas laser was developed by Javan\textsuperscript{1}, \textit{et al.} in 1960. Population inversions between several Ne levels were achieved by means of excitation transfer from the metastable He (2^3S) to the 2s levels of Ne. Laser oscillation was then achieved between the 2s and 2p levels of Ne. The 2s to 2p transitions are all in the infra-red with the strongest transition occurring at 1.1529 \( \mu \).

In this system the He (2^3S) metastables are used to excite the 2s levels of Ne. This process, characterized by

\[
\text{He} (2^3S) + \text{Ne} \,(2p^6\,1\,S_0) \rightarrow \text{Ne} \,(2s) + \text{He} \,(1^1S),
\]

is a resonant transfer process in that the 2s energy levels of Ne lie very close to the He (2^3S) energy level and the excitation cross section is large only to the Ne (2s) levels. The probability of a collision between a Ne atom and He (2^3S) metastable atom resulting in excitation of the Ne to any level other than the Ne (2s) levels is very small. By this method the Ne (2s) levels will be populated preferentially by resonant collisions with the He (2^3S) metastables, and the lower Ne levels will be populated primarily by collisions with electrons in the discharge and by radiative decay from the overpopulated 2s levels. The lifetime of the Ne (2s) levels is determined primarily by radiative decay to the 2p levels.
The 2p levels then decay to the 1s levels, and the lifetimes of all the 2s levels were found by Javan to be about an order of magnitude longer than the lifetime of the 2p levels. Then not only will the upper 2s level be overpopulated due to the resonant transfer process with the He (2^3S) metastables, but it will remain overpopulated because the lower 2p level will decay more rapidly than the 2s level. Thus population inversions could be obtained on each of the thirty allowed 2s - 2p transitions.

In the afterglow of the discharge region, the free electrons thermalize within a few μ seconds; whereas, the He metastables exist for milliseconds and will continue to populate the Ne (2s) levels for as long as they exist. Javan's observations showed that the temporal variations of the populations of the He (2^3S) metastables and the Ne 2s and 2p levels in the afterglow were all identical. This indicated that the He (2^3S) metastable population was controlling the inversion.

White and Rigden produced He - Ne laser oscillation in the visible range in 1962. When helium is excited by an arc discharge, as in the laser of Javan, both the triplet (2^3S) and singlet (2^1S) metastable levels will be populated. As with the excitation transfer process between the triplet metastables and the Ne (2s) levels, the singlet metastables will excite the Ne (3s) levels by the process

$$\text{He (2}^1\text{S)} + \text{Ne (2p}^5\text{ 1S}_0) \rightarrow \text{Ne (3s)} + \text{He (1}^1\text{S)}.$$
The Ne (3s) levels will then decay to the 3p and 2p levels with the (3s - 2p) transitions occurring in the visible range at about 6000 Å, with the primary transition occurring at 6328 Å. However, the inversion will not be as strong between the 3s and 2p levels as between the 2s and 2p levels because there will be more triplet He metastables than singlets which results in more Ne (2s) atoms than Ne (3s) atoms. There will be more triplet metastable He atoms than singlets since the distribution of excited He atoms in the discharge region tends toward a Maxwell-Boltzmann distribution characterized by

\[ N_n = N_0 \, g_n \, \exp \left( -E_n / kT \right) / Z , \]

where the degeneracy, \( g_n \), of the triplets is three and the degeneracy of the singlets is one and the energy of the singlets is about 0.3 ev greater than that of the triplets. This is also a result of the collision process

\[ \text{He (}^2S\text{)} + e \rightarrow \text{He (}^3S\text{)} + e + 0.79 \text{ ev} \]

which has a favorably large cross-section in the discharge region. Figure 1 is an energy level diagram on which are indicated the resonant transfer processes between the He metastable levels and the Ne excited levels and the primary lasing transitions.

Bloom\textsuperscript{9}, et al., in 1963 found laser oscillation between the Ne (3s) and Ne (3p) levels at the 3.39 \( \mu \) radiative transition line. They found the oscillation at the 3.39 \( \mu \)
line to be much stronger than that of the $6328 \text{ Å}$ line and the $1.15 \mu \text{ line}$ of Javan. This was to be expected because the $3.39 \mu \text{ line}$ decays to the $3p_4$ level which is populated primarily by this decay; however, the $1.15 \mu \text{ line}$ and the $6328 \text{ Å}$ line both decay to the $2p_4$ level which is thus populated by the decay of both upper levels.

In the production of the inversion in the gas lasers of Javan$^1$, et al., White and Rigden$^3$, and Bloom$^9$, et al., the He and Ne were pre-mixed and then excited in the arc discharge. This resulted in undesirable population of the Ne metastable levels because of collisions with the energetic electrons. Since the $1s$ levels of Ne are metastable and the $2p$ level populations are determined by radiative decay to the Ne $(1s)$ levels, the degree of inversion is limited because the Ne $(1s)$ metastables can be re-excited to the Ne $(2p)$ levels by collisions with electrons and absorption of radiation. The influence of the Ne $(1s)$ metastables was demonstrated by the observation of Javan$^1$, et al. that a larger degree of inversion occurred during the period of decay of the electron energy when the discharge was turned off.

Hurle and Hertzberg$^{2,3}$ propose a convective flow system whereby the He metastables are produced in a discharge region and then mixed with the Ne in a different region away from the discharge. This separation of He excitation and Ne excitation can be accomplished with a moderately fast flow system because of the relatively long lifetime of the He metastables (milliseconds). In addition, the discharge
process can be adjusted for efficient production of He metastables without the simultaneous undesirable production of the Ne metastables.

In such a flow system the energetic electrons exciting the He in the discharge region will not be present in sufficient numbers in the Ne excitation or mixing region to collisionally excite the Ne to the metastable level since the electrons from the discharge would equilibrate with the translational temperature much faster (microseconds) than the convection period.

In this convective system the production of metastable Ne will be primarily due to radiative decay from the inverted 2p levels. Thus, in such a system, the upper inverted states will not be populated by electron collisions with the Ne (1s) metastables, and the degree of inversion will be improved because of a lack of production of Ne metastables by electron impact.

The degree of inversion can be estimated since the He metastables transfer their energy to the Ne (3s) and Ne (2s) levels through resonant energy transfer and these levels decay radiatively to the Ne (1s) metastable level by way of the Ne (2p) level. Since the radiative lifetime of the 2s - 2p transition is longer than that of the 2p - 1s transition, the inversion will occur between the 2s and 2p levels. By comparison of the radiative lifetimes, which are estimated to be $2 \tau_1 = 1.5 \times 10^{-7}$ sec for the (2s - 2p) transition and $\tau_2 = 6 \times 10^{-9}$ sec for the (2p - 1s) transition, the expected
steady-state population inversion is

\[
\frac{n_{2s}}{n_{2p}} = \frac{\tau_s}{\tau_2} = 25.
\]

In the pre-mixed He - Ne laser, although the population of the 2s level will be about the same as can be produced in the convective flow system, the extent of the inversion \(n_{2s}/n_{2p}\) will be less because of the increased production of Ne metastables. (Effectively this is equivalent to an increased lifetime \(\tau_2\).) Another advantage of the convective system is that higher pressures of He and Ne can be used which will result in higher populations of the Ne 3s and 2s levels for the same fraction of He atoms excited to the metastable state; thus, the light intensity which depends on the upper level population will also be increased.

Hurle and Hertzberg\textsuperscript{2,3} also indicate another fluid-mechanical method of producing population inversions. This method is also discussed by Basov\textsuperscript{10,12}, et al., and Gudzenko and Shelepina\textsuperscript{11}. This is called the free-expansion or rapid-expansion method. In this method an excited gas is allowed to expand rapidly into a low-pressure region through a narrow slit orifice or short converging nozzle. In such an expansion the changes in pressure, density and temperature are given by the relations

\[
\frac{P}{P_0} = \left[ \frac{2 - \frac{\gamma (\gamma - 1)}{\gamma + 1}}{\gamma + 1} \right]^{\frac{2}{\gamma - 1}}
\]

\[
\frac{\rho}{\rho_0} = \left[ \frac{2 - \frac{\gamma (\gamma - 1)}{\gamma + 1}}{\gamma + 1} \right]^{\frac{\gamma}{\gamma - 1}}
\]
\[
\frac{T}{T_0} = \left[ \frac{2 - E(Y-1)}{Y+1} \right]^2
\]

where \( \gamma \), \( x/a_o t \), is called the "self-similar" variable where \( x \) is the distance from the slit, \( a_o \) is the initial sound speed in the heated (excited) gas, and \( t \) is the time for the gas to travel a distance \( x \) from the slit. These expansion rates are about the right order of magnitude to effectively "freeze" the populations of the upper electronic levels of the gas. These levels have radiative lifetimes of \( \mu \) sec and during expansion tend to remain in equilibrium at the electron temperature. At the same time, however, the lower electronic levels of the expanding gas, having radiative lifetimes of about \( 10^{-7} \) - \( 10^{-8} \) sec, will tend to be in equilibrium at the local gas temperature. During the rapid expansion process, the gas temperature drops about an order of magnitude more rapidly than the electron temperature; thus, there will be two adjacent electronic levels with different principal quantum numbers, for which the lower level tends to be in equilibrium at the gas temperature while the upper level is in equilibrium at the electron temperature. The upper state may become inverted in the expansion since in such a situation

\[
\frac{N_u}{N_1} = \frac{g_u}{g_1} \exp \left( \frac{E_u}{kT_e} - \frac{E_1}{kT_g} \right) > 1
\]

since \( T_c \ll T_e \) and \( E_u \) only slightly \( > E_1 \). Such trends have been observed in studies of collisional-radiative recombination made by McGregor and Brewer\(^{13}\), Robben, Kunkel, and
Talbot\textsuperscript{15}, and Adcock\textsuperscript{16}.

McGregor and Brewer\textsuperscript{13} have shown experimentally that the temperature at which the upper electronic levels in the afterglow are in equilibrium is the electron temperature. Since the excited atoms in the expansion region tend to be in Boltzmann equilibrium at the electron temperature, the degree of inversion can be determined by spectroscopically measuring the electron temperature and calculating the energy level population densities from the Boltzmann distribution at that temperature. By measuring the number density of atoms in the electronic levels, one can determine where the inversion begins and the extent of the inversion.

Goldfarb\textsuperscript{4,5,6,7}, et al. have made experimental studies of producing population inversions by rapidly expanding arc-heated argon, hydrogen and helium through the supersonic nozzle of a dc plasmatron. They indicated that population inversions occurred just downstream of the nozzle.

The experimental apparatus utilized in this study combined the features of excitation separation in the convective flow system and rapid expansion to preserve metastable populations in the expansion flow system. In this system, the helium was injected into the arc discharge chamber or stagnation chamber. The arc discharge would excite and partially ionize the helium producing a near-equilibrium population distribution. The excited helium would then exit into a low pressure test section via a converging or converging-diverging nozzle. By injecting the neon into the
emerging helium plasma in the low pressure expansion region, the neon atoms would become excited primarily due to the resonant energy transfer processes with the helium metastables. Since the flow speed in a rapidly expanding system is such that the helium metastables do not decay before they exit from the nozzle, sufficient numbers of the helium metastables should exist in the emerging plasma. The population inversion should occur just downstream of the point of injection into the plasma.
CHAPTER II
EXPERIMENTAL APPARATUS

The experimental study reported in this thesis utilized a plasma arc-jet facility designed by M. A. Frost, III\textsuperscript{14} for study of a recombining argon plasma. This plasma arc-jet is a low density wind tunnel of the type used in previous experimental studies.\textsuperscript{4,5,6,7,13,15,16} A schematic diagram of the facility is shown in Figure 12. A helium plasma was produced by passing helium through a DC arc in the stagnation or arc-discharge chamber. The arc was initiated by a Miller high frequency starter which was shut off when the arc was initiated. The arc was then sustained by a 24-kw Miller welding generator. For the experiments performed, the power to the arc was maintained at 8 kw (200 amps at 40 volts).

The power to the arc was supplied through water-cooled copper coils which were built into the electrodes. These coils also had the desirable effect of magnetically inducing a force on the arc causing it to rotate between the electrodes so as to avoid electrode deterioration. The arc chamber consisted of a tungsten anode one inch in diameter located 0.2 inch below the tungsten cathode; a teflon cylinder separated the electrodes. The helium entered the arc chamber tangentially and traveled in the direction of the rotation of the arc. Helium was supplied at about 890 mm Hg through a 0.043 inch diameter orifice at a flow rate of 0.07 grams/sec at 74°F. The flow rate was measured with a Fischer and
Porter Tri-Flat variable area flowmeter type FP-1/4-25-G-5/84. The flowmeter was calibrated by using the Fischer and Porter handbook.

The excited helium plasma left the arc chamber vertically through an axially symmetric water-cooled converging nozzle whose base is connected to the anode. It exhausted into the test section as a free jet. The pressure in the test section was maintained between one and three mm Hg. The pressure in the arc chamber was normally about 130 mm Hg. Thus, choked flow at the nozzle throat always prevailed. The arc chamber temperature was estimated from the ratio of arc chamber pressure with and without arc operation. The mass flow rate can be shown to be proportional to $P_o^{1/3}T_o$ where $P_o$ and $T_o$ are the arc chamber pressure and temperature. By flowing the helium through the stagnation chamber, measuring the stagnation chamber pressure with and without arc operation, and measuring the stagnation temperature without the arc, the arc chamber temperature when the arc is in operation can be determined to a good approximation. By this method the arc chamber temperature with the arc in operation was found to be approximately 5000 K.

The neon was injected into the expanding helium plasma through a half-inch I.D. ring made of stainless steel tubing which had small exit ports notched in it to permit an axially symmetric distribution of neon into the plasma. A diagram is shown in Figure 13. The neon was injected from a reservoir at 180 mm Hg through a 0.043 inch diameter orifice.
The flow rate was measured with a Fischer and Porter Tri-Flat variable area flow meter type FP-1½-17-G-10/83 to be 0.15 gram/sec.

The free jet was observed to be quite symmetric in appearance, although at times considerable flickering could be noticed in the boundaries of the jet due to attachment of the arc to one side of the anode. Examination of the electrodes showed only small amounts of erosion. With the neon injected into the free jet, it was observed to be less symmetric because of the uneven injection of the neon. However, the jet was determined to be sufficiently symmetric to allow the assumption of symmetry when analyzing the data.

The pressure in the arc chamber and the helium and neon supply pressures were measured with Matheson Bourdon-type vacuum gauges which were calibrated with a 10-inch diameter Heise vacuum gauge. Test section pressure was measured with a Stokes McLeod gauge.

A set of three control consoles designed to automatically run the experiments and record the test data were used during the experiments. These consoles feature programmable plug-boards. The test control plugboard controls all the electronic equipment, generators, and valves in the Plasma Dynamics Laboratory during a test. There are twelve programmable latching relays for control over the operation of any particular device. The test is made fully automatic through the use of a sequential timer and remote control is also available. Several "failsafe" checks are provided to insure
against destruction of equipment resulting from the failure of any subsystem. Considerable flexibility is provided through this programmable control facility.

An instrumentation console, also programmable, handles the excitation circuits for various diagnostic devices, such as pressure transducers, and channels the incoming data through compensating, filtering, or other networks which are available as plug-in cards to a 36-channel Honeywell visicorder. For most of the experiments reported here, the previously mentioned pressure gauges were found to be more convenient during operation.

Spectroscopic measurements were made with a Jarrel-Ash 0.5 meter Ebert astigmatic spectrometer fitted with an exit slit and a photomultiplier tube for direct read-out. The entrance and exit slits were the same size and could be simultaneously varied in width from 0 – 400 μ wide. The RCA-1P21 photomultiplier tube used is designed for wavelengths from 3000 Å to 7000 Å with a peak efficiency at about 6000 Å. Wavelength coverage was obtained by rotation of the grating with read-out on a counter directly in Angstroms. The grating used was designed for operation from 1900 Å to 9100 Å. Thus, measurements in the infra-red range were not possible for these experiments. Photomultiplier output was recorded either on a strip chart recorder or on a Tektronix type 561A oscilloscope. Spectroscopic observations were made through a quartz window located in the test section housing wall.
The optical path consisted of two plane mirrors to reflect a transverse slice of the plasma to the optical bench and a large lens for gathering the light and focusing it on a plane mirror which then reflected the slice to the entrance slit of the spectrometer. Figure 12 shows the optical path used.

The absolute line intensity was determined by calibration with a radiation standard. The standard used was a General Electric 30A/T24/17 tungsten ribbon filament lamp calibrated by Eppley Laboratories to National Bureau of Standards specifications for spectral radiance from 2,500 Å to 26,000 Å when operated at 35.0 amps. The filament current was monitored within 0.1 percent by using an Electro-Instruments precision AC-DC differential voltmeter. The standard lamp was viewed through the identical optical path as the experiments so as to insure the accuracy of the calibration.

Helium, argon, and mercury vapor Pluecker tubes, with a CENCO 5,000 volt power supply, were used for additional spectrometer calibration.

Photographs of the Plasma Dynamics Laboratory are shown in Figures 14 - 17. A schematic of the nozzle assembly showing the neon injection manifold is presented in Figure 13.
CHAPTER III
METHODS OF ANALYSIS

A. Gas Parameter Determination

Certain gas parameters were measured using available instrumentation in the Plasma Dynamics Laboratory. When used with appropriate assumptions, the measured parameters allowed determination of the remaining parameters necessary to describe the expanding gas stream.

The measured gas parameters were the arc chamber pressure, the test section pressure, and the spectral line intensities. The arc-heated helium was assumed to obey the perfect gas equation of state and to expand isentropically as a free-jet from the sonic throat. Although Robben\textsuperscript{15}, et al. found viscosity effects significant in the operation of their arc jet because of the small atomic mass of helium and the resulting low Reynolds number of the flow, these effects were neglected in this analysis. Robben\textsuperscript{15}, et al. noticed the viscosity effects by comparing spectroscopically measured electron densities with the densities predicted from measured pressures and isentropic flow theory. Their spectroscopic measurements indicated the free jet Mach number never exceeded three and the isentropic flow theory predicted at least ten.

The stagnation temperature was estimated by assuming choked flow at the throat, Mach number equal to one. The mass flow rate of a perfect gas through a sonic throat is
proportional to the stagnation temperature and pressure; i.e.

\[ m \propto P_0 / T_0^{1/2} \]

By measuring the arc chamber pressure of room temperature helium flowing through the nozzle without the arc being struck and with the arc struck, the stagnation temperature with the arc on is approximately given by

\[ T_{0\text{arc}} = T_{0\text{cold}} \left( \frac{P_{0\text{arc}}}{P_{0\text{cold}}} \right)^2 \]

By such measurements, \( T_{0\text{arc}} \) was found to be about 50000°K.

Assuming isentropic, choked flow through the nozzle, the flow velocity at the throat was approximated by the relation

\[ V_{\text{throat}} = a_{\text{throat}} = \sqrt{RT_{\text{throat}}} \cong 6 \times 10^5 \text{ cm/sec} \]

where \( \gamma = 1.67 \), \( R = 4.15 \times 10^7 \text{ ergs/s} \cdot \text{cm} \cdot \text{°K} \), \( T_{\text{throat}} = 50000 \text{°K} \).

If this flow velocity is taken as an approximate value of the average velocity of the gas in the jet or afterglow region, an estimate can be made of how far into the test section the helium metastables can be expected to survive. Arrathoon estimated the lifetime of the He (2^1S) metastables in a pre-mixed He - Ne system to be about 50 \( \mu \) sec. The lifetime of the He (2^1S) metastables in the absence of neon quenching is much longer; thus at the average flow velocity and lifetime mentioned, the He (2^1S) metastables would survive to a distance of about 30 cm in the jet as a conservative
estimate. The nozzle throat (exit plane) was about 5 cm above the center of the stagnation chamber; thus, the He \((2^1S)\) metastables could be assumed to last for about 25 cm above the nozzle. Since the spectral intensity measurements were taken at 2 cm - 5 cm above the nozzle throat, the He \((2^1S)\) metastable population at the measurement stations was expected to be approximately the same as produced in the discharge. Similarly, since the He \((2^3S)\) metastables have an even longer lifetime, on the order of milliseconds, they should extend well into the test section. The exact lifetimes of the He \((2^1S)\) and \((2^3S)\) metastables were not necessary for this analysis since they were much longer than the flow times for transporting the helium plasma into the test section. According to Brewer and McGregor\(^{18}\), the presence of these metastables explains the existence of the readily observable afterglow. In the system under study here, their presence is necessary for the excitation of the neon atoms which are injected into the expanding jet near the nozzle throat.

The temperature and pressure along the centerline of the jet at various stations in the flow were estimated by assuming that the jet emerged as a freely-expanding flow into a vacuum. For a slit-orifice nozzle system, a Prandtl-Meyer expansion fan is reflected from the line of symmetry as shown in Figure 2b. Hurle, Hertzberg and Buckmaster\(^3\) used the method of characteristics to estimate the performance of such an orifice. Figure 2a shows how the flow properties along the centerline vary in their system. The arc jet
facility used in these experiments had an orifice diameter of 0.25 inch or 6.4 mm. For a stagnation temperature of 5000°K, a distance of one inch or 25.4 mm is covered in about 4 \( \mu \) sec. During this time the isentropic analysis predicted the pressure and temperature to drop to about 0.002 and 0.1 of their respective stagnation values.

Since the pressure in the test chamber was maintained at about 2.5 mm Hg, the method of characteristics gives a stream pressure of 0.25 mm Hg which is too low. Obviously the real gas effects will affect the flow behavior of the actual flow system. Since the test section was maintained near a vacuum, the flow was bounded by a constant pressure stream surface. The interaction of the expansion waves with this constant pressure stream surface will form compression waves which coalesce into a shock wave downstream of the nozzle throat. Observations of the helium plasma indicated that these "Mach diamonds" occurred at about one inch downstream and again at about 1.75 inches. These compression waves effectively increase the stream pressure to a value higher than the test section pressure. The pressure in the expanding jet where the neon is injected should be below 10 mm Hg. Smith and Hansch\(^{19}\) show that if this is not the case the 6328 Å line will be severely pressure broadened and destroy the inversion. The injection of the neon was at 0.15 inch, 0.75 inch, and 1.15 inches downstream and analysis of the data indicated that the effects of pressure broadening were negligible at the temperatures produced.
B. Interpretation of Spectroscopic Data

When the image of the free jet was focused on the entrance slit of the spectrometer as shown in Figure 12, the light entering the slit corresponded to a transverse slice of the plasma about 100 $\mu$ wide. The entrance and exit slit widths were maintained at 200 $\mu$ for most of the tests run. Because of the astigmatic nature of the curved entrance slit of the spectrometer, there is a one-to-one correspondence of points along the slice of the free jet and points on the entrance slit. Thus, the intensity of a spectral line in the free jet is distributed across the slice of the free jet exactly as it is distributed along the entrance slit.

The spectral line intensities which were measured by the spectrometer-photomultiplier apparatus were recorded on either a strip chart recorder or taken directly from an oscilloscope. These measured line intensities in volts output from either the strip chart recorder or the oscilloscope were not absolute intensities since both the photomultiplier and spectrometer do not have a constant frequency response. If the frequency response of both the spectrometer grating and the photomultiplier were constant over the frequency range desired, a simple calibration at any wavelength would have been sufficient to calibrate the system to measure absolute intensity. However, the RCA 1P21 photomultiplier tube and the 1190 groove/mm grating both were designed for use in the same spectral region. The photomultiplier tube response peaked at about 6000 Å and the grating response peaked at
around 5000 Å. Calibration was performed by using a tungsten ribbon filament Standard Lamp whose radiative intensity was known over a wide spectral range (2500 Å to 26000 Å) when run at 35 amperes ± 0.1%. The Standard Lamp was viewed along the identical optical path as that used when observing the free jet and the output of the photomultiplier was recorded at various wavelengths of interest. The frequency response at slit widths equal to 100, 200, 300, and 400 μ was determined in this manner. The variation of slit width varied the amount of light from the Standard Lamp which reached the photomultiplier tube.

A further difficulty in actually measuring the absolute intensity of a spectral line in the free jet slice is that, since observations at any point in the free jet also included contributions from all regions from the centerline out to the boundary as shown in Figure 3, the measured intensity will be larger than if one could look radially in at the jet or at the core of the plasma itself. The free jet was assumed to be cylindrically symmetric, and the radiation reaching the spectrometer was given by the Abel integral whose inversion is known. However, to invert the Abel integral an intensity profile of each spectral line across the free jet slice must be known. This was accomplished by covering varying amounts of the spectrometer entrance slit and recording the spectral line intensity distribution along the slit.

The spectral lines were checked for self-absorption by using a spherical mirror and focusing the radiation back
through the free jet. However, after a preliminary check of the lines, none of them showed much self-absorption so that the plasma was assumed to be optically thin for the duration of the tests.

Assuming negligible self-absorption, the Abel integral equation describing the radiation measured by the spectrometer is given by $^{15,20}$ as

$$J(\gamma) = \frac{I(r) 2r dr}{(r^2 - \gamma^2)^{\frac{3}{2}}}$$

where $I(r)$ is the intensity of radiation emitted by the plasma, assumed to be a function of radius only, and $J(\gamma)$ is the energy detected by the spectrometer where $\gamma$ is the direction normal to the axis of the free jet. The units of $J(\gamma)$ are watts/cm$^2$ and the units of $I(r)$ are watts/cm$^3$ which are the same as those of radiation from the Standard Lamp. When the Abel equation is inverted, the radial intensity is given by

$$I(r) = \frac{1}{\pi} \frac{d J(\gamma)}{d\gamma} \frac{dy}{(\gamma^2 - r^2)^{\frac{3}{2}}}$$

The plasma is imagined to be divided into concentric rings (Figure 3) where the intensity of radiation from any ring is assumed to be constant in that ring. The intensity observed by the spectrometer is then made up of contributions from one or more of these rings.

Robben, Kunkel and Talbot$^{15}$ found that the inverted Abel equation could be integrated numerically by putting
it in the form

\[ I_m = \frac{1}{Nh} \sum_{n=0}^{N} J_n Z_{n,m} \]

where the radius of the plasma has been divided into \( N \) intervals of size \( h \), such that \( x = nh \) and \( r = mh \). \( Z_{n,m} \) is a matrix of coefficients used when trying various curve fits for numerical interpolation. Values of \( Z_{n,m} \) for three curve fits are given by Robben\textsuperscript{15}, et al. for cubic, linear and a Fourier cosine series interpolating functions and are tabulated in Table I for \( m = 0 \). Thus the radial intensity of the plasma can be determined. Pearce\textsuperscript{20} presents shape factors for determining the radial intensity for each concentric ring. For the analysis of this research, Robben's cubic curve fit interpolation coefficients were used.

C. **Calculation of the Electron Temperature**

McGregor and Brewer\textsuperscript{13} have shown experimentally that the excited atoms in a plasma jet tend to be in Boltzmann equilibrium at the electron temperature. Thus a measurement of the electron temperature permits the calculation of the population densities of the various energy levels. The electron temperature was not measured directly but was determined from the measured spectral line intensities. Pearce\textsuperscript{20} and Adcock and Plumtree\textsuperscript{21} use the method of relative line intensities to calculate the electron temperature. This method is applicable in this analysis since the excited He atoms in the free jet tend to be in Boltzmann equilibrium at the electron temperature.
The intensity of light emitted at a particular wavelength from an excited atom is given by

\[ I_{n,m} = h \nu_{n,m} A_{n,m} N_n \]

where \( I_{n,m} \) is the emitted radiation from an electron transition from upper electronic level \( n \) to lower level \( m \), \( h \nu_{n,m} \) is the energy of the emitted photon, \( A_{n,m} \) is the Einstein coefficient for spontaneous emission, and \( N_n \) is the total number density of atoms in level \( n \).

For a Boltzmann distribution, \( N_n \) is given by

\[ N_n = \frac{N_0 g_n}{Z} e^{-E_n/kT} \]

where \( N_0 \) is the total number density of atoms, \( g_n \) is the degeneracy of electronic level \( n \), \( E_n \) is the energy of level \( n \), \( Z \) is the partition function, and \( T \) is the absolute equilibrium temperature of the distribution.

Comparing the intensities of two spectral lines yields

\[ \frac{I_1}{I_2} = \frac{g_1 A_1}{g_2 A_2} \frac{\nu_1}{\nu_2} \exp \left[ \frac{-(E_1 - E_2)/kT}{\nu_2} \right] \]

\[ = \frac{g_1}{g_2} \frac{A_1}{A_2} \frac{\lambda_2}{\lambda_1} \exp \left[ \frac{-(E_1 - E_2)/kT}{\nu_2} \right] \]

Taking the logarithm of the equality and solving for \( T \) yields

\[ T = \frac{(E_1 - E_2) \left( \log e^{\sqrt{k}} \right)}{\log \left( \frac{g_1 A_1 \lambda_2}{g_2 A_2 \lambda_1} \right) - \log \left( \frac{I_1}{I_2} \right)} \]
For increased accuracy, a number of pairs of lines can be used to give an averaged temperature. For each spectral line

\[ I = K g \frac{A}{\lambda} e^{-E/kT} \quad ; \quad K = \frac{hcN_0}{Z} \]

then

\[ \log \left( \frac{I_A}{g_A} \right) - \log K = -\frac{E \log e}{kT} \]

Thus a graph of \( \log \left( \frac{I_A}{g_A} \right) \) versus \( E \) is a straight line of slope

\[ \text{slope} = -\frac{\log e}{kT} \]

Then

\[ T = -\frac{(\log e)/k}{\text{slope}} \]

Figure 4 shows the results of graphically obtaining the electron temperature shown in Figures 7a, 8, and 9 at various points along the plasma jet axis.

D. Calculation of the Free Electron Density

The collisional-radiative recombination model for a decaying plasma\(^{22,23}\) predicts that the upper quantum electronic levels are populated primarily by electron impact. Thus, the upper electronic levels are assumed to be in equilibrium with the free electrons and the Saha equation may be used to calculate their density:
\[
\frac{N_e N_{\text{He}^+}}{N_{\text{He}(n)}} = \frac{g_e g_{\text{He}^+}}{g_{\text{He}(n)}} \left(\frac{2\pi m_e kT_e}{\hbar^3}\right)^{3/2} e^{-\left(\frac{E_I - E_n}{kT_e}\right)}
\]

where \(E_I\) is the ionization energy and \(n\) is the principal quantum number of an upper level state in Saha equilibrium with the electron temperature. Assuming the plasma to be electrically neutral the electron density can be expressed as \(^\text{14}\)

\[
N_e^2 = 3.63 \times 10^{22} T_e^{3/2} \frac{N_\infty}{g_\infty}
\]

where

\[
\frac{N_\infty}{g_\infty} = \frac{N_n}{g_n} \exp \left[ -\frac{(E_I - E_n)/kT_e}{1} \right]
\]

The value of \(N_\infty/g_\infty\) may be obtained graphically by plotting \(N_n/g_n\) versus \(E_n\) and extrapolate to the ordinate \(E_n = E_I\) as shown in Figure 7b. The electron densities measured at various points in the plasma jet are shown in Figure 5. It should be noted that the electron densities were within the limits \(^\text{22,23}\) for assuming an optically thin plasma.

E. Determination of Helium Metastable Populations

The exact He (\(2^1\text{S}\)) and (\(2^3\text{S}\)) metastable populations were not necessary in this analysis since an approximate population was sufficient to show that enough helium metastables existed to justify the assumption that the neon upper levels populated primarily by resonant energy collisions with the helium metastables. The helium metastable populations
were not measured directly but were determined by extrapolating the plots of \( \log N_n/E_n \) versus \( E_n \) to the metastable energy levels. The metastable populations were estimated to be about \( 2 \times 10^{12} \text{ cm}^{-3} \) for the singlets and \( 10^{14} \text{ cm}^{-3} \) for the triplets. These values are probably high since the lower He energy levels tend to be in equilibrium at a lower temperature than the electron temperature; however, these values indicate that about \( 10^{-4} \) of the total He atoms are in the metastable state which agrees with the discussion by Purle and Hertzberg².

F. Calculation of Population Inversions

The population densities of atoms in each electronic energy level are given by the Boltzmann distribution

\[
N_n = \frac{N_0 E_n e^{-E_n/kT}}{Z}
\]

where \( T \) is the equilibrium temperature. However, since the object of this research is to measure population inversions, there will be some electronic energy levels which have populations different than that given by the Boltzmann distribution. The very nature of the expansion flow system is such that the expanding gas lower energy levels will be in equilibrium at the gas temperature; whereas, the upper levels will be effectively "frozen" and in equilibrium at the more slowly varying electron temperature. The injection of neon into the free jet stream containing helium metastables
results in preferential excitation of the Ne (2s) and Ne (3s) levels.

An alternate method was used to determine the population densities. The intensity of emitted radiation is directly proportional to the population of the upper energy level; thus

\[ N_n = \frac{I_{n,m}}{h \nu_{n,m} A_{n,m}} \]

and can be determined for each measured spectral line. One can then compare the population densities for each of the levels to determine if one level is inverted relative to a lower energy level.

The helium plasma was observed at various axial stations downstream of the nozzle exit and spectral line intensities were measured for certain spectral lines which would yield the population densities of the n = 3, 4, 5 energy levels. The results shown in Figures 7a, 8 and 9 indicate that the n = 3 energy levels have lower population densities than given by the Boltzmann distribution. Although the n = 4 He energy levels were not inverted relative to the n = 3 He energy levels as measured by Goldfarb\(^7\), et al., the results do indicate that the n = 3 He energy levels are in equilibrium at a lower temperature which was predicted by the theory. Similar results were measured with helium by Robben, Kunkel and Talbot\(^15\) and Goldfarb\(^7\), et al.

Neon was injected at three axial locations in the helium
plasma and measurements were made of the intensity of the 6328 Å line, the 6096 Å line, and the 3594 Å line. These spectral line intensities yielded population densities of the Ne (3s₂), Ne (2p₄), and Ne (3p₄) energy levels, respectively. The Ne (2p₄) level is the upper energy level for the 6328 Å line and the "super-radiant" 3.39 μ line found by Bloom⁹, et al. The Ne (2p₄) level is the lower energy level for the 6328 Å line and also the lower energy level for the Ne (2s₂ - 2p₄) transition which radiates at 1.15 μ. The Ne (3p₄) level is the lower level for the 3.39 μ line. The 1.15 μ line and the 3.39 μ line intensities were not measured due to the limitations of the spectrometer grating and photomultiplier tube.

The helium and neon atomic energy levels were tabulated by Moore⁲⁴, and tables of allowed transitions are given by Striganov and Svetitskii²⁵. Most transition probability data was tabulated by Wiese, Smith, and Glennon²⁶ and the others were presented by Lilly and Holmes²⁷ and Faust and McFarlane²⁹. The transition probability for the Ne (3594 Å) spectral line was calculated by the method of Adcock¹⁶. From the equation of absolute intensity of radiation emitted at wavelength λ from a gas in Boltzmann equilibrium at a temperature T:

\[ I = \frac{KgA}{\lambda} \frac{1}{e^{E/kT}} \]
A comparison of the intensities of two spectral lines yields

\[
\frac{A_1}{A_2} = \frac{I_1 \lambda_1}{I_2 \lambda_2} \exp \left[ \frac{E_1 - E_2}{kT} \right]
\]

The intensity of the spectral line at 3454 Å was measured and used since it results from a transition very similar to that of the 3594 Å line. The transition probability of the 3454 Å line is given in Wiese, Smith and Glennon\textsuperscript{26}. The transition probabilities used for He are tabulated in Table II and the transition probabilities used for Ne are tabulated in Table III.

The inversion data is best presented in terms of the classical gain coefficient\textsuperscript{28}:

\[
G = \sqrt{\frac{\ln 2}{\pi}} \frac{\epsilon_u A_{u, 1}}{4 \pi} \left( \frac{N_u}{\epsilon_u} - \frac{N_1}{\epsilon_1} \right) \frac{\lambda_o^2}{\Delta \nu_D}
\]

where u and l denote the upper and lower energy levels of the transition which radiates at wavelength \( \lambda_o \) and \( \Delta \nu_D \) is the Doppler width of the line at half-maximum intensity. In general, the natural linewidths and pressure broadened linewidths are negligible compared with the Doppler width \( \Delta \nu_D \). The Doppler linewidth is given by

\[
\Delta \nu_D = 2 \nu_o \sqrt{\frac{2kT}{mc^2 \ln 2}}
\]

Pressure broadening occurs when conditions in a gas are such that the average time between collisions is much
shorter than the natural lifetime of the excited states of the atoms considered. Then each line frequency from an excited atom is assumed to be altered by the presence of another atom at a distance \( r \) by the amount

\[
\Delta \nu_0 (r) = c/r^6
\]

for Van der Waals interaction. At the temperature measured the plasma contains about \( 10^{16} \) atoms/cc which yields a particle separation of 1400 Å. Kuhn\(^2\) states that Van der Waals forces act at sufficiently large distances (\( \approx > 3\) Å). At the calculated particle separation, pressure broadening linewidths should be small compared to the Doppler linewidth of about 3 Å at the same temperature.

The classical gain expression effectively predicts the fractional energy gain per unit distance one would find from passing one photon of light of wavelength \( \lambda_0 \) into the source and measuring the output from the source. Figure 6 shows the results of the gain measurements for the neon 3.39 μ line.
CHAPTER IV
RESULTS

Neon was injected directly into the expanding helium free jet at three stations downstream from the sonic nozzle exit. Spectroscopic measurements of the free jet were made at various stations downstream from the injection station. The helium and neon spectral line profiles were found to be symmetric and were easily inverted to give the true radial spectral line intensity. The measured spectral lines were assumed to be optically thin for the inversion technique used.

The helium population densities which were calculated from the measured spectral line intensities are shown in Figures 7a, b, 8, and 9 for the three downstream viewing stations. The electron temperatures at the three downstream viewing stations were calculated by the method of spectral line intensities. Figure 4 shows the variation of electron temperature along the axis of symmetry downstream of the nozzle exit. The free electron densities were calculated from the Saha equation assuming an electrically neutral plasma. The variation of free electron density along the axis of symmetry downstream of the nozzle exit is shown in Figure 5.

The electron temperature was found to be about 3200°K which is about the same value measured by others\textsuperscript{7, 15, 16}. It was found to be a more slowly varying quantity than the gas temperature as was consistent with the assumptions of the rapid expansion model.
The free electron densities measured were greater than all helium quantum level densities except the ground state. This is consistent with the radiative-recombination model of a decaying plasma\textsuperscript{22,23} and the assumption of Saha equilibrium of the upper excited levels.

The helium population density data did not indicate an inversion as noted by Goldfarb\textsuperscript{7}, \textit{et al.} between the \( n = 3 \) and \( n = 4 \) electronic energy levels, but at the station \( \frac{1}{2} \) inch downstream from the nozzle exit, the \( n = 3 \) level populations were about the same as the \( n = 4 \) level populations (Figure 7a), although not inverted. At the later points observed; i.e. 1 inch and \( 1\frac{1}{2} \) inches downstream, the \( n = 3 \) levels were more in Boltzmann equilibrium with the \( n = 4 \) levels. This can possibly be explained because of compression waves which result from reflection of the expansion waves from the nozzle exit off the constant pressure stream surface forming the outer boundary of the free jet. These compression waves were observed to coalesce into "Mach diamonds" at a point about 1 inch downstream and again about 1 3/4 inches downstream of the nozzle exit. This results in an increase in pressure and temperature at these locations which interferes with the production of population inversions by the free expansion method.

The most likely reason that an inversion was not observed at the point \( \frac{1}{2} \) inch downstream was that the test section pressure was not low enough to allow a sufficiently rapid flow expansion from the nozzle exit. The vacuum pumping system used was able to evacuate the test section to about
0.1 mm Hg; however, during a test the pressure increased to about two mm Hg in about five minutes of constant operation at the flow rates used. The pumping system was unable to maintain a lower pressure during the course of the test. Since the $n = 3$ He energy levels were out of Boltzmann equilibrium and nearly inverted relative to the $n = 4$ He energy levels at the station 1/2 inch downstream, the production of an inversion of the $n = 3$ He energy levels relative to the $n = 4$ He energy levels could be accomplished by utilization of a better vacuum system or operation at lower flow rates. Operation of the plasma arc jet facility at lower He flow rates then 0.07 gram/sec at a reservoir pressure of 930 mm Hg resulted in considerable "flickering" of the free jet and greatly diminished the size of the free jet.

Neon was injected at three stations downstream of the nozzle exit, and the resulting excited gas stream was examined spectroscopically downstream of the injection location to determine where the inversion occurred. Spectral line intensity measurements were made on the 6328 Å line, the 3594 Å line, and the 6096 Å line which yielded the population densities of the Ne $(3s_2)$, Ne $(3p_4)$ and Ne $(2p_4)$ levels, respectively. The population inversions were then measured and the downstream location of population inversions was determined for the Ne $(3s_2 - 3p_4)$ transition at the 3.39 μ line and the Ne $(3s_2 - 2p_4)$ transition at the 6328 Å line.
The results which were obtained for the population densities of the Ne (3s_2) and Ne (2p_4) energy levels indicate that the Ne (3s_2) level is nearly inverted relative to the Ne (2p_4) level, but an inversion did not exist. These results are presented in Figure 10.

The Ne (3s_2) level may have not been inverted with respect to the Ne (2p_4) level because Ne (2p_4) level is also populated by radiative decay from the Ne (2s_2) level at 1.15 \mu. Extrapolation of the log N_p/N_n curves for helium predicted that the ratio of He (2^1S) metastables to He (2^3S) metastables should be about 1:50, and since the cross section for resonant energy transfer between helium metastables and neon is in the ratio of 10:1 for excitation by collisions with He (2^1S) metastables and He (2^3S) metastables, respectively, one would expect the He (2^3S) metastables to produce about five times more Ne (2s_2) atoms than Ne (3s_2) atoms. Then since both levels have about the same lifetimes, estimated from their transition probabilities, the Ne (2p_4) lower level for both the 6328 Å line and the 1.15 \mu line will become populated by both levels at about the same rate. A higher initial population of the Ne (3s_2) level than the Ne (2s_2) would result in the Ne (2p_4) level being inverted with respect to the Ne (2s_2) level but not inverted with respect to the Ne (3s_2) level. If the free jet could be viewed at a station where the radiation for the Ne (3s_2) and Ne (2s_2) levels has not had time to sufficiently populate the lower Ne (2p_4) level, a scan of the 6328 Å line and the 6096 Å line should show an inversion of the Ne (3s_2) level relative to the Ne (2p_4) level.
A scan of the plasma was tried unsuccessfully to determine the location of this point.

The plasma was then viewed to measure the expected inversion of the 3.39 \textmu{} line. This inversion was expected because of Bloom's \textsuperscript{9} observations and because the Ne (3p) levels are populated by decay of the Ne (3s) levels and not by decay of the Ne (2s) levels. The Ne (3s\textsubscript{2}1) upper level of the 3.39 \textmu{} line is also the upper level of the 6328 Å line; thus a measurement of the 6328 Å line intensity yields the population density of the Ne (3s\textsubscript{2}1) level. The population density of the Ne (3p\textsubscript{4}) lower level of the 3.39 \textmu{} line was determined by measuring the intensity of the 3594 Å line which results from the Ne (3p\textsubscript{4} - 1s\textsubscript{2}) transition. The results of this measurement indicate that an inversion of the Ne (3s\textsubscript{2}1) to the Ne (3p\textsubscript{4}) levels exists as shown in Figures 6 and 11. The inversion data was presented as the difference in populations of the Ne (3s\textsubscript{2}1) and Ne (3p\textsubscript{4}) levels since this difference appears in the gain expression. For an inversion the population difference is positive and the gain is also positive. Gain is the important parameter because it must be larger than the reflectance loss of a laser cavity in order to achieve laser oscillation. Comparing with Bloom's gain measurements\textsuperscript{29}, the maximum gain measured was about 2 \times 10\textsuperscript{-3} cm\textsuperscript{-1} and Bloom measured a gain of at least 4 \times 10\textsuperscript{-2} cm\textsuperscript{-1}. This was because Bloom produced larger population densities of the Ne (3s\textsubscript{2}1) level.

The results indicate that the maximum gain occurs when
the injection is as close to the nozzle exit as possible, indicating that perhaps an injection of the neon into the plasma in the nozzle itself might produce higher gains since there are more He \(2^1S\) metastables than in the free jet. The He \(2^1S\) metastables are destroyed by electron collisions as well as by diffusion; whereas the He \(2^3S\) metastables are destroyed primarily by diffusion. The He \(2^3S\) metastables have a longer lifetime and should extend well into the test section in sufficient numbers to collisionally excite the Ne \(2s\) levels. Although the He \(2^1S\) metastables have a lifetime long enough to exist in the test section and collisionally excite the Ne \(3s\) levels, they are probably not in sufficient amounts to compete with the He \(2^3S\) metastables. This results in the Ne \(2p_4\) energy level being inverted with respect to the Ne \(2s_2\) level but not with respect to the Ne \(3s_2\) level as previously discussed. Thus neon injection as close to the arc as possible should produce the best 6328 Å inversion results.

The results of Figure 6 also indicate that the maximum gain lags behind the injection by a few \(\mu\) sec which is understandable because of the collision frequency involved and the radiative decay time.

A further verification of the results would have been possible by measuring the intensity of the 3.39 \(\mu\) line; however, this was not done. Also, a measurement of the 1.15 \(\mu\) line would have shown if the estimation that the Ne \(2s_2\) level was inverted relative to the Ne \(2p_4\) level was correct.
The Ne \((2s^2)\) level population density could not be measured because all transitions from this level were in the infra-red.

The helium and neon reservoir pressures used in the experiments were established primarily by varying them and using the values which gave the best results. In a pre-mixed laser the pressures of the helium and neon can be measured very easily; however, in a plasma arc jet facility the pressures of both gases in the mixing region are not easily measured. The helium reservoir pressure, 890 mm Hg, was used because the free jet was stable and symmetric. Higher pressures of helium required more electrical power to the electrodes which resulted in a cooling problem and resulted in erosion of the electrodes. At lower pressures the arc would tend to attach to the anode and an unsteady free jet resulted.

Neon was injected at 180 mm Hg. This pressure was varied by \(\pm 200\%\) with negligible influence on the results. It was possible that the free jet velocities were so large that the neon did not penetrate to the center of the free jet before it was swept downstream. This would result in only a small fraction of the neon atoms being collisionally excited to the Ne \((3s)\) energy level as was measured. Another factor resulting in only a small fraction of neon atoms excited to the Ne \((3s)\) energy level was due to the small He \((2^{1}S)\) metastable populations existing in the test section.

The results indicate that one can use a fast flow system to produce population inversions by separating the excitations
of the helium and neon. However, the results of this study do not indicate any significant improvement over existing gas lasers because of the small gains measured. It does appear, however, that if the point of neon injection and the gas pressures were optimized, the resulting gain could well exceed that obtained in conventional gas lasers.
CHAPTER V

CONCLUSIONS

Neon was injected into the expanding helium free jet by a symmetric ring manifold at three downstream locations. Measurements of the line intensities yielded the population densities of the Ne \((3s_2)\) and \((3p_4)\) energy levels and the following results were observed:

1. The maximum inversion of the Ne \((3s_2)\) energy level relative to the Ne \((3p_4)\) energy level occurred about one-half inch downstream of the point of neon injection indicating that the laser cavity or interferometer for measuring gain should be used here.

2. The maximum gain produced was less than that of conventional lasers due to the low population densities produced. This indicates that either the point of neon injection should be as close to the arc discharge as possible, or the injection manifold mechanism should be re-designed to get more neon atoms to the center of the free jet.

3. The population densities of the neon energy levels yielding the 6328 Å line were not found to be inverted. Injection closer to the arc discharge should increase the likelihood of an inversion of this line since more He \((2^1S)\) metastables will exist there; the He \((2^3S)\) density, being relatively constant for the flow speeds produced, should not increase the population of the Ne \((2s_2)\) level significantly at this closer injection station.
The variation of reservoir pressure of the helium and neon did not show much effect largely due to the fact that the plasma jet wind tunnel used operated best in a particular pressure range, and the neon pressure did not result in large population densities because there were not enough He \((2^1S)\) metastables in the flow in the regions investigated at the helium flow rate used. More He \((2^1S)\) metastables would exist in the test section if the reservoir helium pressure were increased significantly. This requires an increase in arc power and an increase in cooling capability.

The method of free expansion to produce population inversions was tried unsuccessfully in the case of helium. The results indicate that, although an actual inversion was not produced, the \(n = 3\) levels were definitely not in Boltzmann equilibrium with the upper levels at the electron temperature and if the system could be modified to produce a faster expansion, it would be possible to produce the desired inversion. By this method an inversion could be produced in a single component gas or an improvement in the gain of the helium-neon system could be achieved.

The results indicate that the technique of using a fast flow system to separate the excitation of the helium and neon can be used to produce population inversions; however, further studies are required in order to achieve a better understanding of some of the problem areas mentioned. By successfully defining and optimizing the major parameters, it should be possible to exceed the production of population inversions of conventional gas lasers.
REFERENCES


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* Author's calculation
** Calculated by author from given line strength
FIGURE 1
Helium-Neon Energy Levels
Non-Dimensional Flow Properties Along Axis of Symmetry

FIGURE 2a

Expansion Flow Through a Sonic Nozzle

FIGURE 2b
FIGURE 3

Diagram of Portion of Cylindrically Symmetric Plasma as Viewed by Spectrometer
FIGURE 4

Variation of Electron Temperature
Along Nozzle Centerline
FIGURE 6

Gain of 3.39 \( \mu \) Line for Various Injection Points of Neon
FIGURE 7a

He Line Intensities at 0.5 Inches Downstream
FIGURE 7b

Determination of $\log \frac{N_\infty}{\bar{n}_\infty}$ at 0.5 inch Downstream
He Line Intensities at 1.0 Inches Downstream
FIGURE 9

He Line Intensities at 1.5 Inches Downstream
FIGURE 10

Variation of Ne \( \frac{^3S_2}{^2P_4} \) Density Ratio With Axial Coordinate for Injection at 1/8" Downstream
FIGURE 11

Variation of Ne \( \left( \frac{N_{3S_2}}{E_{3S_2}} - \frac{N_{3P_4}}{E_{3P_4}} \right) \) Densities

With Neon Injection
FIGURE 12

Schematic of Plasma Jet Wind Tunnel and Auxiliary Equipment
FIGURE 13
Nozzle Assembly and Neon Injection Manifold
FIGURE 14
Plasma Arc Jet Facility and Spectrometer

FIGURE 15
Plasma Arc Jet Facility with Control Consoles in Background
FIGURE 16

View of the Plasma Dynamics Laboratory

FIGURE 17

Nozzle Assemble with Neon Injection Manifold